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RF-EMF Exposure Measurement for 5G Over Mm-Wave Base Station With MIMO Antenna

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ABSTRACT The fifth-generation (5G) technology offers more capacity and data rates than the previous generations. It provides ultra-low latency and ultra-high dependability, allowing for efficient services in many industries. Using radiofrequency electromagnetic fields (RF-EMF) above 6 GHz in 5G millimeter Wave(mm-Wave) base stations has concerned many people due to the potential health risks caused by EMF exposure. This study aims to measure the maximum exposure emitted by a 5G mm-Wave base station by utilizing international standards in both its assessment methodology and exposure limits. In this study, the R&S®TSMA6 scanner, R&S®ROMES4 software, and R&S®TSME30DC down converter have been used for the measurement campaign; in addition to the user equipment device (UE), GPS, and an omnidirectional antenna. The investigation is based on a code selective method due to the radiated power fluctuations over time with data traffic. To conduct the measurement, six tests are taken based on three different time frames, antenna directions, and user equipment device (UE) to investigate the RF-EMF exposure. The maximum and average exposure from the 5G mm-Wave base station are calculated and compared with the ICNIRP standard. The maximum exposure from the 29.5 GHz base station is found to be 5.71 V/m, and the highest amount of average exposure is 2.02V/m. In this study, it was found that the maximum and average exposure (RF-EMF) produced from a single 5G mm-Wave base station are well within the allowed RF-EMF standard limit.

INDEX TERMS 5G mm-Wave BS, massive MIMO, radiofrequency electromagnetic fields (RF-EMF), measurement.

I. INTRODUCTION

The globe is witnessing a massive flood of data because of mobile network subscribers and online platforms [1]. The current development indicates that there are high demands for bandwidth, particularly for smartphones, and is predicted to expand rapidly in the future [2]. In this context, technological advances are required to meet the bandwidth requirements. Because the need for wireless communication grows at an unprecedented rate, a fifth-generation (5G) technology is being considered. 5G promises to provide greater throughputs, more bandwidth, especially in the mm-wave frequencies, higher capacity, and lower latency [3]. 5G networks are predicted to be more adaptable, dependable, and secure than current mobile networks [4], [5]. 5G wireless network is anticipated to address all identified drawbacks of previous wireless networks generations [6]. To meet the aims of 5G mobile communication wireless network new advanced technologies should be utilized in a wireless network such as the use of high frequencies, particularly millimeter-wave (mmWave) frequency ranges, deploy massive multiple-input, multiple-output (MIMO) antennas at the base stations and a huge number of small cells [7]. The Massive MIMO and mm-Wave have become essential enabling components that offer critical means for solving many technical problems and a massive improvement in the throughput system [8], [9]. Millimeter-wave(mm-Wave) has been known as an important technology for 5G wireless communications [10].

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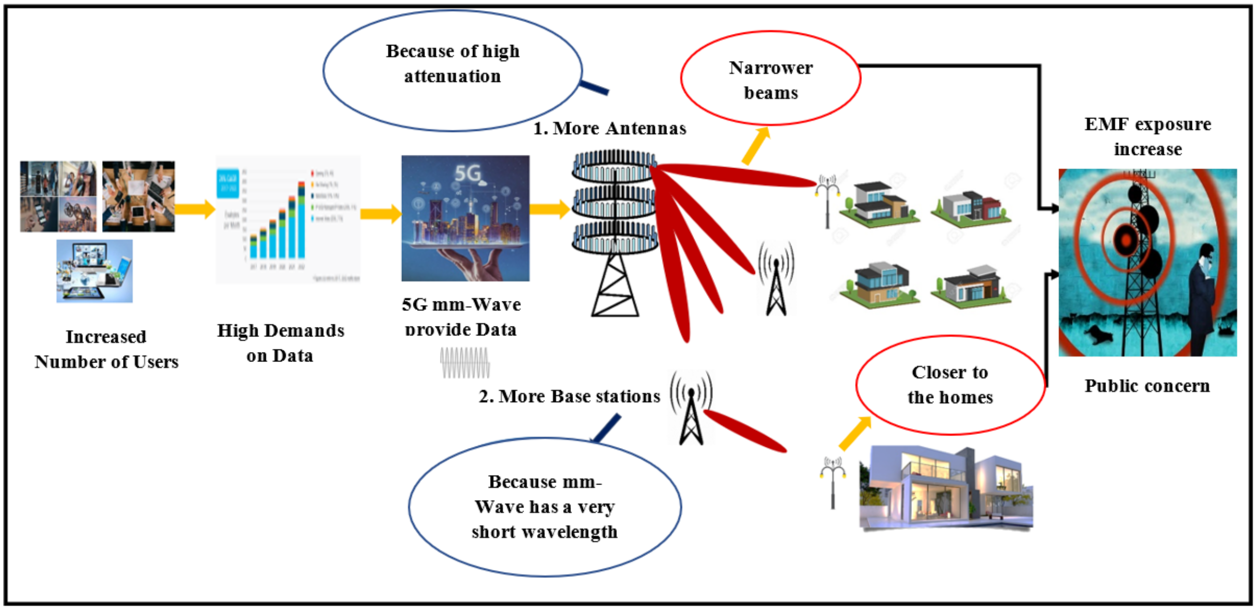


FIGURE 1. **The causes of increasing RF-EMF exposures.**

Usually, mm-Wave refers to frequency bands from 30 GHz to 300 GHz [11], but often 10 GHz to 30 GHz band are known as mm-Wave because of sharing certain propagation characteristics, and it is wavelength ranging located between 1mm and 100mm [12], [13]. Mm-Wave provides a much larger bandwidth, higher throughput, faster data rate, and capacity compared with, 3G, 4G, and 5G C-band frequency ranges [13]–[16]. Massive MIMO is recognized as a key technology in 5G. MIMO is the greatest contender for better transmission rates, wide-coverage, and data security because the number of antenna components on the base station is substantially greater than the number of simultaneously served customers [17]. The massive MIMO system can provide high beamforming gain to compensate for mm-Wave extrema signal attenuation, which is realized by high dimensional antenna array-based directional transmission [15]. However, as these advanced technologies are implemented, there is growing concern about the potential effects on health and safety from exposure to radiofrequency (RF-EMF) emitted by 5G base stations [18]–[25]. People are concerned about EMF exposure because EMF exposure cannot be prevented or managed [26].

To deploy the current system to a 5G system, the system should face three major changes which lead to increasing the amount of RF-EMF exposure as is summarized in Fig.1. First, to provide an extremely high data transfer, the 5G system needs a higher signal power at a receiver to direct energy effectively where needed [27]–[29]. Therefore, the amount of EMF will increase and be in contact with users. Second, the number of transmitters that operate at the base stations is anticipated to increase which means more base stations will be deployed because mm-Wave has a very short wavelength [28], [30], [31], and mm-Wave signals may be absorbed, dispersed, depolarized, and diffracted by the weather. [32]. These base stations will provide a connection for a smaller area and will be located near the users. Therefore, this will result in a higher chance of users being exposed to EMF [33]. Third, the narrower beams will be utilized in the 5G system as a solution for a higher attenuation of signal power due to operation in higher frequency bands. To increase the antenna's gain in the 5G system, multiple antennas are used [34]. A narrower concentration of electromagnetic energy can expose humans to a higher potential for electromagnetic fields [20], [21], [22]. Finally, it is expected that at high frequency like mm-Wave the amount of RF-EMF absorption rate into human skin increases [34], [35].

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronics Engineers (IEEE) have developed guidelines for limiting human exposures to electromagnetic fields (EMF) based on years of scientific investigation [36], [37]. Internationally respected agencies such as the World Health Organization(WHO), the US Federal Communications Commission (FCC) [38], and the International Telecommunications Union (ITU), as well as the Recommendation of the European Council [39], have used these principles to make recommendations. However, some countries (like Brussels, Belgium, Switzerland, Germany, and Italy) have enacted their own, more stringent rules and regulations, that might postpone or even obstruct the implementation of 5G networks due to EMF saturation [40]–[43]. The Malaysian Communications and Multimedia Commission (MCMC), as the sector's operator, has issued the "Mandatory Standard for EMF Emission from radiocommunications base stations. EMF exposure amount from mobile phone BSs and other communication infrastructures are determined in the mandatory standard titled ''Commission Determination on the Mandatory Standard for Electromagnetic Field Emission from Radiocommunications Infrastructure'' (MS for EMF). The limited amount of EMF exposure in the MS is based on the (ICNIRP) guideline set. The MS for EMF is applied to Network Facility Providers (NFP) and Network Service Providers (NSP) who own and operate the radiocommunications infrastructure like transmitter's base station. ICNIRP which is a non-governmental institution has been officially recognized by World Health Organization(WHO). The exposure limit values for EMF fields published by ICNIRP were developed after a thorough evaluation of all peer-reviewed research literature, including both thermal and non-thermal impacts. The fundamental result of the WHO investigations is that EMF exposures under the levels indicated in the ICNIRP worldwide recommendations have no proven health effects. [44].

Many researchers have conducted the RF-EMF measurement to investigate the amount of radiation in the 5G base stations that operate at frequencies below 6GHz. However, there is not much research about the exact level of exposure that is produced in the 5G mm-Wave base stations in the real-world measurement because 5G base stations that operate in mm-Wave frequency ranges have not been massively utilized. Some researchers believe that the maximum exposure in 5G mm-Wave base station is neglected due to it is short wavelength that limits the transmission of data over a long distance [28], while others believe that the level of RF-EMF will increase with increasing the frequency ranges like mm-Wave frequency ranges [45]. Therefore, this study is crucial to show experimentally the level of radiated exposure from a 5G mm-Wave base station. The main contributions of this paper are:

i) Measurement campaign was conducted to identify the amount of RF-EMF exposure at 5G over the mm-Wave base station. The electrical field strength per channel [V/m] and the electrical field of the 5G mm-Wave base station were analyzed.

ii) The maximum exposure (E_{max}), average electric-filed strength (E_{avg}), electric field strength per resource element ($E_{RE,SSB}$), and extrapolation of theoretical maximum and average exposure were analyzed. The maximum field strength over different times, antenna directions, and with and without UE device were investigated.

iii) The most effective factors among those three on the EMF exposure in 5G mm-Wave transmission in the tropical region were analyzed.

Then the amount of exposure produced by the 5G mm-Wave base station is compared to the ICNIRP standard.

II. RELATED WORK

In the last decade's the RF-EMF exposure is become a vital topic for telecommunication companies to ensure safety, so many researchers have investigated in previous wireless networks generations like 2G, 3G, and 4G. Van Wyk, M.J. [46] conducted the measurement for EMF exposure in small cells in three different countries, South Africa, the Netherlands, and Italy, then they compared the results to safety guidelines. The measurement was taken at 295 positions around 98 small cell sites to analyze the maximum level of exposure in small cells over the frequency range 27 MHz– 3 GHz of the measurement devices, as well as over the Mobile DL bands. the study used the frequency selective, and three measurements were conducted at each small cell at three different locations and distances, one of them was 1m far from the antenna, while the other two were taken within 50 m from the site. Depending on the antenna deployment, sites were categorized into three separate installation categories that are 1, 1.5, and 1.7 m high. At each height, a measuring time of 60 s was used; therefore, resulting in a measuring time of 180 s at each position. The results of their experiments indicated that the maximum amount of RF-EMF exposure was 30 times less than the general public standard as defined by ICNIRP.

A group of researchers in Pulau Pinang, located in Malaysia in 2018 conducted RF-EMF exposure for base tower station [47], and they compared it to international standards. Depending on the availability of a location to conduct the measurement, six considered locations were chosen. The RF-EMF exposure measurement was conducted in two scenarios indoor and outdoor. The measurement was conducted in the most crowded area that is surrounded by many base stations. The nearest Base station tower populated area was set 1st location and the farthest base station tower crowded place 6th location. Instrumentation exposure was set up to EMF distribution that emulates the far-field of a base station to guarantee the power obtained by each of the subjects setting to 1 V/m, both from field exposure to LTE 850, LTE 1800, and LTE 2600. In their research, four different types of signals had been used which are 900 MHz, 1800 MHz, 2.1 GHz, and 2.4 GHz at each location. The antenna at the base station was located on the roof which was 6 m higher than the ground. It can be classified as conforming to the public safety requirements of ICNIRP. The findings in this research based on the indoor and outdoor measurements confirm that the level of E-field strength is not significant to consider as a danger. Furthermore, the finding in their research suggests that the use of mobile phones from 2G, 3G, Wi-Fi for indoor and fourth-generation mobile networks (4G) outdoor is safe in terms of the MPE. RF/EMF emitted from the BTS in Pulau Pinang will also be safe for the public, due to the radiation level.

Nowadays, the debate and conflict about the implementation of the new 5G base stations is a hot topic. Therefore, many researchers investigated the amount of radiated exposure RF-EMF from 5G over C-band base stations to ensure the safety of 5G.

Ofcom which is the UK's communications regulator in 2020 had analyzed the result of constructive EMF exposure measurements at locations near 5G-enabled base stations for cell phones [48]. The measurement aimed to confirm that the EMF exposure from 5G BSs stayed within the ICNIRP recommendations. The measurement was carried out near 5G-enabled mobile phone base stations in twenty-two locations 10 of them were across England, Scotland, Wales, and Northern Ireland. In the study, the base station locations had been chosen based on a crowded place that has a high number of smartphone users and those base stations were supporting 2G, 3G, 4G, and 5G (3.4 to 3.6GHz). To carry out their measurement a field strength analyzer (Narda SRM-3006) with an anisotropic electric field (E-field) probe were used. They found that in all the measurement' scenarios and locations, the measured EMF values from 5G base stations are at a small portion of the levels specified in the ICNIRP Standards, and the greatest amount of EMF value was nearly 1.5% of the relevant level.

TABLE 1. Mandatory standard exposure limits by MCMC [50].

Type of Exposure	Frequency range (Hz-GHz)	Electric field strength (V/m)	Magnetic field Strength H (A/m)	Equivalent Plane Wave Power Density S_{eq} (W/m^2)
Occupational	1 – 10 MHz	610/f	1.6/f	-
	10 – 400 MHz	61	0.16	10
	400 – 2000 MHz	$3f^{½}$	$0.008f^{½}$	f/40
	2 – 300 GHz	137	0.36	50
General Public	1 – 10 MHz	$87/f^{½}$	0.073/f	-
	10 – 400 MHz	28	0.073	2
	400 – 2000 MHz	$1.375f^{½}$	$0.0037f^{½}$	f/200
	2 – 300 GHz	61	0.16	10

Another study proposed and measured a novel systematic methodology with spectrum analyzer devices to take a measurement or calculate in-situ the time-averaged simultaneous radiation and the theoretical E_{max} radiation from 5G new radio BSs [39]. In addition, the method also involves several steps that include identifying the SSB, which is the only fifth-generation new radio portion that is transmitted regularly and at constant power. The technique has been evaluated in the LOS of a 3.5 GHz 5G new radio BS in Düsseldorf, Germany. One UE device was accessible for which various tests (100 percent downlink or uplink, voice call, video call, and video streaming) were carried out. The BS was designed to continuously work with a fixed beam to validate the methodology in a well-managed environment. The high of the antennae at the transmitter base station was 12m above the floor level, at the receiver side, the height of the prob was 1.5 meters above floor level. The distance between transmitter and receiver was 62 to 66 meters. The highest maximum exposure from the base station was 5.537 V/m from the Video call test. The results in all the tests were well below the ICNIRP reference level which is 61 V/m at 3.5 GHz [49]. Table 1 demonstrates the MCMC standard exposure limits, which is adopted from the ICNIRP standard, for low and high frequency.

In January 2020, a group of researchers analyzed the RF-EMF exposure level, monitoring the transmission power for twenty-five BSs working in a live 5G network in (Telstra, Australia) [51]. In the base stations, massive MIMO antennas were deployed to utilize beamforming and optimize the signal strength at the mobile phone. These base stations were located in dense urban areas. The base station worked in the NR band 78 (3300-3800 MHz) with a channel bandwidth ranging between 40 and 80 MHz between the sites. Ericsson Network Manager had been utilized to obtain information on the activities of 5G base stations. This paper followed the ICNIRP standard, which means the averaging time to whole-body exposure was 6 mins. About 13 million samples were taken 24 hours over a week in 25 different base stations. The maximum time-averaged power for each beam direction was determined to be less than the theoretical maximum exposure. The results indicate that suggesting constant maximum power transmission in the path of a fixed beam contributes to the unrealistic evaluation of EMF radiation. The authors instead suggested a compliance distance that is less than half than what is obtained for the theoretical maximum EIRP, when considering the effect of beamforming and traffic variation on the EMF exposure level.

III. METHODOLOGY

This section presents the methodology used in performing this work. To conduct the measurement at the base station, different scenarios and tests were chosen. Choosing a location to take the measurement was the second step. After going around the area for a few hours, the location was chosen based on getting the highest received power. The measurement was conducted in the car park of Rekascape Cyberjaya, Selangor at a 5G mm-Wave base station, the distances between the transmitter and receiver were 22 m that the highest amount of power was received. The scenario had been selected in the line of sight (LOS) location; six different tests were selected one of them was measured without connecting the UE device to the base station, while, in the other five tests, the UE device was connected to the base station. The measurement in the LOS scenario had been taken in three different standard times to know when the maximum exposure will be recorded and to illustrate the time effect on the exposure level. Measurement was conducted at 1 minute as a default time, 6 minutes based on the ICNIRP [52] standard, and 30 minutes depending on the IEEE [53] and ICNIRP [54] standard. To analyze the Electrical field strength per channel [V/m] and Electrical field of the 5G mm-Wave base station, the data was extracted from the scanner. Then, the data was sorted in an excel sheet based on the top (n) to normal sorting where every signal synchronization block (SSB) had a fixed column to analyze the electrical field per channel in 5G base station. The maximum electric field strength (Emax) and the average electric-filed strength (Avg) were analyzed. Finally, the maximum exposure and average exposure will be compared to ICNIRP [49] standard to ensure the safety of deploying 5G mm-Wave in Malaysia.

A. MEASUREMENT SETUP

In this project, theR&S® TSMA6 scanner with R&S® ROMES4 software, which is designed to assist 5G new radios measurements below 6 GHz and mm-Wave frequency ranges, and with the help of R&S® TSME30DC downconverter that can analyze signals in the 24 GHz to 44 GHz range, the measurement was conducted as is demonstrated in Fig. 2. From the scanner, some primary parameters were obtained like power levels (e.g., RSRP) and signal-to-noise ratios (e.g., SINR) of the variant signals in the 5G new radios SSB. These parameters were used to conclude the RF conditions at a specific location that form the basis for network access via 5G NR equipment. 26 - 40 GHz Vertically Polarized Omnidirectional Antenna fitted with a K type Connector and Radome in this project was used as a receiver antenna side. This antenna was connected directly by a cable to the scanner. It is receiving the signal automatically. UX241 GPS (TSME-ZA4) was another piece of equipment that was used to know precisely the location. The last equipment was user equipment UE that had been used in this project to justify the gain and to properly measure the entire 5G air interference.

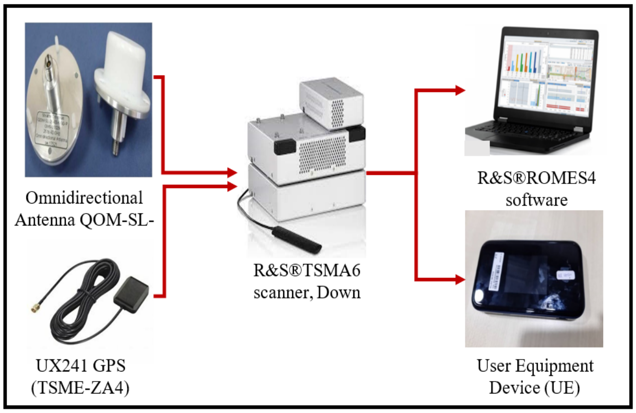


FIGURE 2. Measurement equipment.

B. MEASUREMENT METHOD AND PARAMETERS

Code-selective measurements decode the signal and allocate a level to technology, location, field, and in "SSB beam". Only a part of the signal is determined by code-selective measurements, to be close to ICNIRP. The code-selective method provides all the details and enables operators and infrastructure suppliers to find the maximum possible EMF emission amount to optimize the emissions to go below the level, but not to reduce more coverage as required, it identifies which signal contributes, and what portion of radiation [55]. With the contribution level details, optimization teams can define the setup in this location, capable of passing the EMF limit as well as generating the greatest available capacity and coverage in that location [56]. The measurement in this project is based on code-selective because one of the objectives is finding the maximum possible exposure per SSB and channel accurately with all the details. The type of signal that is chosen for the code-selective method is the Signal Synchronization Block (SSB) which is the only and always ON signal in 5G base stations, it is a sequence signal, it is beamformed, and it can be situated anywhere in the 5G carrier. In the mm-wave base station, each sector (PCI) has 64 different beams. When established, UEs find details on primary and secondary synchronization signals (PSS and SSS) and physical channel broadcasting (PBCH). To measure the EMF exposure from the base station in this study, the RSRP of the secondary synchronization signal (SSS-RSRP) was measured. The RSRP does a better job of measuring signal power from a specific sector while potentially excluding noise, interference from other sectors, and environmental contribution to the signal [57]. RSRP parameter is the most accurate and consistent parameter.

C. RF-EMF MEASUREMENT PROCEDURES

This project is following the novel procedure and the methodology that has been figured out by the authors of this study [39] in German at the end of 2019. They applied their methodology on C-band, at the same time they mentioned that the same methodology can be applied on the mm-Wave band. In this study, after connecting all the equipment, the 29.5 GHz, code selective method, and sector number for mm-Wave which is 257 were selected. The R&S TSMA6 scanner was automatically detected all 5G carriers on air, it was decoded PCI, SSB, and the power was measured on the synchronization signal. The methodology starts with a spectrum overview. At this stage, an overview measurement of the frequency should be conducted to identify the radio frequency signals, presenting at the selected location and especially the 5G new radio (NR) signal from the base station. Secondly, the SSB is identified in the actual location of the SS burst, and SS_{REF} numerology should also be identified. Thirdly, the field level per RE of the SSB is obtained by measuring the electrical-field strength per resource element of dominant SSB and $E_{RE,SSB}$. Fourthly, the measurement is conducted in three different times (1min, 6 mins, 30 mins) to find E_{max} and E_{ave}. Then, the received power P (dBm) of a signal from the scanner, which it must be converted to an electric-field value (E_{field}) V/m by adding the antenna factor AF (dB/m) in the theoretical equation. The extrapolated electrical field strength for each channel should be calculated by summing up all the SSB or beams in one channel and this step should repeat for all channels at the base station. Finally, the total exposure for all channels at the base station should be added together to find the maximum exposure at the BS as is shown in Fig. 3.

D. MEASUREMENT SCENARIO

The measurement was conducted in various outdoor scenarios at the Rekascape base station that operates at 29.5 GHz. In this work, six different tests which were [NO UE, Video Call, Voice Call, Video Streaming, 100% Uplink, 100% Downlink] had been conducted as illustrated in Table 2. Voice

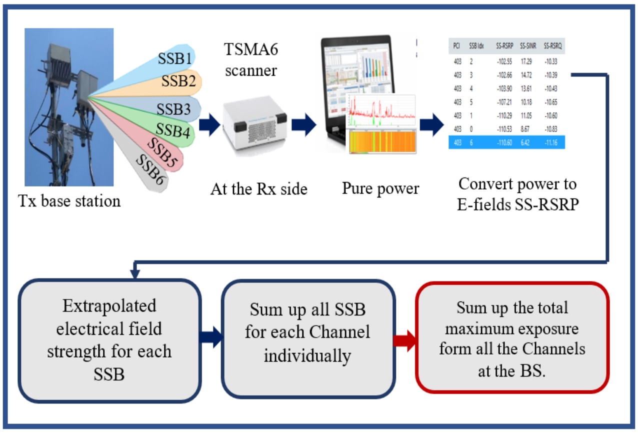
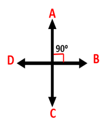


FIGURE 3. RF-EMF measurement procedure.

call and video call tests were taken by using (WhatsApp), and video streaming was conducted by using (YouTube). The 100% downlink and 100% uplink were taken by using the (iPerf tool, https://iperf.fr/), but we did not have the option to force the UE to use all the BS resources. All those tests have been carried out at the same location and LOS scenario. Each test was conducted at three different times which is 1min (chosen by researchers to be sufficient), 6 mins (ICNIRP) [52], 30 mins (IEEE) [53], and (ICNIRP) [54] with various antenna directions.

TABLE 2. Measurement scenario.

NO	Test	Time	Distance Tx & Rx	Antenna Direction
T1	NO UE	[1min,6min,30min]	22 meters	A, B, C, D
T2	Voice Call [WhatsApp]	[1min,6min,30min]	22 meters	A, B, C, D
T3	Video Call [WhatsApp]	[1min,6min,30min]	22 meters	A, B, C, D
T4	Video Streaming [YouTube]	[1min,6min,30min]	22 meters	A, B, C, D
T5	100% Uplink [iPerf]	[1min,6min,30min]	22 meters	A, B, C, D
T6	100% Downlink [iPerf]	[1min,6min,30min]	22 meters	A, B, C, D



E. MEASUREMENT CAMPAIGN

The measurement was taken in outdoor environments LOS of a 5G NR base station, operating at 29.5GHz. The base station is situated on the upper level of a Rekascape building in Cyberjaya, Malaysia. The measurement was conducted from 16 March to 18 March in 2021. The Rekascape base station site was chosen as it was available for testing purposes and the location was suitable to conveniently position the measurement equipment. The base station antenna was situated at a height of about 10 m above ground level. The type of antenna at the base station is MIMO. There is only one sector PCI at the base station and this sector has four channels which are 2098117, 2099783, 2101449, and 2103115 as demonstrated in Table 3.

TABLE 3. Measurement parameters.

Parameters	Values
Carrier frequency	29.5GHz
Number of Sector (PCI) at BS	1 Sector (PCI)
Number of channels	4 channels
Number of SSB in each channel	16 SSB
Transmit power per channel	26.807dbm
Tx antenna	MIMO 4T4R
Rx antenna	26-40GHz Vertically Polarised Omnidirectional
Tx antenna Hight	10 m
Rx antenna Hight	1.5m
Tilt angle	6°
Antenna Factor Rx	57.93
Antenna Gain Rx	1.70

Each channel has 16 different static beams and the total number of beams at the base station was 64 beams. Although the base station was not part of a commercial network, one user equipment (UE) was available for testing purposes. Generally, the measurement points at the receiver side represent the human body height so the R_X antenna's height was 1.5 m. The greatest amount of power was received at the distance of 22 m between the transmitter that is located over the building and the receiver antenna. The distance between T_X and R_X, in all six tests, was the same with a tilt angle of 6° as is shown in Fig. 4. During the measurement, the R_X antenna was facing the sector for all six tests. Except for the first test, the UE device had not been used in the other five tests UE device was used.

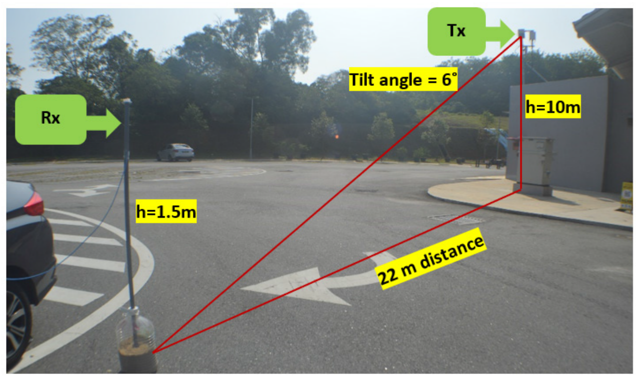


FIGURE 4. Measurement site.

The amount of car traffic during the measurements was minimal and assumed to not influence the measurements because the measurement was taken during the night as is illustrated in Fig. 5.

During the measurement, there were no obstacles between the transmitter and receiver.

F. ELECTRICAL FIELD STRENGTH CALCULATIONS

In this research, there are some equations should be applied to get the total maximum exposure and the average exposure from the base station after exporting the data from the scanner. To find the maximum exposure, which is the worst-case

FIGURE 5. Measurement site at night.

scenario, the exported data from the scanner should be sorted in an excel sheet. Then it should be organized based on the top (n) synchronization signals block (SSB) to down for each channel at the base station as a fixed column. The received 5G power from the base station, SS-RSRP power (dBm), of a signal for each beam, should be converted to an electric-field value (V/m) by adding the antenna factor that is 57.93 dB/m for 29.5GHz in the theoretical equation below [39].

$$E_{field} = E_{SSB} = \frac{1}{\sqrt{20}} 10^{\frac{P+AF}{20}} \tag{1}$$

where E_{field} is an electric-field value (V/m), E_{SSB} is the field level (V/m) per resource element (RE) of the SSB, P is the power(dBm), and AF is the antenna factor(dB/m).

In the next step, the maximum electric field strength (V/m) will be calculated for each beam at the base station by using equation (2). The E_{SSB} that has been found in the first equation for each beam will be added with some other parameters like the extrapolation factor for the beam that is 11dBm which is the difference between NO UE spectrum measurement and UE spectrum measurement, the total number of subcarriers within the carrier bandwidth that is 1584, the power reduction set to 1, and the technology duty cycle set to be 0.75.

$$E_{asmt} = E_{SSB} * \sqrt{F_{extBeam} * F_{BW} * F_{PR} * F_{TDC}} \tag{2}$$

where E_{asmt} is the maximum electric field strength (V/m), $F_{extbeams}$ is the extrapolation factor for the SSB, F_{BW} is the total number of subcarriers within the carrier bandwidth, F_{PR} is the power reduction, and F_{TDC} is the technology duty cycle.

To calculate ($E_{Channel}$) which is the maximum exposure in each channel, the 16 SSB 's E_{asmt} should be summed up by the third equation. This step should be repeated for all the channels at the base station.

$$E_{\text{Channel n}} = \sqrt{E^2_{asmt_1} + E^2_{asmt_2} + E^2_{asmt_n}} \tag{3}$$

Finally, the total exposure for all the channels of the base station (E_{BS}) can be calculated by the equation (4):

$$E_{BS} = E_{\max} = \sqrt{E_{\text{ch}}{}_1^2 + E_{\text{ch}}{}_2^2 + E_{\text{ch}}{}_3^2 + E_{\text{ch}}{}_n^2} \tag{4}$$

After analyzing the data, we can know the maximum amount of exposure (E_{max}) from the 5G mm-Wave base station. Then, the result will be compared to the ICNIRP standard [49]. The main reason for that is to ensure that the amount of exposure is at the safe level, and that can also ensure the 5G can be implemented safely in Malaysia.

In the case of average exposure from the base station, one more equation should be applied before converting pure power to the electrical field. The RMS equation for each beam (SSB) in each channel at the base station must be calculated by using equation 5 [58].

$$RMS = \sqrt{\frac{x_1^2 + x_2^2 + x_3^2 + x_4^2 + x_n^2}{n}} \tag{5}$$

The various parametric metrics such as E_{field}, E_{asmt}, and $E_{channel}$ should be tabulated for each beam, channel, and time slot: 1min, 6 mins, and 30 mins, respectively. Instead of applying the fourth equation, the sixth equation will be applied to sum up the average exposure (E_{avg}) for all channels at the base station.

$$E_{avg} = \sqrt{\frac{E^2_{Ch1} + E^2_{Ch2} + E^2_{Ch3} + E^2_{Chn}}{n}} \tag{6}$$

After analyzing the data for all channels at the base station in each test, the E_{avg} of the base station will be compared to the ICNIRP standard, for being sure that the average amount of exposure is at the safe level.

IV. RESULTS AND DISCUSSION

In this study, the amount of exposure RF-EMF that is radiated from a 5G NR mm-Wave base station for the first time in a real-world experiment was analyzed and investigated. The maximum exposure which is called worst-case scenario and average exposure have been founded theoretically after extracting the data from the scanner for six tests which are [NO UE, Video Call, Voice Call, Video Streaming, %100 Uplink, % 100 Downlink], except the first test the other five tests UE device was used. In the first test which was conducted without UE the power was distributed from all four channels at the base station while in the five tests that UE device was used, the UE device was connected only to the first channel [2098117] at the base station. Each test was conducted at three different times [1min, 6 mins, 30 mins].

After the received pure power from the scanner was applied to the Eq1, Eq2, and Eq3, the maximum exposure in each channel is found. Fig. 6 illustrates the maximum exposure radiated in the first and third test at 30 mins duration. In the first test that the UE device was not used, the same amount of exposure, around 2.84V/m, is emitted in the first and second channels. There is a modest decrease in the amount of exposure in the third and fourth channel which is around 1.40 V/m.

In the Video Call test, the UE device was connected only to the first channel of the base station. The second, third, and fourth channels were not connected to the UE. The amount of

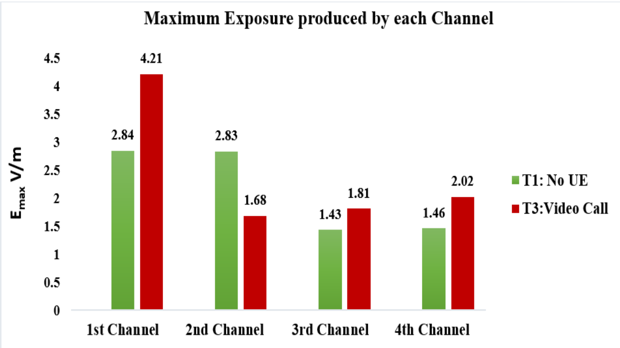


FIGURE 6. Maximum exposure produced by each channel at the BS.

radiated exposure from the first channel is 4.21V/m which is significantly higher than the other three channels, which are 1.68V/m,1.81V/m, 2.02V/m respectively as is demonstrated in the red bar chart.

The maximum exposure from the base station is calculated by equation 4 for each test as is shown in Fig. 7. The E_{max} in the No UE test has increased with increasing the time that the measurement was taken, at 30 mins it reached 4.5V/m. While in the T2 that UE device was connected to the first channel of the base station, the maximum exposure at 1 min was 4.48 V/m and stayed almost the same at 6 mins, and 30 mins. In the T3, the E_{max} at 1 min and 6 mins were 4.47 V/m and 4.85V/m respectively. Then it raised to 5.27 V/m at 30 mins. The fourth test, which was Video streaming from YouTube, at 1 min the maximum radiation was 4.72V/m then decreased to 3.95V/m at 6 mins and at 30 mins picked at 5.71V/m. The maximum radiation from the base station in the uplink test was 0.84V/m at 1 min, increased slightly to 0.91 V/m at 6 mins, and decreased noticeably to 0.23 at 30 mins. In the downlink test (T6), the maximum figure of exposure at 1 min was 1.16 V/m, decreased modestly to 0.95 V/m at 6 mins, then at 30 mins peaked at 1.45 V/m as shown in Fig. 7.

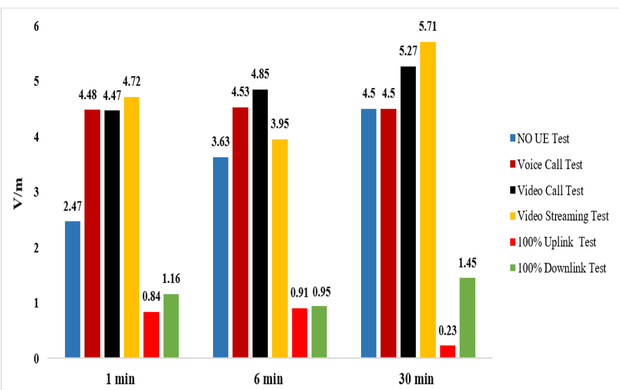


FIGURE 7. Maximum exposure at 5G mm-Wave BS.

To analyze the average exposure from the base station, the measurement scenario that is demonstrated in Table 2 was applied. After extracting and sorting the data, the fifth equation was applied to find the RMS values for each beam at the base station then it was changed to electrical field V/m by adding it with the antenna factor in the first equation. Then the second and third equation was applied to find the average RF-EMF in each beam and channel respectively. The sixth equation was applied to find the average exposure in each test at the base station as is illustrated in Fig. 8.

The average exposure in the first test, NO UE, was 0.88 V/m at 1 min, 1.16 V/m at 6 mins, then increased slightly to 1.25 V/m at 30 mins. In the voice call test, the E_{avg} at 1 min is 1.74V/m, this amount of exposure raised to 1.79 V/m at 6 mins, then decreased to 1.72V/m at 30 mins. The average exposure in the video call test increased gradually from 1.77V/m at 1min to 2.02V/m at 30 mins. In the fourth test, the average RF-EMF from the base station dropped modestly from 1.76 at 1min to 1.61V/m at 30 mins. The average exposure in the 100% uplink was around 0.33V/m at min and 6 mins, then it increased modestly to 0.42V/m at 30 mins. In the last test, 100% Downlink, the (E_{avg}) was 0.31 V/m at 1min, it decreased to 0.27 V/m at 6 mins, then it increased gradually to 0.31 V/m at 30 mins as is illustrated in Fig.8.

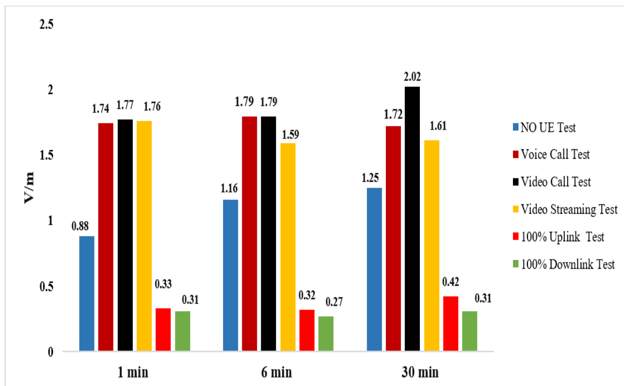


FIGURE 8. The average exposure at 5G mm-Wave BS.

V. CONCLUSION

In this paper, the RF-EMF exposure for 5G over the mm-Wave base station with a MIMO antenna was investigated. From the literature, no study has been carried out analyzing the exact level of exposure from mmWave base station making it the first of its kind in Malaysia. This study investigated and elaborated on how to take the measurement, sort, extract, and calculate the data. Besides, the effect of time duration on the amount of exposure, various antenna directions, and using UE devices on six different tests was elaborated. For all the tests, the distance between the 5G mm-Wave base station (Tx) and the receiver (Rx) was the same, and the location was chosen based on getting the maximum power. It can be noticed from the data that there is a slight difference in the amount of produced exposure between the first test which is without UE, and the other tests that the UE device was connected to the BS, so the UE does not have a noticeable impact on the measurement results. The experimental results ensure that the time has a modest impact on the level of exposure, in the three-time frames. A high level of E_{max} from the 5G mm-Wave base station was recorded in the second, third, and fourth tests. The maximum exposure called the worst-case scenario is much higher than the average exposure emitted at the 5G mm-Wave base station. The maximum exposure at the base station among all the tests is 5.71V/m, which is recorded in video streaming from YouTube, and this value is significantly lower than the ICNIRP standard accepted limit of exposure, which is 61V/m [49]. The highest average exposure, which is 2.02V/m at the video call test, is well below the accepted RF-EMF exposure by the ICNIRP standard at the same time, it was found that the level of exposure at the mm-Wave base station is not zero. It was found that the E_{max} and E_{avg} from 5G mm-Wave selected base station in this work, are within the limits, indicating that it does not have effects on human health. Nevertheless, there is a need for further investigations on the RF-EMF exposure from 5G mm-Wave in areas that are surrounded by many mm-Wave base stations and for a longer measurement time duration.

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