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Indonesian Spectrum Valuation of 5G Mobile Technology at 2600 MHz, 3500 MHz, and 26 GHz and 28 GHz

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Abstract**—**Spectrum valuation is necessary to help regulators set up new technology regulations to overcome specific conditions, such as area-particular treatment in industrial estates, to support vertical industries with wider spectrum bands and various frequencies. This paper delivers the results of a study on spectrum band valuation at various frequencies to speed up Indonesia's Industry 4.0. This work utilised a case study of industrial estates in Jakarta, Indonesia's capital, and research on the impact of frequency bands at 2600 MHz, 3500 MHz, 26 GHz and 28 GHz on three factors of an economic engineering model: Factor 1, the engineering side to maximise fifth generation (5G) cellular coverage; Factor 2, the economic side for a financial aspect in terms of capital expenditures (CAPEX) and operating expenditures (OPEX) per square kilometre and Factor 3, the economic side for spectrum value per MHz per population. This paper will be helpful for both mobile network operators (MNOs) and regulators. For MNOs, this study provides perceptions about spectrum valuation methods and provides data on the value of various frequencies in 5G. For regulators, it provides perceptions of the economic value of various frequencies in 5G, which aids in the assignment of costs for spectrum licenses and the establishment of reserve prices and intended budgets for future spectrum auctions. This work found that using 26 GHz/28 GHz (mmWave) for 5G services necessitates a greater investment in infrastructure than using 2600 MHz and 3500 MHz (midband). In the midband and mmWave bands, the population density has a major impact on the spectrum valuation for 5G.

Index Terms**—**5G, spectrum valuation, 5G mmWave, 5G midband, 5G CAPEX and OPEX, engineering-economic model

I. INTRODUCTION

In 2018, 3GPP Release 15 became the first comprehensive radio network for the fifth generation (5G) mobile technology standard. This network promised a low latency of less than 1 ms, low cost and low power consumption. The peak data throughput was predicted to be 10 gigabits per second (Gbps), with support for up to 20 Gbps under certain scenarios with an operating spectrum in the low, mid and mmWave band [1]. 5G usage scenarios described by the International Telecommunication Union Radiocommunication Sector (ITU-R) include an improved mobile broadband, ultra-reliable and low-latency communications and massive machine-type communications. Not only may 5G be used for human-to-human communication, but it can also be used for human-to-machine and machine-to-machine communication, making 5G particularly helpful in industrial scenarios in the future.

5G will transform the industry into a smart environment, with 5G serving as the critical infrastructure for the Industry 4.0. Smart manufacturing, autonomous drones, safety and security, smart logistics, augmented reality (AR)/virtual reality (VR), smart healthcare, smart homes, smart energy and smart transportation are all examples of things that can become specific, measurable, achievable, relevant, and time-bound (SMART).

As the world's fourth-largest market, Indonesia is a key market for 5G [2], particularly in the industrial sector. Indonesia has a potential 5G market: it has 25 large container terminals in 17 cities; 28 international airports; a booming oil and gas industry, which ranks 10th in the world in terms of natural gas production with a production share of 6.7 percent, and 98 industrial estates across the country [3].

Indonesia has the world's fourth-largest population at around 264.16 million people and a land mass of almost 2 million km^2 divided into 13,000 islands. The country's population is not uniformly distributed over its topography, with roughly 60% of the population concentrated on Java Island and 20% on Sumatra Island [4].

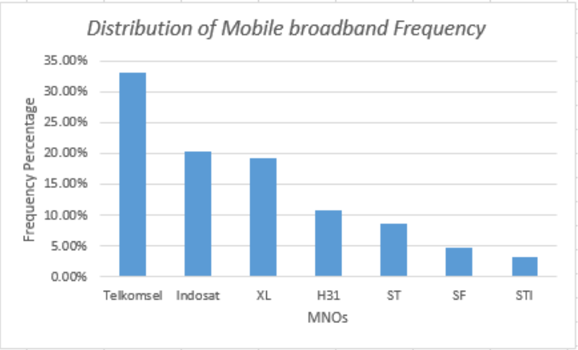

Fig. 1. Mobile broadband frequency allocation for MNOs in Indonesia [5].

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PT Telkomsel, PT XL Axiata (XL), PT Indosat, PT Hutchison 3 Indonesia (H3I), PT Smartfren (SF), PT Smart Telecom (ST) and PT Sampoerna Telekomunikasi Indonesia (STI) are among the licensed Indonesian mobile network operators (MNOs). The frequency distribution of mobile broadband in Indonesia is depicted in Fig. 1 [5].

Human-related applications, scarcity and the development or utilisation circumstances all influence the value of the spectrum frequency band resource [6]. Spectrum valuation is crucial for regulators to design new technological standards to address new conditions and ascertain area services, such as industrial estates with a wider spectrum band.

Researchers have proposed adjustments to engineering-economic models from prior research [7]–[9] to estimate 5G spectrum values to boost broadband expansion in industrial locations for accelerating Industry 4.0. In previous research [9], researchers did an initial analysis on the valuation of the mmWave spectrum for 5G technology. This study only investigated mmWave frequencies with relatively limited capital expenditures (CAPEX) and operating expenditures (OPEX) parameters. In the current investigation, the researchers included two midband frequencies, 2600 MHz and 3500 MHz. The addition of these frequencies was intended to extend the possibilities for the valuation of spectrums that will become frequency candidates used by MNOs in Indonesia.

Herein, we report our work on a valuating spectrum for helping regulators set up 5G technology regulations to overcome specific conditions and ascertain area services in industrial estates to support vertical industries with larger spectrum bands and various frequencies.

Therefore, we constructed a new approach by merging various frequency bands of 2600 MHz and 3500 MHz (midband) and 26 GHz and 28 GHz (mmWave) on three variables of an engineering economic model. The first uses 5G maximum coverage, the second uses the propagation model based on 3GPP 38,901 in the frequency range between 0.5–100 GHz and 5G CAPEX and OPEX per km^2 and the last model is the spectrum value per MHz population for industrial estates in Jakarta because industrial estates in the area have become a role model in the application of mobile broadband technology. Furthermore, practically all of these areas are classified as dense urban or urban.

The following sections comprise the document. The introduction to 5G is covered in Section II. Section III is concerned with engineering-economic and parameter scenarios. Section IV is devoted to a discussion of the findings. Section V brings the research to a conclusion.

II. 5G INTRODUCTION

The fifth generation of mobile communication systems is referred to as 5G. Aside from the present network, this generation is part of the next major phase of the mobile telecommunications standard, which will follow the ITU-R communications standards for International Mobile Telecommunications (IMT)-2020. In comparison to current technologies like Long-Term Evolution (LTE), 5G has significantly better throughput. As a result, this enables the deployment of cutting-edge wireless services [10].

The user experience data rate (Mbps), peak data rate (Gbps), mobility (km/h), latency (ms), network energy efficiency, traffic capacity (Mbit/s), connection density (devices/km^2) and spectrum efficiency are the eight parameters of IMT-2020 capability (Fig. 2).

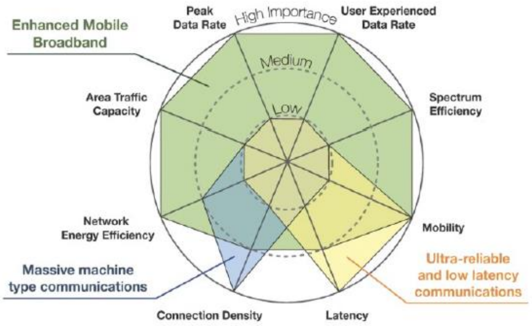

Fig. 2. The eight parameters of IMT-2020 capability [10].

The primary spectrum alternatives towards 5G in its first stage around the world are around 2.6 GHz, 3.5 GHz and mmWave at 26 GHz and 28 GHz with time division duplex (TDD) technology. This is the upcoming generation of technology aimed at improving the service transmission speed and consequently bringing through innovative new services in the vertical industrial sphere.

5G Usage Scenario

The IMT-2020 usage scenarios for 5G are enhanced mobile broadband (eMBB), ultra-reliable and low-latency communication (uRLLC) and massive machine type communication (mMTC). All capabilities may be important to some extent in most usage circumstances. The importance of individual critical competencies, however, can change dramatically depending on the circumstances. The significance of each important parameter for eMBB, uRLLC and mMTC is depicted in Fig. 2. The 5G usage scenario is depicted in Fig. 3.

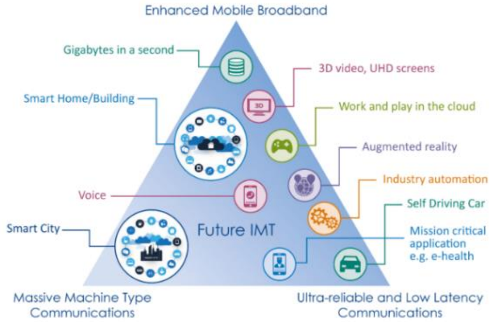

Fig. 3. 5G usage scenarios [10].

Different Frequency Band Options in 5G

5G New Radio (NR) is a mobile broadband technology that can deliver multi-Gbps data rates by leveraging different frequencies from the low band, midband and mmWave (high) band as a way of generating capacity. Fig. 4 depicts the 5G radio spectrum coverage and services in various coverage locations [11].

Low band:

This spectrum is at a frequency lower than 1 GHz to enable widespread 5G coverage. There are 700 MHz, 800 and 900 MHz for this frequency band.

Midband:

A higher frequency spectrum between 1 and 6 GHz that gives the capacity required to assist an enormous amount of linked equipment while also allowing for faster rates for devices connected together. This frequency band has the following frequencies: 1800 MHz, 2100 MHz, 2300 MHz, 2600 MHz, 3300 MHz and 3500 MHz.

High band (mmWave):

This spectrum has an enormous bandwidth, a small coverage area, minimal latency and increased capacity at frequencies above 24 GHz [11]. These bands have frequencies of 26000 MHz and 28000 MHz.

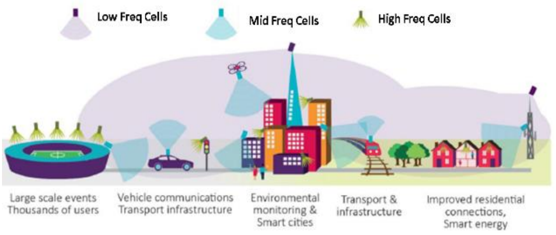

Fig. 4. Different frequency band options and their coverage in 5G [11].

The Indonesian Telecommunication Regulator determines the frequency band candidates to be used for IMT-2020 or 5G [12], [13]. Table I shows the 5G frequency band candidates in Indonesia. The bands were chosen from several factors. The primary factor is the worldwide frequency band test ecosystem and the availability of the equipment utilised by MNOs.

TABLE I: CANDIDATES FOR 5G FREQUENCY BANDS IN INDONESIA

NR operating band	Frequency band (MHz)	Potential bandwidth (MHz)
n28	700	90
n40	2300	90
n41	2600	190
n77	3300	100
n78	3500	200
n258	26000	2750
n257	28000	2500

Pulogadung Industrial Estate

The Pulogadung Industrial Estate is an area where the processing industry is concentrated and is equipped with infrastructure, amenities and other sustaining facilities administered by an Industrial Estate Company located in Pulogadung.

The Pulogadung Industrial Estate is located at 6° 11 54, 106°545 in East Jakarta City, DKI Jakarta Province. This area reflects the regional government's implementation of industrial operations combined in a particular area with the goal of ensuring that the growth of industrial zones is not excessively spread out across various parts of the city. The Pulogadung Industrial estate is intended to be a green industrial development.

PT Jakarta Industrial Estate Pulogadung (JIEP) is a BUMN/BUMD company owned equally by the Indonesian government and the regional government of DKI Jakarta Province. JIEP is the developer and manager of the Pulogadung Industrial Estate, a 500 ha integrated industrial estate. Fig. 5 shows the Pulogadung Industrial Estate [14].

Fig. 5. Pulogadung industrial estate [14].

III. RESEARCH METHOD

A. *Engineering-Economic Models and Parameters Scenario*

The engineering analysis side of this study used coverage planning for the 5G NR network, which will take place in a Jakarta industrial estate. In this study, the frequency bands n41, n78, n257 and n258 were used as possible frequency bands. The coverage computation then used the maximum permitted path loss value and maximal cellular coverage.

The economic analysis side of this study calculated CAPEX and OPEX input parameters to generate the net present value (NPV) output and spectrum value per MHz per population.

In the next part, three engineering-economic model parameters will be discussed:

Factor 1, the engineering side to maximise cellular coverage.

Factor 2, the economic side for financial aspect in terms of CAPEX and OPEX per km^2.

Factor 3, the economic side to determine the spectrum value per MHz per population.

Factor 1: The engineering side to maximise cellular coverage

The maximum cellular coverage is the farthest distance that the approved signal intensity can cover from the cell site's centre to cellular devices.

Data gathering of the suggested link budget assumptions for the 5G NR network was carried out to obtain the maximum distance between the cell and the user terminal (UT) or cellular devices.

The 3GPP 36,901 propagation model was used to calculate the link budget assumption data. This model was applied to frequency ranges from 2–6 GHz and was then expanded to 0.5–100 GHz for urban macrocell (UMa), urban microcell (UMi), indoor hotspot (InH) and rural macrocell (RMa) [15]–[17].

The propagation models used in this study were (1) to (4):

3D-UMi Line of Sight (LOS) Propagation Model

$$PL = 40\log_{10}(d_{3D}) + 28.0 + 20\log_{10}(fc) - 9\log_{10}((d'_{BP})^2 + (h_{BS} - h_{UT})^2) \quad (1)$$

3D-UMi Non-Line of Sight (NLOS) Propagation Model

$$PL3D\text{-}UMi\text{-}NLOS = 36.7\log_{10}(d_{3D}) + 22.7 + 26\log_{10}(fc) - 0.3(h_{UT} - 1.5) \quad (2)$$

InH LOS Propagation Model

$$PL_{\text{InH-LOS}} = 32.4 + 17.3\log_{10}(d_{3D}) + 20\log_{10}(f_c) \quad (3)$$

InH NLOS Propagation Model

$$PL'_{\text{InH-NLOS}} = 38.3\log_{10}(d_{3D}) + 17.30 + 24.9\log_{10}(f_c) \quad (4)$$

where LOS/NLOS represent line of sight/non-line of sight, PL represents path loss, fc denotes the frequency centre (Hz), c = $3*10^8$ m/s represents the propagation velocity in free space, h'_{BS} and h'_{UT} denote the effective antenna heights at the base station (BS) and UT and d3D signifies the resultant distance between h_{BS} and h_{UT} (m).

The radio link budget parameter principle from the central site to the user terminal is depicted in Fig. 6. The radio link budget parameters for calculating the farthest distance between the cell site's centre and the cellular equipment are shown in Table II [15], [16], [18], [19].

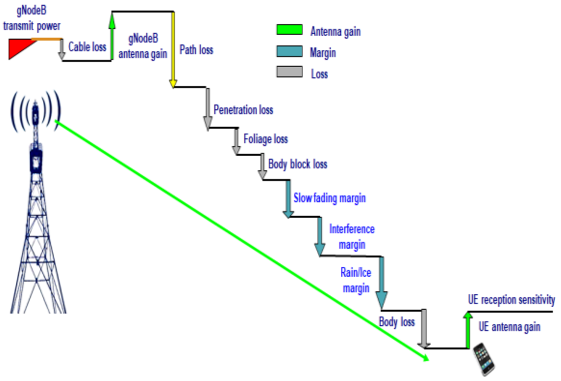

Fig. 6. Radio link budget principle [15], [16].

TABLE II: SYMBOLS, PARAMETERS AND VALUES FOR 5G RADIO LINK BUDGET [15], [16], [18], [19]

Symbols	***Parameters***	***Midband***	***mmWave***
A	*gNB transmitter power* (dBm)	49	49
B	*Resource block (RB)*	273	132
C	*Subcarrier quantity*	3276	1584
D	*gNB antenna gain (dBi)*	2	2
E	*gNodeB cable loss(dBi)*	0	0
F	*Penetration loss (dB)*	22	38
G	*Foliage loss (dB)*	19	19
H	*Body block loss (dB)*	8	15
I	*Interference margin (dB)*	6	1
J	*Rain//ice margin (dB)*	0	3
K	*Slow fading margin (dB)*	8	8
L	*User Terminal antenna gain (dB)*	0	0
M	*Bandwidth (MHz)*	100	100
N	*Boltzmann constant (mWs/K)*	$1{,}38 \times 10^{-20}$	$1{,}38 \times 10^{-20}$
O	*Temperature (Kelvin)*	293	293
P	*Thermal noise power (dBm)*	-153,93	-153,93
Q	*User Terminal noise (dB)*	9	9
R	*Demodulation threshold SINR (dB)*	-3	-3

As shown in Table II, the path loss equation is as follows:

$$\text{Path loss (dB)} = A - 10 \times \log_{10}(C) + D - E - F - G - H - I - J - K + L - P - Q - R \quad (5)$$

Cellular coverage is a crucial cost consideration since the cost of infrastructure is comparable to the number of required cell sites. The scenario parameters for determining cell coverage are shown in Table II [15]–[18].

Factor 2: The economic side for the financial aspect in terms of CAPEX and OPEX/km²

This section details the economic model investigated for a non-virtualised 5G infrastructure for Indonesia's MNOs. The costs of installing and maintaining a cellular network can be calculated as OPEX and CAPEX [8], [17], [20]-[22].

The Capex component is denoted as follows:

$$CAPEX_i = CCells_i + CBackhaul_i + CCore_i \quad (6)$$

$$CCells_i = Cmicro_{cells} + Cpico_{cells} + Cmicro_{build} + Cpico_{build} \quad (7)$$

where $CAPEX_i$ represents the total of all CAPEX charges for every resource cell deployment, including devices, design and installation ($CCells_i$). The researchers only considered 5G microcell and 5G picocell expenditures in their work, and fibre optics-only backhaul for 5G transport (C*Backhauli*) and 5G core network expenditures (C$Core_i$).

The following is a definition of the OPEX component:

$$OPEXi = OCellsi + OBackhauli + BHP\text{-}F + TEi \quad (8)$$

$$OCells_{i} = Omicro_{cells} + Opico_{cells} + Omicro_{build} + Opico_{build} \quad (9)$$

where $OPEX_i$ is the aggregate of all OPEX charges for all property cells ($OCells_i$). The researchers mainly considered 5G microcell and picocell optical fibres just for backhaul ($OBackhaul_i$) in 5G transport, 5G core expenses (OCorei), tower and electricity rental (TEi) and Biaya Hak Penggunaan Frekuensi (BHP-F) or spectrum license fee in this paper.

Cost per cell is the yearly total cost of one cell, which includes both CAPEX and OPEX charges. It is necessary to calculate the CAPEX investments at a yearly interest rate of i over Y years [23], [24]:

$$\boldsymbol{Cost_{per\,cell} = CAPEX * \frac{i(1+i)^{Y}}{(1+i)^{Y}-1} + OPEX} \quad (10)$$

This paper modelled hexagon shapes for cell coverage and estimated the price per km^2 [11]-[15], [21]:

$$Cost_{per\,km^2}(f) = \frac{Cost_{per\,cell}}{Area_{per\,cell}} = \frac{Cost_{per\,cell}}{2.6 * r_{max}(f)^2} \quad (11)$$

Currently, the expenses for 5G equipment are kept private. However, the cost of 5G network equipment with improved performance is likely to be comparable to that of previous technology.

Table III shows the annual CAPEX and OPEX assumption parameters [5], [11], [21], [17].

TABLE III: CAPEX AND OPEX ASSUMPTION PARAMETERS

Parameters	Symbols	Nominal (Kilo IDR)
Core network	*core*	IDR 2.250,000,000
Micro-cell equipment	$Cmicro_{cell}$	IDR 550.000.000
Pico-cell equipment	$Cpico_{cell}$	IDR 550.000.000
Micro build insertion cost	$Cmicro_{build}$	IDR 137,500,000
Pico build insertion cost	$Cpico_{build}$	IDR 137,500,000
Backhaul insertion	$CBackhaul_{insert}$	IDR 100,000,000
Micro-cell site maintenance	$Omicro_{cell}$	IDR 55,000,000
Pico-cell site maintenance	$Opico_{cell}$	IDR 55,000,000
Backhaul site maintenance	$OBackhaul$	IDR 30,000,000
Number of backhaul	NBH	2
Spectrum license fee 2.6 GHz	BHP-F	IDR 887,781,440
Spectrum license fee 3.5 GHz	BHP-F	IDR 831,004,720
Spectrum license fee 26 GHz	BHP-F	IDR 439,282,220
Spectrum license fee 28 GHz	BHP-F	IDR 439,282,220
Loan duration	Y	10 years
Interest rate	i	3.5%

Factor 3: The economic side for spectrum value per MHz population

In spectrum pricing, the fundamental denomination used to describe spectrum value is $(dollars)/MHz (spectrum bandwidth) - population (POP; a resident of the spectrum license coverage region).

The present value of the advantages that MNOs can acquire from the spectrum are like their present value, and the yearly net present value (NPV) is similar to the yearly net return on earnings minus the yearly cost [17], [23].

$$\begin{aligned} &\text{Value (f)} = \text{NPV yearly (f)} \\ &= \text{Area} * (\text{Revenue}_{\text{per km}}{}^{2} - \text{Cost}_{\text{per km}}{}^{2}\text{ (f))} \\ &= \text{Area} * (\alpha * \mu\text{POP} - \text{Cost}_{\text{per km}}{}^{2}\text{ (f))}. \end{aligned} \quad (12)$$

where μPOP denotes people who live in the spectrum licensing-covered region. The yearly revenue is comparable to μPOP, and the population density factor in the area is as follows:

$$\$/\text{MHz} - POP(f) = \frac{\alpha * \mu_{POP-}\, Cost_{per\,km^2}(f)}{Bandwidth * \mu_{POP}} \quad (13)$$

Factor α can be acquired from Equation (14) if the spectrum band and Indonesia currency (IDR)/MHz-POP of a frequency at reference frequency f_0 are acquainted, and the IDR/MHz-POP of the spectrum band at any other frequency in the same frequency range can be accomplished with Equation (14):

Equation (14) can be used to calculate the α factor if the spectrum band and IDR/MHz-POP of a frequency at reference frequency f_0 are known, and Equation (14) can be used to calculate the IDR/MHz-POP of the spectrum band at any other frequency in the equal frequency range.

$$\frac{\$/\text{MHz}-POP(f)}{\$/\text{MHz}-POP(f_0)} = \frac{\alpha * \mu_{POP-}\, Cost_{per\,km^2}(f)}{\alpha * \mu_{POP-}\, Cost_{per\,km^2}(f_0)} \quad (14)$$

TABLE IV: 5G BAND, REFERENCE FREQUENCY, BANDWIDTH

5G Band	Reference Frequency f_0 (GHz)	Bandwidth (MHz)
n41	2.6	100
n78	3.5	100
n258	26	1000
n257	28	4500

Table IV [23]–[25] displays the 5G band, bandwidth, reference frequency and $/MHz-pop values. The $/MHz-pop values for 2.6 GHz, 3.5 GHz, 26 GHz and 28 GHz are derived from benchmark auction data.

The auction benchmarks in South Korea are 3.5 GHz and 28 GHz, Thailand's is 2.6 GHz and Italy's is 26 GHz. Thailand has a population density of 153.7 people per km^2, South Korea has a density of 531.4 and Italy has a density of 201,3 [25]–[27].

IV. RESULT

The input parameters for the discussion of the results can be seen in Tables III–V. Fig. 7–Fig. 9 show the findings of a 3D propagation model at 2.6 GHz and 3.5 GHz for midband and 26 GHz and 28 GHz for mmWave.

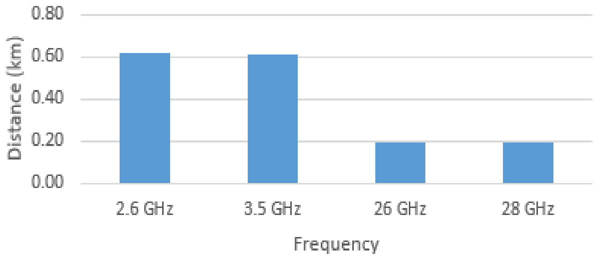

Fig. 7. Results of Factor 1: The engineering side to maximise cellular coverage vs. frequency.

From the mmWave to the midband, Fig. 7 displays the 5G maximal cellular coverage cell (m). The maximum cell coverage diminishes as the frequency band increases. For mmWave, the highest cellular coverage cells are 194.78 meters at 28 GHz and 195.60 meters at 26 GHz. The highest cellular coverage cells at the midband frequencies of 2.6 GHz and 3.5 GHz are 617.42 meters and 608.10 meters, respectively. As a result, the lower the frequency band, the larger the maximum cellular cell coverage, the fewer cell sites allowed to fulfil the region, and the less cell coverage required.

As a result, if the frequency band is higher, MNOs will need to make significant investments to maintain and install the cellular network within the target area. As a result, as the frequency range widens, the cost of cellular network infrastructure is projected to climb.

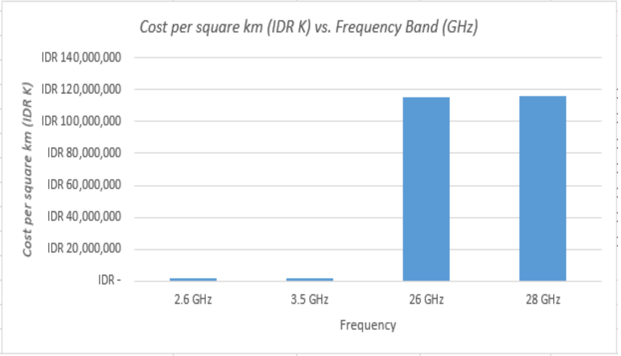

Fig. 8. Results of factor 2: Cost per km^2 vs. frequency band (GHz).

TABLE V: COST PER KM^2 VS. FREQUENCY BAND

Cost Per km (IDR K) vs. Frequency (GHz)		
Frequency	Cost per cell	Cost per km^2
2.6 GHz	IDR 3,586,018	IDR 1,904,260
3.5 GHz	IDR 3,529,242	IDR 1,931,981
26 GHz	IDR 21,777,502	IDR 115,222,969
28 GHz	IDR 21,777,502	IDR 116,092,732

Fig. 8 and Table V show the CAPEX and OPEX per km^2 from the mmWave frequency band to the midband frequency in kilo Rupiah or IDR. According to projections, the mmWave frequency range will cost MNOs more than this to install and maintain than the midband frequency in the Pulogadung Industrial Estate. Fig. 8 depicts the increasing tendency for infrastructure expenses to rise from 2.6 to 28 GHz.

Fig. 9 shows the spectrum value IDR/MHz population versus the mmWave frequency band (26 GHz and 28 GHz) to the midband frequency (2.6 GHz and 3.5 GHz). The midband frequency (2.6 GHz and 3.5 GHz) indicates that the appraised spectrum value is higher than the mmWave frequency band (26 GHz and 28 GHz). The cost variations for the spectrums at the two frequency band ranges evaluated were IDR 4,538.96 and IDR 4.363.98 for midband frequency and IDR 3,933.04 and IDR 2,545.70 for mmWave, respectively (Fig. 9). For 5G spectrum valuation, Fig. 9 demonstrates that the midband frequency band is higher than the mmWave frequency band.

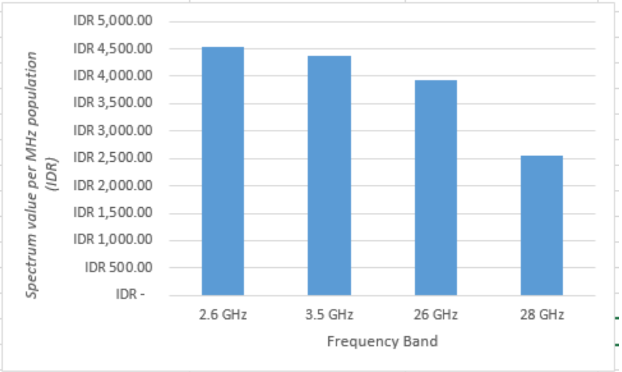

Fig. 9. Results of factor 3: Frequency band in GHz vs spectrum value per MHz population in IDR

V. CONCLUSION

In a case study of Indonesian industrial estates, this study amended previous research to recommend the economic valuation of 5G spectrum at midband and mmWave for accelerating broadband growth. We applied engineering-economic modelling depending on three factors: the engineering side to maximise cellular coverage; the economic side for financial aspects in terms of CAPEX and OPEX per km^2 and the economic side for spectrum value per MHz per population.

For location-specific services, such as in industrial estates in Jakarta, spectrum frequencies of 2600 MHz, 3500 Mhz, 26 GHz and 28 GHz were investigated. In most cases, as the frequency band lowered, MNOs' installation and operation costs lowered as well, even though the spectrum valuation IDR/MHz-POP increased. In conclusion, mmWave deployment for enhanced cellular broadband services requires greater infrastructure expenses. Population density, on the other hand, has a significant impact on spectrum valuation, not only in the midband frequency regions, but also in the mmWave frequency bands.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Alfin Hikmaturokhman wrote the paper cooperatively. Kalamullah Ramli and Muhammad Suryanegara provided recommendations about the paper and checked the paper. All authors approved the final version.

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REFERENCES

[1] G. Barb and M. Otesteanu, "4G/5G: A Comparative Study and Overview on What to Expect from 5G," in *Proc. 43rd International Conference on Telecommunications and Signal Processing*, 2020, p. 37.

[2] S. Muhammad, "Managing 5G technology: Using Quality of Experience (QoE) to identify the innovation enhancement pattern according to the Indonesian Market," *IEEE Access*, vol. 8, pp. 165593-165611, 2020.

[3] Kementrian Perindustrain RI, Kajian Infrastruktur Digital Nasional 2019, 2019.

[4] H. Alfin, K. Ramli, and M. Suryanegara, "On developing a new 5G spectrum usage fee model for Indonesia," *International Journal on Advanced Science Engineering Information Technology*, vol. 9, no. 6, pp. 1968-1975, 2019.

[5] Kemenkominfo, "Rencana Strategis 2020-2024 Kementerian Komunikasi dan Informatika"

[6] I. K. Rohman and E. Bohlin, "An assessment of mobile broadband access in Indonesia: A demand or supply problem?" *Internetworking Indonesia Journal*, vol. 3, no. 2, pp. 15-22, 2011.

[7] Y. Wei and S. H. Hwang, "Investigation of spectrum values in rural environments," *ICT Express*, vol. 4, no. 4, pp. 234-238, 2018.

[8] C. Bazelon and G. McHenry, "Spectrum value," *Telecommunications Policy*, vol. 37, no. 9, pp. 737-747, 2013.

[9] H. Alfin, *et al*., "5G spectrum valuation of milimeter wave technology: A case study of Indonesia industrial estate for acceleration of broadband development," *Journal of Theoretical and Applied Information Technology*, vol. 99, no. 5, pp. 1209-1218, 2021.

[10] Recommendation ITU-R M.2083-0, IMT Vision: Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond, 2015.

[11] N. Maziar and R. Rudd, "5G spectrum sharing," arXiv preprint arXiv: 1708.03772, 2017.

[12] S. A. A. Febian, W. R. Adinah, and S. Ariyanti, *Studi Lanjutan 5G Indonesia 2018. Spektrum Outlook Dan use Case untuk Layanan 5G Indonesia*, Jakarta: Tim Peneliti Puslitbang SDPPI KOMINFO, 2018.

[13] S. A. Ekawibowo, M. P. Pamungkas, and R. Hakimi, "Analysis of 5G band candidates for initial deployment in Indonesia," in *Proc. 4th International Conference on Wireless and Telematics*, 2018.

[14] Pengertian Kawasan Industri dan zona Industri. (2014). [Online]. http://www.bumn.go.id/kiw/berita/360/%20Pengertian.Kawasan.Industri.dan.Zona.Industri

[15] J. T. Penttinen, *5G Explained: Security and Deployment of Advanced Mobile Communica-tions*, Wiley, 2019.

[16] Huawei, 5G Link Budget, 2018, pp. 5-14.

[17] E. J. Oughton and Z. Frias, "The cost, coverage and rollout implications of 5G infrastructure in Britain," *Telecommunications Policy*, vol. 42, no. 8, pp. 636-652, 2018.

[18] A. Sukarno, A. Hikmaturokhman, and D. Rachmawaty, "Comparison of 5G NR planning in mid-band and high-band in Jababeka Industrial Estate," in *Proc. IEEE International Conference on Communication, Networks and Satellite (Comnetsat)*, 2020, pp. 12-17.

[19] 3GPP TS 38.521-4 version 15.1.0 Release 15, 5G; NR; User Equipment (UE) Conformance Specification; Radio Transmission and Reception; Part 4: Performance, 2019

[20] T. S. Rappaport, S. Sun, and M. Shafi, "Investigation and comparison of 3GPP and NYUSIM channel models for 5G wireless communications," in *Proc. IEEE 86th Vehicular Technology Conference*, 2017, pp. 1-5.

[21] 3GPP TR 38.901 V15.0.0, 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on Channel Model for Frequencies from 0.5 to 100 GHz (Release 15), 2018.

[22] W. Guo and T. O'Farrell, "Capacity-energy-cost tradeoff in small cell networks," in *Proc. IEEE 75th Vehicular Technology Conference (VTC Spring)*, 2012, pp. 1-5.

[23] Y. Wei and S. H. Hwang, "Investigation of spectrum values in rural environments," *ICT Express*, vol. 4, no. 4, pp. 234-238, 2018.

[24] G. Smail and J. Weijia, "Techno-economic analysis and prediction for the deployment of 5G mobile network," in *Proc. 20th Conference on Innovations in Clouds, Internet and Networks*, 2017, pp. 9-16.

[25] Samsung Electronics. Case study 5G launches in Korea. [Online]. Available: https://images.samsung.com/is/content/samsung/p5/global/business/networks/insights/white-paper/5g-launches-in-korea-get-a-taste-of-the-future/5G-Launches-in-Korea-Get-a-taste-of-the-future.pdf

[26] Populationof.net. (2021). The latest in demographic and population data online. [Online]. Available: https://www.populationof.net.

[27] European Commission. 2021. Italian 5G spectrum auction. [Online]. Available: https://5gobservatory.eu/italian-5g-spectrum-auction-2

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