Output Power Levels of 4G User Equipment and Implications on Realistic RF EMF Exposure Assessments

Paramananda Joshi, Davide Colombi, Björn Thors, Lars-Eric Larsson, and Christer Törnevik

***Abstract*—The aim of this paper is to present results on output power level distributions of 4G user equipment (UE) using data applications based on a very large number of samples collected over seven days in a Long Term Evolution (LTE) operating network. The output power data have been obtained through network-based measurements conducted for about 7000 UE connected to 41 LTE radio base stations (RBSs) located in rural, suburban, urban and indoor environments in Sweden. More than 300,000 power samples were collected. In rural environments, the 95th percentile time-averaged output power values were found to be 2.2% of the maximum available power for LTE UE, while the corresponding values were less than 1% in other environments. The mean output powers in all the environments were found to be less than 1% of the maximum available output power. These values are in line with results obtained for 3G UE despite an almost tenfold increase in the achievable peak data throughput. The findings show that knowledge on realistic power levels is important for accurate assessments of the radio frequency electromagnetic field exposure from mobile communication equipment.**

***Index Terms*—4G mobile communication, LTE, user equipment, RF EMF exposure, output power, power distributions.**

I. Introduction

SINCE the commencement of fourth generation (4G) Long Term Evolution (LTE) mobile communication network in 2009, the number of LTE user equipment (UE) in the market has grown rapidly. LTE UE, which use Orthogonal Frequency-Division Multiplexing (OFDM) based radio access technologies, have higher user throughput than the second generation (2G) and the third generation (3G) UE. The achievable peak uplink throughput in LTE for a UE category three terminal is 50 Mbps [1].

Human exposure to radio frequency (RF) electromagnetic fields (EMF) emitted from a UE is directly proportional to its output power. Before placing on the market, RF EMF compliance assessments of UE are conducted by the equipment manufacturers to ensure compliance with EMF exposure limits such as the ones recommended by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [2]. Compliance assessments are generally conducted according to international standards such as [3, 4], which require that the UE transmits continuously at the maximum output power while being tested for compliance with the applicable EMF exposure limits.

Output power levels of a UE in real operation, however, are generally much less than the maximum possible output power because of different factors, such as traffic variation, fast and advanced power control mechanism, discontinuous transmission (DTX) and soft handover [5]. This indicates that the standardized procedures may lead to very conservative estimations of EMF exposure, which is further emphasized by the fact that the ICNIRP exposure limits for mobile communication frequencies are intended to be taken as an average over 6 minutes [2]. Knowledge of the actual transmit power levels is therefore of fundamental importance in accurately evaluating real EMF exposure from UE such as for epidemiological investigations of potential associations between mobile phone usage and adverse health effects.

Low average UE output power levels have been reported in previous studies in which output power measurements of UE in 2G mobile networks were conducted [6-9]. In [7], the mean output power of UE in a Global System for Mobile communication (GSM) based 2G network was found to be 50% of the maximum[1]. In a network-based measurement conducted in a GSM network in Sweden, the maximum power level was reported to be used 50% of the time in rural areas and 25% of the time in urban areas [8].

Much lower UE average output power levels, compared with 2G networks, have been reported in previous studies of 3G networks [9-12]. In a drive-test study conducted in a Wideband Code Division Multiple Access (WCDMA) based 3G network in France [10], the mean output power in outdoor environments was found to be less than 1% of the maximum power[2]. A network-based measurement study conducted in a WCDMA network in Sweden [11] showed that the mean output power was less than 1% of the maximum available power for voice

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[1] The maximum peak output power for a GSM 900 MHz class 4 UE is equal to 2 W (33 dBm). For a DCS 1800 and PCS 1900 class 1 UE the maximum peak output power is 1 W (30 dBm).

[2] The maximum output power for a 3G class 3 UE is 250 mW (24 dBm).

calls, while data applications resulted in about 4 to 6 times higher output power levels. In a network-based measurement conducted in a 3G WCDMA network in India [12], the mean UE output power for voice calls and data applications were found to be around 1% and 3% of the maximum power, respectively.

Only a few studies have been conducted to date to assess the UE output power and the realistic EMF exposure from UE in 4G LTE networks [13, 14]. These studies had limited scope as they were based on a relatively small amount of data obtained for a single UE. In [13], which was based on comparative near-field radiated power measurements of a UE by using a miniature electric field probe in a stationary environment, the multiplication factor of the transmitted power for LTE as compared to WCDMA was found to be 15.3 on average, ranging from 9.3 up to 31.6, depending on different considered application services. In a drive and walk test study conducted for an LTE UE in Stockholm in 2012, the mean output power of the UE averaged over 6 minutes for an application with a data rate comparable to voice call was found to be 0.3% of the maximum available power [14]. In the same study, the mean output power averaged over 6 minutes for a file uploading activity using File Transfer Protocol (FTP) with the average uplink throughput of around 26 Mbps was found to be about 14% of the maximum possible power.

This work makes up for the lack of comprehensive studies concerning realistic uplink power levels and EMF exposure assessments in 4G LTE networks by utilizing network-based measurements to obtain large data sets directly via the operations support system (OSS), normally employed for network management. With this approach it was possible to simultaneously collect output power data for about 7000 UE during a time period of 7 days. To our knowledge, this is the first extensive study to date that assesses the realistic uplink power levels in an LTE network.

II. METHODS

Network-based measurements of UE using data applications were conducted in the Telia LTE network in Sweden using the Operation Support System – Radio and Core (OSS-RC, Ericsson AB, Stockholm, Sweden) via the so called Cell Trace function. The OSS-RC is part of the LTE radio access network (RAN) system, and comprises a collection of functions for network management. The Cell Trace function records performance events from all UE, or a subset of them, in one or more selected cells that belong to the same RBS. It provides monitoring and evaluation capability of different traffic scenarios, and gives visibility of air interface quality and UE performance, and is used by the network operators for troubleshooting and optimization of the network. The recordings were collected in files for each RBS for all UE and every result output period (ROP) of the OSS-RC, which is 15 minutes long. The measurements were made during a full week from July 25 to July 31, 2016 in 235 LTE cells belonging to 41 eNodeBs (RBSs) in the LTE network. Each cell in this context corresponds to a geographical area in which LTE UE have access to the radio signals emitted by a RBS transmitter in a specific LTE channel. The cells are sorted into one of the categories rural, suburban, urban, and indoor-office depending on the environment in which they are located. The cells in rural environments used LTE Band 20 (uplink 832 MHz - 862 MHz) with a channel bandwidth of 10 MHz, while cells in other environments used LTE Band 3 (uplink 1710 MHz – 1785 MHz) and LTE Band 7 (uplink 2500 MHz – 2570 MHz) with a channel bandwidth of 20 MHz. This study also includes measurements conducted during a music concert at Friends Arena in Stockholm on July 26, 2016, with 55,000 people in the audience. Only single carrier uplink feature was supported in the LTE network in all the environments.

One of the parameters collected was the so called power headroom (PH) [15], which is a measure of the difference between the maximum per-carrier transmit UE power and the estimated transmit power of the UE [16]. The PH, given with a step size of 1 dB, can be negative, indicating that the actual per-carrier transmit power of the UE is limited by the per-carrier transmit power limit, at the time of power headroom reporting. The RBS takes the PH report (PHR) into consideration for efficient scheduling of uplink resources and link adaptation. For single carrier uplink, as employed in the considered network, PH can be translated to UE output power according to

$$P_{\text{tx}} = \min\left(P_{\text{CMAX}}, P_{\text{CMAX}} - PH\right) \quad (1)$$

where, P_{tx} is the output power of UE, and P_{CMAX} is the configured maximum possible output power of the UE, i.e. 23 dBm (200 mW) [17]. The PH samples were collected every 200 ms. For the post-processing, all UE Tx power samples of all events in all cells were amassed.

Knowledge of UE transmission time is vital to assess the realistic exposure from the UE, since the internationally recognized EMF exposure limits such as those given in [2] are provided in terms of the exposure averaged over 6 minutes. With this in mind, another parameter collected in the measurements was the effective uplink transport time, which is basically the uplink data volume transfer time on the air interface between UE and RBS. This parameter was recorded per event. The uplink transmission time of events was later filtered out and summed per UE for each ROP in the measurement data file.

A simple approach was developed to derive time-averaged output power levels from the UE uplink transmission time samples and maximum possible UE output power. This approach takes into consideration the fact that the ICNIRP exposure limits [2] for frequencies below 10 GHz are intended to be averaged over 6 minutes (360 seconds). The time-averaged output power (in mW) can be written as

$$P_{\text{tx\_avg}} = \min\left(T_{\text{tx}}, T_{\text{exp}}\right) \times \frac{P_{\text{CMAX}}}{T_{\text{exp}}} \quad (2)$$

where, $P_{\text{tx\_avg}}$ is the time-averaged output power of the UE, T_{tx} is the uplink transmission time of the UE in seconds for the corresponding 15 minutes long ROP, and T_{exp} is the exposure time over which the ICNIRP [2] exposure limits for mobile communications are intended to be averaged. Thus, the time-averaged output power is equal to P_{CMAX} for the case $T_{\mathrm{tx}} \geq T_{\mathrm{exp}}$, and scaled-down by the factor $\frac{T_{\mathrm{tx}}}{T_{\mathrm{exp}}}$ for shorter transmission times. The maximum possible value of T_{tx} is 15 minutes, equal to the ROP.

III. RESULTS

Peak UE output power results, corresponding to P_{tx} in Equation (1), are provided in Figure 1 in the form of cumulative distribution function (CDF) curves for different environments. These samples represent raw, i.e. non-time-averaged, UE output power values. The significantly lower output power levels for the indoor office environment compared with outdoor environments can be attributed to more advantageous propagation conditions and shorter distances between UE and RBSs.

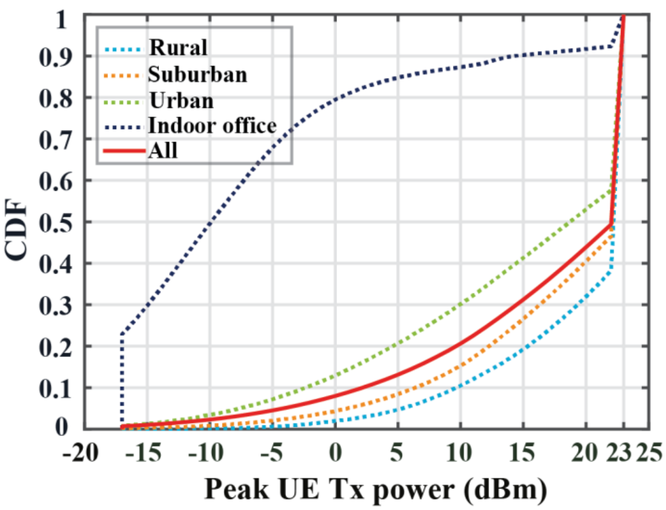


Figure 1. Distribution of peak UE output power in different environments

In order to determine time-averaged UE output power values of relevance for RF EMF exposure, the transmission times of UE in the LTE network were collected for every ROP. Therefore, the maximum UE transmission time possible in this measurement is 15 minutes. Shown in Figure 2 are CDFs of uplink transmission time of the UE in different environments based on 332541 collected samples, see TABLE I. While the maximum uplink transmission time of all the samples was more than 11 minutes, 95 percent of the samples were 3.8 s or shorter considering all the environments. The 95$^{\mathrm{th}}$ percentile uplink transmission time varied between 1.3 s in indoor office environments to 7.9 s in rural environments.

TABLE I
LTE UE UPLINK TRANSMISSION TIME STATISTICS IN DIFFERENT ENVIRONMENTS

Environments	Uplink UE transmission time (s)			Number of samples
	Mean	95$^{\mathrm{th}}$ percentile	Max	
Rural	2.0	7.9	445.3	59707
Suburban	0.8	2.4	662.8	79480
Urban	0.9	3.0	442.9	192907
Indoor-office	0.4	1.3	19.8	447
All	1.1	3.8	662.8	332541

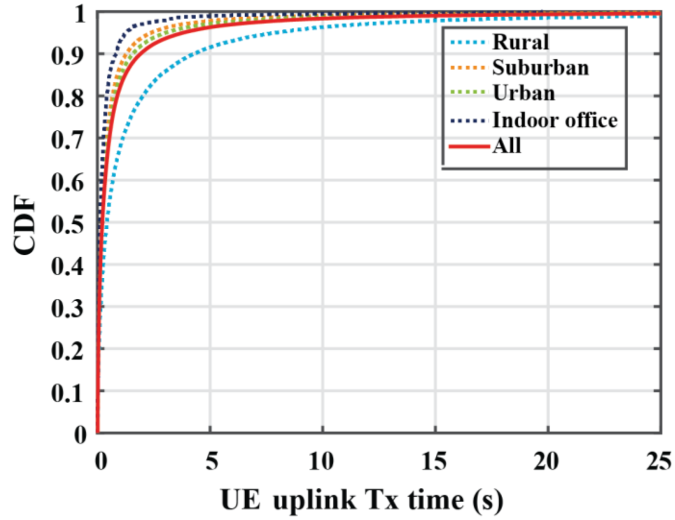


Figure 2. Distribution of uplink transmission time of UE in different environments

The UE output power levels in Figure 3 and TABLE II correspond to the time-averaged UE output power levels obtained from the UE uplink transmission time samples collected over 15 minutes according to Equation (2). Higher UE output power levels were observed in rural environments, which can be attributed to larger distances between UE and RBSs. In rural environments, the 95$^{\mathrm{th}}$ percentile time-averaged output power level of UE was found to be 6.4 dBm (4.4 mW), which is 2.2% of the maximum possible output power from

TABLE II
LTE UE TIME-AVERAGED OUTPUT POWER STATISTICS IN DIFFERENT ENVIRONMENTS

Environments	Realistic output power levels of UE (dBm)				
	Mean	Median	90$^{\mathrm{th}}$ percentile	95$^{\mathrm{th}}$ percentile	Max
Rural	0.5	-6.3	3.8	6.4	23.0
Suburban	-3.7	-9.9	-1.5	1.2	23.0
Urban	-3.1	-9.6	-0.6	2.3	23.0
Indoor-office	-6.1	-11.8	-3.2	-1.4	10.4
All	-2.3	-9.1	0.3	3.3	23.0

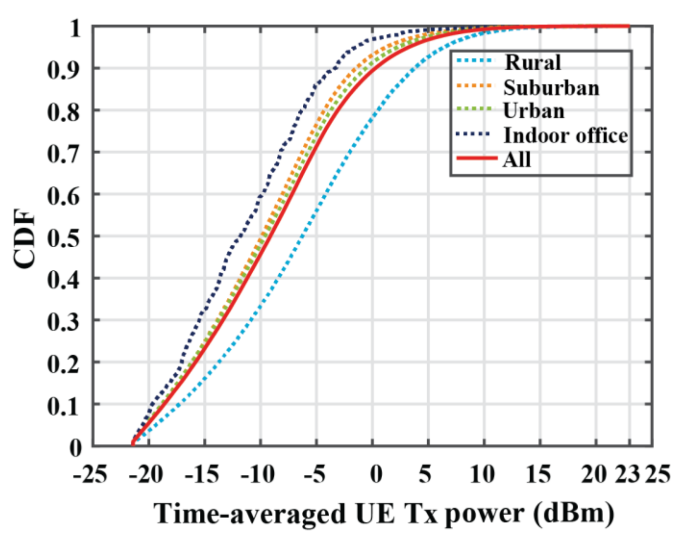
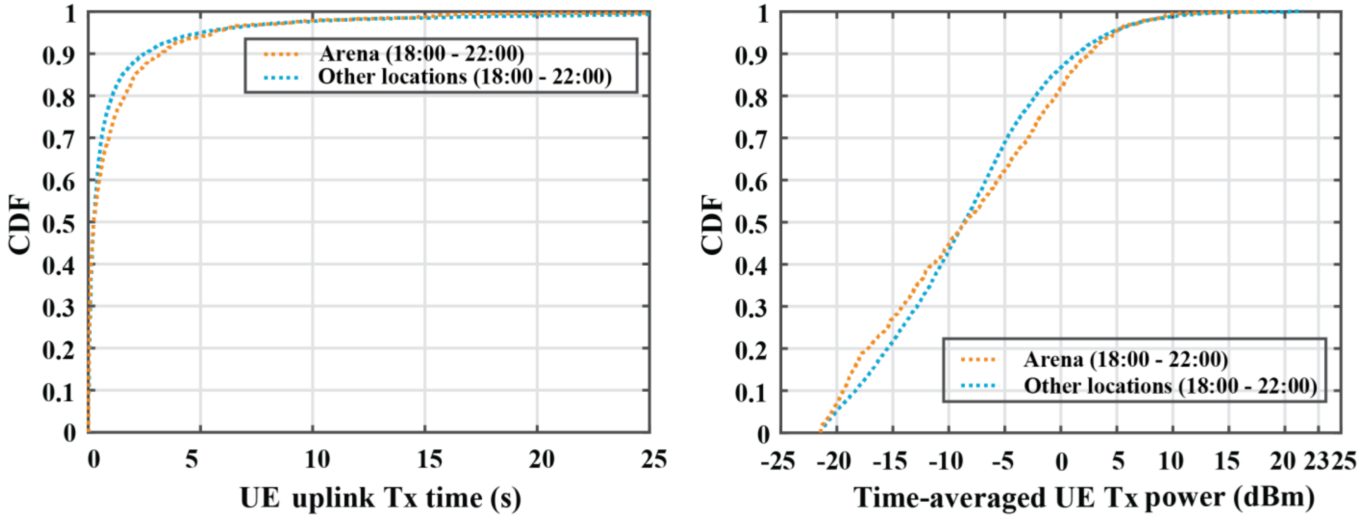


Figure 3. Distribution of time-averaged output power of UE in LTE network in different environments



(a) (b)

Figure 4. (a) Distribution of uplink transmission time of UE, (b) Distribution of time-averaged output power of UE, in arena and other locations

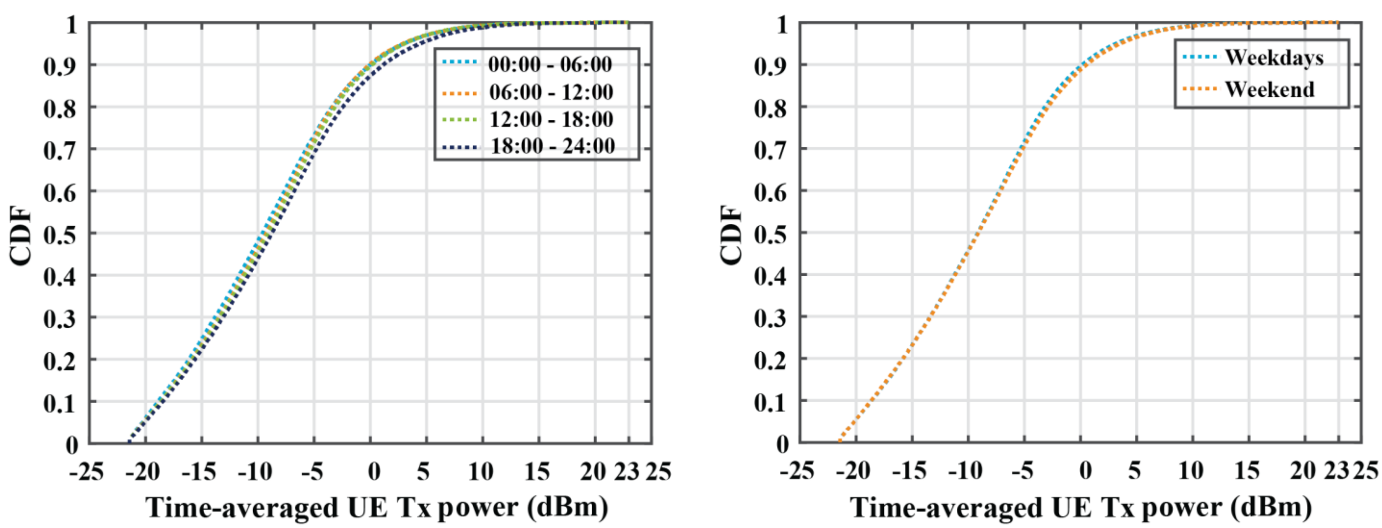
LTE UE (200 mW). The corresponding values for suburban, urban and indoor office environments were found to be 1.2 dBm (1.3 mW), 2.3 dBm (1.7 mW) and -1.4 dBm (0.7 mW), respectively, which are all less than 1% of the maximum possible output power. Also, the mean UE output power levels in all the environments were found to be less than 1% of the maximum possible output power.

Comparison has been also made between the measurements in the arena and other locations during the concert program from 18:00 to 22:00 on July 26, 2016. Distributions of UE uplink transmission time and time-averaged output power levels are shown in Figure 4a and Figure 4b, respectively. As shown in the figures, no big difference is seen between the results in the arena and other locations during the concert period.

The distribution of time-averaged UE output power for different time periods in a day, and for weekdays and weekend are shown in Figure 5a and Figure 5b, respectively. According to the figures, there is much similarity between the results of different time periods of a day, and also between weekdays and weekend.

IV. DISCUSSION

Most RF EMF compliance assessment standards require testing of UE at the maximum available power level. As shown in this work, however, the actual transmitted power levels of 4G LTE devices are usually significantly below the maximum. Since the RF EMF exposure is directly proportional to the transmitted power, the obtained statistics on normalized actual output power values of UE to the maximum available power also represent statistics on actual exposure levels normalized to the maximum possible exposure. This type of information is of fundamental importance for epidemiological investigations of potential associations between mobile phone usage and adverse health effects and for communications related to actual RF EMF exposure levels.



(a) (b)

Figure 5. Distribution of time-averaged output power of UE, (a) in different time periods of a day, and (b) in weekdays and weekend

The LTE power control algorithm in uplink tends to maintain the average output power values on a low level by maximizing the throughput and therefore reducing the transmission time. As indicated in Figure 1, the UE might momentarily transmit at or close to the maximum power but, as shown in Figure 3, the time-averaged power values are well below the maximum.

The similarity of the output power distributions in Figure 4b for the crowded area (arena) and other less crowded locations is most likely due to the fact that the LTE system is robust to the uplink interference because of its use of orthogonal frequency resources [18]. This also holds for Figure 5 where very similar distributions are obtained for low and high traffic periods.

The fact that the uplink transmission time samples were summed over 15 minutes for each UE while considering the 6 minutes duration as recommended by ICNIRP [2] to calculate the transmission time fraction in Equation (2) leads to a conservative estimation of realistic exposure values. While it was not possible to sum the transmission time samples every 6 minutes because the shortest possible ROP of the OSS system was 15 minutes, transmission time samples summed over 6 minutes would have resulted in even lower exposure results. Furthermore, the usage of maximum possible UE output power in (2) instead of a time-dependent ditto will slightly overestimate the realistic exposure. As shown in Figure 1, for all environments except indoor, the UE were found to transmit at maximum power for about 40% to 60% of the samples whereas in (2) it is assumed that maximum power is always used. This also explains why the difference in time-averaged output power levels between indoor office and outdoor environments shown in Figure 3 is less distinct compared with the peak output power levels in Figure 1.

The mean 4G UE output power level was found to be less than 1% of the maximum power, which may be compared with the mean 3G UE output power level for data application in [12], which was found to be about 3% of the maximum power. In [12], the UE output power samples were collected every 2 seconds, and it was not possible to obtain power values time-averaged over 6 minutes.

V. CONCLUSION

Output power measurements for a large number of 4G user equipment using data applications were conducted in a LTE network in Sweden. The output power levels were found to be significantly below the maximum possible power, with the mean output power being less than 1% of the maximum for all considered environments.

The normalized realistic output power also represents an estimate of realistic uplink exposure level with respect to the maximum possible exposure. This implies that EMF compliance assessments of UE, which are usually conducted at the maximum possible output power levels, provide very conservative results. In line with previous findings for 2G and 3G radio access technologies, knowledge on realistic output power levels is important for accurate assessments of RF EMF exposure from 4G mobile communication UE.

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