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Measurement analysis and performance evaluation of mobile broadband cellular networks in a populated city

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Data rate

Abstract Enhanced mobile broadband is an essential target in fifth-generation (5G) networks with higher demands among service consumers. It offers very high-speed Internet connections for several geographical areas: urban, suburban, and rural. Many mobile network operators (MNOs) continuously monitor the quality of service in terms of multiple services to guarantee high network performance. To the best of our knowledge, no extensive studies and analyses are conducted on mobile broadband (MBB) services that cover various implementation scenarios and several performance metrics. This study comprehensively analyzes the existing MBB performance in an urban area: Cyberjaya City, Malaysia. The measurement data were collected through drive tests from various MNOs supporting 3G and 4G technologies: Maxis, Celcom, Digi, U Mobile, and Unifi. Several performance metrics, such as signal quality, throughput (downlink and uplink), ping, and handover, were measured during the drive tests. The data measurements were conducted in two scenarios: outdoor and indoor environments. Measurement results of the outdoor drive test demonstrate that the maximum average throughput with downlink and uplink data rates is 14.3 and 7.1 Mbps, respectively, whereas the minimum average ping and loss are 36.5 ms and 0.14, respectively, for all MNOs. However, the in-building measurements achieve an acceptable overall average data rate of 2 Mbps. This paper provides several suggestions and recommendations for MBB providers to improve their performance networks and quality of experience to meet customers'

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satisfaction. Several limitations not considered in this study and can point to possible future work are presented.

1. Introduction

Mobile broadband (MBB) networks are growing extremely fast with the support of high-speed Internet access. The demand for data is rapidly increasing due to a massive number of users accessing data through several cellular technologies and various Internet services. Thus, monitoring network performance is extremely important to improve the quality of service (QoS). With an increasing load on existing networks and an increasing user base taking Internet connection for granted, performance and quality measurement become essential for all concerned stakeholders. Therefore, next-generation networks provide enhanced MBB, which supports high-speed data, video streaming with low latency, and seamless mobility. Several factors, such as a variety of user devices, physical impairments, mobility, and accessibility configuration, affect the real measurement of MBB performance [1]. The measurement experiment is conducted on end-users with the support application to collect various network data to verify the QoS and quality of experience (QoE). QoS measures key network performance metrics (signal quality, throughput, ping, available bandwidth, packet loss, jitter, and delay). QoE focuses on actual individual user experience factors beyond the service (content, user, context, and system factors). In [2], the authors highlighted the importance of QoE in cellular networks with various radio access technologies (4G, 5G, and beyond), where they provide the literature on the most developed measurement methods in QoE. The QoE is further investigated by using different metrics and models for web QoE estimation [3]. The Web QoE helps mobile network operators (MNOs) understand their end-user's usage service pattern, perceive quality, and point toward areas to be improved. In [4,5], the authors investigated the QoS and QoE by conducting an experimental study of the current MBB supporting 3G and 4G networks in Malaysia. The data are collected through a drive test by running a specific application installed on smartphone handsets from several rural regions. The measurement data of three MNOs are associated with several performance indicators, such as coverage, latency, satisfaction, and speed for two MBB services: web browsing and video streaming. The measurement data presented in [6] are used to analyze several key performance indicators (KPIs), such as signal quality and download throughput of an operational 4G long-term evolution (LTE) network. The data measurements are conducted by drive test at a relative speed of up to 30 km/h. The KPI results are analyzed based on probability distribution functions and statistical models. However, these data measurements are insufficient to evaluate the performance of MNOs that consider different technologies and operators. Aceto G. et al. [7] analyzed and estimated the available bandwidth and measured the Transmission Control Protocol (TCP) achievable throughput of different MNOs in Europe for 3G and 4G technologies. The intrusiveness and time cost are two performance metrics used for analyzing the MNO. The experimental results show that the achieved throughput leads to different profiles in terms of time evolution. This condition affects the accuracy of available bandwidth estimation due to similar differences between estimated bandwidth and throughput for small measurement intervals. In [8], the authors presented a data collection survey to analyze the signal strength and throughput at public transit bus trips at three different times of the day. In [9], two MNOs were investigated to analyze their actual mobile service providers in terms of latency. This study examined whether the existing network infrastructure is suitable for the implementation of vehicle-to-vehicle and vehicle-to-infrastructure to enable vehicular applications. Arshad et al. [10] conducted a study to benchmark and analyzed the QoE of five MNOs in Pakistan. The network performance is measured using various metrics over 3G and 4G mobile networks. In [11], the authors performed 4G data measurements across different mobility scenarios: static, pedestrian, car, bus, and train. This work focused on the throughput performance metric for two major Irish MNOs. Table 1 summarizes several studies that focus on investigating mobile network performance in different countries. These studies are basic and only limited to a few KPIs and measurement scenarios. Thus, this study provides the customers with a good insight into subscribing to the best MNO. Customers can choose the MNO based on network coverage and data rate. The currently deployed networks are mostly 4G and 3G networks in the tested area. In this context, this study aims to measure and study the performance of the current 3G and 4G mobile networks to pinpoint the lack of the current networks in the tested area. This will be helpful for operators to understand these limitations in order to consider them in the planning strategy of 5G networks. It will also be helpful for researchers to understand the main challenges facing the implementation of mobile networks in various areas based on different KPI. We have tried to offer a large set of measurements in order to provide a more comprehensive study that can consider more KPI and investigate the performance of the various networks from different perspectives.

The readers who are more interested in such studies from the operators' side or researchers from the academic side will better understand the users' experiences and related issues of the current networks from different operators and will try to contribute to solving these issues more efficiently. In addition, it enables all experts in this field from academic and industry sides to contribute and provide suggestions and solutions for the highlighted challenges. Consequently, the comprehensive and detailed performance evaluation that we have done of different mobile network operators is providing a significant scientific outcome to the academic and industrial sides.

1.1. Key contributions

This study investigates and evaluates the performance of recent MNOs in Cyberjaya City, Malaysia, for user plane

Table 1 Summary of comparison between several studies.

Ref/year	Country	Scope		Environment		Signal quality			Throughput		Latency		Handover	Free-device
		urban	rural	outdoor	indoor	RSRP	RSRQ	SNR	DL	UL	Ping	Loss		
Aceto et al. [7], 2018	Europe	√		√		√			√		√			
Shayea et Al. [4], 2020	Malaysia		√	√		√			√		√			√
Imoize et al. [6], 2020	Nigeria	√		√		√	√	√	√					
Shayea et al. [5], 2017	Malaysia	√			√	√								√
Elsherbiny et al. [8], 2020	Canada	√		√		√			√					√
De Andrade et al. [9], 2016	Brazil	√		√							√			√
Arshad et al. [10], 2016	Pakistan	√		√		√			√	√	√	√		√
Raca et al. [11], 2018	Ireland	√		√					√					√
Aljahdhami et al. [12]	Oman		√	√		√	√		√	√	√			√
This work	Malaysia	√		√	√	√	√	√	√	√	√	√	√	√

and control plane. Cyberjaya City is known as an "intelligent city" where it is equipped with high-technology infrastructure, facilities, and amenities. Thus, it should support high Internet access with high speed of MBBs. This work is a comprehensive experimental study that evaluates and analyzes the performance of existing biggest main MNOs from different perspectives. This study is useful for those working on industry and academic sides to get more understanding of the users' experiences and related issues of the current networks. The key contributions of this paper are summarized as follows:

1. We provide an overview of the spectrum bands for each technology assigned to existing MNOs in Malaysia, where the regulator allocates each operator a licensed frequency band. We clarify the spectrum gap that causes the MNOs to acquire new spectrums or refarming the existing ones due to tremendous growth in MBB services and applications.
2. We conduct a field data measurement of all existing MNOs in a dense urban city. The data measurements are collected in two different environments between February and April 2021 at off-peak and peak hours.
3. We evaluate and analyze the existing network performance by using several performance metrics, such as signal quality: (reference signal received power [RSRP], reference signal received quality [RSRQ], signal-to-noise ratio [SNR]), throughput (downlink [DL] and uplink [UL]), ping and loss, and handover.
4. We provide several suggestions and recommendations for MBB providers to improve their performance networks and QoE to meet customers' satisfaction.
5. Several limitations of this study that point to possible future work are presented. Guidelines and an excellent platform are provided for researchers in their study on MBB evaluation. This work benefits the MNOs to improve their performance networks in a particular tested area.

1.2. Paper organization

The rest of this paper is organized as follows: Section 2 provides a background on the spectrum bands assigned to MNOs in Malaysia. Section 3 describes the methodology of the data measurements in terms of geographical area, drive test tools, and MNOs. Section 4 explains the performance metrics used for network performance evaluation. Section 5 discusses the experimental results and performance evaluation. Section 6 highlights the research finding and future directions. Section 7 concludes the paper. The structure of this paper is shown in Fig. 1.

2. Background on Malaysia MNO

This section presents the background on the spectrum bands assigned to Malaysia MNOs. The network performance of MNOs and the optimization process are discussed.

2.1. Spectrum bands

MBB subscriptions in Malaysia increase yearly, with 17.6 million and 38.8 million subscriptions recorded in 2014 and 2019, respectively. The population coverage of MBB service is 94.7 % and 79.7 % for 3G and 4G technologies, respectively, at the end of 2018 [13]. Five national MNOs: Maxis, Celcom, Digi, U-mobile, and Unifi (known as "Webe," which is a subsidiary of Telekom Malaysia) are providing MBB services in Malaysia. Each operator is allocated a licensed frequency band by the regulator known as the Malaysian communications and multimedia commission (MCMC), a Malaysian agency regulating the communications and multimedia industries. Fig. 2 shows the number of spectrum holdings by MNOs. Six spectrum bands, namely 850, 900, 1800, 2100, 2300, and 2600 MHz bands, are assigned or allowed to be used by oper-

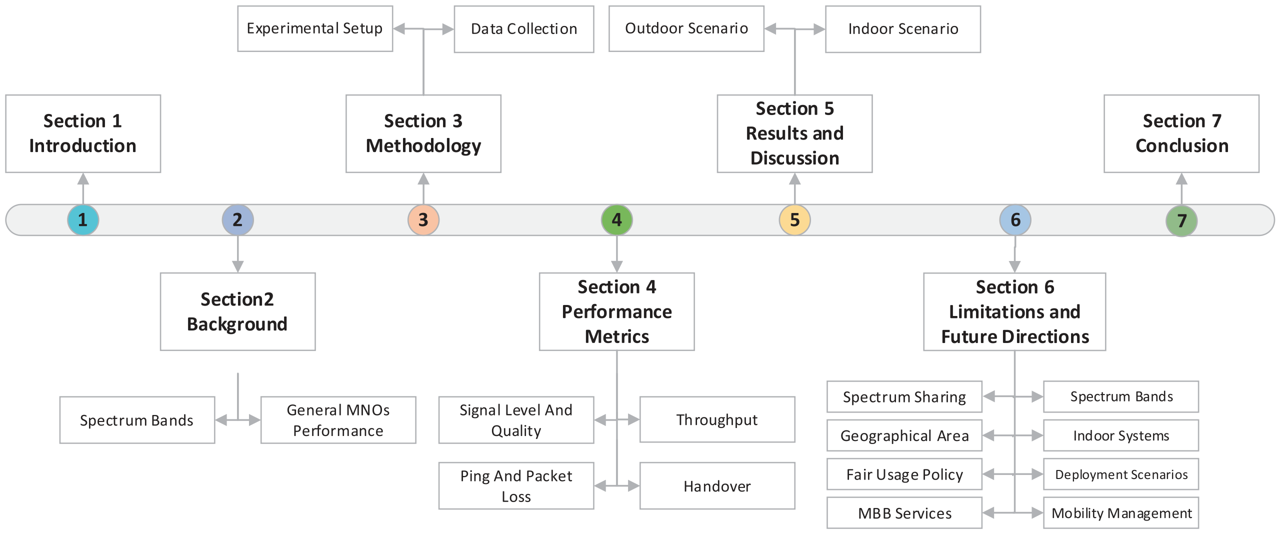


Fig. 1 Diagrammatic view of this paper.

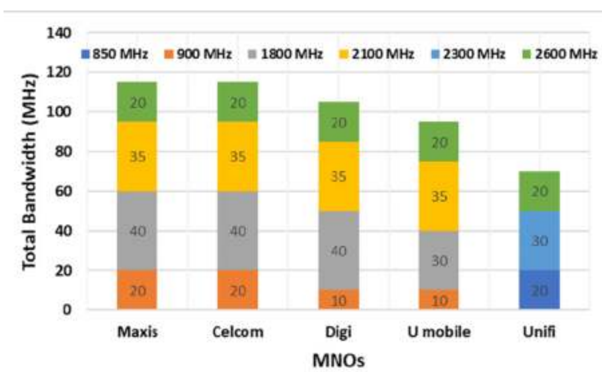


Fig. 2 Allocated spectrum bands for all national MNOs.

ators to provide MBB service [13]. In [14], MCMC presented spectrum policies to enable mobile broadband goals in Malaysia. These spectrum policies highlight various experiences and approaches related to Malaysia's market conditions and connectivity goals.

All MNOs hold approximately 74 % of the spectrum available for MBB service. However, three MNOs (Maxis, Digi, and Celcom) have deployed 2G, 3G, and 4G/LTE technologies and covered at least 85 % of the population with MBB services. Celcom provides Unifi with domestic roaming on 3G and 2G [15]. The tremendous growth in MBB services and applications, such as the Internet, video streaming, and gaming, has contributed to a great rise in the spectrum demand. However, most spectrum bands are allocated, and the residual bands are extremely expensive and limited. Consequently, the MNOs are forced to choose between two costly options: acquiring a new spectrum or refarming the used spectrum.

In [16], the authors developed a forecast model to predict the expected needed spectrum and determine the spectrum gap in the future. This study was conducted in 2018, aiming to predict and calculate the spectrum needs for available MNOs (Maxis, Digi, Celcom and U mobile) in Malaysia, 2020. The spectrum bands for the four MNOs were 430 MHz in 2015, and the study forecast spectrum bands in 2020. Several metrics were considered for developing the forecast model: growth of data traffic, spectrum efficiency and site number, currently available spectrums, and average network utilization. The results show that Malaysia requires an additional spectrum of around 307 MHz to accommodate the tremendous rise in the increase in mobile data demands. Thus, the crucial need for the spectrum gap becomes a significant problem that needs to be resolved to meet the expected data requirements. However, this study did not include MNOs such as Webe and YTLC, where both operators occupied a spectrum band with a total of 120 MHz. Moreover, operators such as REDtone, Altel and AsiaSpace do not provide MBB service to end-users with a total spectrum band of 90 MHz [14]. In terms of 5G spectrum bands, MCMC offers 100 MHz of the 3.5 GHz band and 2x30 MHz of the700 MHz band for the first stage [13]. Therefore, the total current of MBB spectrum bands is 710 MHz, including 5G spectrum bands. A good spectrum allocation strategy can enhance mobile coverage and quality and develop affordable digital innovation to maximize socioeconomic benefits.

2.2. Optimization process

The MNOs are required to monitor their networks continuously to improve or maintain performance and provide better QoS to the customers. Various improvements can be conducted in terms of network coverage, capacity, and service quality. These improvement elements are important to keep QoS consistent and deliver an optimal QoE to the customers. The MNOs consider capital expenditures and operating expenses during the optimization process.

Call trace and drive test data are data measurements that help MNOs monitor their network performance over a specific period of time and solve the network problems affecting the QoS. Consequently, this process minimally affects the customers' satisfaction levels and the MNO's business. The optimization process can be summarized in three sets of activities, as shown in Fig. 3.

- *Drive test*: it is the common measurement tool utilized by MNOs to evaluate and improve their network performance in terms of coverage, capacity, and QoS after upgrading and reconfiguring the network. This test is used in the planning stage of network development. Drive tests can be classified into several types: optimization and troubleshooting, network benchmarking, and service quality monitoring. The drive test is usually conducted with the assistance of a motor vehicle equipped with a measurement tool that can record and detect various parameters of serving MNO in a given geographical area. The collected data are stored in log files and then analyzed using post-processing tools.
- *Data analysis* is the second optimization process used to determine if problems or performance degradation that make the network perform poorly are found. In this process, large amounts of drive test data analysis are conducted in terms of received signal quality, throughput, network coverage, latency, and handover. The analyzed data help to improve the customer experience through troubleshooting, new technology roll-out, and efficient network optimization. Data analysis is used to prepare reports and make suggestions and recommendations to MNOs for further improvements.
- *Action Step:* it is the last optimization process used to refine network performance and provide a better user experience in terms of addition or deletion of neighbor cells, redesigning of radio planning, parameter optimization on cell towers (i.e., adjusting antenna azimuth, tilt, type, and tuning handover margin), and reducing the power levels of sectors to avoid cell overshooting. Consequently, properly tuning these network optimization measures leads to improved data rate, coverage and reduced call drops and handover failure.

3. Methodology and experimental design

This section presents the test methodology of the measurement campaign to evaluate the existing MNOs with several performance metrics relevant to user experience. The data collection was conducted on a commercial Android application developed by Gyokov Solutions called "G-NetTrack" installed in OPPO F1s handset [17]. Several applications were initially tested in terms of performance metrics, logfile recording, testing continuity, and steadability. After careful comparison and investigation, G-NetTrack was selected for the data measurements for the following reasons.

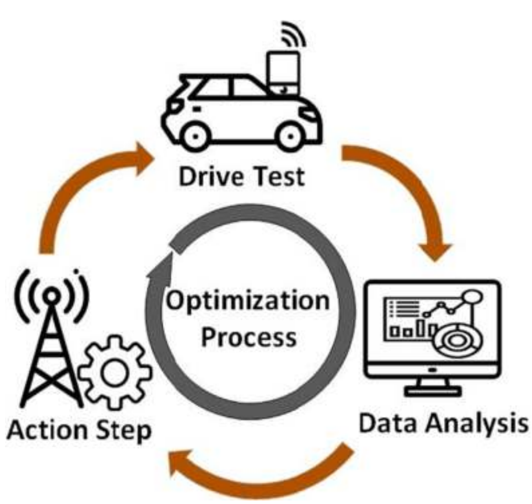


Fig. 3 Optimization process of mobile network performance.

- G-NetTrack allows customizing test sets close to the consumer experience of MBB access. These datasets are then tested locally in the test device.
- The application does not require any modification of the handsets.
- The application is set to run the test in the testing cycle continuously. This condition makes the testing process more practical and convenient because minimal interaction is required between the tester and the phones.
- It allows monitoring and logging of mobile network parameters without using specialized equipment.
- This app uses Android functions and classes where it collects the data on the basis of user device specifications. Thus, the collected data are considered accurate, showing their reliability similar to the phone.
- It records and stores data correctly without countering any problem of generated gaps or blank plots along the route. It also supports dual measurements of a mobile network at the same time.
- It has been evaluated and used in many studies across different countries stated in [8–11,18–20]. This condition makes this app more accurate, reliable, and suitable for an actual drive test.

Consequently, the G-NetTrack app was selected for data measurements. The accuracy of data measurements in Android applications depends on mobile devices, which the application displays whatever mobile devices report. Besides, the application depends on various commands provided by android developers in Android Open Source Project to record several KPIs [21]. These KPIs are determined based on the 3rd generation partnership project (3GPP) with technical specifications: TS 27.007 [22], TS 36.214 [23] and TS 36.331 [24]. Thus, this is as reliable as the mobile phone is. G-NetTrack also supports indoor and outdoor scenarios and provides a wide range of features, such as map visualization, cell scanning loading cells, and cell measurement for serving and neighbor cells.

The data measurements are performed in Cyberjaya City, also known as an intelligent city. It is located in Selangor, Malaysia, with coordinates of 2.9213°N, and 101.6559°E, and its population is approximately 102,000. This city is chosen to evaluate the performance of the Internet access of MBBs because it is an intelligent city equipped with high-technology infrastructure, facilities, and amenities. Thus, the MNOs should support high Internet speed with extensive mobile service coverage. In this regard, the MBB performance of five MBOs (Celcom, Maxis, Digi, U mobile, Unifi) is investigated and evaluated.

This research aims to analyze and understand the Malaysian MBB but does not benchmark the performance of MNOs. Thus, the existing five MNOs are labeled as A, B, C, D, and E in the discussed and demonstrated results for the sake of protecting the identity of the MNOs. Prepaid subscriber identification module cards were used for each MNO with the same data package to ensure apple-to-apple comparison. Fig. 4 displays the general methodology of data measurements and analysis. The mobile device collects the data from the MNO towers and then stores it on the device's memory or sends them to data that can be used for analysis after completing the data campaign.

Fig. 5 displays the experimental testbed (measurement area), where the data measurements were taken on the white route. It shows the starting and ending points, where the red arrow indicates the direction of the drive test. In this regard, we planned to minimize repeated data measurement at the same route, where only two routes (heightened in yellow color) represent the repeated measurement. Thus, predefining the tested routes is extremely important to avoid or minimize repeated data.

Fig. 6 shows the flowchart of the general data measurement. The drive test starts by setting up several parameters of data sequences, such as ping upload time and URL link, data rate time (down/upload), and tested files of 1 GB in size. Once these parameters are set, the drive test starts logging the data measurement from the starting point and stops at the ending points. The sequences of data measurements during the drive test are shown in Fig. 7. The ping sequences and data rates are demonstrated, where the ping starts first, followed by data rates. The signal level and quality are measured continuously during the drive test. Several events, such as cell reselection and handover, are recorded during the data measurements. All the above data measurements are associated with the timestamp and global positioning system (GPS) coordinates (longitude and latitude). Table 2 displays several measurement parameters that are stored in a log file.

Fig. 4 General methodology of data collection and analysis.

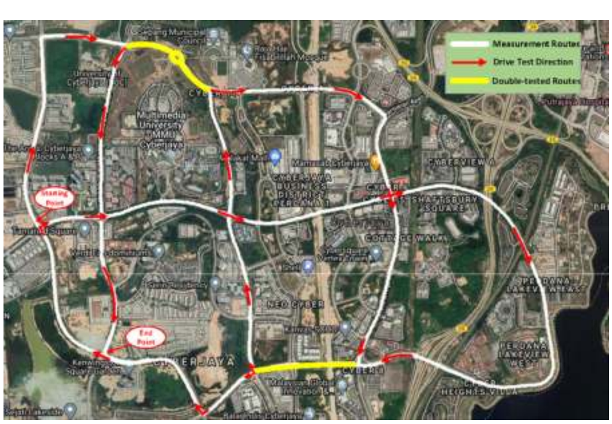


Fig. 5 Tracking route of the measurement area.

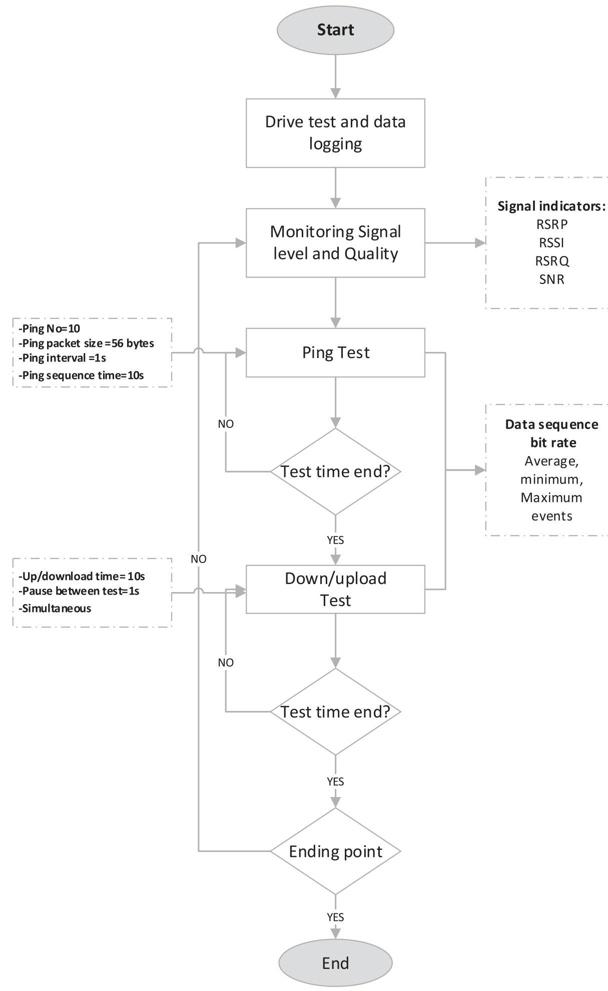


Fig. 6 Flowchart of measurement methodology.

4. Performance metrics

In this work, several performance metrics are used to analyze the performance of MNOs. These metrics are mostly related to QoS and user experiences, which are explained as follows:

Signal strength level: signal strength levels of 3G and 4G networks are considered in our data measurements. In a 3G network, the measurement of received signal code power (RSCP) level denotes the power level measured by the end-user on a particular physical communication channel. In a 4G network, RSRP indicates the average received power from a single reference signal (special signal depends on *PCI - Physical Cell ID* value) over a specified bandwidth.

Signal Quality level: RSRQ is used to measure the quality of radio channel LTE networks. In some cases, it is extremely useful for handover decisions when the RSRP information is insufficient. RSRQ is given as $(N \times RSRP)/RSSI$, where N denotes the number of resource blocks. EcNo is a term used in a 3G network and indicates the ratio between the received energy per chip (Ec) of the pilot signal to the noise density

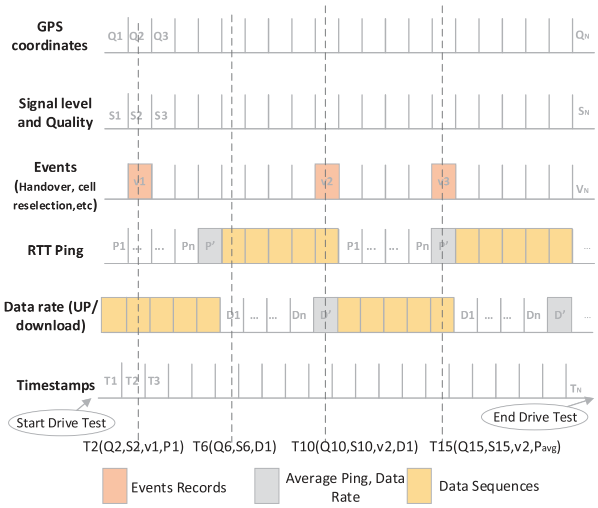


Fig. 7 Mapping of data measurements.

Table 2 Measurement parameters stored in a log file.

Parameter	Description
CGI	cell global identity of a serving cell
LAC	LAC of serving cell
Node	RNCID on 3G, eNodeBID on 4G
Cellname	name of serving cell – from cellfile
CellID	CELLID of serving cell
NetworkTech	current technology – 2G, 3G, 4G
NetworkMode	current network mode
Accuracy	GPS/network accuracy of location
Height	height over ground level
Serving time	serving cell serving time in seconds
Bearing	serving bearing
Distance	distance from serving cell

(No). It is determined by dividing RSCP with RSSI, EcNo = RSCP/ RSSI.

SNR: The SNR value in (dB) indicates the network quality that measures a serving cell signal-to-noise ratio. Theoretically, a lower value introduces Gaussian noise and causes random noise and data corruption, whereas a higher SNR value indicates that the signal is excellent and clear. When the SNR value falls below one, the signal becomes unusable, thereby degrading wireless throughput and latency. By contrast, the wireless throughput increases when the SNR value rises. Thus, the SNR metric is widely used by MNOs and industries that quantify the relationship between radio link condition and throughput. It is internally captured by most mobile devices and experimentally measured by drive test tools which carry a value between (-20 to 30) dB. The drive test application records the SNR value directly reported from the mobile device. In this work, interference is not considered since the drive test application does not support it.

Network Latency/Ping: ping test measures the latency when an end-user sends a fixed number of TCP pings to the server and the time taken to receive the response at a user device in milliseconds (ms). MCMC introduced guidelines for determining the mandatory standards for QoS (wireless Broadband access service) [25]. These guidelines set out the testing procedures for network performance in terms of wireless network latency, packet loss and throughput. Network latency can be classified into one-way delay and round-trip time (RTT). The former measures the packet delay sent from the source (user) to the destination (application server). The latter measures the delay of the packets sent from the source to the destination and back to the source. The mobile device sends ten ping packets to accurately detect the network status based on the number of ping packets successfully returned to the mobile device.

The RTT latency is estimated in terms of ping and is represented by end-to-end (E2E) latency. Fig. 8 visualizes the two types of latency. HTTP test (e.g., https://www.google.com) is performed to measure the ping of RTTs several times and calculate the average, minimum, maximum, and standard deviation values for each ping test. The E2E latency must be lower than 200 and 100 ms for 3G and 4G networks to ensure a good user experience.

Throughput/data rates: It is evaluated as a function of bandwidth and SNR based on Shannon's law. Also, it is evaluated as a function of system spectral efficiency (Mbps/Hz) and system bandwidth. A network's "performance" in the context of wireless communication can still be evaluated based on data rate for different reasons. The data rate can show the performance of two different technologies and different operators in that specific tested area. An individual user's data rate also depends on network loading, which means an MNO with a higher data rate than others could be due to greater bandwidth and/or less loaded network. Even though this will not change the fact that each operator considers the number of users in that area and should provide enough bandwidth for that area. Thus, the data rate is sufficient to determine or evaluate the network performance. The system data rate can be evaluated for a cell, or even it can be for one connected user individually. Many works in wireless communication systems have used data rate as one of the main KPIs, such as works in [26,27] and also the measurement studies as stated in Table 1. Moreover, most drive test applications do not measure spectral efficiency. In [4,28], the authors used data rate as the main KPI recommended by HUAWEI for evaluating network performance. Besides, MCMC and other industries released many technical reports, such as [29,30], which only considered data rate rather than spectral efficiency. In this work, the DL and UL throughputs are measured simultaneously. An audio file is selected to test the download and upload at a particular time. Data rates are used to measure the rate of transferred data from the Internet to the end-user. The data rates obtain several values for DL/UL, such as minimum, maximum, average, and standard deviation. These values are used to monitor the throughput of serving network performance.

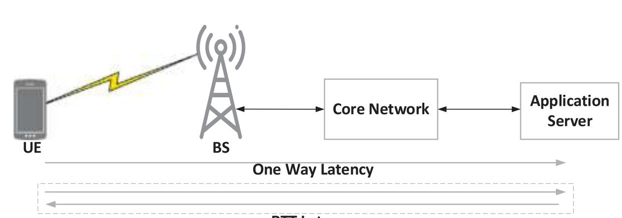


Fig. 8 Latency visualization.

Handover: handover plays an important role in mobile network performance due to the limited coverage area of base stations. It refers to a process of transferring data or calls when a mobile device moves from a serving base station toward another. Fig. 9 demonstrates an example of the handover process between 3G and 4G networks. Handovers can be classified into two types: horizontal and vertical. The former occurs when a user moves within the same network technology (e.g., sector-to-sector, cell-to-cell in 2G, 3G or 4G). The latter occurs when a user switches between different technologies or operators (e.g., 2G to 3G, 4G to 3G, and vice versa). Domestic roaming is a type of variceal handover, which is an agreement between two MNOs to provide a subscriber with the ability to connect to another network when a subscriber's network is unavailable. Therefore, counting the handover events is extremely important to visualize and analyze the network performance.

5. Performance evolution

The evolution of existing MBBs is paramount to ensuring that the network provides a high-quality user experience. This experimental research was conducted to analyze the actual performance of five national MNOs in Cyberjaya City. Two scenarios were used for the data collection: outdoor and indoor environments for each MNO separately. All the measurements were conducted at the same time, operating system, and test sequences for a fair comparison. The measurement results were analyzed over all data collections (one measurement each month) and demonstrated and discussed for each KPI, as illustrated in the following subsections.

5.1. Outdoor scenario

The measurements were collected at two different times of the day: early morning at 7–8 am (off-peak time) and afternoon at 2–4 pm (peak time) during daytime for all MNOs. In the peak period, most subscribers are likely to be online and demand more resources, whereas the data rate demand is low in the off-peak period. For all outdoor scenarios, the car speed is limited to 70 km/h. Figs. 10 and 11 illustrate the car speeds during the drive test. It can be observed that the car's speed is maintained below 70 km/h and sometimes reaches 0 km/h at traffic lights.

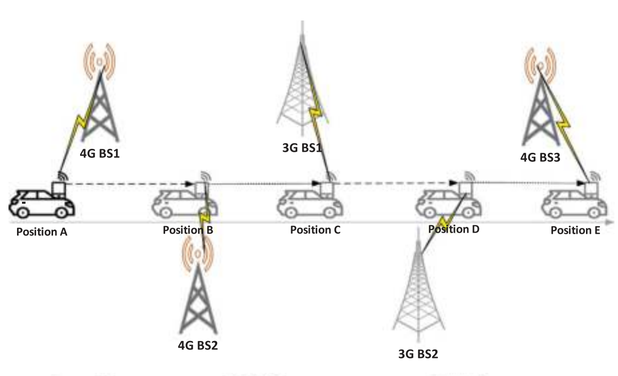


Fig. 9 Example of a handover process.

Fig. 12 visualizes measured KPIs (RSRP, RSRQ, SNR, throughput, and ping) of one mobile operator. The route colors represent the measured values of each KPI. Each KPI has been discussed in the following subsections.

5.1.1. Signal level and quality

Fig. 13 illustrates the average RSRP for the MNOs in off-peak and peak times. The signal level varies between −88 and −96 dBm for all MNOs. The signal level at the off-peak time is better than at the peak time due to much noise. All the MNOs cover the test area with 4G networks, except for operator E, where some routes are covered with 3G networks.

Fig. 14 displays the average RSRQ of off-peak and peak hours. Here, a number of resource blocks with measured RSRP and RSSI is used over the same bandwidth for each MNO. The RSRQ value helps the base station decide whether to perform cell reselection or intra-inter handover. The RSRO level varies between −9 and −14 dB for all MNOs, where the RSRQ experiences a low level at the peak time scenario. RSRQ and SNR are the key metrics for LTE systems and are usually used by MNOs to determine the relationship between radio link conditions and throughput.

Fig. 15 shows the SNR ratio at off-peak and peak hours for all MNOs. The average SNR levels vary between 7 and 9 dB and between 4 and 8 dB at off-peak and peak hours, respectively, for all MNOs. The results indicate that each MNO's SNR level is approximately 3 dB at off-peak and peak hours. For example, the SNR level achieved by operator A is 9.63 and 6.82 dB at off-peak and peak hours, respectively. The low level in SNR ratios due to high noise floor depends on numerous factors, including sound and radio wave density, temperature, and humidity. The noise floor is defined as a cumulative effect on communications signals of all unwanted noise sources signals within a system where it is measured by the total noise power. The noise floor rises in a small area containing various noise sources, such as cellular phones and computers. Thus, all the operators should improve the SNR ratio by reducing the noise floor and improving the signal power.

Tables 3 and 4 display a summary of the average signal qualities of MNOs during the off-peak hour and peak hours, respectively. The highest average values of RSRP, RSRQ, and SNR recorded at off-peak hours are −88.10 dBm, −10.06 dB, and 9.63 dB, respectively.

5.1.2. Data rate (throughput)

Data rate testing is used to evaluate the performance of the Internet speed for a wireless network, known as connection

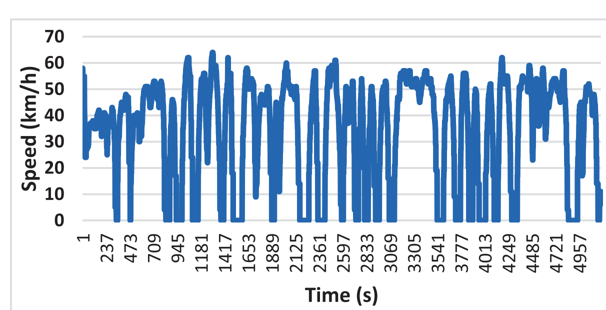


Fig. 10 Car speed versus time.

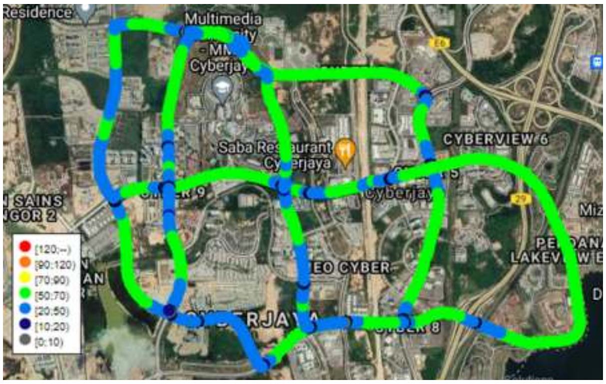


Fig. 11 Tracking visualization of car speed.

speed, data transfer rate, and throughput. Fig. 16 displays the data rate: DL and UL for all MNOs. The data rate was combined of 3G and 4G networks, where most of the data is 4G because the mobile device is mostly connected to 4G networks. Thus, the tested area mostly coverage with the 4G networks. However, there was a limited 3G connection in a particular area. During off-peak hours, the maximum and minimum average data rates in DL obtained by operators B and E are approximately 14.2 and 2.4 Mbps, respectively. Similarly, operators B and E achieve the maximum and minimum average data rates in UL of approximately 7.1 and 1.6 Mbps, respectively. In peak hour scenarios, the maximum and minimum average data rates in DL obtained by operators A and E are approximately 8.6 and 1.3 Mbps, respectively. It notices that operator E achieves the lowest data rate for DL and UL. Operator B obtains the highest data rate in DL during off-peak hours and UL during peak hours.

These demonstrated results of each operator depend on several factors, such as bandwidth capacity, number of sites, and number of active subscribers. These factors significantly affect the data rate and consequently degrade the network performance. The displayed data rate for all MNOs in Cyberjaya (as an intelligent city) is insufficient to deliver a high-speed transmission for accommodating various services and applications. To solve this problem, MNOs are required to upgrade their network to be up to 4G + and increase the number of sites or implement 5G networks.

5.1.3. Latency (ping, packet loss)

Ping measures the reaction time of speed connection and is recorded as ping count, where a lower ping rate is better than a higher rate. In practice, the RTT of many deployed 4G networks ranges from 30 ms to 100 ms. Fig. 17 illustrates the average ping achieved by MNOs for off-peak and peak hours. The results reveal that all the MNOs achieve an average ping lower than 100 ms, except for operator E, whose average ping exceeds 200 ms. Higher ping leads to users' dissatisfaction with streaming and online games. Fig. 18 demonstrates the average packet loss counts during off-peak and peak hours for all MNOs. All MNOs achieve acceptable ping loss rates during off-peak hours, except for operator D, whose value exceeds 1.2.

The high ping loss rate occurs when one or more travel data packets fail to reach their destination. The ping times depend on server distance, bandwidth, and area congestion. Thus, the ping counts do not affect the download/upload speed, and a high download/upload speed can be achieved with a high ping. In other words, the user may receive strong SNR with high throughput but experience high ping times due to physical distance from the server. Tables 5 and 6 summarize the overall average throughput and ping of MNOs during the off-peak and peak hours, respectively. The highest average values of DL throughput and ping recorded at off-peak hours are 14.2 Mbps and 25 ms, respectively.

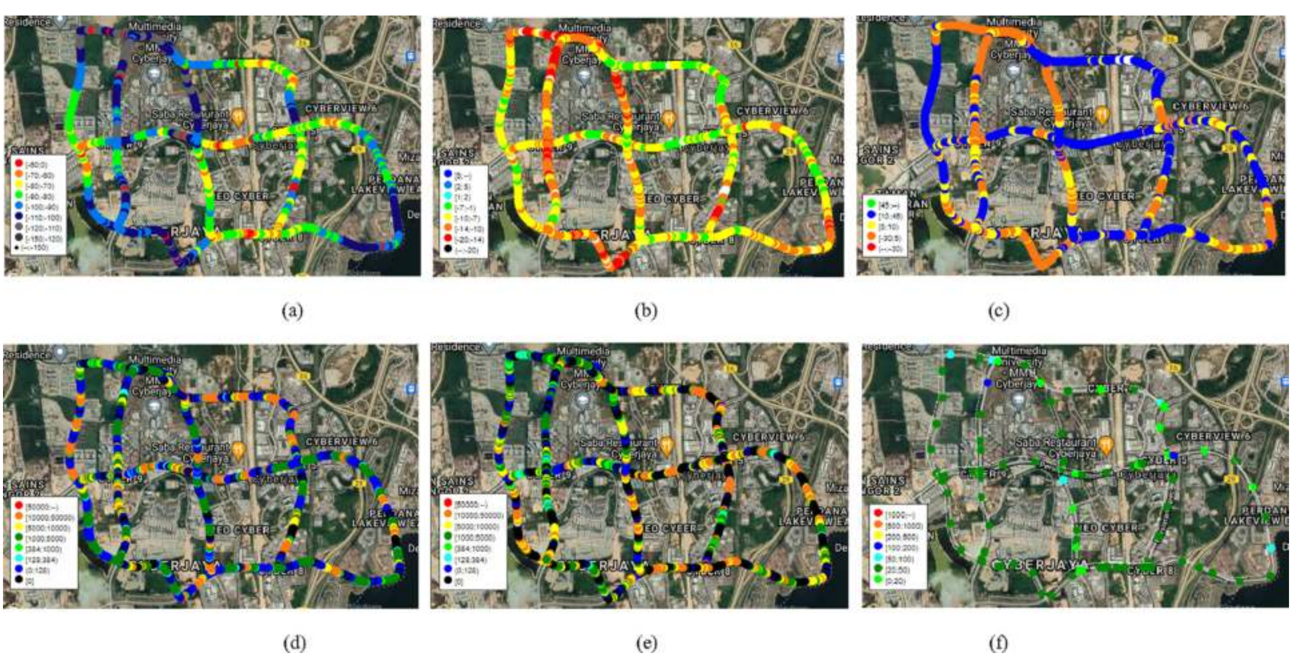


Fig. 12 Example performance metric visualization of one operator: (a) RSRP level (b) RSRQ (C) SNR (d) average DL data rate (e) average UL data rate (f) average ping.

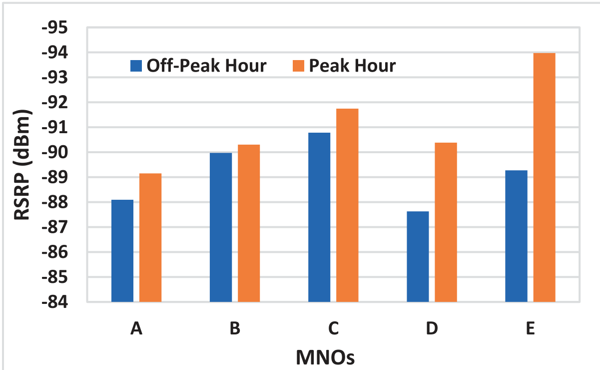


Fig. 13 Average RSRP during off-peak and peak hours.

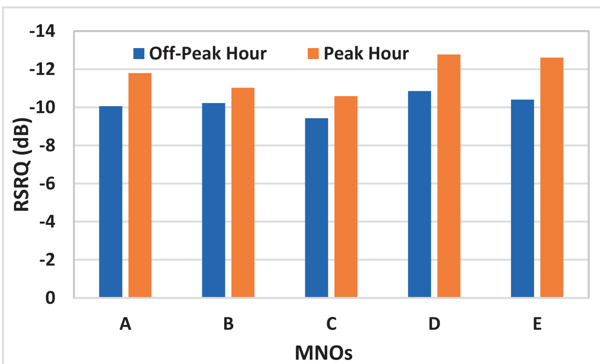


Fig. 14 Average RSRQ during off-peak and peak hours.

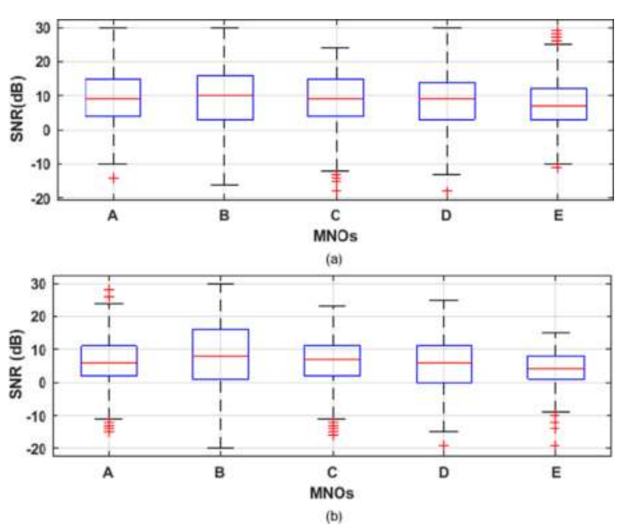


Fig. 15 Average SNR during (a) off-peak hour and (b) peak hour.

5.1.4. Handover

MBB heterogeneous networks (HetNets) are the common communication networks that provide wireless services in wide-area coverage. HetNet cells can be classified into several types: macrocells, microcells, and picocells. Deployment of different scenarios is crucial in increasing network performance regarding system capacity and network coverage. The major rising issue in 4G/5G HetNet deployment is user mobility, which produces a high handover rate, such as ping pong and radio link failure. These conditions directly affect communication quality in terms of long interruption time and throughput degradation. The base station executes handover within the Evolved Universal Terrestrial Access Network (E-UTRAN/UTRAN) (intra-eNB and inter-eNB scenarios) between legacy radio access technologies. Hence, the handover counts when the radio link communication of a user changes from a serving cell to a target cell. Fig. 19 shows the average intra-handover rate and reselection cells versus off-peak and peak hours for all MNOs. It can be seen that there are no handover records in 3G-to-3G technology during off-peak hours for all operators, whereas operator E achieves a higher handover rate compared with other operators during peak hours. The 4G-to-4G handover rate during the off-peak hours is slightly higher than during peak hours. The reason is that the user hands over to another base station due to coverage distance and traffic load. In the case of the off-peak hour, there is only one reason for the handover (the coverage distance due to moving user); thus, the user hands over to 4G base stations (as there is no effect on the traffic load). However, during peak hours, the coverage distance and traffic load significantly affect the user. Thus, the overloaded 4G base stations may handover several users to 3G networks. A significant high handover rate occurs when the user hands over 4G severing cells to another 4G target cells compared with 3G-to-3G handover in the same technology networks during off-peak and peak hours. This condition is because the 4G coverage serving cell is smaller than the 3G serving cell. In other words, the tested area is covered with few 3G cells compared with 4G cells. The handover rates over 4G and 3G networks are mostly similar during off-peak and peak hours for all MNOs, except for operator E, who achieves a high handover rate during peak hours over 3G networks.

Fig. 20 shows an example of data visualization of the serving technology during off-peak and peak hours for operator E. Green track represents the 4G technology, and the red track represents the 3G technology. In Fig. 20(b), the dominant serving network is 3G due to offloading data traffic from the 4G network. This condition occurs when the data traffic on 4G cells increases during peak hours; the network offloads the data traffic on the 3G cells. Operator C records the highest handover rate compared with others. The number of 3G/4G cells is unknown in the measured city; however, the 4G cell changes its operation to 3G due to data traffic on its cell. One possible explanation is that the operator has deployed many 4G sites to improve its network capacity or adjusted handover control parameters (time-to-trigger and handover margin) with high values to avoid handover failure. Similarly, a slightly high reselection rate occurs when the user reselects 4G to 4G rather than 3G to 3G technology. However, the reselection rates over 4G and 3G networks are mostly similar during off-peak and peak hours for all MNOs.

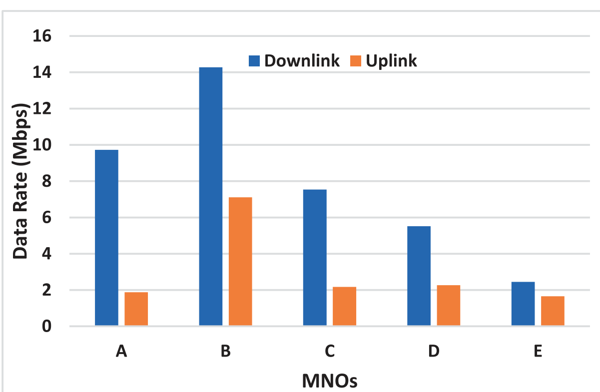
Fig. 21 displays the average inter-handover rate and reselection cells versus off-peak and peak hours for all MNOs. All operators did not record any reselection cell during off-peak and peak hours, except operator A, which records a very low rate during peak hours. It observes that the inter-handover and reselection rates are extremely low compared with intra-handover (see the previous figure). The results indicate that there are not many changes in inter-frequency between two different cells. This is because the tested area is mainly covered by

Table 3 Summary of signal strength and quality at off-peak hours for all MNOs.

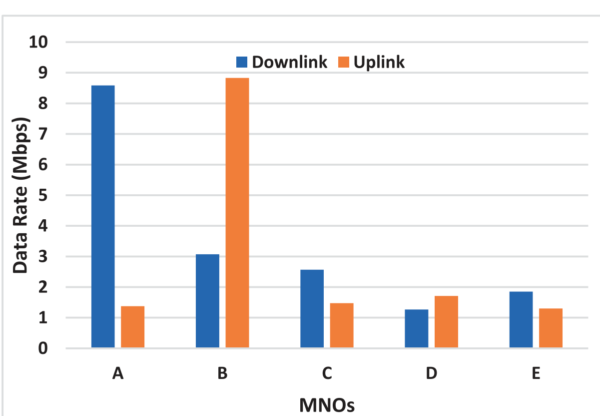
	RSRP (dBm)				*RSRQ (dB)*				*SNR (dB)*			
MNO	*Min*	*Max*	*Sdv*	*Avg.*	*Min*	*Max*	*Sdv*	*Avg.*	*Min*	*Max*	*Sdv*	*Avg.*
A	−117	−60	10.51	**−88.10**	−20	−2	2.65	**−10.06**	−14	30	7.34	**9.63**
B	−119	−58	13.24	−89.97	−20	−4	2.90	−10.22	−16	30	8.41	9.49
C	−122	−62	9.49	−90.60	−20	−2	2.83	−9.43	−18	24	6.99	9.14
D	−118	−56	10.51	−87.63	−20	−5	2.91	−10.85	−18	30	7.33	8.89
E	−112	−56	9.80	−89.2	−19	−5	2.04	−10.40	−11	29	6.77	7.70

Table 4 Summary of signal strength and quality at peak hours for all MNOs.

	RSRP (dBm)				*RSRQ (dB)*				*SNR (dB)*			
MNO	*Min*	*Max*	*Sdv*	*Avg.*	*Min*	*Max*	*Sdv*	*Avg.*	*Min*	*Max*	*Sdv*	*Avg.*
A	−119	−53	11.03	**−89.05**	−20	−2	2.82	−11.80	−19	29	6.82	6.82
B	−121	−56	13.06	−90.30	−20	−5	3.12	**−11.03**	−20	30	11.18	**8.51**
C	−124	−67	8.99	−91.69	−20	−2	2.58	−10.59	−16	23	6.31	6.75
D	−124	−63	10.19	−90.36	−20	−2	3.20	−12.77	−20	30	7.12	5.99
E	−114	−55	9.55	−93.97	−20	−2	4.15	−12.69	−19	15	5.25	4.19



(a)



(b)

Fig. 16 Average data rate over MNOs at (a) off-peak hours (b) peak hours.

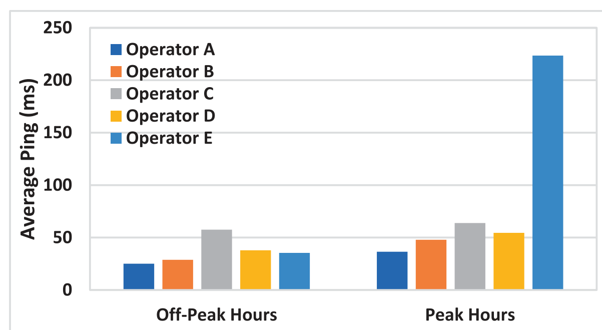


Fig. 17 Average ping of MNOs at off-peak hours and peak hours.

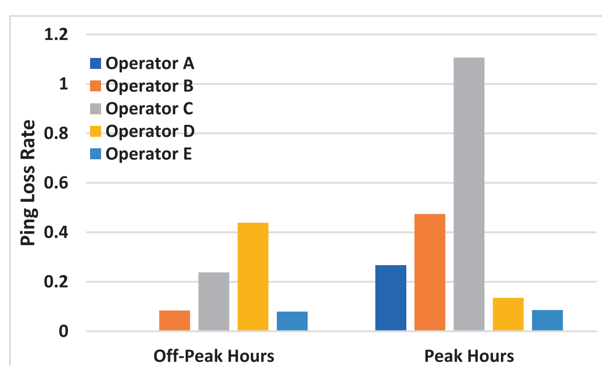


Fig. 18 Average ping loss over MNOs at off-peak hours and peak hours.

Table 5 Summary of average throughput and ping at off-peak hours for all MNOs.

	Average Throughput (kbps)				Ping (ms)				
	DL	UL	Max DL	UL Max	Avg	Min	Max	Stdev	Loss
A	9729.34	1874.85	14684.35	2442.44	**25.03**	17.23	48.15	9.25	**0.00**
B	**14279.34**	**7114.54**	18926.93	9635.14	28.85	18.92	63.82	14.24	0.08
C	7539.16	2171.26	13629.77	2736.75	57.49	22.25	134.37	37.10	1.04
D	5518.87	2263.04	8400.66	2858.07	37.86	17.46	86.96	22.62	0.44
E	2447.30	1657.33	3388.18	2212.63	35.33	25.29	67.67	13.67	0.09

Table 6 Summary of average throughput and ping at peak hours for all MNOs.

	Average Throughput (kbps)				Ping (ms)				
	DL	UL	Max DL	UL Max	Avg	Min	Max	Stdev	Loss
A	**8585.87**	1377.72	12491.98	1924.14	**36.55**	17.39	100.31	25.84	**0.27**
B	3071.41	**8828.55**	4171.45	11110.42	47.89	20.81	120.82	32.49	0.47
C	2570.11	1475.59	4278.16	2017.47	63.80	29.02	155.93	39.58	1.11
D	1268.63	1711.75	2051.75	2235.08	54.49	18.63	130.32	36.84	0.14
E	1853.02	1300.16	2769.23	1860.38	223.44	40.40	586.10	179.69	1.01

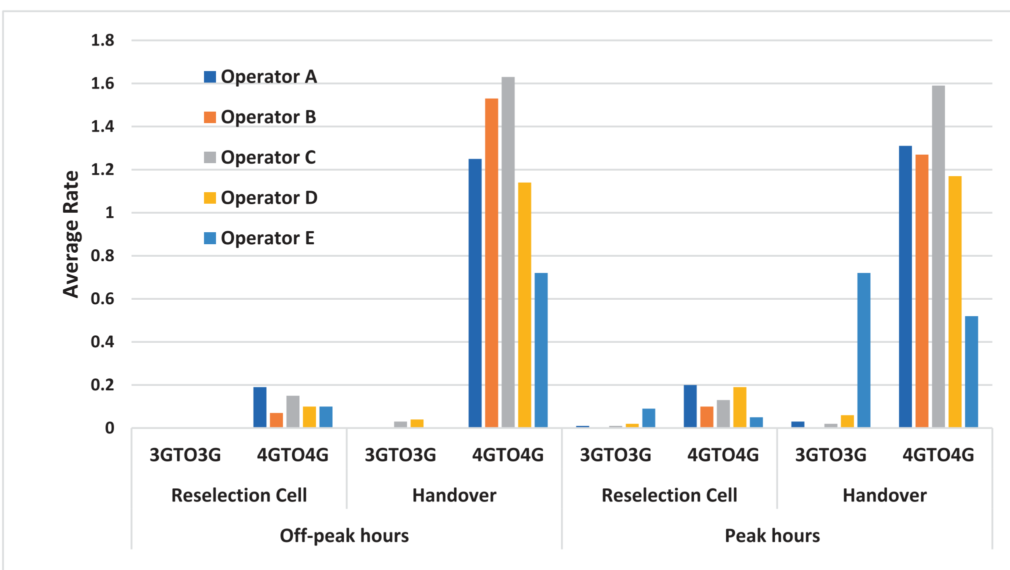


Fig. 19 Average rate of intra-handover and reselection cell during off-peak and peak hours.

4G networks, where the user's communication links are handed over the same networks (intra-eNBs). Similar to the previous figure, operator C achieves a slightly higher inter-handover rate than others during off-peak and peak hours. Table 8 summarizes the intra and inter-handover rates during off-peak and peak hours for all MNOs.

5.1.5. Analysis summary for outdoor scenarios

The results of investigated performance metrics obtained from five Malaysian MNOs of urban morphology are summarized in Tables 5, 6, and 7. The RSRP and RSRQ ranges are acceptable for all MNOs, with low levels experienced at off-peak hours. All the MNOs cover the test area with 4G except operator E, where some routes are covered with 3G networks. The tested area is affected by a noise floor that contains various noise sources that reduce the SNR. All MNOs achieve an average SNR level of 6.5 dB and 9 dB for peak and off-peak hours, respectively. The typical DL speeds of 4G and 3G networks are around 2Mbps and 20Mbps, and theoretical ones of 7.2Mbps and 150Mbps, respectively. From our results, most MNOs achieved an average of 2Mbps (except one operator) during peak hours, although they have a network coverage with 4G. Thus, all the operators should improve the SNR ratio by lowering the noise floor and improving the signal power. Also, some operators perform better than others in several KPIs for different reasons, as illustrated in the result section. For example, some operators may have fewer connected users in that area, some may have good coverage, and others may

Fig. 20 Example of data visualization of the serving technology for operator E during (a) off-peak and (b) peak hours.

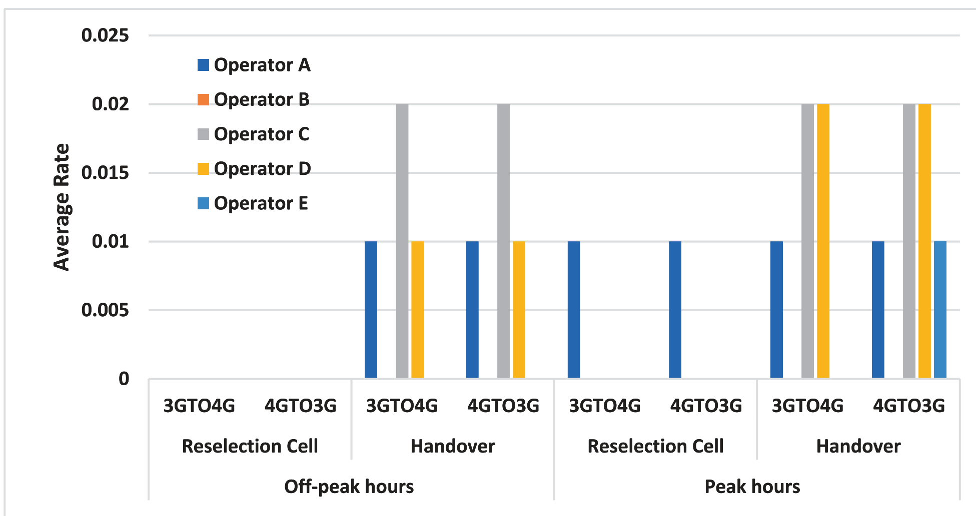


Fig. 21 Average rate of inter-handover and reselection cell during off-peak and peak hours.

Table 7 Summary of average intra and inter-handover during off-peak and peak hours for all MNOs.

	Off-peak hours				**Peak hours**			
	Intra Handover		Inter Handover		Intra Handover		Inter Handover	
MNO	3GTO3G	4GTO4G	3GTO4G	4GTO3G	3GTO3G	4GTO4G	3GTO4G	4GTO3G
Operator A	0	1.25	0.01	0.01	0.03	1.31	0.01	0.01
Operator B	0	1.53	0	0	0	1.27	0	0
Operator C	0.03	1.63	0.02	0.02	0.02	1.59	0.02	0.02
Operator D	0.04	1.14	0.01	0.01	0.06	1.17	0.02	0.02
Operator E	0	0.72	0	0	0.72	0.52	0	0.01

use 4G more than 3G, so the performance of different operators will be different. Also, most of the measured MNOs achieve an average ping lower than 100 ms, which is within an acceptable range for 3G and 4G networks. In general, the current MNOs may require to improve the data rate for delivering a high-speed transmission with low-latency communications.

5.2. Indoor scenario

Indoor measurements were collected on several floors in DPulze, which is the central shopping mall in Cyberjaya City, with coordinates of 2.9221° N, and 101.6510° E, as shown in Fig. 22. In this scenario, three floors were considered: lower ground (LG), ground (G), and upper ground (UG).

Table 8 Summary of the average signal qualities of indoor scenario.

	RSRP (dBm)				RSRQ (dB)				SNR (dB)			
MNO	*Max*	*Min*	*Sdv*	*Avg.*	*Max*	*Min*	*Sdv*	*Avg.*	*Max*	*Min*	*Sdv*	*Avg.*
A	−61	−99	7.65	−82.98	−4	−11	1.68	−8.64	30	0	7.14	19.64
B	−63	−105	7.91	−85.41	−7	−14	1.39	−10.77	27	−2	5.92	18.20
C	−62	−113	9.91	−85.85	−3	−20	2.78	−6.27	30	−16	7.95	18.41
D	−56	−108	8.08	−76.15	−4	−14	0.94	−9.99	30	−1	7.38	20.30
E	−65	−104	8.20	−85.32	−3	−15	1.48	−10.34	30	−4	7.40	19.95

Fig. 23 shows the floor plans of the measurement testbed. The red dots indicate the collected data for each MNO. Good network coverage is essential for mobile users to connect to subscribed network services. Mobile users sometimes experience inadequate coverage in general indoor environments, especially in large-scale multi-floor indoor spaces. Thus, establishing an Internet connection becomes boring and unpleasant due to a slow connection. Poor indoor cellular coverage can occur due to several reasons. (1) construction materials used for roofs, external and internal walls and windows, including glass, make the mobile signal bounce, diffract, and attenuate at a long distance (2) the human body can absorb and block mobile signals.

5.2.1. Signal level and quality

Fig. 24 illustrates the average RSRP of each floor plan for all MNOs. Operator D obtains the strongest average signal levels of −88.64, −73.92, and −73.80 dBm for LG, G, and UG, respectively. This is because the operator may deploy external antennas to improve the indoor signal level. All MNOs achieve high and low RSRP levels on UG and LG. All the MNOs cover the test floor plans with 4G technology, and no 3G signals are discovered. This is because the threshold signal level in 4G networks is lower than the required level in 3G networks. 4G subscribers can receive a signal level that is weaker than the 3G threshold level.

Fig. 25 displays the average RSRQ of each tested floor plan for all MNOs. The RSRQ on all floor plans is mostly at the same level, with a slight difference of approximately −1 dB. All MNOs record RSRQ levels within the range of −8 dB to −11 dB, except for operator C, whose RSRQ level ranges from −6 dB to 7 dB. Operator C achieves a good RSRQ level compared with other operators. The signal quality in a number of used resource blocks is used to measure RSRP and RSSI over the same bandwidth for each MNO. The RSRQ value helps the base station to make a decision whether to perform cell reselection or intra-inter handover.

Fig. 22 Location map of the indoor experiment at "DPulze Shopping Center.".

Fig. 26 demonstrates the average SNR on the tested floor plans for each MNO. The SNR levels on the G floor are better than those on the LG and UG. This condition occurs due to less noise and fewer obstacles on the G floor. The SNR levels on the G floor reach up to 25 dB, whereas the SNR levels on the LG and UG reach 20 dB. Overall, all MNOs achieve good SNR levels on the tested floor plans with average SNR of approximately 22 dB. This finding indicates that the MNOs may implement internal antennas to amplify the transmitted signals in different areas inside the shopping center.

Fig. 27 shows the total average of RSRP, RSRQ, and SNR on the tested floor plans. Operator D achieves good RSRP and SNR levels compared with other operators. Operator C obtains a better RSRQ level compared with other operators. Overall, the shopping center has a 4G network coverage for all MNOs because it is located in the city center. Table 8 summarizes the average signal qualities of the indoor scenario.

5.2.2. Throughput and ping

Fig. 28 shows the average and maximum data rate for each MNO. Operator B achieves the highest data rate in DL and UL with approximately 3.7 and 5.3 Mbps, respectively, compared with other operators. By contrast, operator E records the lowest data rate in DL and UL, with approximately 1.7 and 1.6 Mbps, respectively. The maximum DL and UL obtained by operator B with data rates are approximately 9.8 and 11.8 Mbps, respectively. Other operators achieve an average DL and UL data rate of 2 Mbps. The network performance of each operator is highly variable and depends on several metrics, such as infrastructure, deployment scenario, and radio conditions.

Fig. 29 illustrates the average ping and standard deviation for all MNOs. Operators A and D achieve lower ping and standard deviation with a latency of 24.4 and 23.4 ms, respectively, compared with other operators. Operators B and E obtain a high average ping of 60.4 and 63.5 ms, respectively. Operator B achieves the highest data rate (Fig. 28) and the highest ping (Fig. 29). No relation is found between data rate and ping, where the user may receive high throughput but experience high ping times due to physical distance from the server. Overall, the operators achieve an average ping below 100 ms, which is the maximum ping for 4G networks.

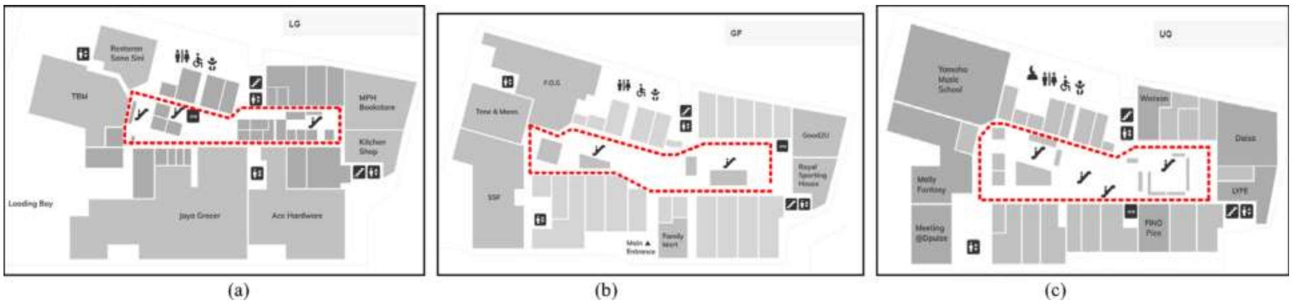


Fig. 23 Floor plan of measurement testbed (a) LG floor (b) G floor (c) UG floor.

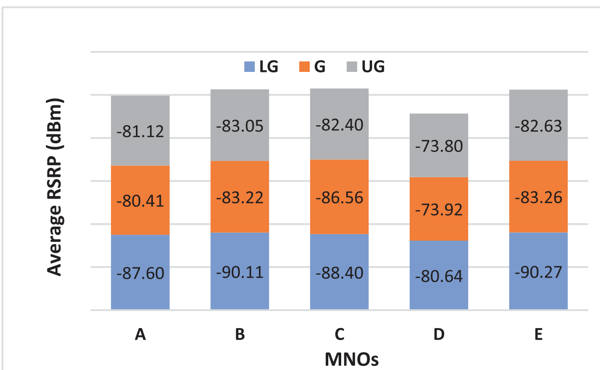


Fig. 24 Average RSRP of each floor plan for all MNOs.

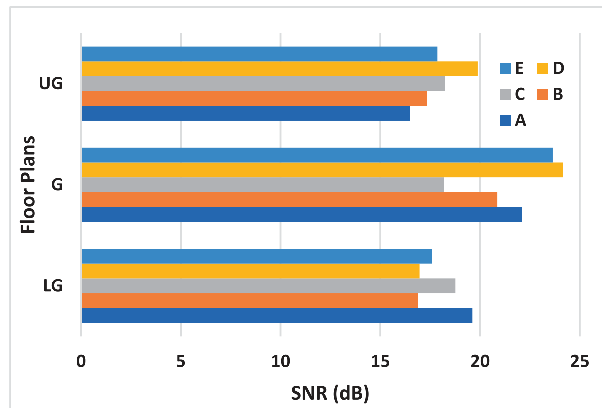


Fig. 26 Average SNR of each floor plan.

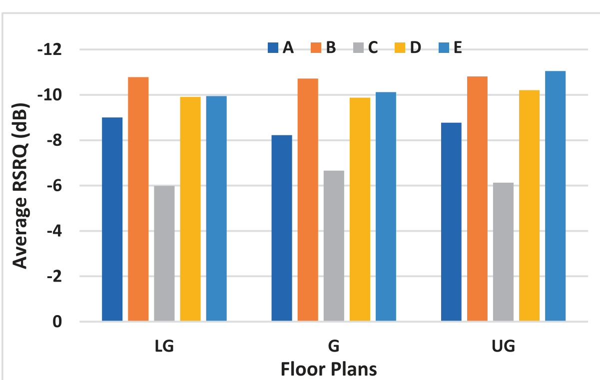


Fig. 25 Average RSRQ of each floor plan for all MNOs.

5.2.3. Indoor handover

MNOs deploy more indoor systems or multiple access points to provide high-performance indoor coverage to meet customers' satisfaction in terms of high data because approximately 80 % of total MBB traffic utilizes in-buildings despite high building penetration loss. Thus, multiple handover events occur when end-users move into multifloor buildings. Fig. 30 demonstrates the handover rate in the DPulze shopping center for all MNOs. Operator D achieves a high handover rate of 13 % compared with others. By contrast, operators A and B record equal handover rates of 4 %. The higher handover rate is due to the handover strategy or sometimes congested access points caused by increased data traffic.

5.2.4. Analysis summary for indoor scenario

The results of investigated performance metrics obtained from five Malaysian MNOs in the DPulze shopping center are summarized in Tables 9 and 10. In-building mobile coverage is the most challenging environment. In this study, all the investigated MNOs provide better in-building mobile coverage ranging from −76 dBm to −85 dBm. However, they achieve an acceptable average data rate of 2 Mbps. The data rate can be improved further by deploying more indoor hotspots that increase the network capacity. In 5G technology, more buildings are experiencing poor indoor mobile coverage due to building structures, capacity requirements, and radio frequency. It is more complicated to provide deep indoor coverage in the 5G mobile network, which uses a frequency band higher than 4G. Higher frequency bands experience higher penetration and space propagation losses through building materials.

6. Limitations and future directions

This study presented the evaluation results of the current MBB with various MNOs. However, several limitations are ignored in this study and can point to possible future work.

6.1. Study limitations

6.1.1. MBB services

This study included the most relevant performance metrics and MBB services usually analyzed by MNOs. However, several

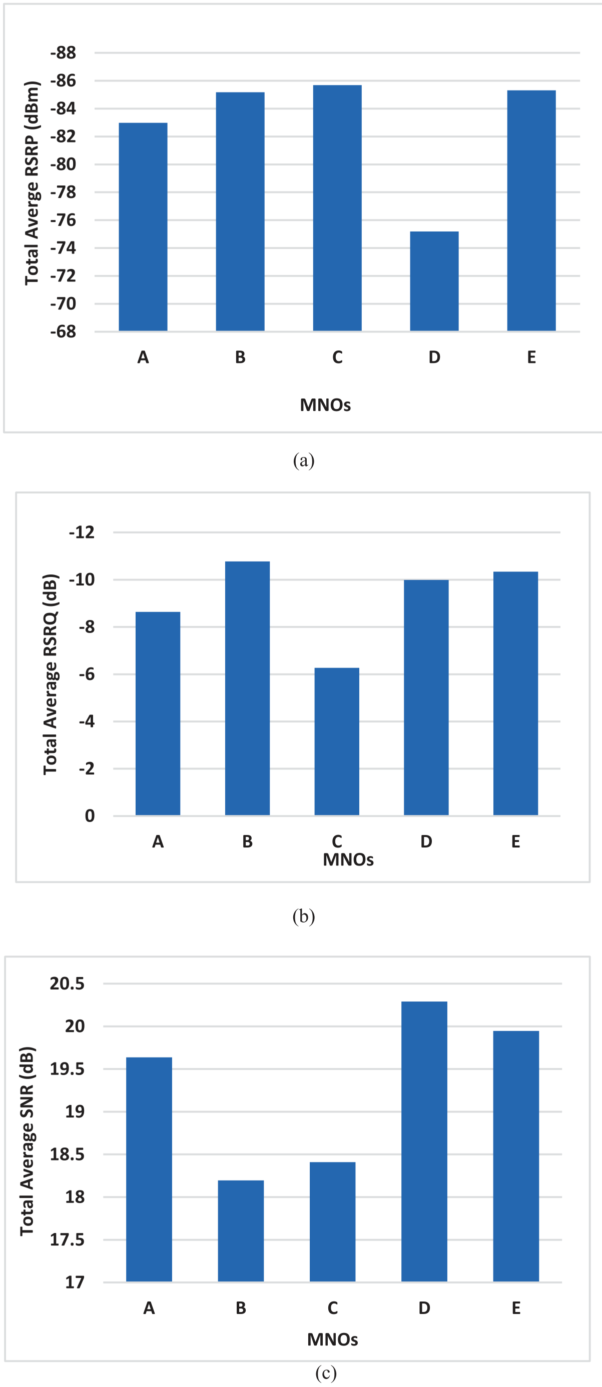


Fig. 27 Total average overall floor plans (a) RSRP (b) RSRQ (c) SNR.

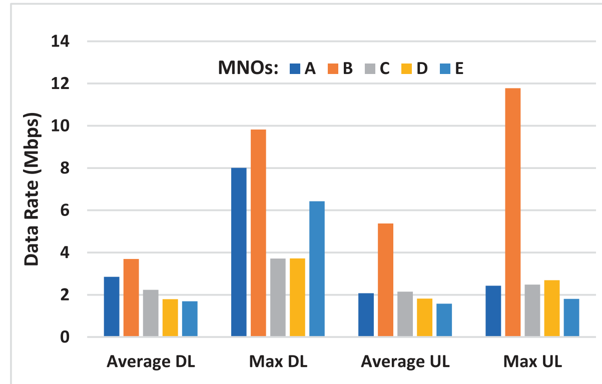


Fig. 28 Total average and maximum data rate for each MNO.

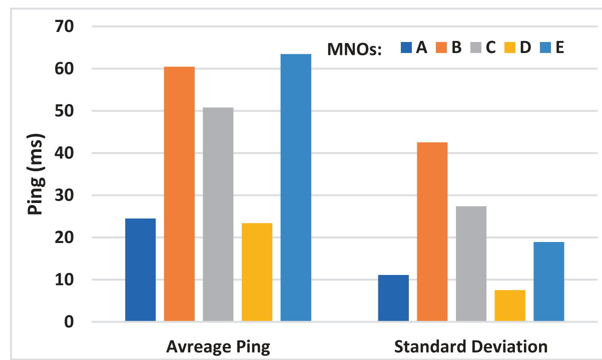


Fig. 29 Total average ping and standard deviation for all MNOs.

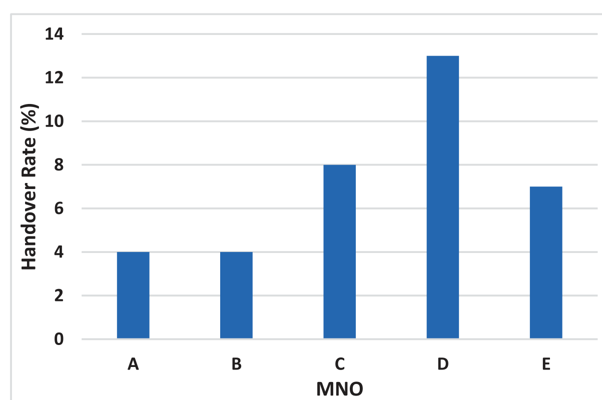


Fig. 30 Average handover rate for all MNOs.

MBB services, such as video streaming and web browsing speeds, can be considered for further investigation. This study does not discuss various factors related to mobile subscribers, such as traffic management policies, customer service, data allowances, billing, and price.

6.1.2. Geographical area

The scope of this research is focused on a particular populated urban area, Cyberjaya City, where it does not represent the overall actual performance of MBB networks. Thus, the scope can be further extended and include different geographical areas, such as suburban and rural areas. The performance of MBB is heavily reliant on the network coverage available. Although this study contains some coverage information, it does not measure the whole network coverage levels. Thus, investigating and analyzing the network performance of each MNO are challenging.

Table 9 Summary of the average signal qualities of indoor scenario.

	Average Throughput (kbps)				Ping (ms)				
MNO	DL	UL	Max DL	UL Max	Avg	Min	Max	Stdev	Loss
A	2849.46	2074.89	15,850	3043	24.5	16.44	54.47	11.12	0
B	4218.08	5347.29	28,980	13,323	60.45	31.18	170.55	42.53	0
C	2238.37	2147	7596	3124	50.8	30.11	124.31	27.37	0.57
D	1792.56	1821.95	4174	3310	23.38	17.59	42.64	7.54	0
E	1691.80	1580.4	10,416	2684	63.46	44.72	108.46	18.92	0.26

Table 10 Summary of the overall average KPI of indoor and outdoor scenarios.

	Outdoor Scenario						Indoor Scenario					
	RSRP (dBm)	RSRQ (dB)	SNR (dB)	Throughput (Kbps)		Ping (ms)	RSRP (dBm)	RSRQ (dB)	SNR (dB)	Throughput (kbps)		Ping (ms)
MNO				DL	UL					DL	UL	
A	-88.58	-10.93	8.23	9157.61	1626.29	30.79	-82.98	-8.64	19.64	2849.46	2074.89	24.5
B	-90.14	-10.63	9	8675.38	7971.55	38.37	-85.41	-10.77	18.2	4218.08	5347.29	60.45
C	-91.15	-10.01	7.95	5054.64	1823.43	60.65	-85.85	-6.27	18.41	2238.37	2147	50.8
D	-88.99	-11.81	7.44	3393.75	1987.39	46.18	-76.15	-9.99	20.3	1792.56	1821.95	23.38
E	-91.59	-11.55	5.95	2150.16	1478.75	129.39	-85.32	-10.34	19.95	1691.8	1580.4	63.46

6.1.3. Indoor environment

The performance evolution of QoS in indoor environments is extremely important because most mobile applications and MBB services are utilized in indoor environments, such as government buildings, shopping malls, indoor train stations, airports, and offices, rather than outdoor. The primary consideration for any MNOs to design indoor systems is to increase the revenue factor and decrease the traffic cost with a low-cost deployment. Consequently, the MBB connectivity occurs within buildings where the indoor mobile connections are approximately more than double the total mobile connections in indoor and outdoor settings [5], where approximately 80 % of mobile data traffic is generated indoors [31]. Thus, the indoor users connect to indoor MBB rather than outdoor MBB networks because the outside mobile signals are extremely weak to penetrate larger buildings. Therefore, deploying indoor MBB networks is essential to provide end-users with better coverage and network capacity. In this regard, more performance investigation of indoor MBB networks is extremely necessary to improve the QoE.

6.1.4. Fair usage policy

More studies should investigate the fair usage policy, which refers to the agreement between MNO and customers (subscribers). The policy ensures that all customers have a good experience; however, it can affect the user experiences regarding sharing bandwidth. The number of subscribers sharing a connection is called the "contention ratio," which measures the subscribers' ratio per unit of bandwidth, where a lower ratio indicates high QoS. Thus, the user experiences slow connection when sharing connections with other users simultaneously. However, MNO provides a fair usage policy in terms of performance by limiting one user's usage over a group at peak times [32]. In this regard, fair usage policies play an important role in user experience, where a customer's usage over others is limited depending on their policies. For instance, the Internet speed depends on the purchase bundle, where each bundle has a limited Internet speed. Some MNOs offer several advantages to the postpaid subscriber over prepaid, such as high download speed and priority of 4G connection. All these factors can be further investigated to evaluate each MNO independently.

6.1.5. Dynamic spectrum sharing (DSS)

This study is limited to 3G and 4G MBB networks, whereas the 5G NSA networks are not commercialized in Malaysia. However, several countries, including Malaysia, will gradually shut down the 3G networks in the coming years. The 5G networks will support a wide range of services with enhanced MBB performance. The MNOs aim to have a seamless transition path from 4G to 5G new radio. At the early stages of 5G commercial deployment, the 5G networks operate in low- and mid-frequency bands, including the sub-6 GHz spectrum. However, most sub-6 GHz frequency bands are occupied by 4G frequencies. The existing 4G spectrum is refarmed for 5G networks to address occupied bands. This refarming spectrum is called DSS, which refers to simultaneously sharing resource allocations between 4G and 5G [33]. The DSS technology aims to eliminate acquiring a new spectrum allocation for 5G because it enables coexistence with multi-radio access technologies. Thus, the performance evolution of 5G NSA can be considered in the near future.

6.2. Future directions

In preparation for 5G roll-outs, the MCMC launched a project called JENDELA, a comprehensive digital infrastructure plan that aims to address the increasing data demand and improve the user experience for fixed and MBB [34]. JENDELA supports several activities: operating businesses online, working remotely, online education, and social communications. The JENDELA plans to expand the 4G coverage and shutdown 3G networks. However, existing networks play a key role in ensuring a smooth transition to 5G networks. The JENDELA was introduced to implement its plan with a five-year plan starting in 2021 and ending in 2025 in several phases. The first phase starts now until the end of 2022 and involves optimizing the current infrastructure and resources for fixed and MBB connectivity in the following directions:

- Expanding 4G coverage of MBB from 91.8 % to 96.9 % in urban areas;
- Increasing MBB speed from 25 Mbps to 35 Mbps; and
- Supporting access to gigabit speeds with fixed broadband services for 7.5 million premises.

The second phase is beyond 2022 and involves activities that are not covered in the first phase. This phase aims to utilize fixed wireless access and other fit-for-purpose technologies. It also paves the way for the country's digital transition toward 5G technology after building a robust 4G and fiber platform in the first phase.

The MCMC and other mobile operators: Maxis, Celcom, Digi, Telekom Malaysia, and U Mobile, are currently running 5G demonstration projects in six states. Cyberjaya is one of the targeted cities that will be covered with 5G networks in the near future. Several showcases have been conducted in Malaysia and other countries to explore the capability of 5G technology. Several 5G trends can be summarized as follows:

Spectrum bands: the MCMC suggested various 5G spectrums, such as 700, 3500, 26 GHz, and 28 GHz [35,36]. Currently, several MNOs have started numerous 5G trials using the lower bands (sub-6 GHz) as non-standalone (NSA) deployment associated with 4G networks. The high spectrum band is suitable for mmWave, providing extremely limited coverage but supporting higher bandwidth and lower latency. The estimated number of 5G subscriptions will be approximately 2.1 million by 2025, with a penetration of 6.6 mobile 5G subscriptions per 100 people [36].

Indoor systems: traffic utilizes approximately 70 % to 80 % of total MBB traffic. Thus, the MNOs are required to deploy more efficient indoor systems in buildings where outdoor macro signals cannot penetrate. Indoor coverage becomes important in 5G due to the high demands of modern usage cases. The use of high band frequencies of 3.5 GHz makes indoor signal penetration from outdoor macro sites more challenging. The existing 4G indoor systems cannot support the 3.5 GHz or 28 GHz spectrum. The unused mm-wave spectrum provides an excellent chance to boost MBB capacity due to the available wide bandwidth [37]. This condition causes MNOs to deploy 5G indoor systems to satisfy the high demand from subscribers. Indoor system solutions can be classified into passive indoor and digital indoor systems [38]. The former uses low future-proof capabilities, whereas the latter improves higher-quality network coverage and flexible capacity expansion to support the 5G data explosion. A digital indoor system provides an excellent solution for complicated internal building structures, such as multi-floor and multi-walls that can interfere with radio frequencies. 5G indoor systems will play an important role in property infrastructures, such as electricity, gas, and water. Thus, they become a driving force for MNOs to market their 5G networks.

Deployment scenarios: In the past, the deployment of base stations deepened on the tall structure and heavy-duty of the ground-based tower, where a certain area has its own special structures and improved designs. However, 5G trends move to various deployment types, such as rooftop towers, rapid assembly poles, and rooftop poles (e.g., lamp poles). The 5G trend expects to have several special structures that depend on improved capacity and coverage. For instance, massive 5G antennas in urban areas will be deployed on street furniture to expand the network coverage. Thus, 5G networks require denser architecture than 4G networks to deliver their required performance. Due to limited space, street furniture is considered suitable for small cell deployment. 5G deployment with the right design and deployment strategy that supports ultra-reliable low-latency communication (URLLC) use cases, such as smart cities, autonomous and connected vehicles, and unmanned aerial vehicles, becomes essential. Moreover, URLLC promises to improve information transfer up to roughly-one Tbps data throughput while attaining 0.1-millisecond transmission latency in the sixth generation (6G) wireless communication networks [39]. However, the ability of street furniture can be limited to accommodate 5G/6G deployment due to space and loading capability constraints.

Mobility management: The deployment of a large number of small cells in 5G networks is expected to enhance total system performance by enhancing coverage and improving user experience. However, this condition increases the number of handovers when a user moves among those cells and where 5G ultradense small cells coexist with current 4G networks. The major rising issue in 4G/5G heterogenous network deployment is user mobility, which produces a high handover rate, such as high handover probability, radio link failure, and unnecessary handover [40,41]. These conditions directly affect communication quality in terms of high drop calls, long interruption time, and high-throughput degradation.

Power consumption: The 5G networks consume more power to deliver more data than the 4G networks. A typical 5G base station consumes up to twice or more the power of a 4G base station. The disparity can grow at higher frequencies due to the need for more antennas and a denser layer of small cells [42]. Thus, power-supplying equipment requires more substantial upgrades at existing 5G sites. This condition leads to an increase in network operating expenses. Several issues, such as insufficient battery capacity, insufficient alternating current power supply, and inability to support high-power long-distance transmission, are found due to the increased power demands of a 5G site.

7. Conclusion

This study provided an extensive performance evaluation of five national MNOs in Malaysia. The data measurements were conducted in an intelligent city with good technology infrastructure. In this work, the existing networks were tested and evaluated in several scenarios with various performance metrics, such as RSRP, RSRQ, SNR, throughput (DL/UL data rates), ping, and handover. In the outdoor scenario, the tested area experiences a noise floor with various noise sources that reduce the SNR level. Thus, all the MNOs should improve the SNR ratio by lowering the noise floor and improving the signal power. The maximum average DL and UL data rates are 14.3 and 7.1 Mbps, respectively, whereas the minimum average ping and loss are 36.5 ms and 0.14, respectively, for all MNOs. Therefore, the current MNOs should improve the data rate for delivering a high-speed transmission with low-latency communications. In the indoor scenario, in-building mobile coverage is the most challenging environment. In this study, all the investigated MNOs provide better in-building mobile coverage ranging from −76 dBm to −85 dBm. However, they achieve an acceptable average data rate of 2 Mbps. The data rate can be improved further by deploying more indoor hotspots that increase the network capacity. Several suggestions and recommendations for MBB providers are provided to improve their network performance and QoE for meeting customers' satisfaction. Several points on 5G trends that potentially affect the near future 5G deployments are highlighted. The same methodology and tools can be used for data collection in 5G networks where the G-NetTrack app supports the data measurements in NSA 5G networks. In addition, several limitations not considered in this study and can be a point to possible future work are presented. Guidelines and a suitable platform are provided for researchers to enhance their MBB evaluation studies. This work benefits the MNOs to improve their network performance in a particular tested area.

Abbreviation List

List of abbreviations in alphabetical order

Item	Description
2G	second generation
3G	third generation
3GPP	3rd generation partnership project
4G	fourth generation
5G	fifth generation
6G	sixth generation
CAPEX	capital expenditures
DL	downlink
DSS	dynamic spectrum sharing
E2E	end-to-end
EUTRAN	evolved universal terrestrial radio access network
ITU	international telecommunication union
HetNets	heterogeneous networks
KPIs	key performance indicators
LTE	long-term evolution
MBB	mobile broadband
MCMC	Malaysian communications and multimedia commission
mmWave	millimeter wave
MNOs	mobile network operators
NSA	non-standalone
OPEX	operating expenses
QoE	quality of experience
QoS	quality of service
RSCP	received signal code power
RSRP	reference signal received power
RSRQ	reference signal received quality
RTT	round-trip time
SBB	satellite broadband
SNR	signal-to-noise ratio
UL	uplink
URLLC	ultrareliable low-latency communication

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] B.J. Lobo, M.R. Alam, B.E. Whitacre, Broadband speed and unemployment rates: Data and measurement issues, Telecommun. Policy 44 (1) (2020) 101829.
[2] K. Bouraqia, E. Sabir, M. Sadik, L. Ladid, Quality of experience for streaming services: measurements, challenges and insights, IEEE Access 8 (2020) 13341–13361.
[3] H.Z. Jahromi, D.T. Delaney, A. Hines, Beyond first impressions: Estimating quality of experience for interactive web applications, IEEE Access 8 (2020) 47741–47755.
[4] I. Shayea, M. Ergen, M.H. Azmi, D. Nandi, A.A. El-Salah, A. Zahedi, Performance analysis of mobile broadband networks with 5G trends and beyond: Rural areas scope in Malaysia, IEEE Access 8 (2020) 65211–65229.
[5] I. Shayea, T.A. Rahman, M.H. Azmi, C.T. Han, A. Arsad, Indoor network signal coverage of mobile telecommunication networks in West Malaysia: Selangor and Johor Bahru, in: *2017 IEEE 13th Malaysia International Conference on Communications (MICC)*, 2017, IEEE, pp. 288-293.
[6] A.L. Imoize, K. Orolu, A.-A.-A. Atayero, Analysis of key performance indicators of a 4G LTE network based on experimental data obtained from a densely populated smart city, Data Brief 29 (2020) 105304.
[7] G. Aceto, F. Palumbo, V. Persico, A. Pescapé, Available bandwidth vs. achievable throughput measurements in 4G mobile networks, in: *2018 14th International Conference on Network and Service Management (CNSM)*, 2018, IEEE, pp. 125-133.
[8] H. Elsherbiny *et al.*, 4G LTE Network Data Collection and Analysis along Public Transportation Routes, in: *GLOBECOM 2020-2020 IEEE Global Communications Conference*, 2020, IEEE, pp. 1-6.
[9] H.G.V. De Andrade, C.C. Ferreira, A.G. da Silva Filho, Latency analysis in real lte networks for vehicular applications, in: *2016 VI Brazilian Symposium on Computing Systems Engineering (SBESC)*, 2016, IEEE, pp. 156-161.
[10] T. Arshad, M.F. Awan, T. Ahmad, S. Qaisar, Performance evaluation of mobile broadband cellular networks in Pakistan, in: *2016 IEEE 41st Conference on Local Computer Networks Workshops (LCN Workshops)*, 2016, IEEE, pp. 104-111.
[11] D. Raca, J.J. Quinlan, A.H. Zahran, C.J. Sreenan, Beyond throughput: a 4G LTE dataset with channel and context metrics, in: *Proceedings of the 9th ACM Multimedia Systems Conference*, 2018, pp. 460–465.
[12] M.A. Al Jahdhami, A. El-Saleh, A. Alhammadi, I. Shayea, Performance Analysis of Mobile Broadband Networks in Ibra City, Oman, in: *2021 International Conference on Artificial Intelligence and Big Data Analytics*, 2021, IEEE, pp. 1-6.

[13] MCMC, Allocation of spectrum bands for mobile broadband service in Malaysia, Malaysian Communications and Multimedia Commission, Public Inquiry Report, 2019. Accessed: 03-02-2021. [Online]. Available: https://www.mcmc.gov.my/skmmgovmy/media/General/pdf/Public-Inquiry-Allocation-of-spectrum-bands-for-mobile-broadband-service-in-malaysia.pdf.

[14] MCMC, Spectrum Policies to Enable Mobile Broadband Goals in Malaysia, 2019.

[15] MCMC, "Mobile Broadband Self-Declaration Report," Malaysian Communications & Multimedia Commission, Technical Report, 2020. [Online]. Available: https://www.mcmc.gov.my/skmmgovmy/media/General/pdf/Self-Declaration-Report_Mobile-BB_MCMC_H1-2020.pdf.

[16] I. Shayea, M.H. Azmi, T.A. Rahman, M. Ergen, C.T. Han, A. Arsad, Spectrum gap analysis with practical solutions for future mobile data traffic growth in malaysia, IEEE Access 7 (2019) 24910–24933.

[17] G. Solutions. "G-NetTrack Pro." https://gyokovsolutions.com/g-nettrack/ (accessed 03-02-2021, 2021).

[18] M.A. Zulkifley, M. Behjati, R. Nordin, M.S. Zakaria, Mobile Network Performance and Technical Feasibility of LTE-Powered Unmanned Aerial Vehicle, Sensors 21 (8) (2021) 2848.

[19] M.J.C. Jimenez, K. Arana, M.R. Arias, Outdoor-to-indoor propagation mechanisms in multistorey building for 0.85 GHz and 1.9 GHz bands, in: *2017 IEEE 37th Central America and Panama Convention (CONCAPAN XXXVII)*, 2017, IEEE, pp. 1-6.

[20] A.A. El-Saleh et al, Measuring and assessing performance of mobile broadband networks and future 5G trends, Sustainability 14 (2) (2022) 829.

[21] Google. "Phone signal strength related information." https://android.googlesource.com/platform/frameworks/base/+/jb-mr1.1-dev-plus-aosp/telephony/java/android/telephony/SignalStrength.java (accessed).

[22] 3GPP, AT command set for User Equipment (UE), *TS. 27.007,* 2008.

[23] 3GPP, Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer; Measurements, *TS. 36.214,* 2008. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2428.

[24] 3GPP, Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification, *TS 36.331,* 2009.

[25] MCMC, Guidelines to the commission determination on the mandatory standards for quality of service (wireless broadband access service), Malaysian Communications and Multimedia Commission, 2016.

[26] W. Hofer, P. Svoboda, W. Kastner, V. Raida, M. Rupp, Open Monitoring Platform for Mobile Broadband, in: *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*, 2020, IEEE, pp. 1-5.

[27] V. Raida, P. Svoboda, M. Rupp, On the Inappropriateness of Static Measurements for Benchmarking in Wireless Networks, in: *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*, 2020, IEEE, pp. 1-5.

[28] I. Shayea et al, Performance analysis of mobile broadband networks with 5g trends and beyond: Urban areas scope in Malaysia, IEEE Access 9 (2021) 90767–90794.

[29] H. Khatri, Malaysia Mobile Network Experience Report September 2020, Opensignal, Technical Report, 2020. Accessed: 03-02-2021. [Online]. Available: https://www.opensignal.com/reports/2020/09/malaysia/mobile-network-experience.

[30] MCMC, Measuring Malaysia Broadband and Voice Performance, Malaysian Communications and Multimedia Commission, Technical Report, 2019. Accessed: 03-02-2021. [Online]. Available: https://www.mcmc.gov.my/skmmgovmy/media/General/pdf/QoS-Network-Performance-Report-2019.pdf.

[31] Huawei, Huawei Releases LampSite3.0 for Indoor MBB. [Online]. Available: https://www.huawei.com/en/news/2017/2/huawei-releases-lampsite3-indoor-mbb.

[32] D. Warner. "What is a "Fair Usage Policy"?" Uswitch. https://www.uswitch.com/broadband/guides/fair-usage-policy/ (accessed 2021).

[33] Samsung, Dynamic Spectrum Sharing, Samsung, Technical White Paper, 2021.

[34] MCMC. Jalinan Digital Negara (JENDELA). Malaysian Communications and Multimedia Commission. https://myjendela.my/ (accessed 2021).

[35] MCMC, 5G Key Challenges and 5G Nationwide Implementation Plan, National 5G Task Force Report (2019).

[36] MCMC, Industry Performance Report, 2019. [Online]. Available: https://www.mcmc.gov.my/skmmgovmy/media/General/pdf/MCMC_IPR_2019.pdf.

[37] A.M. Al-Samman, T.A. Rahman, M.H. Azmi, A. Sharaf, Y. Yamada, A. Alhammadi, Path loss model in indoor environment at 40 GHz for 5G wireless network, in: *2018 IEEE 14th International Colloquium on Signal Processing & Its Applications (CSPA)*, 2018, IEEE, pp. 7-12.

[38] HKT, Huawei, and GSA, Indoor 5G Scenario Oriented White Paper, Huawei Version 3.0, 2019.

[39] A. Salh et al, A survey on deep learning for ultra-reliable and low-latency communications challenges on 6G wireless systems, IEEE Access 9 (2021) 55098–55131.

[40] A. Abdulraqeb, R. Mardeni, A. Yusoff, S. Ibraheem, A. Saddam, Self-optimization of handover control parameters for mobility management in 4g/5g heterogeneous networks, Autom. Control Comput. Sci. 53 (5) (2019) 441–451.

[41] A. Alhammadi, M. Roslee, M.Y. Alias, I. Shayea, A. Alquhali, Velocity-aware handover self-optimization management for next generation networks, Appl. Sci. 10 (4) (2020) 1354.

[42] M. Walker, Operators facing power cost crunch, March 27, 2020. mtnconsulting https://www.mtnconsulting.biz/product/operators-facing-power-cost-crunch, 2020.