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EMF Levels in 5G New Radio Environment in Seoul, Korea

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ABSTRACT This paper reports the electromagnetic field (EMF) exposure levels from fifth generation (5G) services. Three mobile operators in South Korea launched the world's first 5G New Radio networks using the 3.5 GHz band in April 2019. The transmitted power of the uplink slots and the synchronization signal reference signal received power (SS-RSRP) from user equipment (UE) were measured in Seoul. The power samples, averaged over a 1-s duration, were obtained for a traffic period of approximately 270 h from October 2019 to early February 2020 using the file transfer protocol while driving along the side streets in residential areas of Seoul. The measurement results show that the time-average level when exposed to a beam sweep of the base stations was less than 5 μW/m^2. However, the UE transmitted power level approached the maximum for a considerable period of the total measurement time owing to the extremely low SS-RSRP level of the base stations.

INDEX TERMS 5G NR, EMF exposure, mobile phone, base station, Seoul.

I. INTRODUCTION

Even before the start of the fifth generation (5G) new radio (NR) service, a significant debate had generated regarding the health effects on the human body. However, to the best of our knowledge there have been no reports on the actual exposure levels in 5G NR networks to date.

South Korea commercialized the world's first 5G NR service in early 2019, and in the second half of the same year, the level of exposure was measured in Seoul, providing a scientific basis for dispelling public concerns despite the early stages of service. Three mobile operators in South Korea launched 5G NR networks in the 3.5 GHz band in April 2019. Two mobile operators were allocated the 100 MHz band, and the other operator was allocated 80 MHz. As of April 2020, the number of 5G subscribers in South Korea had reached nearly 6 million. In addition, the total number of 5G base stations installed is approximately 115,000, which is still quite small compared to the number of LTE base stations.

This paper aims to report the EMF exposure levels from the 5G NR services in Seoul during the second half of 2019 (at the time of measurement). The evaluation described in the present study is based on a real environment, which differs from compliance tests conducted under the maximum traffic conditions of a specific base station within the safety limits under discussion by the international standards body [1]–[3]. In Section II, the characteristics essential for an exposure assessment of the 5G NR systems operated by the three carriers in Seoul are addressed. The methods for measuring the transmitted (Tx) power of the uplink (UL) slots, the synchronization signal reference signal received power (SS-RSRP), and the total power received within a given bandwidth of each operator are described in Section III. Finally, Section IV presents the measurement results and evaluates the uplink and downlink (DL) exposure levels from 5G NR services in a real environment.

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II. 5G NR SYSTEMS OF KOREAN OPERATORS

Table 1 shows the characteristics of 5G NR systems used by the Korean mobile operators, O_A, O_B, and O_C. The systems are still applied in the same way as they were when the measurements were taken for the present study, and the number of SS blocks (SSBs) can change depending on the communication environment.

The maximum number of SSBs in a single burst is frequency dependent and eight blocks per burst can be applied in the 3.5 GHz band. The transmission of SSBs within a single SS burst set is confined to within a 5 ms window. Each

TABLE 1. Characteristics of 5G NR systems currently in operation.

Item	O_A	O_B	O_C
Frequency band (GHz)	3.60–3.70	3.50–3.60	3.42–3.50
Number of SSBs per SS burst	1	1	7
Transmission period of SSB (ms)	20	20	20
SCS (kHz)	30	30	30
S Slot format #	32	32	32
Frame structure	DDDSU	DDDSU	DDDSU

SSB: synchronization signal block
SCS: subcarrier spacing
D, S, and U of DDDSU: DL slot, special slot, and UL slot, respectively.

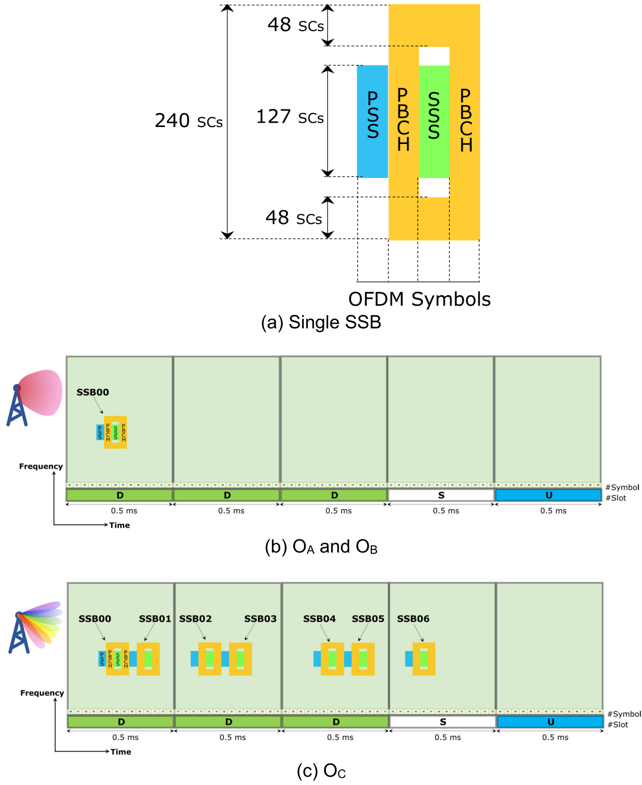


FIGURE 1. SSB and slots.

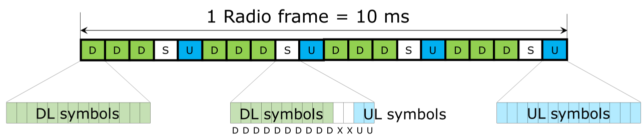


FIGURE 2. Configuration of Korean 5G NR frame.

SSB occupies four symbols and the primary synchronization signal (PSS), secondary synchronization signal (SSS), and physical broadcast channel (PBCH) signal are transmitted within one SSB [4], [5] (see Fig. 1 (a)). At present, two operators in Korea transmit only a single SSB every 20 ms, and the other operator, O_C, transmits seven SSBs (see Fig. 1 (b) and (c)).

The S slot format indicates how each of the symbols within a single slot is used. The 3rd Generation Partnership Project allows 62 predefined symbol combinations within a slot. Korean operators adopted the radio frame structure DDDSU with S slot format #32, which indicates that the special slot ''S'' format used in the subcarrier spacing (SCS) for a 30 kHz 5G NR DDDSU frame is configured with a ratio of 10 DLs, a 2-symbol guard period, and 2 ULs (10:2:2) (see Fig. 2) [6]. These characteristics should be considered in the evaluation of a time-averaged EMF exposure level.

III. MEASUREMENT METHODS

Seoul has a population density of approximately 16,500 persons/km^2 and a total of 25 administrative districts. Each district is further divided into approximately 10 to 25 neighborhood units. Measurements were conducted within an area covering more than 90% of Seoul's 423 neighborhoods.

An OPTis-M(II) system (Innowireless Co., Ltd.) consisting of a device and control software was used to collect data provided by the chipset of user equipment (UE). The measurement method when using this equipment is similar with that described in [7]. Voice calls are not yet supported on a 5G NR network. The power data (Tx power and SS-RSRP) provided by the chipset of one UE per operator are averaged over a 1-s period and recorded during the upload and download of files (10 and 100 GB file sizes, respectively) between the file transfer protocol (FTP) server and the UE. The measured Tx power of the UE used in this study indicates the arithmetic average of the UL slot power data over a 1-s duration.

SS-RSRP is defined as the linear average over the power contributions (in watts) of the resource elements (REs) that carry the SSS [8]. The UE can measure the SS-RSRP by decoding the demodulation reference signal (DMRS) associated with the PBCH [9]. As mentioned in Section II, O_A and O_B transmit a single beam (SSB), whereas O_C transmits multiple beams every 20 ms. The sum of the power transmitted by all SSBs as well as that of the serving beam were recorded for O_C.

For the UEs, the same mobile phone model (LM-V500N, LG Electronics, Inc.) with a 5G NR main antenna built at the bottom of the phone body was used. They were connected to and controlled by the OPTis-M(II) system, which was connected to a laptop computer. All UEs inside the vehicle were lined up and fixed using a transparent acrylic apparatus with low dielectric properties, and the back surface of the UEs faced the windscreen of the vehicle, as shown in Fig. 3.

Meanwhile, additional measurement equipment was employed to obtain the total power received within a given bandwidth for each operator: a radio frequency scanning receiver (PCTel Hbflex, 10 MHz to 6 GHz), hereafter referred to as a ''scanner,'' and a receiving (Rx) antenna (PCTel OP691, 600–6000 MHz, gain of 3 dBi ± 2 dB). The antenna was directly connected to the scanner to avoid cable loss. The same placement between the scanner antenna and the UE was maintained throughout the measurements (see Fig. 3). As a result, such an arrangement between the UEs and the scanner can be applied when observing the EMF exposure

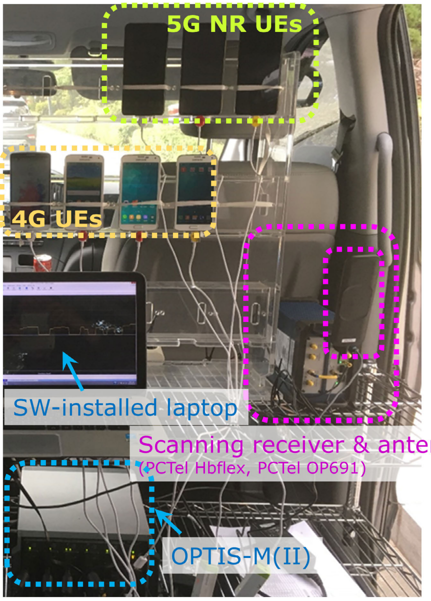


FIGURE 3. Measurement system and 5G NR UEs in the vehicle.

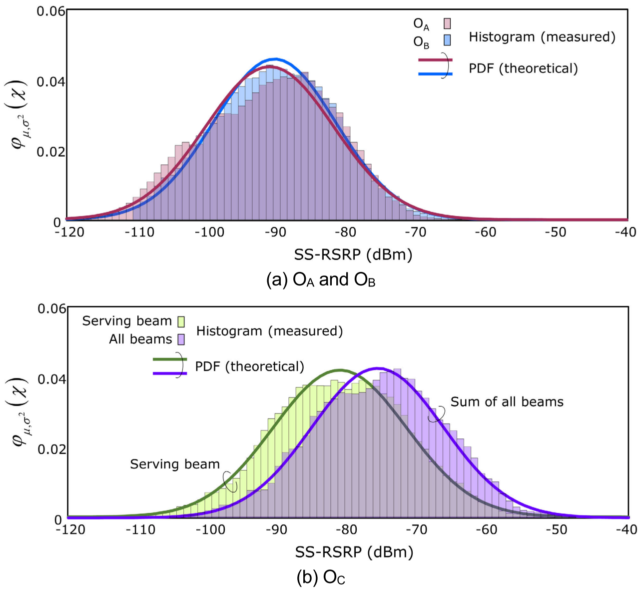


FIGURE 4. Histogram of SS-RSRP.

level within the vicinity of a 5G network cell phone user. The scanner provides power samples of 15-kHz channels within a given frequency bandwidth, and thus the sum of all channel powers within the band was recorded every second.

Power samples provided from the UEs and the scanner were collected while driving along the side streets in residential areas for longer than 40 min in each neighborhood.

IV. MEASUREMENT RESULTS AND EXPOSURE EVALUATION

A. SSBs

As stated in Section II, O_A and O_B transmit only one SSB in a single burst, whereas O_C transmits seven SSBs. Fig. 4 shows the histogram of SS-RSRP for the three operators. All probability distributions were close to a Gaussian distribution on a logarithmic scale. For each operator, the number of 1-s averaged SS-RSRP values was between approximately 9×10^5 and 1×10^6. The mean SS-RSRPs of O_A and O_B were similar at approximately −90 dBm. The mean SS-RSRP for the serving beam of O_C was −81 dBm, and the summed SS-RSRP of all SSB beams of O_C was 5.4 dB higher than that of the serving beam. The summed power was applied to the exposure evaluation.

The SSB periodicity was assumed to be 20 ms, which indicates the default periodicity during the initial cell search or idle mode mobility. An SSB spans across four OFDM symbols in the time domain, and 127, 240, 223, and 240 subcarriers (SCs) are occupied in the four symbols, respectively, as shown in Fig. 1 (a). The symbol duration corresponding to an SCS of 30 kHz is 33.3 μs. Assuming that the power levels of all REs constituting one SSB are the same, the time-averaged beam power (in watts) received from the base station based on the SS-RSRP measured by the UE can be calculated using the following equation:

$$
\begin{aligned}
\langle \mathrm{P_{SSB}} \rangle &= \frac{1}{\mathrm{T}} \int_0^T \mathrm{P_{SSB}}\, dt \\
&= \sum_{\mathrm{index}=0}^{\mathrm{L\text{-}1}} \left(\frac{\mathrm{SS\text{-}RSRP_{index}} \times (127+240+223+240) \times 33.3\ \mu s}{20\ ms} \right), \\
&= \sum_{\mathrm{index}=0}^{\mathrm{L\text{-}1}} \mathrm{SS\text{-}RSRP_{index}} \times 1.38 \qquad (1)
\end{aligned}
$$

where the total number of operating beams is L. The time-averaged power density (PD), $\langle \mathrm{PD_{SSB}} \rangle$ (W/m^2), contributed to by the time-averaged SSB beam power, $\langle \mathrm{P_{SSB}} \rangle$ (W), is obtained as follows:

$$
\langle \mathrm{PD_{SSB}} \rangle = \frac{4\pi}{\lambda^2 \cdot \mathrm{g_r}} \cdot \langle \mathrm{P_{SSB}} \rangle, \qquad (2)
$$

where λ is the wavelength (m), and $\mathrm{g_r}$ is the antenna gain of the UE. In this study, the antenna gain was assumed to be 0.1 (−10 dBi). For reference, Gati *et al.* assumed the gain to be −6 and −9 dBi at 900 and 1800 MHz, respectively [10].

Table 2 shows the 10th, 50th, and 90th percentiles and the mean values of the SSB beam power in 5G NR networks in Seoul. The two types of mean power were calculated as described in [7]; one is obtained by averaging the power samples in decibel milliwatts, and then converting the power into milliwatts, and the other is obtained by converting each power sample in decibel milliwatts into the corresponding sample in milliwatts, and then calculating the arithmetic mean. Hereafter, the former and latter averages are referred to as mean (log) and mean (linear), respectively.

The mean (log) and 50th percentile are not extremely different because the probability distributions of the SS-RSRP samples had close to a normal distribution, as shown in Fig. 4.

TABLE 2. Received SSB beam power and estimation of power density.

	Operator	Rx power (nW)					Mean $\langle PD_{SSB}\rangle$ (μW/m^2)
		10th	50th	90th	Mean (linear)	Mean (log)	
SS-RSRP[1)]	O_A	4.14E-04	9.14E-04	1.15E-02	4.79E-03	7.93E-04	0.089
	O_B	6.49E-05	9.48E-04	1.17E-02	6.92E-03	9.29E-05	0.122
	O_C	4.73E-04	7.59E-03	1.26E-01	6.54E-02	7.55E-03	1.093
Sum of SS-RSRP[2)]	O_C	1.54E-03	2.84E-02	4.23E-01	1.93E-01	2.55E-02	3.223
Time-avg. SSB power	O_A	5.71E-04	1.26E-03	1.59E-02	***6.61E-03***	1.09E-03	***0.123***
	O_B	8.96E-05	1.31E-03	1.61E-02	***9.56E-03***	1.28E-03	***0.168***
	O_C	2.13E-03	3.92E-02	5.84E-01	***2.67E-01***	3.52E-02	***4.447***

[1)] SS-RSRP for the serving beam.

[2)] Sum of SS-RSRPs of all SSB beams of O_C. It was used to calculate the time-average SSB power of O_C.

The mean $\langle PD_{SSB}\rangle$ in the rightmost column of the table was obtained from the mean (linear) power; even for O_C, whose SS-RSRP was the highest among the three operators, the PD was lower than 5 μW/m^2. This represents the exposure level from the SSB beam signals, which are always present in the air regardless of whether the 5G UE is idling or in connected mode.

B. Tx POWER OF UEs

Fig. 5 shows a histogram of the Tx power samples of the UE collected during the upload and download of files. For all three operators, the distribution is far from Gaussian, and it can be seen that the power close to the maximum output of the UE has been transmitted for a considerable amount of time. The maximum power observed from the measured data was 23 dBm.

Fig. 6 shows a scatterplot between the UE-Tx power and SS-RSRP used to determine whether 5G UL power control is properly achieved. The Tx power and RSRP measured for the same period in the main 4G network of each operator are also given in the figures; the measurement was conducted in voice call mode. It is impossible to directly compare the UE-Tx power between 5G and 4G networks. However, it should be noted that the SS-RSRP of the 5G networks of O_A and O_B is much lower than the RSRP of a 4G network; the RSRP mean (log) of the 4G network was −78 dBm, and the SS-RSRP mean (log) of the 5G networks of O_A and O_B was −90 and −91 dBm, respectively. Specifically, two branches were observed on the scatterplot, i.e., a clear branch in O_A and a blurred branch in O_B. It was estimated that this power distribution is due to the different settings of the power control parameters according to the cell site by the corresponding operator. The upper and lower branches are the results of data collected in cells whose mobile phone output power is set relatively higher to improve the UL performance, and set lower for a stable power consumption of a mobile phone.

The O_C in Fig. 6 (c) shows a similar range for the SS-RSRP of a 5G network and the RSRP of a 4G network, the mean (log) of which was −81 and −80 dBm, respectively.

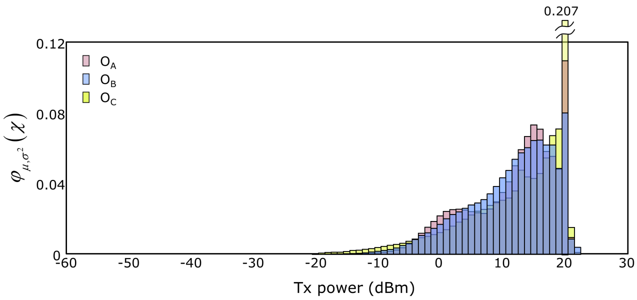


FIGURE 5. Histogram of UE-Tx power.

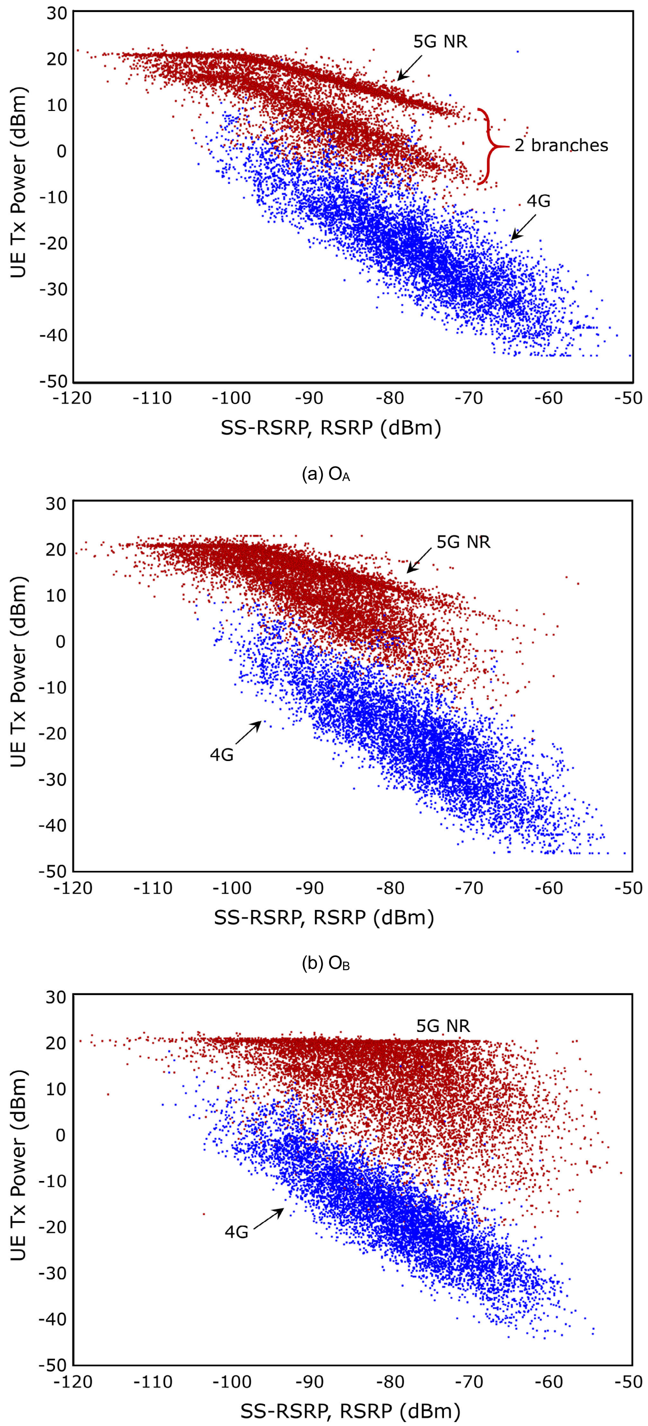
Nevertheless, the power control performance in a 5G network seems poor.

As mentioned in Section III, the logged Tx power sample of the UE is the 1-s average (temporal) power of the UL slot, and hereafter is referred to as P_{UL}. According to the configuration of the 5G NR frame, as shown in Fig. 2, the UE power is transmitted for 16 UL symbols of 2,500 μs corresponding to "DDDSU" slots. Therefore, the time-averaged Tx power, $\langle P_{Uplink}\rangle$, can be expressed as (3), where the power transmission of the UE has a duty cycle of 0.2132 under slot format #32.

$$\begin{aligned}\langle P_{Uplink}\rangle &= \frac{1}{2500\,\mu s}(P_{UL}\times 16\times 33.3\,\mu s)\\ &= 0.2132\times P_{UL}\end{aligned}\tag{3}$$

The mean $\langle P_{Uplink}\rangle$ for the three UEs was within the range of 6–10 mW, and the mean P_{UL} was approximately 31–43 mW. This corresponds to 15%–22% of the maximum available power of the UE.

Meanwhile, various portable devices operating at below 6 GHz have been tested for compliance with the peak spatial-average specific absorption rate (psSAR) limit based on the standard SAR measurement procedure [11]. The psSAR is defined as the maximum SAR averaged within a local region based on a specific averaging mass, e.g., any 1 or 10 g of tissue. A mobile phone model for market release in Korea should be compatible with the psSAR limit of IEEE-1999 [12], that is, 1.6 W/kg for 1g of mass for the general



(a) O_A

(b) O_B

(c) O_C

FIGURE 6. Scatter plot of UE-Tx power and SS-RSRP for 5G (RSRP for 4G). To reduce the plotting load caused by the large number of power samples (9×10^5 to 1×10^6), only 1% of the total number of samples were used in the plots.

public. Hereafter, the psSAR averaged over a 1-g mass is referred to as 1-g psSAR.

The rightmost column of Table 3 shows the 1-g psSAR in the human body at the mean (linear) Tx power, which was calculated based on the 1-g psSAR measured at the maximum output for an SAR compliance test of the LM-V500N phone model; the maximum 1-g psSAR of the device was reported to be 0.9 W/kg by the National Radio Research Agency (https://rra.go.kr/ko/license/D_c_sarlist.do). However, information on the communication technology or frequency for the SAR value is not provided. In this paper, 0.9 W/kg was assumed to be the SAR result for 5G NR.

C. TOTAL BAND POWER

As shown in Fig. 3, the Rx antenna of the PCTel scanner was positioned near the UEs in the vehicle. The distance between the Rx antenna of the scanner and the Tx antenna of the three UEs was approximately 55–70 cm. The summed power of all channels within the given frequency bandwidth of each operator was recorded. Therefore, the scanner-Rx power includes an SSB beam power, radiation of UL-Tx power of the UE, and the UE-specific DL beam power.

Fig. 7 shows a histogram of the power samples received by the scanner. It appears that the radiation from the UE significantly affects the level of the scanner-Rx power because it shows a left-skewed distribution, similar to the Tx power distribution of the UE, as shown in Fig. 5. The UE-Tx power, the scanner-Rx power, and the number of UL RBs in the time domain are shown in Fig. 8 and their coincident periodicity indicates that the scanner-Rx power and UE-Tx power are closely related.

Assuming that the Tx antenna gain (g_t) of the UE and the Rx antenna gain (g_r) of the scanner at 3.5 GHz are −6 dBi and +3 dBi (see Section III), respectively, the Rx power (P_r) is reduced by more than 40 dB from the UE-Tx power (P_t) using the Friis Transmission Formula (4).

$$\frac{P_r}{P_t} = \frac{g_t g_r \lambda^2}{(4\pi d)^2} \tag{4}$$

Because the rear surface of the UE with the antenna was facing the windshield of the vehicle, the radiated field from the UE was further attenuated when reaching the scanner antenna. As the measurement results indicate, the median (50^{th} percentile) scanner-Rx powers shown in Fig. 7 were −52.94 dBm (O_A), −44.64 dBm (O_B), and −35.04 dBm (O_C), which are 43–60 dB lower than the median (50^{th} percentile) for the time-averaged Tx powers of the UEs listed in Table 3 for the three operators. There were no significant differences in the Tx power of the UEs between the three operators (Table 3 and Fig. 5), whereas the scanner-Rx power showed wider differences (Table 4 and Fig. 7). To clarify these differences in power between the operators, the power levels of a UE-specific traffic (DL) beam for each operator also need to be identified.

Table 4 lists the statistical results of the scanner-Rx power samples. The mean PD based on the mean (linear) Rx power was estimated in the same way in which the PD for the SSB beam was calculated with SS-RSRP using (2). The Rx antenna gain of the scanner is +3 dBi. The PD result is shown in the rightmost column of the table and is much higher than the PD of the SSBs shown in Table 2. However, even the

TABLE 3. Time-averaged Tx power of UEs <P_{Uplink}> and estimation of 1-g psSAR.

Operator	Tx power (mW)					Mean 1-g psSAR (W/kg)
	10th	50th	90th	Mean (linear)	Mean (log)	
O_A	0.25	4.66	20.45	***7.13***	3.08	***0.15***
O_B	0.27	4.00	18.36	***6.57***	2.85	***0.14***
O_C	0.22	6.22	22.48	***9.25***	3.58	***0.20***

TABLE 4. Rx power of the scanner and estimation of power density.

Operator	Rx power (nW)					Mean PD (μW/m²)
	10th	50th	90th	Mean (linear)	Mean (log)	
O_A	9.02E-02	5.08	55.85	***20.55***	3.15	***19.12***
O_B	6.98E-01	34.36	391.74	***134.03***	21.80	***117.92***
O_C	1.87	313.33	1,721.87	***640.32***	137.37	***535.16***

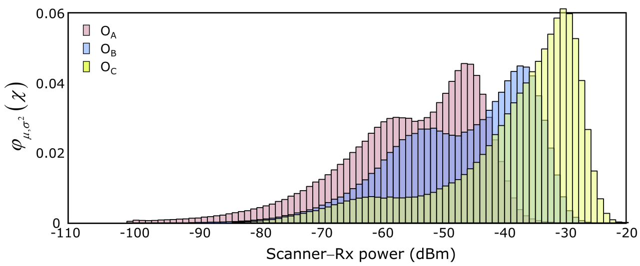


FIGURE 7. Histogram of scanner–Rx power.

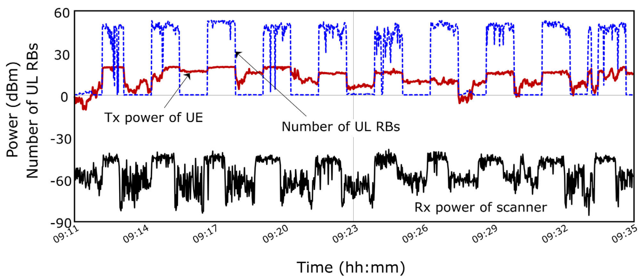


FIGURE 8. Data comparison in the time domain (O_A).

PD corresponding to the Rx power (1,722 nW) in the upper 90th percentile for O_C is approximately 1.4 mW/m^2, which is much lower than the whole-body exposure limit of the general public, i.e., 10 W/m^2 based on IEEE Std. 95.1 and the ICNIRP Guidelines [13], [14].

V. DISCUSSION

Approximately 20% of the total population of South Korea is concentrated in Seoul. In this study, to evaluate the level of exposure to radiation of 5G mobile phones and base stations for the three operators in a real environment, using a vehicle, measurements were conducted from late 2019 to early 2020 in residential areas having a significant number of neighborhoods.

According to the Ministry of Science and Information and Communication Technology (ICT), the number of 5G base stations installed nationwide as of May 1, 2020 is approximately 115,400. This is only approximately 13% of the number of 870,000 LTE base stations. The number of 5G base stations will increase rapidly over the next few years. Therefore, the measurement results of this paper only indicate the very early status of 5G NR service in Seoul.

From a significant number of power sample measurements, the exposure levels were evaluated when considering the characteristics of the 5G NR systems adopted by the Korean mobile operators, the main findings of which can be summarized as follows:

- The SSB beam is the only always-on signal in a 5G NR network. Its time-averaged mean exposure level evaluated along the side streets of Seoul was less than 5 μW/m^2, which is much lower than the exposure limit of the general public. It was observed that the mean SS-RSRP in a 5G network of mobile operators O_A and O_B was more than 10 dB lower than the mean RSRP measured in a 4G network during the same period. The main reason for these results seems to be due to the extremely small number of 5G base stations installed at the time of measurement. In the case of O_C, it was observed that the power control performance in a 5G network was poor although the mean RSRP and SS-RSRP levels of 4G and 5G networks are similar.
- Because the Rx power (SS-RSRP) level from the base stations was low, a Tx power level close to the maximum output power of 23 dBm of the UE was observed for a considerable amount of time, and the mean Tx power of the UL slots was 31–43 mW. This mean power produces a 1-g psSAR of approximately 0.14–0.20 W/kg when considering a 1-g psSAR of 0.9 W/kg reported in the SAR compliance test result at the maximum power of a UE.
- The total Rx power of each operator within a given bandwidth was measured using the antenna of the scanning receiver at a location approximately 55 to 70 cm

from the UEs. Although the traffic beam of an operator is mainly focused on the corresponding active UE in a 5G network, the scanner Rx antenna at this distance will likely coexist with the UE inside the corresponding traffic beam. The EMF level observed at the scanning receiver could be the level of exposure for people near an active UE. It was impossible to identify the amount of exposure contributed to by only the traffic beam. The total mean PD level owing to the traffic beam, SSB beams, and Tx power of the UE for each operator was less than 1 mW/m^2.

VI. CONCLUSION

Because 2G to 5G technologies coexist in the current mobile communication environment, an evaluation of the total EMF exposure owing to mobile communication technology services in a real environment should be based on the results of a large-scale survey. Therefore, the evaluation of the EMF exposure level owing to the 5G NR service reported in this paper can provide fragmentary knowledge of the total EMF exposure. Unlike the existing 2G (CDMA), 3G (WCDMA), and 4G (LTE FDD) technologies, which have been serviced in Korea, 5G NR technology uses steerable beams in a 2D or 3D space, and its DL and UL transmissions share the same carrier frequency band and are separated by a rigid time schedule. In this paper, we attempted to evaluate the EMF exposure when considering these technical differences. The results of this study will be employed in a future total exposure assessment of a mobile communication environment.

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