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Actual Output Power Levels of User Equipment in 5G Commercial Networks and Implications on Realistic RF EMF Exposure Assessment

PARAMANANDA JOSHI, FATEMEH GHASEMIFARD, DAVIDE COLOMBI, AND CHRISTER TÖRNEVIK, (Member, IEEE)
Ericsson Research, Ericsson AB, 164 80 Stockholm, Sweden

Corresponding author: Paramananda Joshi (paramananda.joshi@ericsson.com)

ABSTRACT Here, the results on actual output power levels of the fifth generation (5G) user equipment (UE) operating in commercial 5G networks are presented. Using a network management platform, output power data for several UE were collected over fifteen days. Out of about 545 million power samples obtained from UE operating in two 5G commercial networks, the time-averaged output power, of relevance for electromagnetic field (EMF) exposure assessment, was found to be always less than 43% of the maximum time-averaged UE output power considering time division duplexing. In addition, 95% of the time-averaged power samples were found to be less than 8% of the maximum while the mean value was less than 2%. Despite very conservative assumptions in the applied method, the time-averaged 5G UE output power levels were found to be well below the maximum. These results are in line with the output power levels observed for 3G and 4G UE in previous studies and is of importance to characterize the actual EMF exposure of 5G devices during operation.

INDEX TERMS 5G mobile communication, NR, user equipment, output power, RF EMF exposure, network-based measurement.

I. INTRODUCTION

Radio frequency (RF) electromagnetic field (EMF) compliance assessments of radio equipment are conducted before placing on the market to ensure conformity with EMF exposure limits such as those specified by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1]. Test methodologies for mobile network user equipment (UE) are described by standards such as IEC/IEEE 62209-1528 [2] and IEC 62209-3 [3]. For frequencies below 6 GHz, such procedures are based on the measurement of the specific absorption rate (SAR), i.e. the rate of absorbed energy per unit mass of body tissue. According to the existing requirements, UE are typically configured to continuously transmit at the peak power level while measuring SAR.

RF EMF exposure limits are typically intended to be averaged over a certain time period and the UE time-averaged transmit power is therefore more relevant than the instantaneous one. For instance, according to the ICNIRP guidelines [1], localized SAR limits are intended to be averaged over 6 minutes. Over this period, the uplink (UL) data transmission and hence the UE output power normally varies a lot. In addition, other features such as power control mechanism and discontinuous transmission in mobile communication systems contribute to a lower time-averaged output power than the maximum UE power. Thus, configuring UE to the maximum output power for EMF compliance assessment might result in an overly conservative EMF exposure estimation. Several studies conducted for the second generation (2G) [4]–[7], third generation (3G) [7]–[10] and fourth generation (4G) [11], [12] mobile networks, have shown that the time-averaged UE output power levels in real operations are lower than the peak power.

In a multinational study conducted in Global System for Mobile (GSM) communication based 2G networks [5], the mean time-averaged output power of UE was reported to be 50% of the maximum time-averaged power. In a network-based study conducted in a 2G/GSM network in Sweden [6], 50% and 25% of the collected power samples in rural and urban areas, respectively, were reported to transmit with the maximum power.

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Output power levels of UE in 3G and 4G networks were found to be significantly lower than the actual output power levels reported for 2G networks. In a study conducted in a Wideband Code Division Multiple Access (WCDMA) based 3G network in France [8], the reported mean time-averaged output power levels were varying between less than 1% to 2% of the maximum UE power depending upon the environments. In two other network-based studies conducted in 3G/WCDMA networks in Sweden [9] and in India [10], the mean time-averaged UE output power levels were found to be less than 1% of the maximum for voice and up to about 4-6 times higher for data and video transmissions. In an extensive network-based study conducted in a Long Term Evolution (LTE) based 4G network in Sweden [12] in which the output power of about 7000 UE were collected over a week, the mean time-averaged output power levels were found to be below 1% of the maximum UE power.

Due to the benefits of the fifth generation (5G) New Radio (NR) mobile communication networks over 4G networks such as higher throughput, lower latency, and more reliable connection [13], many operators in several countries have deployed or are on the process of rolling-out 5G networks. According to Ericsson Mobility Report published in June 2020 [14], 5G subscriptions are expected to reach 190 million by the end of 2020 and forecasted to be around 2.8 billion globally by the end of 2025. The report also estimates that 5G networks will carry nearly half of the world's mobile data traffic by 2025.

To our knowledge, as of today there is no available study providing information on the actual output power levels of 5G UE in real operation. With the aim to fill the gap, an extensive study by collecting about 545 million UE power samples within two 5G commercial networks over 15 days was conducted. More details about how the data was collected and analyzed is presented in the Section II. The results are demonstrated in Section III, followed by a discussion in Section IV and a conclusion in Section V.

II. METHOD

For this study, a few relevant network parameters were recorded in two commercial 5G NR networks, Telstra in Australia and SK Telecom in South Korea, using the Ericsson Network Manager (ENM), which is an Operation Support System (OSS) platform. ENM provides access to many network parameters, used by operators to observe, manage and troubleshoot the networks. The data collected from ENM in this study did not include any mobile network subscriber information. The data were collected for all UE connected to 31 cells in the Telstra network and 28 cells in the SK Telecom network from March 5 to 19, 2020. A cell in this context corresponds to a geographical area in which 5G UE has access to the radio signals emitted by a Radio Base Station (RBS) transmitter in a specific 5G channel. The 5G networks of both operators were operating in the mid-band frequency range with carrier frequencies varying from 3.3 GHz to 3.8 GHz. Most of the cells in both networks were located in dense-urban areas and a few in urban areas.

A. INSTANTANEOUS UE OUTPUT POWER

One of the parameters collected for this study was the power headroom (PH), expressed in decibel (dB) and defined as the difference between the maximum instantaneous output power of the UE ($P_{\max}$) and the estimated UE output power for transmission on Physical Uplink Shared Channel (PUSCH) [15] which is the transport channel used for transmission of uplink data in NR,

$$PH = P_{\max} - P_{\text{PUSCH-estimated}} \tag{1}$$

The parameter $P_{\max}$ is usually configured by the network on a cell level. In the networks selected for this study, the $P_{\max}$ was configured to 23 dBm (200 mW), corresponding to the maximum power of commercially available 5G enabled mobile devices.

It is noteworthy that PH can be negative indicating that the UE is power limited in the scheduled slot (i.e. the UE is already operating at $P_{\max}$). In such cases, the RBS adjusts the resource allocation, modulation and coding schemes in the scheduled slot to bring up the PH to a positive value [16]. If PH is positive, the transmit power of the UE is equal to the estimated one. Therefore, the instantaneous UE output power on the PUSCH scheduled slot (in dBm) is $\min(P_{\max}, P_{\max} - PH)$ and in linear scale (in mW) it is expressed as,

$$P_{\text{tx-inst}} = 10^{\left(\frac{\min(P_{\max}, P_{\max} - PH)}{10}\right)} \tag{2}$$

In this article, $P_{\text{tx-inst}}$ when normalized to $P_{\max}$ is denoted as $\bar{P}_{\text{tx-inst}}$, where $0 < \bar{P}_{\text{tx-inst}} \leq 1$ with the value of 1 indicating that the UE is transmitting at $P_{\max}$ within the scheduled slot.

PH values are periodically reported by each UE during the scheduled period for PUSCH transmission. In the analyzed networks in this study, this periodicity was set to 100 ms. Each PH sample is reported according to the indices defined by 3GPP [17] and shown in Table 1. There are 64 power headroom report (PHR) indices defined in the table, and each index corresponds to a PH interval of 1 dB for up to PHR index 54 and 2 dB thereafter. The reported PH samples are organized and reported by the ENM into bins. In each bin, the number of PH samples lying within four consecutive PHR indices are logged. For example, PH samples corresponding to PHR indices 0,1,2 and 3 are logged in 'Bin 0', those corresponding to PHR indices 4,5,6 and 7 are logged in 'Bin 1', and so on. Therefore, each bin corresponds to PH values within a 4 dB range up to 'Bin 12' and within an 8 dB range for next bins. In this study, the PH value of the logged samples in each bin was conservatively assumed equal to the lowest value of PH for that bin interval. This means that the $P_{\text{tx-inst}}$ obtained using (2) is an overestimate of the actual instantaneous UE output power.

TABLE 1. Power headroom report mapping.

PHR index	PH (dB)	Measurement bins
0	PH < -32	Bin 0
1	-32 ≤ PH < -31	
2	-31 ≤ PH < -30	
3	-30 ≤ PH < -29	
4	-29 ≤ PH < -28	Bin 1
5	-28 ≤ PH < -27	
6	-27 ≤ PH < -26	
7	-26 ≤ PH < -25	
...	...	...
52	19 ≤ PH < 20	Bin 13
53	20 ≤ PH < 21	
54	21 ≤ PH < 22	
55	22 ≤ PH < 24	
56	24 ≤ PH < 26	Bin 14
57	26 ≤ PH < 28	
58	28 ≤ PH < 30	
59	30 ≤ PH < 32	
60	32 ≤ PH < 34	Bin 15
61	34 ≤ PH < 36	
62	36 ≤ PH < 38	
63	PH ≥ 38	

B. TIME-AVERAGED UE OUTPUT POWER

Since every reported *PH* sample corresponds to the output power availability for a UE in the corresponding scheduled slot for PUSCH transmission, the instantaneous output power of a UE ($P_{tx-inst}$) given by (2) is valid for one slot of 500 μs duration corresponding to the subcarrier spacing of 30 kHz implemented by the networks. However, as described in Section I, the UE output power averaged over longer periods, such as 6 minutes, is a more relevant metric for the evaluation of EMF exposure according to applicable guidelines (e.g. [1]).

The ENM used to collect data for this study logs the distribution of *PH* samples in a cell for every result output period (ROP), which was equal to 15 minutes (900 seconds), without providing the timestamp of the logged samples and UE identification. To obtain the time-averaged UE output power distribution, two additional network parameters were collected. The first one was $T_{PUSCH-available}$ which provides the total duration of the slots available for uplink transmission on PUSCH within a ROP. Using this parameter, the maximum available time-averaged UE output power is specified as

$$P_{max-avail} = \frac{T_{PUSCH-available}}{ROP} \times P_{max} \quad (3)$$

Both networks considered in this study applied time division duplexing (TDD), and $T_{PUSCH-available}$ varied from 20% to 25% over the ROP depending on the measurement cells and networks.

The second collected parameter was $T_{PUSCH-scheduled}$ which is the total duration of slots in a ROP in which at least one UE in the cell was PUSCH-scheduled. This parameter was aggregated on a cell level without UE identification possibility. Therefore, by dividing $T_{PUSCH-scheduled}$ by the estimated (as described below) number of continuously PUSCH scheduled UE in a cell, $N_{cont-PUSCH-scheduled}$, the average fraction of $T_{PUSCH-scheduled}$ that one continuously PUSCH-scheduled UE transmits in uplink was determined. Finally, the UE output power (in mW) averaged over a ROP was calculated by scaling each $P_{tx-inst}$ sample as

$$P_{tx-avg} = P_{tx-inst} \times \frac{T_{PUSCH-scheduled}/N_{cont-PUSCH-scheduled}}{ROP} \quad (4)$$

Note, rather than scaling the average of all reported $P_{tx-inst}$ in a ROP, P_{tx-avg} was obtained by scaling each $P_{tx-inst}$ sample with the estimated uplink transmission time as shown in (4), which results in a conservative estimate of P_{tx-avg}. Therefore, the total number of P_{tx-avg} samples is equal to the number of reported $P_{tx-inst}$ samples. This approach, which is equivalent to the one used in [12], was used since the reported samples of $P_{tx-inst}$ in a ROP were aggregated on a cell level without the possibility to discriminate among different UE.

Furthermore, the time-averaged UE output power P_{tx-avg} was normalized to $P_{max-avail}$. In this article, the normalized time-averaged UE output power is denoted as $\bar{P}_{tx-avg}$.

C. ESTIMATION OF $N_{cont-PUSCH-scheduled}$

The actual number of active UE to be used in (4) was not directly available through the ENM. Therefore, $N_{cont-PUSCH-scheduled}$ was estimated in two steps. First, the total number of *PH* samples logged during a ROP (900 seconds) was divided by 9000, which is the maximum number of *PH* samples a cell would log for one continuously-connected UE (at the rate of one sample per 100 ms). Then, the obtained number was rounded up to avoid ending up with a decimal number for the continuously scheduled users. $N_{cont-PUSCH-scheduled}$ obtained in this way would be equal to the actual number of active UE only if they were continuously scheduled for transmission during the ROP. For realistic cases, where UE uplink transmission is characterized by bursts of traffic, $N_{cont-PUSCH-scheduled}$ provides a large underestimate of the number of active UE in the cell. For example, in [12], the mean uplink transmission time of 4G UE in a 15-minute interval has been reported to be 1.1 second. Consequently, the transmission time for one UE, expressed as $T_{PUSCH-scheduled}/N_{cont-PUSCH-scheduled}$, is much larger and the time-averaged UE output power, P_{tx-avg}, as determined in (4), is a highly conservative estimate.

III. RESULTS

About 545 million *PH* samples, corresponding to about 122 hours of UE uplink data transmission, in Telstra and SK Telecom 5G networks (denoted 'Operator 1' and 'Operator 2' hereafter in no particular order) were recorded and analyzed. The cumulative distribution functions (CDF) for $\bar{P}_{tx-inst}$, i.e. $P_{tx-inst}$ normalized to P_{max}, is depicted in Fig. 1a. The curves present a step behavior since values of $\bar{P}_{tx-inst}$ are (conservatively) discretized with a step size of 4 dB or larger

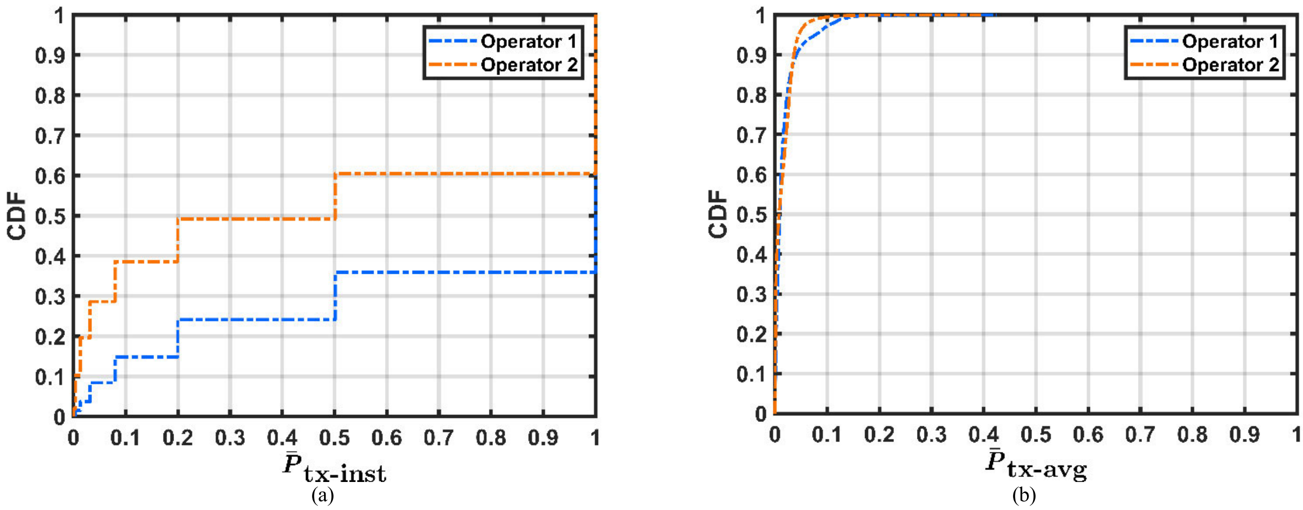

FIGURE 1. Cumulative distribution function of (a) $\bar{P}_{tx-inst}$, and (b) $\bar{P}_{tx-avg}$. The level '1' on the horizontal axis in (a) corresponds to P_{max}, while in (b) it corresponds to $P_{max-avail}$.

TABLE 2. Statistics of $\bar{P}_{tx-avg}$.

Network operator	1	2
Mean	1.8%	1.5%
Median	0.9%	0.8%
95th percentile	7.7%	4.5%
Max.	42.5%	39.5%
Number of samples	~243 million	~302 million
Total uplink transmission time	~55 hours	~67 hours

TABLE 3. Statistics of P_{tx-avg}.

Network operator	1	2
Mean	0.9 mW	0.6 mW
Median	0.4 mW	0.3 mW
95th percentile	3.7 mW	1.8 mW
Max.	21.3 mW	15.8 mW

as described in Section II. The results show that around 64% and 40% of the UE instantaneous power samples collected from Operator 1 and Operator 2, respectively, correspond to P_{max}.

The distribution of $\bar{P}_{tx-avg}$, i.e. P_{tx-avg} normalized to $P_{max-avail}$, is shown in Fig. 1b and the statistical data are summarized in Table 2. The results show that the maximum time-averaged UE output power values are 42.5% and 39.5% of $P_{max-avail}$, respectively, in Operator 1 and Operator 2 networks. In addition, the 95th percentile of the $\bar{P}_{tx-avg}$ samples correspond to 7.7% and 4.5% of $P_{max-avail}$ in the two networks. Mean and median values are even lower and less than 2% and 1% of $P_{max-avail}$ in both networks. Note that $P_{max-avail}$ varies between 20% and 25% of P_{max} because different TDD schemes were implemented in different cells in the considered networks, as discussed in Section II. Statistical data for the time-averaged UE output power in mW are summarized in Table 3.

The cumulative distribution of $N_{cont-PUSCH-scheduled}$, i.e. the equivalent number of continuously PUSCH-scheduled users in a ROP, for each operator is shown in Fig. 2a. The distributions for the two operators are very similar. Note that $N_{cont-PUSCH-scheduled}$ is obtained from the number of reported *PH* samples and it largely underestimates the actual number of served UE as discussed in Section II. In addition, the time-variation of $N_{cont-PUSCH-scheduled}$ averaged among all the cells is shown in Fig. 2b. It can be seen in this figure that, as expected, a higher number of UE is scheduled for PUSCH transmission during rush hours compared to the nights and early mornings. This figure also shows that the average number of scheduled users in the uplink were higher during the weekdays compared to the weekends.

To evaluate the impact of the network traffic on the UE output power, the distributions of $\bar{P}_{tx-avg}$ for different time periods in a day were calculated from the recorded data for 15 days and depicted in Fig. 3. The results indicate that $\bar{P}_{tx-avg}$ is not significantly affected by the traffic or by the number of UE in the network. Moreover, the results in Fig. 4 that compare the distributions of $\bar{P}_{tx-avg}$ in weekdays and weekends for both networks, confirm that the network traffic has a negligible effect on the distribution of time-averaged UE output power.

IV. DISCUSSION

While a UE is required to transmit at its maximum available time-averaged output power ($P_{max-avail}$) during RF EMF compliance assessments, the results presented in this article demonstrate that the time-averaged UE output power when operating in a real 5G network is significantly below this maximum. Since RF EMF exposure is directly proportional to the time-averaged transmitted power, the obtained statistics are representative for the actual exposure levels from UE in commercial 5G networks.

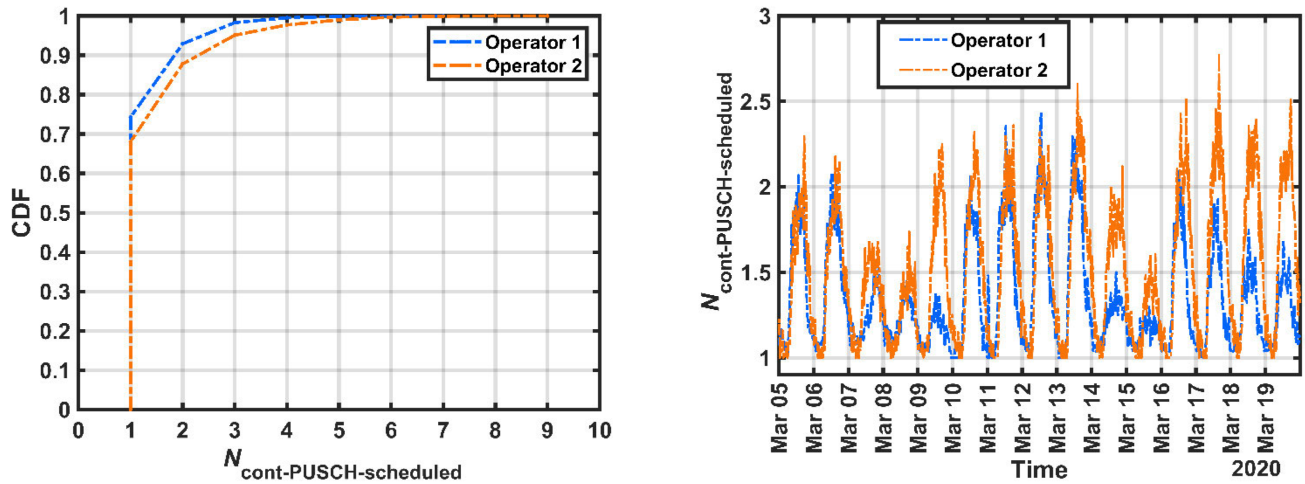

FIGURE 2. (a) Distribution of $N_{cont-PUSCH-scheduled}$, and (b) Time variation of $N_{cont-PUSCH-scheduled}$ averaged over all the cells.

The presented results can be interpreted as the upper bound of the actual UE output power levels since several conservative approaches are taken in the presented method. First, for each bin in Table 1, the minimum value of the *PH* range (corresponding to the maximum instantaneous UE output power) is assumed for all the *PH* samples in that bin. Second, as mentioned in Section II, because of the anonymity of the collected samples, the time-averaged 5G UE output power levels are obtained by scaling each of the instantaneous UE output power samples rather than scaling the mean of the samples of each UE, which results in overestimated time-averaged UE output power values. Third, since in this study the data was collected on a cell level and it was not possible to find the actual number of UE scheduled for PUSCH transmission, the minimum possible number of UE, assuming they are continuously scheduled, are estimated and used in evaluating the time-averaged output power of one UE. This conservative approach to estimate the number of UE causes an overestimation in the PUSCH-scheduled time for individual UE.

The actual time-averaged UE output power presented in this study are obtained using a few relevant network parameters collected in 15-minute time-intervals. This means the presented results are time-averaged over 15 minutes. However, since the uplink scheduling decision in 5G networks are taken for the time intervals in the range of slot duration (microseconds), a linear relation between the distribution of power headroom samples in 15 minutes and 6 minutes (specified as the averaging time by ICNIRP [1] for localized RF EMF exposure) seems reasonable. In addition, according to studies evaluating different time-averaging schemes for downlink in-situ measurements [18], [19], the difference in output power levels averaged over 1 minute, 6 minutes, and 15 minutes are were found to be small. Therefore, the obtained results can be considered representative also for EMF exposure assessments over 6 minutes.

In this study, the output power levels of UE are obtained from power headroom reports for PUSCH transmission on a carrier. As the current release of NR does not support simultaneous transmission on the PUSCH and Physical Uplink Control Channel (PUCCH), the uplink control information is multiplexed with the data on the PUSCH channel when the UE are scheduled for PUSCH transmission [20]. Therefore, the *PH* values and hence UE output power levels reported in this study correspond to the simultaneous transmission of data and control information from 5G user equipment. In addition, this study does not include cases with no PUSCH data transmission, such as when the UE is transmitting only the uplink control information on the PUCCH or the UE is transmitting Sounding Reference Signals (SRS) for channel sounding, etc., which might result in lower UE output power levels compared to PUSCH transmission. This might add additional conservativeness to the UE output power results presented in this study.

In case of uplink carrier aggregation, the maximum power for the UE is divided between the carriers and *PH* is reported for each carrier separately. In such cases, the sum of the maximum allowed output power of all the carriers is less than or equal to the maximum allowed output power of the UE [16]. When there is no uplink carrier aggregation, as for the investigated networks, the output power obtained from the *PH* report can be interpreted as the total UE output power allocated for NR. The NR networks considered in this study allowed for dual connectivity with LTE, which imply that UE may be simultaneously connected to both LTE and NR cells. In this case, similar to the carrier aggregation case, the total maximum UE output power is dynamically divided between the NR and LTE carrier, implying that the output power is totally allocated to one carrier when the UE is not connected to the second carrier [16]. In this study, since the *PH* samples were collected on a cell level and only NR cells were considered, the presented results correspond to the UE

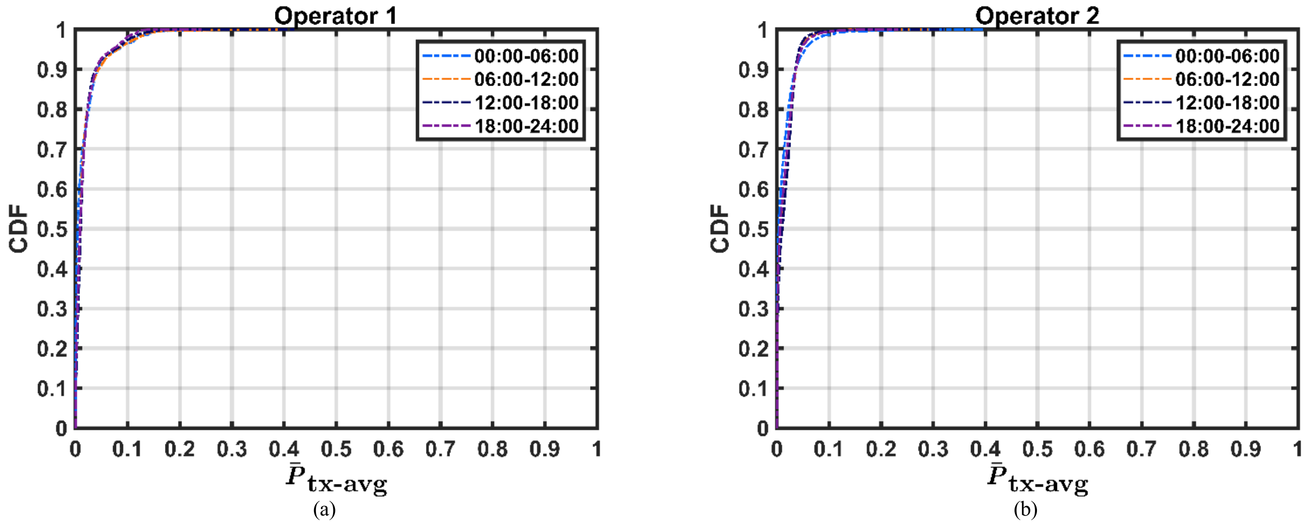

FIGURE 3. Distribution of $\bar{P}_{\text{tx-avg}}$ in different time periods of a day for – (a) Operator 1 and (b) Operator 2.

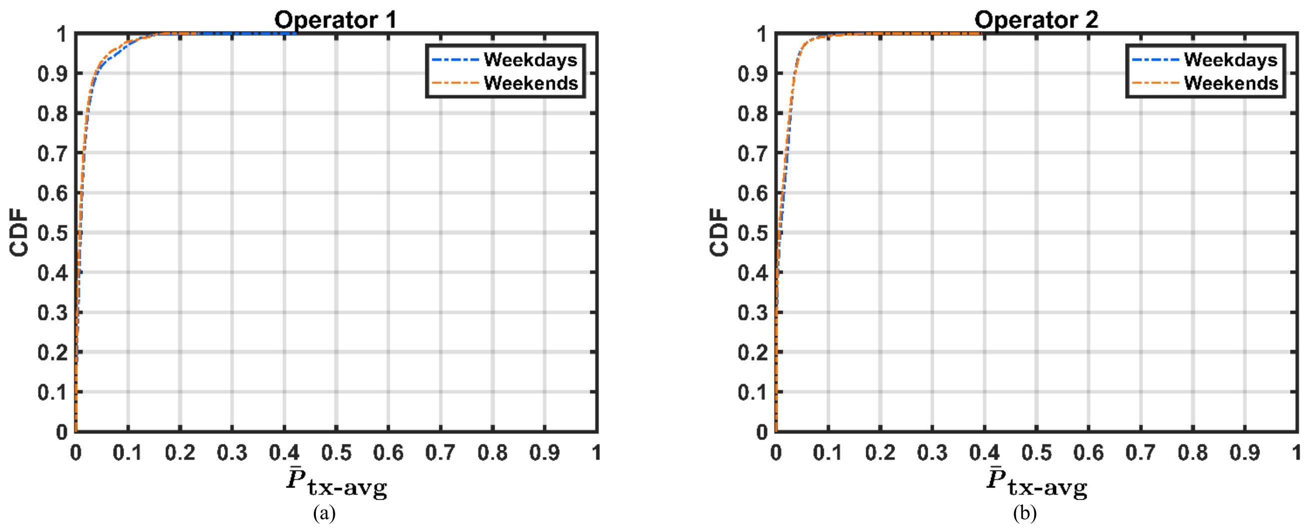

FIGURE 4. Distribution of $\bar{P}_{\text{tx-avg}}$ during weekdays and weekends for – (a) Operator 1 and (b) Operator 2.

output power levels obtained for NR component carriers of UE. Nevertheless, based on the actual output power levels of 4G UE reported in [12], which are comparable to the 5G UE output power levels obtained in this study, it is safe to say that the total output power levels considering both 4G and 5G carriers in dual connectivity cases would result in similar output power levels reported in this study and in [12].

Finally, as discussed in Section III, the number of active users seems to have a negligible effect on the time-averaged 5G UE output power. A similar observation has also been reported for UE in 4G networks in [12]. This result is attributed to the fact that both LTE and NR systems are robust to the uplink interference due to employing Orthogonal Frequency Division Multiplexing (OFDM) as the baseline transmission scheme and Discrete Fourier Transform-precoded OFDM as a complement transmission scheme [21],[22]. Therefore, while the number of 5G users will increase in the future, this is not expected to have a substantial impact on the UE output power. However, it might be of relevance to compare the results of this study with the UE output power levels in the future 5G networks with higher data traffic.

V. CONCLUSION

The distributions of actual time-averaged output power levels of 5G NR user equipment operating in the mid band were obtained using about 545 million UE power headroom samples, corresponding to about 122 hours of UE uplink data transmission, collected over fifteen days in two different 5G commercial networks. In both networks, the time-averaged UE output power levels, of more relevance for EMF exposure assessments, were significantly below the maximum available time-averaged output power, with none of the time-averaged samples being higher than 43% of the maximum value. The 95th percentile, the mean and the median values were found to be less than 8%, 2% and 1%, respectively, of the maximum UE transmission power. In addition, analyzing the data for different time intervals during a day, and comparing data for weekdays and weekends, demonstrate that the number of active users in the network have a negligible effect on the actual 5G UE output power.

The time-averaged 5G UE output power levels presented in this article are conservative and represent the upper bound of actual output power values. These results are of considerable importance to characterize the actual exposure of 5G devices and show that EMF compliance testing for the maximum possible output power levels provides very conservative and unrealistic results.

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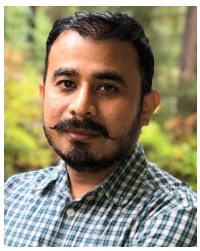

PARAMANANDA JOSHI received the B.E. degree in electronics and communication from Tribhuvan University, Kathmandu, Nepal, in 2008, and the M.Sc. degree in wireless communication from Lund University, Lund, Sweden, in 2012. Since 2012, he has been with Ericsson Research, Stockholm, Sweden, where he is currently working as a Senior Researcher and also involved in research activities related to realistic radio frequency (RF) electromagnetic fields (EMF) exposure from radio base stations and user devices. Since 2016, he has been working as the Technical Manager of the Ericsson EMF Research Laboratory, Stockholm.

FATEMEH GHASEMIFARD received the Ph.D. degree in electromagnetics engineering from the KTH Royal Institute of Technology, Stockholm, Sweden, in 2018. She did one-year Postdoctoral Research at the KTH Royal Institute of Technology. She is currently working as an Experienced Researcher with the Electromagnetic Fields Health and Safety Group, Ericsson Research, Ericsson AB, Stockholm. Her current research interests include metasurfaces, higher symmetric periodic structures, analytical and numerical methods in electromagnetics, lens antennas, array antennas, and electromagnetic field exposure assessments and methodologies. She was a recipient of the Program of Excellence Award offered by the Electrical Engineering School, KTH Royal Institute of Technology, in 2013. In 2020, she was a recipient of the EurAAP Per-Simon Kildal Award for Best Ph.D. in Antennas and Propagation.

DAVIDE COLOMBI received the M.Sc. degree *(summa cum laude)* in telecommunication engineering from the Politecnico di Milano, Italy, in 2009. Since 2009, he has been with Ericsson Research, Stockholm, Sweden, where he is currently working with research related to radio frequency exposure from wireless communication equipment, particularly for 5G. He has contributed to the development of IEC, ITU, and the IEEE standards on the assessment of radio frequency exposure from wireless equipment as an Expert, an Editor, and a Convener. He was a recipient of the 2018 IEC 1906 Award.

CHRISTER TÖRNEVIK (Member, IEEE) received the M.Sc. degree in applied physics from Linköping University, Linköping, Sweden, in 1986, and the Licentiate degree in materials science from the Royal Institute of Technology, Stockholm, Sweden, in 1991.

He joined Ericsson in 1991. Since 1993, he has been involved in research activities related to radio frequency exposure from wireless communication equipment. He is currently a Senior Expert with responsibility for electromagnetic fields and health within the Ericsson Group. From 2003 to 2005, he was the Chairman of the Mobile and Wireless Forum, where he is also the Secretary of the Board. Since 2006, he has been leading the Technical Committee on electromagnetic fields of the Swedish Electrotechnical Standardization Organization, SEK, and he has as an Expert contributed to the development of several CENELEC, IEC, ITU and IEEE standards on the assessment of RF exposure from wireless equipment.