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Predicting required licensed spectrum for the future considering big data growth

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This paper proposes a new spectrum forecasting (SF) model to estimate the spectrum demands for future mobile broadband (MBB) services. The model requires five main input metrics, that is, the current available spectrum, site number growth, mobile data traffic growth, average network utilization, and spectrum efficiency growth. Using the proposed SF model, the future MBB spectrum demand for Malaysia in 2020 is forecasted based on the input market data of four major mobile telecommunication operators represented by A–D, which account for approximately 95% of the local mobile market share. Statistical data to generate the five input metrics were obtained from prominent agencies, such as the Malaysian Communications and Multimedia Commission, OpenSignal, Analysys Mason, GSMA, and Huawei. Our forecasting results indicate that by 2020, Malaysia would require approximately 307 MHz of additional spectrum to fulfill the enormous increase in mobile broadband data demands.

KEYWORDS
big data growth, forecasting spectrum, licensed spectrum, required spectrum for future, spectrum gap

1 | INTRODUCTION

Mobile broadband has become an essential service in the lives of most mobile cellular users, which has contributed to the exponentially increase in mobile data demands [1–4]. Important factors contributing to this data demand surge are the massive and diverse developments of new portable devices such as smart phones, tablets, laptops, e-book readers, gaming consoles, and dongles, which has led to the evolution of various mobile applications covering numerous areas of a user's life; such as social and educational applications, and those relating to information, news, science, health, trading, entertainment, Internet-of-things (IoTs), and machine-to-machine (M2M) applications [5–11]. Most of these applications require a fully functional Internet service, which in turn has led to an increase in mobile data demands. Thus, regulators, industries, and operators must determine means to provide such services efficiently to meet users' demands. They need to be proactive and flexible while delivering innovative services to accommodate new mobile applications and services for customers, while accounting for a larger number of connections, higher download speeds, and high quality, as targeted in fifth-generation (5G) systems.

The growth rate of mobile data demand can be predicted through the utilization of the developed forecasting models that yield an informative perception of the general trends in MBB growth. Furthermore, forecasting is a significant tool that can be employed by direct regulators and mobile operators to examine the relevant strategies for tackling future demands of the forthcoming-required spectrum and deploying future MTOs. To this end, several forecasting models have been developed to predict mobile data traffic (MDT), and used to forecast the required licensed MBB spectrum. Some of the developed models used to forecast mobile data demands include the Delphi model [12, 13], data translation model [14], combining time series models for forecasting [15], Sungjoo Lee model [12], diffusion modeling [16], Analysys Mason model [17], GSMA model [18], and the model by István Z. Kovács et al [19]. According to the licensed MBB spectrum, which is the main focus of this study, several models have been developed to forecast the future-required spectrum [20–27]; for example, the International Telecommunication Union (ITU) model [21–23], Federal Communications Commission (FCC) model [24], Plum Insight model [25], ACMA-engaged Analysys Mason model [26], and Pyramid Research model [27]. All these models forecasted the MBB spectrum required in the future for different markets by using various input parameters and statistics.

The main challenge in using the current models to forecast the MBB spectrums required in the future is that the statistical input data in each model are different, and there are cases in which the required statistics are not available for a particular country. Thus, a new spectrum forecasting (SF) model that considers the availability of statistics from that specific country is needed. In this work, a new SF model is introduced to provide an indication of the required licensed MBB spectrum and spectrum gap for Malaysia's future. This new model is developed as a simple yet efficient predicting model based on five main input metrics: current available spectrum (CAS), site number growth (SNG), mobile data traffic growth (MDTG), average network utilization (ANU), and spectrum efficiency growth (SNG). The estimation is performed based on the input market data for four main MTOs in Malaysia, which are represented by A, B, C, and D, utilizing all available statistics from prominent bodies such as the MCMC, OpenSignal, Analysys Mason report, GSMA, and Huawei.

The rest of this paper is organized as follows. The details of the proposed model are explained in Section 2, the spectrum gap analysis is presented in Section 3, and the conclusion is summarized in Section 4.

2 | PROPOSED FORECASTING SPECTRUM MODEL

This section discusses the proposed forecasting model that can estimate the licensed spectrum required for future use. Although our proposed model is developed to estimate the spectrum needed for Malaysia, it can be applied to estimate the spectrum needed for any country, by only changing the input parameters in accordance to that specific country. To determine the requirement of additional spectrum for future mobile broadband services, the first step is to analyze the drivers of mobile traffic demand and the total available network capacity. The future spectrum needs can be mathematically defined as a function consisting of several multipliers and the current spectrum used for mobile broadband nationwide. In this work, the multipliers are generated based on the metrics that contribute directly to either the mobile traffic demand or to the network capacity. On one hand, the traffic demand depends on the data consumption by device type and the numbers of each type of device in use, which contribute to the growth of MDT. Note that the positive growth of the mobile broadband traffic demands additional spectrum. On the other hand, the network capacity can be understood as the amount of data a network can manage, which depends directly on the spectral efficiency of wireless technologies (ie, the amount of spectrum needed to transmit a given amount of data), available spectrum, utilization of the network, and number of cell sites. The improvement to any of these four input metrics will increase the network capacity, and consequently, reduce the need for additional spectrum. Figure 1 shows the general description concerning our model, which depends primarily on five metrics that affect either the mobile traffic demand or the network capacity to estimate the future spectrum need; these five metrics are defined as: SNG $(\mathcal{S}_{fy})$, MDTG $(\mathcal{M}_{fy})$, ANU $(\mathcal{U}_{cy})$, SEG (η_{fy}), and CAS $(\mathcal{W}_{cy})$, (A). The five main metrics are considered as input metrics owing to their significance for producing an accurate prediction assessment of the required spectrum. The relationship between the forecasted spectrum and these five input metrics is summarized in Table 1. The MDTG, ANU, and CAS exhibit a direct relationship, whereas the SNG and SEG demonstrate an inverse relationship with the spectrum requirement. In addition, the four metrics exhibit a direct relationship with the spectrum gap, except for CAS, which is inversely proportional to the spectrum gap.

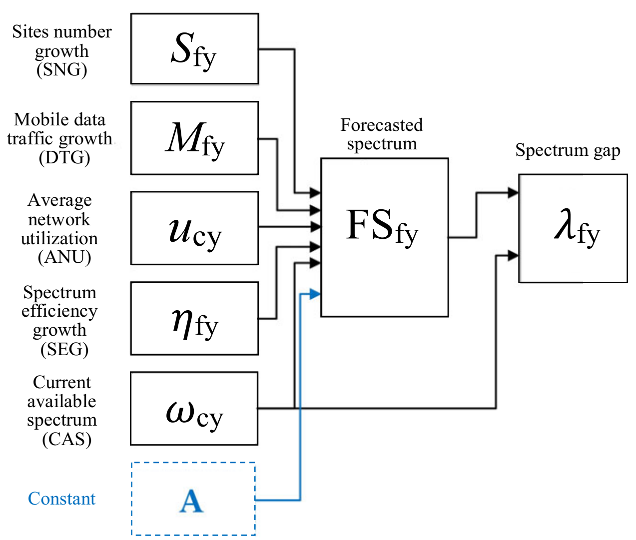


FIGURE 1 Proposed forecasting model to estimate spectrum gap

TABLE 1 Relationship between FS and input metrics

Input metrics	Action	Spectrum need in 2020	Spectrum gap
Mobile data traffic growth	Up	Up	Up
Average network utilization	Up	Up	Up
Current available spectrum	Up	Up	Down
Sites number growth	Up	Down	Down
Spectrum efficiency growth	Up	Down	Down
A	*A* is a constant metric in our study, in which was assumed to be equal to "1"		

Based on the direct and inverse relationships of the five considered input metrics, the forecasted spectrum, FS_{fy}, for any future year (fy) is mathematically formulated as in (1).

$$FS_{fy} = \frac{\mathcal{M}_{fy} \times \mathcal{U}_{cy} \times \mathcal{W}_{cy}}{\mathcal{S}_{fy} \times \eta_{fy}} A, \tag{1}$$

where a constant metric, *A*, represents other contributing parameters to the forecasted spectrum. In this work, we set *A* to 1. The constant *A* generalizes our proposed model as it provides flexibility to add or subtract the input metric based on the statistical input market specific to other countries or when a new technology must be considered; these aspects were not considered in this work.

The spectrum gap can be calculated based on the forecasted spectrum need in (1) and the CAS. It should be noted that the spectrum gap is the final output of this analysis, and it represents the amount of spectrum needed over the CAS. This value can be computed mathematically as the difference between the forecasted spectrum and the CAS, as expressed by (2).

$$\lambda_{fy} = FS_{fy} - \mathcal{W}_{cy}. \tag{2}$$

In summary, the proposed SF model mainly depends on five metrics: CAS, SNG, MDTG, ANU, and SEG. These five metrics were considered owing to their importance in forecasting the required spectrum with reasonable accuracy. The justification, details, and evaluation for these five metrics are described in the following five subsections.

2.1 | Site number growth

The site number growth is defined as the annual growing proportion of site numbers for MTOs. This growth contributes to the increase in system capacity (for fulfilling mobile data demands), which indicates that the increase in SNG reduces the spectrum gap. The SNG can be calculated as a ratio of the equivalent site numbers for the forecasted year "fy" and the current year "cy," as represented mathematically by (3):

$$\mathcal{S}_{fy} = \frac{N_{fy}^{eS}}{N_{cy}^{eS}}, \tag{3}$$

where N_{cy}^{eS} is the equivalent site number (ESN) for "cy," for example, the year 2015, while N_{fy}^{eS} is the ESN for "fy," for example, the year 2020.

The ESN for the year "cy" or "fy" can be evaluated by the formulated model in (4). The input data for this model is based on the corresponding year, which can be "cy" or "fy".

$$N_x^{eS} = \sum_{i=1}^{N_G} \left(\frac{\sum_j^{N_{nt}^{iG}} C_j^{iG}}{N_{nt}^{iG}} \frac{N_{nt}^{4G}}{\sum_j^{N_{nt}^{4G}} C_j^{4G}} \frac{N_y^{M_{iG}}}{N_y^{MT}} \frac{N_{y-1}^{ST}}{y_n} \sum_{y=y_1}^{y_n} \frac{N_y^{ST}}{N_{y-1}^{ST}} \right), \tag{4}$$

where, the parameters can be described as follows:

x	Year "cy," or "fy"
i	Technology type
N_G	Total number of technologies deployed by one operator
j	Network type, for example, network types for the third generation (3G) are HSDPA, HSUPA, and HSPA+
N_{nt}^{iG}	Total number of network types belonging to one technology
C_j^{iG}	Site capacity (system channel capacity of a cell site) for network type "*j*"
N_{nt}^{4G}	Total number of types of networks in the fourth generation (4G)
C_j^{4G}	Site capacity for network type "*j*" under 4G technology
$N_y^{M_{iG}}$	Number of mobile connections for technology "*i*" in the year "*y*"
y	Corresponding year
N_y^{MT}	Total number of mobile connections countrywide [18]
N_{y-1}^{ST}	Total number of sites for the previous year "*y* − 1"
y_n	Total number of years (last 5 years)
N_y^{ST}	Total number of sites for the year "*y*"

2.2 | Current available spectrum

The current available spectrum is the total frequency band allocated to every MTO by the regulators, such as the MCMC in Malaysia [28]. The spectrum allocated by MCMC to the four main MTOs in Malaysia, that is, A, B, C, and D, was presented in [28]. These accessible spectrums are continuously extended in order to meet the rapid increase in various mobile data services such as the Internet, video streaming, and the excessive amounts of various application services. In addition, this spectrum is a part of the total spectrum needed in the future. Re-farming of the current spectrum, especially the second-generation (2G) spectrum band, to long-term evolution (LTE) and LTE-advanced can be part of the solution for reducing the spectrum gap in the following years. Thus, the total spectrum allocation for one operator is the summation of all frequency bands allocated to that operator, as represented in (5).

$$\mathcal{W}_{\text{cy}} = \sum_{u}^{N_F} \omega_{f_u}, \tag{5}$$

where f_u is the frequency band, ω_{f_u} is the spectrum bandwidth of the frequency band "f_u," and N_F is the total number of frequency bands allocated to the corresponding operator.

2.3 | Growth in mobile data traffic

Mobile data traffic is always expanding rapidly [29] owing to several factors, as previously described in Section 1. This tremendous increase leads to the escalation of spectrum requirements in the coming years. Therefore, MDTG is considered as one of the main metrics to forecast the required spectrum and spectrum gap in the proposed SF model. The evaluation of MDTG is performed as a ratio of the annual forecasted MDT ($\mathcal{M}_{\text{FMDT}}$), for example, for 2020, to the annual current MDT ($\mathcal{M}_{\text{CMDT}}$), for example, for 2015, as represented in (6).

$$\mathcal{M}_{\text{fy}} = \frac{\mathcal{M}_{\text{FMDT}}}{\mathcal{M}_{\text{CMDT}}}, \tag{6}$$

where $\mathcal{M}_{\text{FMDT}}$ and $\mathcal{M}_{\text{CMDT}}$ represent the annual forecasted and current MDT for one operator, for example, for 2020 and 2015, respectively. These can be estimated based on historical data collected from the Analysys Mason report for the years 2012 to 2019 [17]. The estimation begins by evaluating the MDTG for the years 2012 to 2019 using the formula given in (7).

$$\beta_Y = \frac{\mathcal{M}_y^t}{\mathcal{M}_{y-1}^t}, \tag{7}$$

where β_y is the annual MDTG for Malaysia for year "y," $\mathcal{M}_y^t$ is the annual MDT for Malaysia for "y," and $\mathcal{M}_{y-1}^t$ is the annual MDT for the previous year "y – 1."

Subsequently, the average MDTG ($\bar{\beta}$) across the years 2012 to 2019 was evaluated by the formula given in (8).

$$\bar{\beta} = \frac{\sum_{y=1}^{N_y} \beta_y}{N_y}, \tag{8}$$

where N_y is the total number of years, which is seven.

From the calculated average MDTG ratio, $\bar{\beta}$, and MDT for the year 2019, $\mathcal{M}_{2019}^t$, the MDT for the year 2020, $\mathcal{M}_{2020}^t$, can be then predicted by the formula given in (9).

$$\mathcal{M}_{2020}^t = \bar{\beta} \times \mathcal{M}_{2019}^t. \tag{9}$$

Then, the annual MDT is distributed across the operators based on their capabilities, which can be evaluated as a ratio between the number of mobile connections of the operator N_{mc}^{o}, collected from the GSMA and the total number of connections in the entire country, N_{mc}^{t}. This can be expressed as in (10).

$$\mathcal{M}_y^o = \mathcal{M}_y^t \frac{N_{\text{mc}}^{\text{o}}}{N_{\text{mc}}^{\text{t}}}. \tag{10}$$

2.4 | Average network utilization

Network utilization is defined as the ratio of the actual network traffic (ANT) to the maximum network traffic (MNT) that can be handled by the site, and it is used to measure the percentage of spectrum occupation. This metric is radically increasing with the rapid boost of mobile data demands, causing further increase in spectrum needs. The actual network utilization can be obtained from the operators; however, the operators' policies make this utilization difficult to be obtained. Therefore, a new method was derived based on the current network traffic (CNT) and the MNT.

The CNT can be defined as the total data that can be simultaneously downloaded by all connected subscribers from the serving network. Thus, it can be calculated as a function of the total number of subscribers and the average equivalent download speed per subscriber. Because all the mobile subscribers are not simultaneously connected to the network, the subscriber's connection probability must be considered. Consequently, to solve this, a new parameter pertaining to the accessing network probability was introduced. Thus, the actual network traffic, $\mathcal{M}_{\text{ANT}}$, can be evaluated as a function of the total number of subscriber $\left(N_{\text{UEs}}^{\text{T}}\right)$, average equivalent download speed per subscriber $\left(B_{\text{DL}}^{\text{UE}}\right)$, and accessing network probability (F), as given in (11).

$$\mathcal{M}_{\text{ANT}} = N_{\text{UEs}}^{\text{T}} B_{\text{DL}}^{\text{UE}} F, \tag{11}$$

where, $B_{\text{DL}}^{\text{UE}}$ is the average equivalent download speed per subscriber, which represents the average value over all the technologies.

The maximum network traffic can be defined as the maximum data provided by the serving network. It can be calculated by multiplying the total number of sites by the number of sectors per site and the sector's (cell) capacity. Because the actual network consists of different technologies, and each technology has various number of sites and sectors, and differing sectors capacities, the equivalent number of sites, average number of sectors, and equivalent sector capacity values over all technologies were used to evaluate the maximum network traffic.

The equivalent number of sites of all technologies was evaluated by using (4). The average number of sectors over all technologies is assumed to be three, while the equivalent cell's capacity is proportional to the 4G cell capacity since the equivalent site number was evaluated to be equal to the 4G site. Consequently, the maximum network traffic can be simplified as shown in (12).

$$\mathcal{M}_{\mathrm{MNT}} = N_y^{\mathrm{eSO}} \overline{N_{\mathrm{sctr}}} C_{\mathrm{cell}}^{\mathrm{eq}}, \quad (12)$$

where $\overline{N_{\mathrm{sctr}}}$ is the average number of sectors over all technologies, $C_{\mathrm{cell}}^{\mathrm{eq}}$ is the equivalent cell's capacity, which corresponds to the 4G cell's capacity.

Consequently, network utilization can be mathematically represented as in (13).

$$\mathcal{U}_{\mathrm{cy}} = \frac{\mathcal{M}_{\mathrm{ANT}}}{\mathcal{M}_{\mathrm{MNT}}} = \frac{N_{\mathrm{UEs}}^{\mathrm{T}} B_{\mathrm{DL}}^{\mathrm{UE}} F}{N_{\mathrm{Y}}^{\mathrm{eSO}} \overline{N_{\mathrm{sctr}}} C_{\mathrm{cell}}^{\mathrm{eq}}}. \quad (13)$$

2.5 | Spectrum efficiency growth

The spectrum efficiency is a significant metric that is normally enhanced by nearly two times when a new technology is introduced [4] in place of a previous technology. This growth contributes to the surge in mobile data demands and in turn contributes to reducing the spectrum gap. The spectrum gap has an inverse relationship with the spectrum efficiency [20]. To estimate the SEG, η_{fy}, can be calculated as a ratio between the spectrum efficiencies of the corresponding year to the previous year; as simplified in (14).

$$\eta_{\mathrm{fy}} = \frac{\overline{\eta_{\mathrm{fy}}}}{\overline{\eta_{\mathrm{cy}}}}, \quad (14)$$

where $\overline{\eta_{\mathrm{fy}}}$ and $\overline{\eta_{\mathrm{cy}}}$ represent the average spectrum efficiencies per site over all technologies belonging to one operator for "fy," that is, 2020, and "cy," that is, 2015, respectively.

The average spectrum efficiency per site over all technologies belonging to one operator at any year can be estimated by the formula presented as (15).

$$\overline{\eta_y} = \frac{\sum_{i=1}^{N_G} \left(\overline{\eta_{iG}} N_y^{S_{iG}} \right)}{\sum_{i=1}^{N_G} N_y^{S_{iG}}}, \quad (15)$$

where $\overline{\eta_{iG}}$ is the average spectrum efficiency (ASE) for technology "*i*," while $N_y^{S_{iG}}$ is the number of sites (SN) for technology "*i*" belonging to one operator in the year "*y*".

The ASE for technology "*i*" can be calculated by the simplified formula given as (16).

$$\overline{\eta_{iG}} = \frac{\sum_j^{N_{nt}^{iG}} \eta_j}{N_{nt}^{iG}}, \quad (16)$$

where η_j is the spectrum efficiency for network type "*j*".

Furthermore, the SN for technology "*i*" can be determined by the expression given in (17).

$$N_y^S = \frac{N_y^{M_{iG}}}{N_y^{\mathrm{MT}}} \frac{N_{y-1}^{\mathrm{ST}}}{y_n} \sum_{y=y_1}^{y_n} \frac{N_y^{\mathrm{ST}}}{N_{y-1}^{\mathrm{ST}}}. \quad (17)$$

3 | SPECTRUM GAP ANALYSIS

In this section, the proposed model explained in the previous section is used to analyze the future spectrum gap required in Malaysia. First, the performance of the current mobile cellular networks is presented and discussed briefly in subsection 3.1 to provide a general overview of the performance of the deployed mobile broadband networks in Malaysia. Subsequently, the SNG, MDTG, ANU, and SEG are discussed, followed by a description of the forecasted spectrum for Malaysia in 2020.

3.1 | Mobile broadband performance

This subsection highlights current MBB performance and the actual user MBB experience in Malaysia. This contributes to illustrating the enhancements provided by the new technology in comparison to the previous one. The presented results were analyzed based on the collected data from a measurement campaign conducted between January and February 2016, using Samsung Galaxy S6 smartphones across five different morphologies (dense urban, urban, suburban, rural, and indoor) in Klang Valley, Selangor, Johor, Sabah, and Sarawak. The measurements covered two MBB services, web browsing of three distinct webpages (ie, Google, Instagram, and Mstar web pages), and video streaming of 720p low and 1,080p high resolution videos. Our MBB research gathered performance data key performance indicators (KPIs; Table 2) on three Malaysian MTOs: A, B, and C. This test measured four metrics: coverage, latency, satisfaction, and speed. The main aim of this comparison is to portray the enhancements provided by 4G over the 3G networks, neglecting data for 2G technology, as it is meager and not all 2G networks can provide mobile data.

Figure 2 shows the performance of 3G and 4G networks measured by the MBB Explorer (WEB) and Speed-Video (VIDEO). The results indicated that 4G networks perform much better than 3G networks; 4G technology has superior MBB performance to 3G technology over all KPIs. These differences were consistent across all mobile operators and

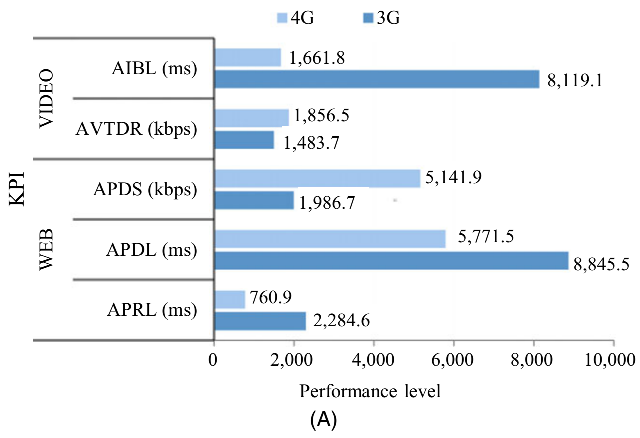
TABLE 2 Measured key performance indicators (KPIs)

Software testing application	Measured KPIs
MBB explorer (WEB)	Average page download speed (APDS)
	Average page response latency (APRL)
	Average page display latency (APDL)
	Average of PING RTT (APRTT)
Speed-video (VIDEO)	Average mobile vMOS score [30]
	Average video total download rate (AVTDR)
	Average initial buffering latency (AIBL)
	Average of average video E2E RTT ping delay (AVRTT)

are unsurprising, as we would expect consumers to experience a noticeable improvement in using a mobile broadband service over a 4G network compared to a 3G network. Even with these enhancements provided by the 4G network, on average, over all morphologies and operators, the 3G network is still the dominant network compared to both 2G and 4G networks in Malaysia, as illustrated in Figure 3. Consequently, most mobile handset subscribers do not have 4G service, especially at main roads between states, suburban areas located far from big cities, and rural morphologies. One of the main reasons for this is the unavailability of 4G coverage. Once the coverage issue is resolved, 4G will change everything. Although the 4G network can contribute to fulfilling mobile data demands, the rapid and tremendous surge in such demand may not be completely met by only upgrading all 2G and 3G networks to 4G and 4G+ networks. Additional spectra may still be needed in 2020, even with the extension of 4G coverage.

3.2 | Site number growth

The collected historical site number data from MCMC [31] were used to evaluate the site number growth, SNG. Then, SNG is used with the site capacity and the number of mobile connections, utilizing (4), to evaluate the ESN. The site number growth is presented in Figure 4, while the ESN is presented in Figure 5. The results in Figure 4 show the high SNG from 2015 to 2020 for four main operators in Malaysia. The results indicated that the SNG will continue to increase in the next few years. The predictable average SNG ratio in 2020 will reach up to 278% in comparison to 2015. The results in Figure 5 present the site numbers of three technologies, and the ESN based on the four main operators in Malaysia. The presented site numbers are for the year 2015, while the ESNs are for the year 2015 and 2020. The results confirmed that presented in Figure 3, which indicates that the 3G network is still the dominant network as compared to both the 2G and 4G networks. The results also indicated that the ESN will continue to increase in the next few years. However, the total predictable ESNs of all operators in 2020 will reach up to 191.8% in comparison to 2015. These increases in SNG and ESN will contribute to the reduction of the spectrum gap in 2020 due to the inverse relationship between SNG and the spectrum gap. Nevertheless, there is still a deficiency in the spectrum gap, which requires addressing by 2020.



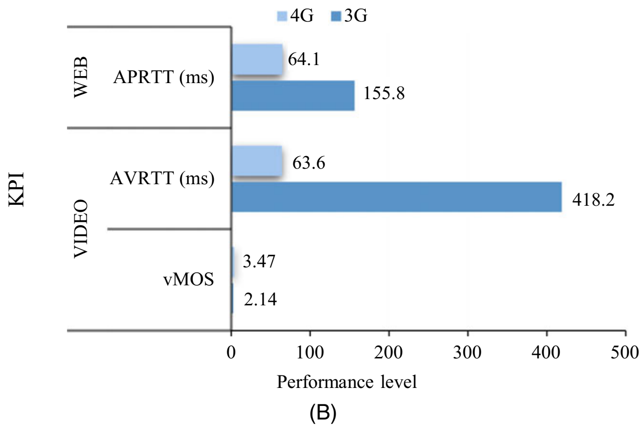


FIGURE 2 Average measured key performance indicators for 4G and 3G technologies: (A) The AIBL, AVTDR, APDS, APDL, and APRL and (B) The average ATRTT, AVRTT, and vMOS

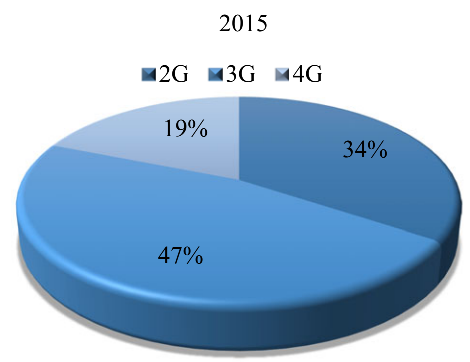


FIGURE 3 Current mobile connections in Malaysia

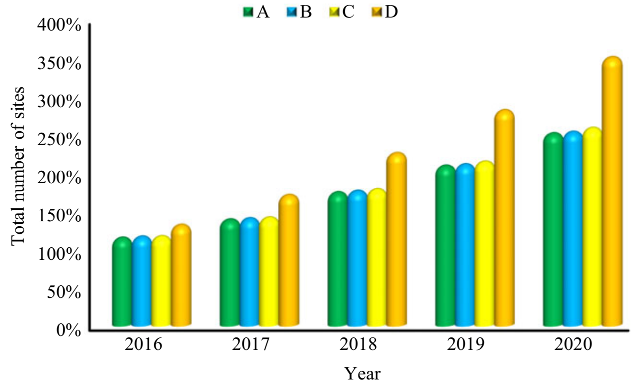


FIGURE 4 Site number growth in Malaysia

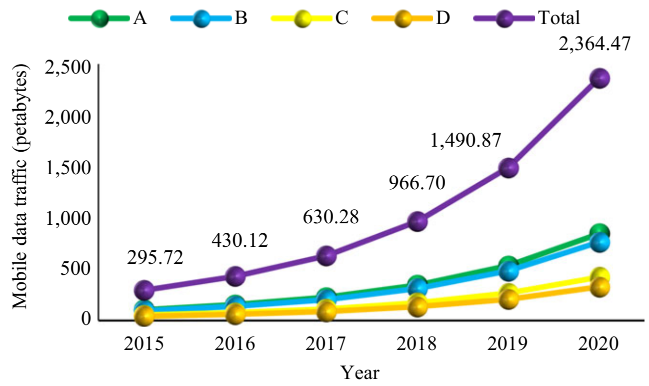


FIGURE 6 Mobile data traffic growth in Malaysia

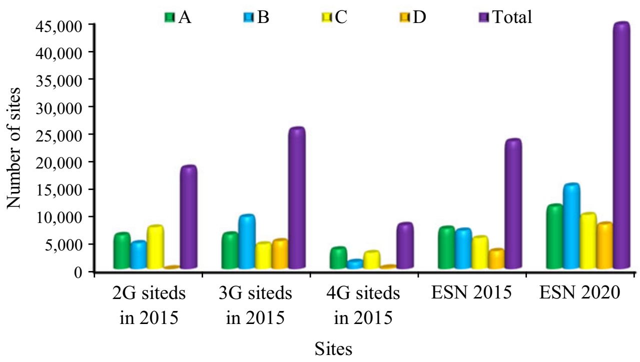


FIGURE 5 Site numbers and equivalent site numbers for various operators in Malaysia

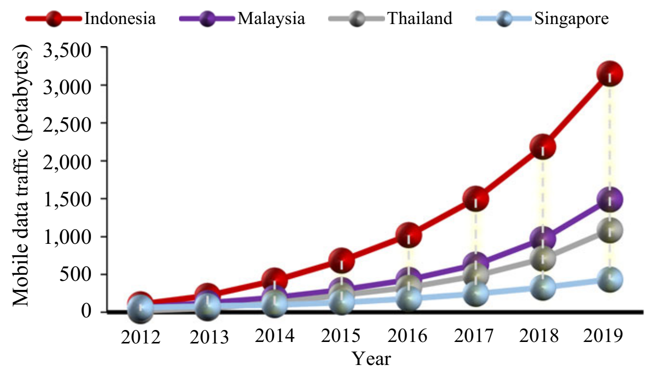


FIGURE 7 Mobile data traffic growth for Malaysia and neighboring countries

3.3 | Mobile data traffic growth

The forecasted MDT for Malaysia is discussed in this subsection. Figure 6 illustrates the increase of MDTG in Malaysia between the years 2015 and 2020. The results show that the total MDT for Malaysia is dramatically high, reaching up to 2,364.47 petabytes in 2020. That means that the total MDT is expected to increase by around eight times compared to 2015. This fast growth can be attributed to several factors; some of them mentioned in Section 1. The predicted MDTG of Malaysia is also compared to the predicted MDTG by Analysys Mason [17], of Indonesia, Thailand, and Singapore, as presented in Figure 7. From these predicted results, the average annual MDTG for Malaysia will be 159% per year, while that for Indonesia, Thailand, and Singapore will be around 164%, 183%, and 132%, respectively. These results demonstrate that the growth rates vary significantly from country to country, where Indonesia has the highest MDTG rate, followed by Malaysia, Thailand, and Singapore. In general, the significant increase in MDT will lead to the increase of the required spectrum in the future, as illustrated in Figure 8.

3.4 | Average network utilization

The ANU is also one of the significant input metrics used for forecasting the future-required spectrum in the proposed model. Figure 9 shows the relation between the forecasted spectrum and spectrum gap with the ANU. From the presented results, it can be seen that the relationship between the forecasted spectrum and spectrum gap with the ANU is a linear relationship. For example, when the ANU is around 55%, the forecasted required spectrum and spectrum gap will be 710 MHz and 280 MHz, respectively; when the ANU increases up to 95%, the forecasted required spectrum and spectrum gap will be increased to around 1,097 MHz and 796 MHz, respectively. These results show the significant effect of ANU on the forecasted spectrum and spectrum gap in the future.

3.5 | Spectrum efficiency growth

The spectrum efficiency will also keep increasing in the next few years, as illustrated in Figure 10. The results indicate that the enhancement of spectrum efficiency in 2020 will reach up to 167%, on average, over all operators. The

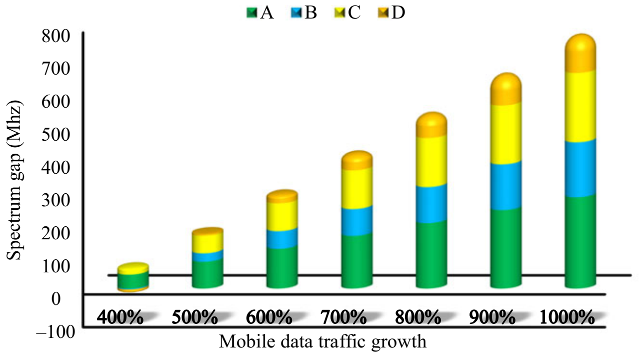


FIGURE 8 Effect of mobile data traffic growth on spectrum gap

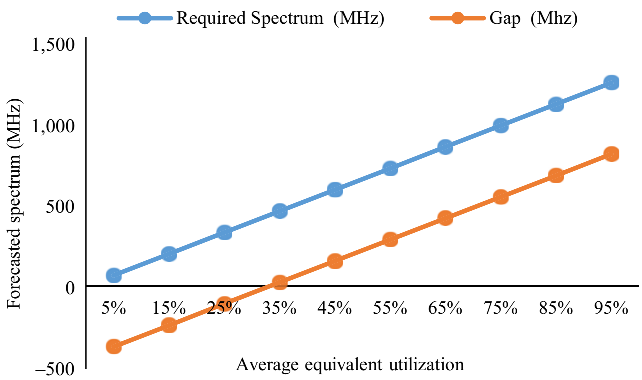


FIGURE 9 Effect of average network utilization on the proposed SM (MDTG = 300%; SEG = 100%; SNG = 100%, CAS = 430 MHz, A = 1)

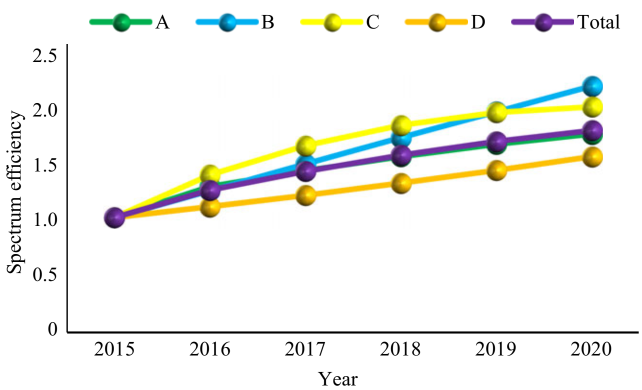


FIGURE 10 Spectrum efficiency growth in Malaysia

reason for this growth in enhancement is the continued extension and upgrading of network coverage. Figure 11 shows the predicted network coverage for all technology types; such as 2G, 3G, and 4G+. The coverage percentages are estimated based on the mobile connection number reported by GSMA for every individual technology in Malaysia. From the results in Figure 11, in 2015, 3G is still the dominant network while 4G is the less deployed network. However, in 2020, the predicted coverage

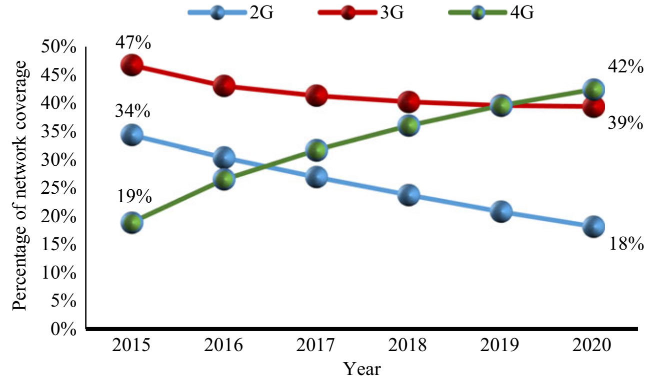


FIGURE 11 Network coverage growth in Malaysia

provided by 4G will increase up to 42% while the 2G and 3G networks will decrease to 18% and 39%, respectively. This signifies that the deployment of 4G networks in 2020 will be increased to 224% compared to 2015, while 2G and 3G will reduce to 52% and 84%, respectively, as compared to 2015. This upgrading of 4G networks is the main key to enhancing the spectrum efficiency up to 1.67 times compared to 2015. This enhancement in the spectrum efficiency will contribute to fulfilling future data demands, which will also lead to the reduction in the spectrum gap.

3.6 | Forecasted spectrum

The forecasted spectrum is the total spectrum required in the future to fulfill the users' data demand. This is forecasted for Malaysia in 2020 based on the proposed SF model, utilizing (1). Then, the spectrum gap was calculated using (2). Here, the spectrum gap analysis is conducted using the input data of the four main MNOs in Malaysia, which account for approximately 95% of the Malaysian mobile market share [18]. The prediction was executed for every individual operator, and then the total forecasted spectrum was combined to present the entire spectrum required for Malaysia.

Figure 12 shows the forecasted spectrum needed for the years 2016 and 2020 by the proposed model. These results were presented to prove the validity of the proposed model. From the presented results, it can be seen that the forecasted required spectrum by our mode for the years 2016, 2017, and 2018 are still less than that allocated by MCMC [32]. However, the actual allocated spectrum by MCMC in Malaysia for the years 2016, 2017, and 2018 is 650 MHz [32]. This allocated spectrum is still sufficient at the moment, even though part of it has not been used. Since the forecasted spectra for these 3 years are less than that allocated by MCMC, the proposed model seems to be more accurate, which gives an indication of the validity of our model.

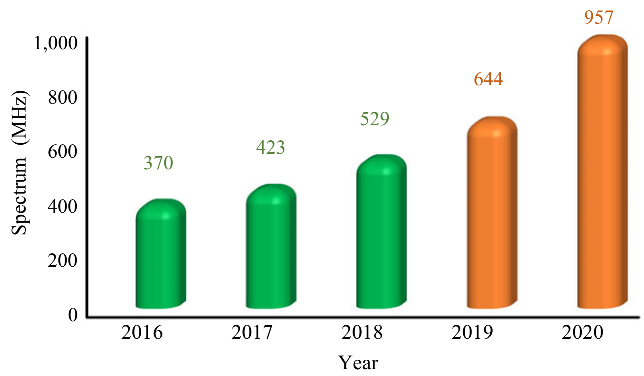


FIGURE 12 The forecasted spectrum for mobile broadband in Malaysia (2016-2020)

TABLE 4 Spectrum gap analysis for three neighboring countries to Malaysia from other sources

Country	Current spectrum (MHz)	Forecasted required spectrum (MHz)	Spectrum gap (MHz)	Period
Singapore	450	900	450	2015 and 2020 [32]
Thailand	390	800	410	2015 and 2020 [32]
Indonesia	547	1,172	625	2015 and 2020 [27]

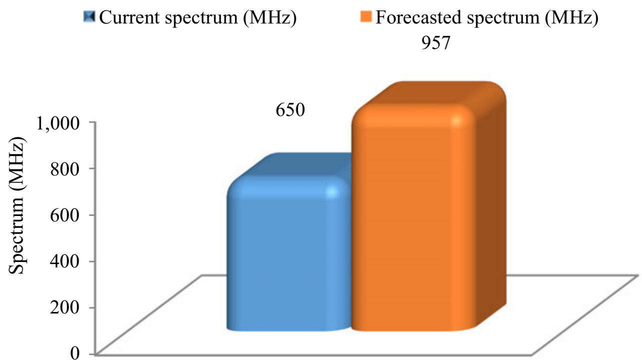


FIGURE 13 The current and forecasted spectrum for mobile broadband in Malaysia

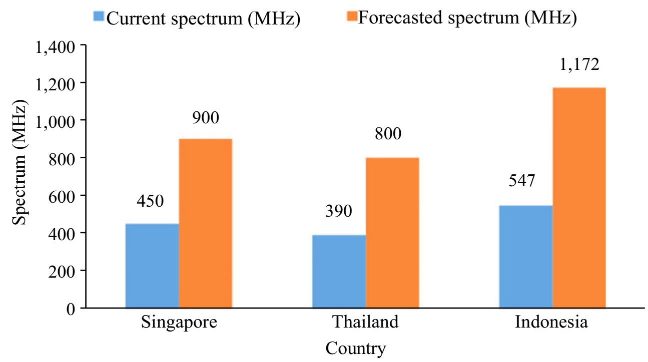


FIGURE 14 The current and forecasted spectrum in 2015 and 2020, for Malaysia's neighboring countries, Singapore, Thailand, and Indonesia

TABLE 3 Key result of the spectrum gap analysis for Malaysia

Country	Current spectrum (MHz)	Forecasted required spectrum (MHz)	Spectrum gap (MHz)	Period
Malaysia	650*	957	307	2015 and 2020

*650 MHz is the total spectrum allocated to all MNOs in Malaysia.

Figure 13 shows the current available spectrum, CAS, and the required spectrum needed in 2020 for Malaysia. In 2017, the total current available spectrum for MBB in Malaysia is 650 MHz. Based on this current value and utilizing the developed model, the forecasted required spectrum for MBB in Malaysia by 2020 will reach up to 957 MHz. Consequently, by 2020, Malaysia will need around 307 MHz of additional spectrum to fulfill the high increase in data demand. This provides the spectrum gap of 307 MHz. These results are summarized in Table 3.

From another study adopting a different prediction model, conducted by Pyramid Research, the spectrum gap for Malaysia's neighboring countries (Singapore, Thailand, and Indonesia) in 2020 are 450 MHz, 410 MHz, and 625 MHz, respectively. These spectrum analysis results are illustrated in Table 4. The current and forecasted spectrum for Singapore, Thailand, and Indonesia in 2015 and 2020 are plotted in Figure 14.

This big spectrum gap is becoming a serious issue which requires consideration by regulators (eg, MCMC in Malaysia), vendors, and operators, to establish the best solution that can fulfill the data demands of 2020.

4 | CONCLUSION

In this study, a new forecasting spectrum model is proposed to estimate the spectrum gap depending on five main input metrics (CAS, SNG, DTG, ANU, and SEG) and one constant metric. The constant metric can be replaced by a new metric that can represent the technological changes in the future or any other effective metric in any another country. This model is then used to estimate and analyze the spectrum gap for Malaysia by 2020 by utilizing input data for four major MTOs in Malaysia. Based on these estimations, Malaysia needs around 307 MHz of additional spectrum to fulfill the tremendous increase in future mobile data demand. The crucial need of the spectrum gap is becoming a serious issue, which must be addressed to fulfill the anticipated data demand. Meeting these data requirements can be achieved by either finding a potential spectrum band, off-loading MDT to unlicensed bands, increasing site number growth, or enhancing spectral efficiency growth. The main limitations in this developed model can be the collection of input data from various accurate resources. However, some of the operators and developers will not easily share their historical data with academic researchers.

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