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Comparison of Average Total EMF Exposure for Microcell/Macrocell Topologies Using Novel Methodology Based on Operational Network Measurements

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ABSTRACT Two outdoor base station macrocell/microcell topologies in operational Global System for Mobile communications (GSM) and Universal Mobile Telecommunications Service (UMTS) networks are compared with respect to average Electromagnetic Field (EMF) exposure over population in an area. A novel joint metric is used, accounting for exposure from both base stations and user equipment. The demonstrated method tends to use as much data as possible that can be extracted from various network systems, for the exact time of measurements or on long-term basis, with the aim of identifying the potential for EMF-awareness of future networks. The reduction of total exposure with the introduction of the microcell layer is shown using the proposed method with experimental measurements and compared by mobile network technologies. The introduction of the micro layer brought reduction to total population exposure of 84.6%, in the micro base station coverage area, mostly due to user device exposure reduction in GSM. UMTS user device exposure reduction was even more pronounced, 97.8%, but having less impact on overall exposure, contributing only 1%. Even with the increase in exposure originating from base stations, the reduction of total exposure was visible over the macro area as well, measuring 2.22%. The uncertainties of the evaluation method are identified and usage of advanced tools and methods is proposed to mitigate them.

INDEX TERMS Actual SAR, EMF exposure, GSM/UMTS network topology, micro/macro base stations, uplink/downlink exposure.

I. INTRODUCTION

Contemporary wireless networks need to provide ubiquitous coverage and huge capacity to meet ever-increasing demands, all with low power consumption. The advent of smartphones yielded exponential growth of data traffic, driven to the large extent with video applications [1]. The Internet of Things (IoT) brought new wireless standards and massive number of connected devices. Commercial 5th generation cellular technology (5G) is at the door, while 4th generation (4G), Long Term Evolution (LTE), took the lead over 2nd generation (2G), Global System for Mobile communications (GSM), in 2018, in number of mobile connections, and continues to grow [2]. Among young people, it is hard to find someone who does not use mobile technologies [3]. Time of usage is prolonged, whether it is about social networking, gaming or watching video [4]. At the same time, we are being surrounded by more and more wireless devices, many in the proximity of our bodies, or, with wearable technologies, on our bodies. This multiplication of sources brings the new requirement for as low Electromagnetic Field (EMF) radiation as possible, from mobile equipment and devices. 5G introduces additional challenges for EMF exposure evaluation, as another overlapping technology with high base station density, and further, as a technology using higher frequencies than those currently used and

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advanced techniques such as massive Multiple Input and Multiple Output (MIMO) and beamforming. This complexity suggests statistical approach for EMF exposure evaluation as likely the most appropriate [5]. EMF-aware 5G network planning implies careful site selection in 2G/3G/4G (3G: 3$^{\text{rd}}$ generation) surroundings with EMF-saturated spots, and with EMF restrictions affecting achievable performance i.e. quality of service [6].

The public concern regarding EMF exposure was at first directed at big antennas of macro base stations, as people paid little attention to access points in their homes or own devices [7]. This imposed conflicting demands to the operators – more and more throughput and coverage with no antennas in plain sight. Meanwhile, public attention was drawn to user devices as well, and subsequently, 5G stirred concern with huge number of both user devices and base stations foreseen. Current regulations in the area imply use of developed methods for checking compliance with the basic restrictions and reference levels, and these methods treat exposure from user devices and exposure from access equipment (base stations) separately. Further, they cannot be directly compared as user devices are tested for compliance by lab testing while exposure from base stations is measured on-site, using different measures and different values (mainly assuming the most critical case and extrapolation to maximum values). This way, hardly there may be a notion on the actual contributions and joint exposure during a period of time and under specific conditions, and conclusions drawn by general public are often with no technical ground.

At present, we lack a method to assess actual exposure of a person or population in an area, for the actual usage, both from user devices and base stations, using measurements from the operational network, on real-time or longer-term basis, taking into account user age and habits, actual services used and actual use durations. Striving to shed light on the matter of actual, joint exposure from base stations and user devices, we propose a novel method for exposure assessment using real-time real-network measurements and other data that could be extracted from the operational network, in a statistical manner, along with external data and on-site measurements. Our aim was to use data from an operational network to the maximum possible extent, including data on real users and their usage under real network conditions. We further demonstrate the method by comparing two real-network architectures in terms of average actual exposure of population and point out the exposure reduction when using smaller cells. We compare exposure from user devices and base stations, per technologies, per layers (micro and macro base stations) and in two coverage areas (micro and macro). Finally, we propose ways to mitigate the method uncertainties using applied statistics and systems collecting big-data from the network.

The novel joint metric proposed for assessing average actual exposure originating from both base stations (far-field exposure or downlink exposure as it corresponds to the downlink direction of communication) and user devices (near-field or uplink exposure), for the population in an area, is based on average actual Specific Absorption Rate (SAR) and dose (SAR in time in [J/kg]) of radio frequency (RF) EMF energy absorbed in human body. A number of papers in literature treating joint exposure used the dose to sum and compare exposure from base stations and from user devices, but none of them used such various and extensive real network data as the method proposed here. Utilizing as many information from the network itself as could be obtained with available tools, we assessed power levels, network and radio conditions, user devices and behavior. To the authors' knowledge, such exposure assessment using comprehensive data extracted from the operational network has not been performed so far.

A calculation that combined near and far-field exposure to average organ and whole-body SARs, based on dose, was proposed in [8]. It used data collected with personal exposure meters by a number of volunteers and numerically derived SARs to measure the contribution of particular mobile systems and user devices to a person's exposure, emphasizing the use of band-selective exposure data in epidemiological studies. Authors of [9] combined near-field and far-field exposure components based on dose, for adolescent participants in a study. The former was assessed using questionnaires and mobile operator's records and the latter was modelled by propagation modelling and regression modelling using personal measurements of a subgroup of participants. SAR values from literature were used. The contributions of different wireless systems and user devices when using typical services (voice, data) were assessed. In [10], the impact of using an indoor femtocell on mobile phone user's joint exposure was assessed again based on dose, by combining near-field and far-field exposure. Measurements of average transmitted and received user device power during a phone call, with varying call-time following the values reported in literature, were conducted with mobile phone. A spectrum analyzer was used to calibrate received signal strength to power density of the incident downlink signal needed for exposure assessment. Authors of [11] calculated the average global exposure of the population in an area over the considered time-frame through the Exposure Index, using simulations, radio-planning predictions for power values, realistic population statistics, and user traffic data. Novel metric proposed in this paper is based on Exposure Index framework, but uses real network power measurements, not predictions as in [11], and it is adapted to measurements and statistics that could be obtained from the network, for actual power levels, actual services used and their use durations. In [12], the authors evaluated the total EM dose, from fixed antennas and mobile devices, for a number of hypothetical network topologies, various usage scenarios and user locations. The dose was extrapolated from power measurements in 4G network and by means of Monte Carlo analysis. The study did not analyze absolute values but rather differentiated various 5G scenarios, and found that the reduction in cell size and the separation of indoor and outdoor coverage could substantially reduce the total dose, by more than 10 dB.

Several studies used network measurements of power levels [13], [14] to make conclusions on average exposure levels, but did not combine exposure from base stations and mobile phones, nor took into account the actual SAR values for population and usage. In most recent studies concerning 5G the focus is on the distribution of power in the downlink (spatio-temporal distribution of base station transmit power), so the power density is used to quantify exposure [15]–[17]. In [15], a theoretical model was presented to evaluate time-averaged realistic maximum power levels for the assessment of RF exposure for 5G base stations using massive MIMO. Scenarios with beamforming in both azimuth and elevation were taken into account, and maximum levels were found to be well below theoretical maximum. The aim was to assess the actual maximum exposure conditions and a key parameter of the model was found to be how the users were assumed to be distributed within the cell. In [18], the authors derived the analytical modelling of the downlink exposure in 5G massive MIMO networks using stochastic geometry and highlighted that the high dependence of the received power on the channel and the mobile terminals distribution made the analysis of the measurements especially challenging. In [16], base stations' transmit power samples were gathered from the network during 24 hours in order to characterize the actual EMF exposure. Network power measurements were found to represent a powerful tool, especially when using beamforming and looking for spatial distribution of power, whereas measurements conducted in-situ might be used as complementary and provide a direct measure of the typical EMF exposure in areas accessible to general public. In [17], personal exposure to RF-EMF was evaluated using exposimeters indoor school buildings and outdoor, in the surroundings. The authors expressed exposure in terms of power density, for WiFi band, GSM 900 MHz downlink (DL), Digital Cellular System (DCS) 1800 MHz DL and Universal Mobile Telecommunications Service (UMTS) 2100 MHz DL bands.

The aim of our research was to assess joint, uplink and downlink, exposure of population based on dose, more precisely on actual average SAR, and to shape a method that would make use of comprehensive data already present in the network, including power measurements (real-time network reports), cell statistics, and usage data (users, their habits, services used and usage durations, devices used), along with real-time on-site measurements and external data. We analyzed the addition of a microcell, which is a common topology in Serbia, comparing and adding contributions of two systems, GSM and UMTS, for two topologies (with and without a microcell), near-field (uplink) and far-field (downlink) components, in macro and micro area, for the population in the area, considering the impact of all carriers of all surrounding base stations. The novel methodology is demonstrated using measurements conducted for the purposes of this research, including both network power measurement and in-situ measurements, and making use of additional data extracted from the mobile network (long-term cell statistics for user traffic profiles, actual cell statistics during testing periods for actual voice/data usage, data from probes in the core network for the usage of applications, data from signaling messages for the distribution of users per network layers) and additional external data (normalized SAR values obtained by numerical simulations, census for the distribution of age groups, literature for indoor/outdoor distribution, assumptions based on ICT surveys, assumptions on posture based on usage patterns). The only simulated values in this study are normalized SAR values. The purpose of extracting this much live-network data was to assess the real, actual exposure conditions, and to explore network capabilities for future EMF awareness.

Comparing two 2G and 3G network topologies, we show the advantages of the introduction of the layer with microcell base stations, with the gain strongly dependent on technology used. The conclusions are in line with previous research in this area concerning small cells [19]–[21] and the impact of mobile phone usage on person's exposure [22]. The layer with smaller cells (micro, pico, femto) is added to the macro layer to increase capacity or to improve coverage in smaller zones [23]. New services requiring high throughput, low latency and high availability lead to usage of smaller (and smaller) cells, and this architectural change may also yield lower EMF exposure. In [19], the use of femtocells indoors reduced user device transmit power, with indiscernible increase of EMF in front of the unit, at values that were extremely low compared with reference levels of exposure guidelines. User equipment (UE) transmit power and received power were measured for scenarios with femtocell turned on and off, and frequency selective measurements were performed in front of the femtocell. UE transmit power was reduced by at least 7 dB in 90% of measurement points. These measurements did not deal with the actual SAR values, but if we consider that actual exposure is proportional to power levels, we may deduce whether our results are in line with those presented in literature. In [20], three scenarios were compared by electric field and localized SAR using heuristic network calculator with calibrated prediction models. Voice over UMTS macrocell, UMTS femtocell and Voice over IP (VoIP) over Wi-Fi were compared and the benefits of the UMTS power control mechanisms were demonstrated. When the macrocell signal was bad, usage of femtocell was extremely beneficial, as it reduced the exposure dose up to 5000 times (for the assumed long conversation time). In [21], uplink and downlink exposure were also combined using the dose, for comparing connections to the macrocell and the small cell in a train. Received Signal Strength Indicator (RSSI) and UE transmit power were measured on mobile phone, and a model was used to obtain actual received power. Here, the downlink measurements did not take into account other macrocells. For GSM in the 1800 MHz band, the study found that connecting to the small cell in a train could reduce whole-body exposure by a factor of 11, and brain exposure by a factor of 35. In [22], personal exposure measurements were used along with dose calculations to quantify the contribution of various sources to the daily dose of adolescents. The study found that the main contributors to person's exposure were mobile phones (67.2%) and base stations (19.8%). In [12], the authors found that the peak dose is always dominated by individual's own mobile phone, and that the user's own usage behavior has the strongest effect on the personal peak dose, followed by indoor coverage. In our study, summing contributions of both GSM and UMTS systems, the actual whole-body SAR averaged in time and over population was reduced by a factor of 6.5, or 8.13 dB, with cell size reduction, with overlaid macro cell on, and without separating indoor and outdoor coverage. Average UE transmit power was reduced 8.5 dB for GSM and 17 dB for UMTS in the coverage area of the micro layer. These results may be considered in line with previously cited ones [12], [19], and especially comparable with [21], as the dominant reduction came from the GSM system. Looking at power density results, in [17], the average values recorded during weekdays (6 minutes averaging) were 300 μW/m2 from GSM DL band and 214 μW/m2 for UMTS DL band. In our study, in weekday heavy load hours, the average recorded power density outdoor was 108 μW/m2 for UMTS DL band and 38.8 μW/m2 for GSM DL band, in the coverage zone of the micro base stations with macro base stations turned ON. The results differ due to different network characteristics, topology of the area and its main purpose.

Further, this paper identifies the data needed for more precise EMF assessment using the network as the main source of data, with the final goal of creating an EMF-aware future network that has the means to assess exposure of population and self-optimize, accounting for exposure as another key performance indicator (KPI) [24]. The idea was to collect the data already present in the network and analyze it to extract parameters for exposure evaluation. The concept of EMF exposure evaluation exposed in this paper is SAR-based and might be applied to any wireless network with the appropriate collection of network data.

In section 2, the scenarios of interest are presented. Section 3 describes the novel methodology for exposure assessment, whereas section 4 demonstrates this novel methodology with actual measurement data and evaluation results. In section 5, the assessment methodology and results are discussed, concerning usage of live network data inputs, technology and topology impact, future instruments for more precise assessment and future EMF-awareness of the network. Section 6 highlights the main conclusions.

II. SCENARIOS

Scenarios for evaluating exposure variation with topology changes in a live network involved GSM (900 MHz band) and UMTS (2100 MHz band) microcells with overlaid macro layer, in the urban outdoor environment in Belgrade. The scenarios were intended to show the exposure variation with the introduction of the micro layer, as well as to demonstrate exposure calculation using measurements and data extracted from the network. The environment is shown in Fig. 1. LTE base stations were not deployed in the area during the measurement campaign.

FIGURE 1. The environment of interest, Belgrade, Mirijevo market.

The micro layer consisted of one GSM cell and one UMTS cell, collocated at site denoted as BGQ134. The overlaid macro layer consisted of two sectors/cells per collocated GSM and UMTS macro base stations located at site denoted as BGU49. The properties of transceivers are given in Table 1. Coverage was checked by performing measurements with drive-test tool in the area and comparing with radio planning tool prediction. Due to base station density, we could consider the borders of coverage for GSM and UMTS macrocells to be alike, representing the area of interest.

TABLE 1. Characteristics of the macro and the micro layer.

Site type	Technology and frequency band	UMTS carriers/ GSM TRXs	Transmit power
Macro site	GSM 900 MHz	4	42dBm per TRX
BGU49	UMTS 2100 MHz	3	43dBm per carrier
Micro site	GSM 900 MHz	2	37dBm per TRX
BGQ134	UMTS 2100 MHz	2	34dBm per carrier

The exposure was calculated and compared for two scenarios: micro layer turned on and turned off. Measurements were performed in two consecutive hours during high load period of the day, as per long-term observation of cell statistics. Coverage area of micro base stations is considered "micro area", and it looked like an island within the "macro area", covered by macro base stations. For each scenario, exposure was assessed for both the micro area and the macro area. It was calculated for the daytime and it represented the contribution of Telekom Srbija, as one of three mobile operators in the area, to the overall daytime population exposure.

III. METHOD FOR ASSESSING EXPOSURE

The exposure of a person from all surrounding wireless communication systems can be divided into downlink exposure, originating from base stations (BS) and access points (AP), and uplink (UL) exposure, originating from the person's own devices, if present. Uplink and downlink exposure are observed relative to a person. Uplink exposure is near-field exposure from UE, where the notion ''uplink'' corresponds to the ''UE to base station'' direction of communication. Downlink exposure is far-field exposure from surrounding BS and AP, and the notion ''downlink'' corresponds to the ''base station to UE'' direction of communication. Average global EMF exposure was assessed by a novel method taking into account actual, both uplink and downlink exposure and averaging them over population and over time. Exposure from user devices of the users in the proximity of the observed person was neglected.

The basis for assessing the average exposure of the population in an area was the Exposure Index (EI) [11], [25], developed within the LEXNET project [26], [27]. It averages the actual SAR by summing the received total doses of exposure (uplink and downlink), i.e. SAR [28] in time, over the population and over time, by statistical categories. It combines exposure for different population categories (children/adults), for all radio access technologies (RAT), under the 3rd Generation Partnership Project (3GPP) and non-3GPP, cell types (micro, macro), environments (indoor, outdoor), user profiles (heavy, moderate, light), usages (voice, data), postures (standing/sitting) and user devices (phone/laptop), taking into account multiple time periods in which these categories may be considered stationery. EI depends strongly on the usage of wireless devices and network load, thus depending on time of day (busy hours or not), day in a week (working day or weekend) and in a year (holiday season or not). Network traffic statistics per hour and per day had been collected in several months period in order to observe its variations and regularities, and thereof choose the testing period.

The mathematical formulation of the EI [W/kg] is the sum of received doses (SAR in time), per all categories stated above, divided by the observed period. In a time interval, population in the area may be segmented by age, usage (service and device type), posture, environment, per each RAT and cell type. Such segments, or user configurations, correspond to fractions of total population. The doses for the uplink exposure per configuration and time interval are calculated based on normalized (per 1W) uplink SAR values per configuration multiplied by average transmitted power from the user device, fraction of population and time spent in the configuration. The doses for the downlink exposure are similarly calculated using the normalized (per 1W/m^2) downlink SAR values per configuration multiplied by average incident power density, fraction of the population and time spent in the configuration [11]. These values are then summed per configuration and further by all time intervals in the observed period, and divided with total time of observation.

In this paper, based on EI definition and available data from various live network systems and external sources, including simulated SAR values per user configuration, a novel methodology is developed and new formulas derived for assessing an average actual SAR ($\overline{SAR}_{actual(area,population)}$) over population in a defined area of interest and over time.

The average actual SAR was calculated for exposure generated by Telekom Srbija 2G and 3G base stations and connected users, for the population in the observed coverage area. All other networks and operators would contribute the total average actual SAR, where similar results would be expected, due to small differences in user behavior and similar network configurations. Looking into the average actual SAR induced on population by its own network, an operator could monitor it and take steps for decreasing it.

A. SOURCES OF DATA

In this research, the aim was to use as much possible data that could be obtained from the operational network in a near-real-time manner, then statistical data from the network obtained on a longer-term basis, i.e. predefined values, and external sources and measurements. Such a methodology was intended to reveal the potential of the network to be EMF-aware, and further, EMF-self-optimizing. The analysis opens space for the development of tools that could decrease the assessment uncertainties by means of advanced data collection and correlation. Such an EMF-awareness requires big data systems and complex analysis, but the principle does not much differ from collecting and correlating available network data from the radio and core parts of the network, mapping radio signaling data with user plane data, in customer experience management (CEM) systems.

Sources of data used in this assessment include: cell statistics, triggered network reports, drive-test measurements, call data records, customer analytics system, automatic device configuration (ADC) platform, probes on network interfaces, on-site field measurements with laboratory equipment, census, regulatory reports, and information and communication technology (ICT) surveys. Cell statistics is a set of KPIs calculated from event counters on cell level. UE exchanges different control messages with the network, especially for the purposes of power control, and these may be recorded for analysis using triggered network reports, from network management system (NMS). Data on usage of different applications as well as signaling messages may be obtained from probes that collect traffic on network interfaces. Call data records (CDR) serve for billing purposes and they may be used to extract valuable data on user statistics in a cell. Customer analytics system (SAS) contains usage statistics for registered users. Automatic device configuration (ADC) platform serves for sending automated configuration messages to user equipment and keeps track of all devices in the network. The purpose of each source in the exposure assessment will be explained later on.

Sources of data related to the network itself are depicted in Fig. 2. Some of them were used for the observed period, and some in the longer period for assessing load patterns [29],

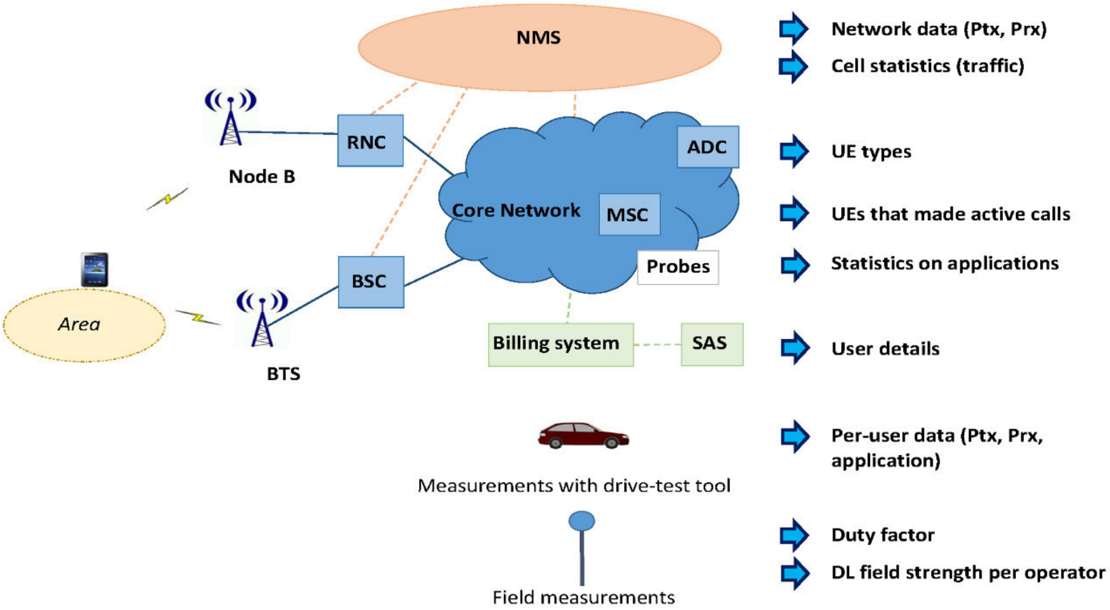

FIGURE 2. **Sources of data related to the network.**

user profiles, used applications, to compare power samples in network reports and drive-test measurements, etc.

During the test period, the following data were collected:

- UE transmitted (Tx) and received (Rx) power distribution (P_{TX}, P_{RX}) taken from per-cell network reports, for 2G voice service, for both micro and macro cells;
- UE Tx and Rx power distribution taken from per-cell network reports, for 3G voice and data service, for both micro and macro cells;
- Cell statistics: average voice and data usage duration, average data volume for 3G;
- Frequency selective electric field strength measurements taken with field measurement equipment in a number of locations within the area of interest;
- Signaling messages from the probes in the core network.

The above data were obtained for a two-hour period, 10-12 a.m. The two scenarios, micro layer turned on and off, were tested one after the other, one hour each. These are normally heavy load hours, whereby higher global exposure is expected. However, the actual load of a particular cell depends on its coverage area, e.g. whether it is a business or residential area, whether people just pass through or reside in it during the period.

Per-cell network reports for GSM and UMTS were triggered and logged from different modules of network management platform Ericsson Operations Support System, Radio and Core (OSS-RC), version 12.3.1. Cell statistics was also collected using this system. Calibrated Rohde&Schwarz (R&S) portable measurement system consisting of spectrum analyzer R&S FSH6 (frequency band 100kHz-6GHz) and R&S TS-EMF Tri-Axis Probe (frequency band 30MHz-3GHz) was used to perform frequency selective measurements on-site. This system is designed for band- and frequency-selective measurements of electric field strength in the frequency range from 30 MHz to 3 GHz. System was controlled by software module White Tigress Baby - Measurements, specially developed for the space measurements in Radio-communications Laboratory, School of Electrical Engineering, University of Belgrade. Band selective measurements of electric field strength were conducted for the GSM 900MHz and UMTS 2100MHz frequency bands of operator Telekom Srbija. The following parameters were used for the measurements:

- Central frequency - 944.3MHz and Channel bandwidth – 9.6MHz (GSM 900MHz band), and
- Central frequency – 2132.5MHz and Channel bandwidth - 15MHz (UMTS 2100MHz band).

In order to determine the spatial distribution of the electromagnetic field strength, the measurements of electric field strength were carried out in a number of measurement positions approximately uniformly distributed within the outdoor areas of considered micro and macro cells. Measurements were performed with a measurement probe mounted on a tripod and the person operating with measurement equipment was at least 2 m away from the probe.

Normalized whole-body SAR values were previously computed using simulation platforms, for two anatomic human body models (child and adult), two postures (standing and sitting) and several usages (mobile phone close to the head for voice usage, data usage with mobile phone or tablet, or laptop in the lap or on the desk), for uplink and downlink, in different frequency bands [25].

B. BASELINE

The averaging method was determined with respect to available operational network data and available SAR data.

TABLE 2. Fractions of users per technology and layer.

Technology (r) and cell type (c)	Fractions of users ($f_{r,c}$)
GSM macrocell	45.59%
GSM microcell	1.52%
UMTS macrocell	52.03%
UMTS microcell	0.86%

Network data were collected on cell level, which determined the cell as the baseline for statistical averaging. Cell is characterized by technology (RAT) and cell type (micro/macro). Users within the area may be divided into fractions pertaining to each cell or a layer as a group of cells, neglecting the soft handover state in Wideband Code Divison Multiple Access (WCDMA) [30], and these fractions allow for statistical combining of data for different cells. Within each cell, the mixture of users connected to it, their services and their usage duration, as well as their postures, contribute to the average actual SAR for the uplink. Within the cell coverage area, the population is exposed to downlink of that cell and of all collocated and surrounding cells. Exposure from devices of users in the proximity was neglected in this calculation.

Fractions of users ($f_{r,c}$) per technologies (r) and cell types (c) were obtained from signaling Location Update messages [31], as an average for the observed period, and the corresponding values are presented in Table 2. These messages are sent to the network by user device, contain the information on cell used, and their frequency depends on network settings. Fractions of users per cells change in time with changing radio and load conditions and user's movements [32]. Not all changes can be captured using these messages. In 3G, the user may be connected to several cells simultaneously [30], and usually temporary, while only one is reported. Even at the same place, the user may "drop" out of coverage of the dominant cell and return to it in in short time. The usage of advanced tools for processing network data could decrease uncertainties to some extent.

Voice and data services are characterized by specific traffic patterns, and statistics for native voice and data can be obtained separately within a cell. Usage of each service is characterized by specific position of the user device relative to the body, and SAR values are simulated and grouped accordingly. Voice and data services therefore present the second level for statistical averaging.

Looking at voice service in a cell, different population categories having different user load profiles use this service in some time intervals. The same is with data service, where people may use different applications with different traffic profiles, inducing different profiles of user device transmitted power, and thereof, having different impact on average exposure. Same users use both voice and data service, and the calculation of average exposure must take into account usage durations for both services.

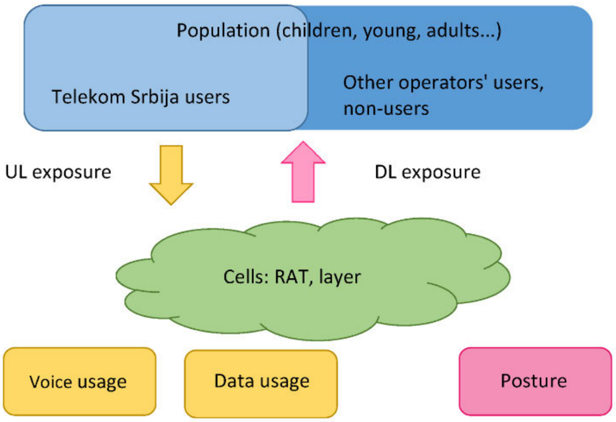

FIGURE 3. Components of the average actual SAR: UL component of users depending on usage of voice and data service, and the DL component for the population depending on posture, for each technology.

Finally, part of the population in general does not use mobile technology, which must also be taken into account when averaging over population in an area.

The process of average actual SAR calculation is depicted in Fig. 3. Here we assess exposure of general population originated from Telekom Srbija network equipment (base stations) and devices of users connected to this network. The UL component ($\overline{SAR}^{UL}_{actual\,(area,\,population)}$) is dependent on the usage of voice and data services, per RAT and layer (micro/macro); while the DL component ($\overline{SAR}^{DL}_{actual\,(area,\,population)}$) is dependent on postures, per frequency band i.e. RAT. Average actual SAR for an area ($\overline{SAR}_{actual\,(area,\,population)}$) is the sum of the uplink and downlink components for the population in an area (1):

$$\overline{SAR}_{actual\,(area,population)} = \overline{SAR}^{UL}_{actual\,(area,population)} + \overline{SAR}^{DL}_{actual\,(area,population)} \tag{1}$$

C. UPLINK EXPOSURE ASSESSMENT

Average uplink exposure of Telekom Srbija users ($\overline{SAR}^{UL}_{actual\,(area,operator'susers)}$) in a time period T, in the area covered by cells of technologies r and cell types c, was assessed based on the following formula (2). For each fraction of users $f_{r,c}$ served by cell type c of technology r, the contribution to the average actual SAR for the UL is calculated. This calculation involves average transmit power of user devices ($\overline{P}^{r,c}_{TX}$) in cells of the layer (r, c), average time durations of voice ($\overline{TD}^{UL}_{r,c,voice}$) and data ($\overline{TD}^{UL}_{r,c,data}$) service for the uplink communication in these cells, as well as average normalized SAR values for these usages ($\overline{SAR}^{UL,norm}_{r,voice}$, $\overline{SAR}^{UL,norm}_{r,data}$).

$$\overline{SAR}^{UL}_{actual\,(area,operator'susers)} = \frac{1}{T}\sum\nolimits_{r}^{GSM,UMTS}\sum\nolimits_{c}^{macrocells,microcells} \times f_{r,c}\overline{P}^{r,c}_{TX}\left\{\overline{TD}^{UL}_{r,c,voice}\overline{SAR}^{UL,norm}_{r,voice}+\overline{TD}^{UL}_{r,c,data}\overline{SAR}^{UL,norm}_{r,data}\right\} \tag{2}$$

This statistical method is based on combining average usage durations for voice and data services in cells of the same layer with average normalized SAR values for these usages. The contribution of the specific layer to the average actual SAR for the UL is then calculated by multiplying the obtained value with the average transmit power of user devices of the layer and a corresponding fraction of users served by cells of that layer ($f_{r,c}$) in a time period T, and dividing the value with this period of observation. The sum of contributions of cells of interest represents the average actual SAR generated by uplink communication for all operator's users in the observed area covered by observed cells.

Mean transmit power, average usage duration and average normalized SAR values all take into account the mixture of users, their user devices, services used and their postures, as it is explained below.

It should be noted that the UL component is calculated for users of the Telekom Srbija network, according to their usage times. In order to calculate average actual SAR for the whole population, the UL component ($\overline{SAR}^{UL}_{actual\,(area, operator'susers)}$) needs to be scaled down i.e. averaged over population ($\overline{SAR}^{UL}_{actual\,(area, population)}$), using the share of Telekom Srbija users in the overall population (3). This share was obtained from the percentage of usage of mobile phones in the population (*share of users*, 91.4% based on ICT usage data survey [33]) and Telekom Srbija market share by the number of active users (*operator share*, 44.56% [34]), leading to a value of 40.73%. Hence, by summing the calculated DL component with the 40.73% of the calculated (2) UL component, the average actual SAR for the whole population in the area related to exposure from Telekom Srbija network could be obtained (1).

$$\begin{aligned} &\overline{SAR}^{UL}_{actual\,(area, population)} \\ &\quad = \overline{SAR}^{UL}_{actual\,(area,\ operator's\ users)} \\ &\qquad * operator\ share\,[\%] * share\ of\ users\,[\%] \end{aligned} \tag{3}$$

1) MEAN TRANSMIT POWER

Mean transmit power depends on the technology (2G/3G), network load, position in a cell (good, medium, bad radio conditions), and service used (voice or data, which application for data usage). For each service used over a specific technology and in specific radio and network conditions, the transmit power will differ as well as the silent periods when the user device transmitter is not transmitting. Each application has its traffic pattern, and its packets are processed for the transmission on the physical layer, where the added overhead depends on radio conditions, and the transmission time depends on network and radio conditions. For averaging the transmit power over a period, it is important to know the time pattern of the transmit power on the radio interface.

The main challenge in the actual average SAR calculation in a live network was mapping user plane data with radio measurements. Cell measurements in network reports give a power profile of a cell [35], based on a statistical sample of users, and there is no connection between power samples and applications used, that directly affects the time averaging of power. Power samples are taken when the transmitter is actually transmitting (both in network reports and using the drive test tool), and the silent periods in between need to be determined statistically, with on-site measurements, for each type of application, technology, network load (high/low), radio conditions (strong/weak received signal). The factor of activity on the radio interface, or the duty factor, takes into account both the application activity brought down to the radio interface (includes lower-layer processing, i.e. headers, coding) and the specific properties of the radio interface (in GSM, 1 time slot is used for voice and 1-3 for most UE types for data [36]; UMTS Radio Resource Control (RRC) state transition for data [37]). The activity (duty) factor determined with field measurement equipment serves for scaling the network-measured samples, which corresponds to time averaging. Scaling implies the correlation between recorded UL power levels over time with the radio conditions (received signal strength) and application used. High UE Tx power samples may be attributed to a demanding data upload near to the base station or to less demanding services when the user is far from the base station - two situations with different duty factors [38]. Without the correlation, we cannot exactly map the recorded power levels with the exact duty factor for the application used and radio conditions. Mapping data on UE Tx and Rx power levels would be possible only on per-user basis.

The introduction of software tools that combine radio and core data (geolocation, probes in the core, customer experience management tools) would eliminate part of uncertainties in exposure evaluation. For instance, geolocation tools collect messages in the radio network and, using patented algorithms, determine the position of individual users, along with radio parameters in a period of time. Probes in the core network collect signaling and user plane messages and may be useful to determine the applications used. Customer experience management tools combine the data from radio and core network in order to identify and solve network issues and enhance user experience. These big-data systems could be used to further correlate data on power levels and applications used, which could not be done with available tools. Moreover, introducing agents on phones, that would send correlated data on radio parameters and applications used, or even some customer data, would also decrease the uncertainties. Note that the correlated radio and application data could be obtained through simulations as in [39], using traffic assumptions on user profiles and actual usage derived from the network on long-term basis.

In order to obtain the actual time-averaged value of UE transmit power ($\overline{P}^{r,c}_{TX}$), the mean value extracted from UE Tx power per-cell reports ($average\left\{P^{r,c}_{TX1}, P^{r,c}_{TX2}, \ldots, P^{r,c}_{TXn}\right\}$) had to be scaled for the average duty factor for the layer and RAT ($\overline{DF}^{r,c}$, (4)). Since the power samples are representative for the mixture of all user configurations and services, the duty

TABLE 3. **Distribution of traffic types per time of usage.**

Traffic type	%time
Browsing	59.39%
Audio streaming	1.65%
Video streaming	11.42%
TV	0.79%
Skype VoIP	4.55%
Skype video	0.10%
File upload	15.71%
File download	6.39%

factors for various applications and radio conditions needed to be reduced to a single value, based on durations of these services (4):

$$\overline{P}_{TX}^{r,c} = average\left\{P_{TX1}^{r,c}, P_{TX2}^{r,c}, \ldots, P_{TXn}^{r,c}\right\} * \overline{DF}^{r,c},$$
$$P_{TXi}^{r,c} \neq 0, \quad i = 1\ldots n \tag{4}$$

Duty factor was measured using field measurement equipment for GSM 900 MHz and UMTS 2100 MHz, in good, medium and bad radio conditions, for nine typical traffic types: voice, browsing, audio and video streaming, TV, upload, download, Skype VoIP and video [38].

Based on UE Rx power samples, the statistical distribution of service duration in good, medium and bad radio conditions was assessed, presuming the uniform distribution of services used in these three areas, for each group of cells (same technology and layer). The boundary values for received signal strength were determined per technology. This was a basis for statistical averaging of the duty factor per technology, and good/bad/medium radio conditions. In case of GSM, power samples were recorded only for voice service. In case of UMTS, recorded power samples refer to both voice and data usage, so the statistical averaging of the duty factor had to take into account additionally:

- Voice and data service usage percentages by overall duration: this was obtained from cell statistics [40];
- For data service, distribution of used applications in percentage of time: this was evaluated by analyzing data from probes in the core network. Applications were separated into categories for which the duty factor was measured (Table 3).

To summarize, duty factor for GSM voice was statistically combined considering radio conditions, while the duty factor for UMTS voice and data was statistically combined considering, besides radio conditions, the type of service and used application. The process of averaging the duty factor and applying it to the average UE transmit power that was recorded for the RAT and layer (aggregated values for cells of the same RAT and layer) is graphically represented in Fig. 4.

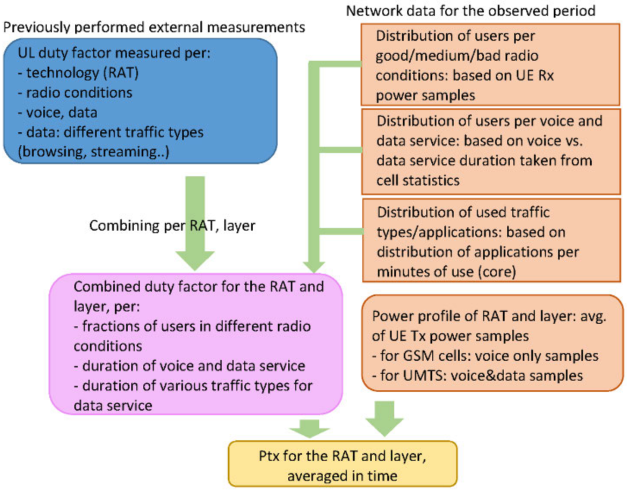

FIGURE 4. **Duty factor averaging per RAT and cell layer and obtaining the P_{TX} factor.**

TABLE 4. **Population categories.**

Population (census)	% of population	Population categories	% of population
Children (under 15)	13.50%	Children (under 15)	13.50%
Young (15-29)	18.40%	Adults (15 and over)	86.50%
Adults (30-59)	43.60%		
Seniors (60 and over)	24.50%		

TABLE 5. **Indoor and outdoor users.**

Population category	% of population Indoor	% of population Outdoor
Children (under 15)	80%	20%
Adults (15 and above)	70%	30%

TABLE 6. **Usage of phone and laptop.**

User device	% of users
Phone	98.56%
Laptop	1.44%

2) NORMALIZED SAR VALUES AVERAGED OVER USER CONFIGURATIONS

User configuration includes population category (p), environment (e), posture during usage (pos), user device, for voice and data service (u). Normalized SAR values are given accordingly ($SAR_{p,pos,voice,r}^{UL,norm}$, $SAR_{p,pos,data,r}^{UL,norm}$). In order to get the normalized SAR values averaged over user configurations, for voice and data service ($\overline{SAR}_{r,voice}^{UL,norm}$, $\overline{SAR}_{r,data}^{UL,norm}$), (5a),(5b), it is necessary to determine the share of each configuration ($f_{p,e,pos,device,voice}$, $f_{p,e,pos,device,data}$) in the user population of the area.

$$\overline{SAR}_{r,voice}^{UL,norm} = \sum\nolimits_{p}^{child,adult} \sum\nolimits_{e}^{indoor,outdoor} \sum\nolimits_{pos}^{sitting,standing} \times \sum\nolimits_{device}^{phone} f_{p,e,pos,device,voice} SAR_{p,pos,voice,r}^{UL,norm} \tag{5a}$$

$$\overline{SAR}_{r,data}^{UL,norm} = \sum\nolimits_{p}^{child,adult} \sum\nolimits_{e}^{indoor,outdoor} \sum\nolimits_{pos}^{sitting,standing} \times \sum\nolimits_{device}^{phone,laptop-lap,\ laptop-desk} \times f_{p,e,pos,device,data} SAR_{p,pos,data,r}^{UL,norm} \tag{5b}$$

TABLE 7. User segmentation matrix.

User	User %	Device	Device %	Environment	Environment %	Posture	Position for laptop	Position %	Share
Child	13.50%	Phone	98.56%	Indoor	79,71%	Sitting			10.61%
	13.50%		100.00%	Outdoor	20,00%	Standing			2.70%
	13.50%	Laptop	1.44%	Indoor	100,00%	Sitting	Lap	10%	0.02%
	13.50%					Sitting	Desk	90%	0.17%
Adult	86.50%	Phone	98.56%	Indoor	69,56%	Sitting			59.31%
	86.50%		100.00%	Outdoor	30,00%	Standing			25.95%
	86.50%	Laptop	1.44%	Indoor	100,00%	Sitting	Lap	30%	0.37%
	86.50%					Sitting	Desk	70%	0.87%

Data used for this segmentation are as follows:

- Population categories share: taken from the census data [41], for urban environment, by averaging data for Belgrade municipalities (Table 4); furthermore, based on available SAR values, values were reduced to two categories (children, adults); we assumed that Telekom Srbija users' distribution per population category was the same as for the population in general. Data on registered users in Telekom Srbija network could not be taken as relevant since these are only adult or business users, whereas actual users are sometimes their children.
- Indoor vs. outdoor per time of usage: taken as an assumption (Table 5), based on statistical surveys in different countries [39].
- Phone and laptop users: taken from ADC system (Table 6); we assumed that data service was used with both phone and laptop, while voice service was used only with phone; laptops and phones were proportionally used by adults and children.
- Posture: there was no statistical data on posture, it was therefore assumed that all users indoors were sitting, while all outdoor users were standing (during usage) [39]; furthermore, we also took assumptions about the position of the laptop (lap, desk).

Combinations of the above categories gave the user segmentation matrix presented in Table 7.

In order to calculate the percentage of users per voice and data service, the data from customer analytics system was taken for voice-only, data-only and voice and data users. By combining these data with previous user segmentation, the matrix of usage of voice and data service was made (Table 8), to be further combined with available SAR values. It should be noted that in UMTS, the percentage of users of voice service was 98.56%, while only 28.74% of users were using data services. In GSM, since power measurements included voice usage only, the corresponding percentage for voice service was 100%.

The shares of users presented in Table 8 were combined respectively with normalized whole-body SAR values (UL) for the population, posture, usage and position in order to get average normalized (per 1 W of power) whole-body SAR values for voice and data usage (Table 9).

TABLE 8. Matrix of usage for combining with SAR values.

Service	Population	Posture	Device	Position for laptop	Share UMTS [%]	Share GSM [%]
Voice	Child	Sitting	Phone		10.61	10.80
	Child	Standing	Phone		2.70	2.70
	Adult	Sitting	Phone		59.31	60.55
	Adult	Standing	Phone		25.95	25.95
Data	Child	Sitting	Phone		7.38	
	Child	Standing	Phone		1.88	
	Child	Sitting	Laptop	Lap	0.02	
	Child	Sitting	Laptop	Desk	0.17	
	Adult	Sitting	Phone		12.55	
	Adult	Standing	Phone		5.49	
	Adult	Sitting	Laptop	Lap	0.37	
	Adult	Sitting	Laptop	Desk	0.87	

TABLE 9. Average normalized SAR values for uplink calculation, per technology and service.

Average normalized UL SAR per technology and service [(W/kg)/W]	GSM900	UMTS1940
Voice	0.014295	0.005870
Data	-	0.002477

3) USAGE TIME DURATION

Usage time duration needed to be determined for voice and data service, for statistical combining with average normalized SAR values obtained above for voice and data. Usage time duration was calculated based on user profiles, considering previous analysis of user data. User profiles were derived using customer analytics system and billing information with monthly cell statistics, from base station controllers, in urban, suburban and rural cells, for 2G and 3G, and presented in [25], [39]. For each category of RAT and area morphology, heavy, moderate and light users were defined, with day and night statistics on: voice communication duration and volumes of data traffic in the uplink (transmitted) and in the downlink (received). Data for urban environment was taken in this calculation, and only for daytime, since the measurements were made during daytime. The distribution of user profiles (heavy/moderate/light) per population category is given as an assumption (Table 10) [25], [39].

Average voice call durations for GSM and UMTS in UL ($\overline{TD}^{UL}_{r,c,voice}$) were calculated by combining user profiles by their shares in population. Average data call duration

TABLE 10. Distribution of user profiles per population and service category.

Population category	Service	User load profile share		
		Heavy	Moderate	Light
Children	Voice	25.00%	50.00%	25.00%
	Data	60.00%	20.00%	20.00%
Adults	Voice	47.00%	25.00%	28.00%
	Data	26.28%	20.40%	53.32%

($\overline{TD}^{UL}_{r,c,data}$) in UL was calculated based on combined user profiles (per-user data volume in UL) and cell statistics data (overall data volume in UL, overall duration of data calls), taken for daytime.

D. DOWNLINK EXPOSURE ASSESSMENT

The downlink exposure is related not only to users of the observed network, but also to all people in the area. We are exposed to DL signals of all surrounding base stations all the time, so the duty factor for the DL transmission is 100%. Downlink exposure depends on frequency band, population category, environment and body posture, and network usage data may be valuable for estimating postures of the general population. We may estimate postures of Telekom Srbija users during usage (uplink and downlink usage) based on network data, but we further have to assess their behavior when they're not using mobile services, as well as the behavior of other operators' users and people who do not use mobile telephony, for 100% time. Here we assumed the behavior of all users to be alike and similar during usage and non-usage. Further, we assumed that the behavior of non-users, who represented a small percentage of population [33], might be subsumed under the same pattern as for the users.

Average downlink exposure of population ($\overline{SAR}^{DL}_{actual\,(area,population)}$) in the area covered by cells of types c and technologies r, during the period T, was assessed based on the following formula (6). Whole-body SAR values for the downlink normalized to 1 W/m^2 incident power density ($SAR^{DL,norm}_{p,pos,r}$) are combined with person-time shares ($f_{p,e,pos}\frac{TD^{DL}_{p,e,pos}}{T}$) of overall 100% person-time (whole population for the observed period T), in order to get the average normalized SAR per RAT (r) for the downlink. $f_{p,e,pos}$ represents the share of population in specific environment having a specific posture, while $TD^{DL}_{p,e,pos}$ represents the time spent in this posture. $\overline{S}^r_{RXinc,area}$ represents the mean incident power density over time and over population, for RAT r, averaged over the *area*, where *area = (micro area, macro area)*.

$$\begin{aligned}\overline{SAR}^{DL}_{actual\,(area,population)} &= \sum\nolimits_r^{GSM,UMTS} \overline{S}^r_{RXinc,area} \\ &\quad\times \sum\nolimits_p^{child,adult} \sum\nolimits_e^{indoor,outdoor} \\ &\quad\times \sum\nolimits_{pos}^{1\ldots6} f_{p,e,pos}\frac{TD^{DL}_{p,e,pos}}{T} SAR^{DL,norm}_{p,pos,r}\end{aligned} \qquad (6)$$

The person-time shares were obtained based on user segmentation matrix (Table 7) and cell statistics, more precisely average voice and data usage in Erlang for cells of interest. The shares apply to population and the same shares are used for both technologies that population is exposed to in the downlink. The shares differ for macro and micro area, which will be explained later on.

For the downlink calculation, body posture (*pos*) takes one of six values: *sitting-voice-phone*, *sitting-data-phone*, *sitting-data-laptop-lap*, *sitting-data-laptop-desk*, *standing-voice-phone*, and *standing-data-phone*. These postures are named after usages and they actually correspond to respective poses, e.g. sitting with the hand near the head, or with the hand in front of the body etc.

TABLE 11. Person-time shares for combining normalized SAR values for downlink calculation, for macro area in scenario micro ON.

Population (p)	Environment (e)	Posture (pos)	Person-time share in macro area
Child	Indoor	Sitting-voice-phone	4.99%
Child	Outdoor	Standing-voice-phone	1.25%
Adult	Indoor	Sitting-voice-phone	27.97%
Adult	Outdoor	Standing-voice-phone	11.99%
Child	Indoor	Sitting-data-phone	5.71%
Child	Outdoor	Standing-data-phone	1.45%
Child	Indoor	Sitting-data-laptop-lap	0.01%
Child	Indoor	Sitting-data-laptop-desk	0.09%
Adult	Indoor	Sitting-data-phone	31.91%
Adult	Outdoor	Standing-data-phone	13.96%
Adult	Indoor	Sitting-data-laptop-lap	0.20%
Adult	Indoor	Sitting-data-laptop-desk	0.47%

Table 11 shows person-time shares per population (p), environment (e) and posture (pos) categories, for macro area in scenario with micro layer turned on. These values serve for combining respective normalized whole-body SAR values. They show that e.g. 31.91% of adults in the area, at any moment, were sitting with hands down, as when using data service on phone.

Table 12 shows the average normalized downlink whole-body SAR for macro area and for micro area, for GSM and UMTS, in two considered scenarios.

In order to evaluate $\overline{S}^r_{RXinc,area}$, two types of measurements could have been used, each of them having its advantages and drawbacks:

- Measured samples of electric field strength in a number of particular points within the area, per operator and band;
- UE Rx samples from network reports.

First, electric field strength measurements were performed with measurement equipment with isotropic probe so as to consider the whole electric field vector. These measurements were made per operators' bands, so the impact of all surrounding base stations, other sectors of the same base station and different carriers in the band was taken into account. These measurements were taken outdoors, which presents the drawback for exposure assessment, as a high

TABLE 12. **Average normalized SAR values for downlink calculation, per technology and area.**

Average normalized DL SAR [(W/kg)/(W/m^2)]	Area	GSM900	UMTS1940
Scenario MICRO ON	Macro area	0.005570377	0.004792494
	Micro area	0.005678153	0.004784687
Scenario MICRO OFF	Macro area	0.005562891	0.004793037
	Micro area	0.005678153	0.004784687

percentage of population is indoor. For the averaging purposes, the samples may be scaled down according to the percentage of population that is indoor and with indoor attenuation factors from the literature. Since more than 70% of population was assumed to be indoor (Table 5), these assumptions might lead to a rather high uncertainty.

Second, UE Rx samples from network reports take into account users in bad, medium and good radio conditions. They are based on a sample of users (measurement methodologies differ per RAT, refer to [42] for more details). In UMTS, the whole carrier is measured, meaning that the measurement of target cells with different carriers contains power levels received from surrounding base stations/sectors as well. The drawback is that the Rx power measured by the UE cannot be directly linked to power density, needed for exposure calculation, since the link depends on the type of antenna and its relative position to the incident wave vector [43]. In other words, the Rx samples do not capture the whole field.

For the DL calculation, first method was used, i.e. on-site measurements in a number of points grouped by area: micro area (coverage zone of the micro BS, *zone1*) and macro area excluding micro (coverage zone of the macro BS excluding micro zone, *zone2*). The measured average field strength for both zones ($\overline{E}^r_{out,zone}$), where $zone = (zone1, zone2)$, was scaled considering percentages of population indoor and outdoor, according to the following formula (7), in order to estimate the average field strength ($\overline{E}^r_{zone}$) for the population in the zone of measurements, where *AttFactor* is equal to 0.5 (6 dB), as suggested in [44]. The distribution of population indoor (*In*) and outdoor (*Out*), according to Table 4 and Table 5, was 71.35% indoor and 28.65% outdoor.

$$\overline{E}^r_{zone} = \sqrt{\overline{E}^{r2}_{out,zone} * Out + \left(\overline{E}^r_{out,zone} * AttFactor\right)^2 * In} \tag{7}$$

Further, in order to quantify the average value of E-field experienced by population in both zones, i.e. over the whole macro area, the average values for two zones were combined again using the similar (square root) formula (8), and taking into account the percentage of people within each zone, estimated using percentages of users by layers ($f_{r,c}$, Table 2).

$$\begin{aligned} \overline{E}^r_{macroarea} &= \sqrt{\overline{E}^{r2}_{zone1} * f_{microcell} + \overline{E}^{r2}_{zone2} * f_{macrocell}}, \\ \text{where } f_{microcell} &= f_{GSM,microcell} + f_{UMTS,microcell}, \\ \text{and } f_{macrocell} &= f_{GSM,macrocell} + f_{UMTS,macrocell}. \end{aligned} \tag{8}$$

If we look the micro area only, the average value of E-field from RAT *r* experienced by population is the average value of E-field in *zone1*.

$$\overline{E}^r_{microarea} = \overline{E}^r_{zone1}$$

The average power density for the frequency band of the specific RAT in a specific *area* ($\overline{S}^r_{RXinc,area,}$) was then obtained as: $\overline{S}^r_{RXinc,area} = (\overline{E}^r_{area})^2/Z_0$, where Z_0 is the characteristic impedance of the vacuum.

E. TOTAL EXPOSURE ASSESSMENT

The evaluated scenario involved two network layers: macro and micro, with corresponding coverage areas. Hereafter, the variation of the $\overline{SAR}_{actual(area,population)}$ may be observed over the micro and over the macro area (1), i.e. within the coverage area of the micro base station and within the coverage area of the overlaid macrocells (including the micro area). To this aim, both data extracted from the network and data from measurements in the field had to be grouped with respect to these areas. On-site measurements of electric field strength were performed for both scenarios, micro layer turned on and off, for micro area and for macro area excluding micro (2 groups of measurements per each of two scenarios, in each of the two zones). All the inputs concerning cell measurements and statistics were taken as an average for all cells of the corresponding layer and RAT, per scenario. The way we combine data depends on whether we're looking into the micro or the macro area.

1) MICRO AND MACRO AREA

If we consider the micro area for scenario with micro base station turned on, we assume that all users in the micro area were connected to the micro base station. Hence, the UL component of $\overline{SAR}_{actual}$ $(i.e.\overline{SAR}_{actual\,(area,population)}))$ is just related to the micro layer (GSM and UMTS microcells), while the downlink component is related to all cells radiating towards the micro area. The UL components were combined considering the percentages of users per technologies and layers $f_{r,c}$ (Table 2) relative to micro layer only. The downlink component is related to the average field strength measured within the micro area, and person-time shares of postures were calculated from cell statistics of micro layers.

If we consider the macro area, we still assume that all users within the coverage area of the micro base station were connected to it, while those outside were connected to the macro layer. Hence, the UL components of the micro and macro cells needed to be combined considering the percentage of users per each technology and layer (Table 2). The DL component is related to the average field strength experienced by population in the whole macro area. It was obtained by combining average values of samples taken in the micro area and the macro area excluding micro, considering the percentage of users in the micro and macro area (Table 2) and assuming that the space distribution of population follows the distribution of users. Person-time shares of postures for

TABLE 13. Input data for scenario micro ON.

Scenario MICRO ON								
Source	Data	UMTS macro layer			UMTS micro layer			Used to calculate
Triggered network report	Avg. UE Tx power [dBm]	-7.19			-23.68			$\bar{P}_{TX}^{r,c}$
Triggered network report	Percentages of UE Rx power samples for good, medium and bad radio conditions [%]	Good 38.73%	Medium 39.40%	Bad 21.87%	Good 64.19%	Medium 31.98%	Bad 3.83%	$\overline{DF}^{r,c}$
Cell statistics	Average voice usage in time (per 1h), all users [Erl]	33.22			1.99			$\overline{DF}^{r,c}, TD_{p,e,pos}^{DL}/T$
Cell statistics	Average data usage UL in time (per 1h), all users [Erl]	38.13			1.48			$\overline{DF}^{r,c}, \overline{TD}_{r,c,data}^{UL}$
Cell statistics	Average data (UL and DL) usage in time (per 1h), all users [Erl]	148			6.02			$TD_{p,e,pos}^{DL}/T$
Cell statistics	Average data volume UL (per 1h), all users [kbits]	3,412,947.00			101,895.00			$\overline{TD}_{r,c,data}^{UL}$
Measurements in the field with laboratory equipment	Recorded average field strength [V/m]^{a}	0.152			0.202			$\bar{S}_{RXinc,area}^{r}$
Source	Data	GSM macro layer			GSM micro layer			Used to calculate
Triggered network report	Avg. UE Tx power for voice service [dBm]	29.79			22.28			$\bar{P}_{TX}^{r,c}$
Triggered network report	Percentages of UE Rx power samples for good, medium and bad radio conditions [%]	Good 15.30%	Medium 59.05%	Bad 25.65%	Good 35.50%	Medium 58.93%	Bad 5.57%	$\overline{DF}^{r,c}$
Measurements in the field with laboratory equipment	Recorded average field strength [V/m]^{a}	0.103			0.121			$\bar{S}_{RXinc,area}^{r}$

[a] The value given for the macro layer is related to the macro area excluding micro area, while the value given for the micro layer is for the micro area

the DL component were calculated from cell statistics of both macro and micro layers.

In case the micro base station is turned off, all users are connected to the macro layer. Without geolocation tools, in this scenario we lack information on the share of users within the micro area, total and per technology. Two scenarios were tested subsequently, one after the other, so we assumed the relative shares of users per technology and area to follow the distribution recorded for the scenario with micro layer turned on. If we consider the macro area, UL component of the $\overline{SAR}_{actual(area,population)}$ is calculated straightforward. For the DL component, we combine the average values of field strength samples taken in the micro area and the macro area excluding micro using the percentage of users in the micro and macro area from the scenario Micro ON. If we consider the micro area, for calculating the UL component we had to take some assumptions on the average transmitted power as well. We assumed that the UL component per technology equaled the average for the macro area, implying the same usage pattern per technology and radio conditions. Geolocation tools that map position and radio conditions per user would give valuable data for this assessment. UL components of GSM and UMTS were combined using relative shares of users per technology in the micro area for scenario Micro ON. For the DL calculation, power samples taken within the micro area were accounted for average incident power density. Person-time shares of postures in the micro area were taken as for the calculation when micro layer was turned on, since testing took place one hour after the other and we assumed that the population in the micro area did not change behavior in this period.

IV. EXPOSURE CALCULATION AND RESULTS

The data recorded during testing hours for the exposure calculation are shown in Table 13 for the scenario with micro layer turned on, and in Table 14 for the scenario with micro layer turned off.

The calculated values for the average actual SAR, for the macro and for the micro area, for the two scenarios, are shown in Table 15.

The overall results show the decrease of the population exposure with the introduction of the micro layer, both in the macro and in the micro area. The overall reduction of the $\overline{SAR}_{actual}$ was more than 84% in the micro area, and more than 2% in the macro area. Small exposure reduction over the macro area was expected considering the small fraction of users in the micro area (Table 2). Micro layer is generally being added for coverage and/or capacity reasons [23]. High reduction in the micro area was due to the fact that users in the micro area had lower average transmitted power than they would have had without the micro base station turned on. Even though the addition of the new layer increased the average field strength in the micro area, this increase was, in terms of total EMF exposure, multiple times overcompensated with the reduction of user devices' transmit power.

TABLE 14. Input data for scenario micro OFF.

Scenario MICRO OFF					
Source	Data	UMTS macro layer			Used to calculate
Triggered network report	Avg. UE Tx power [dBm]	-6.2			$\bar{P}_{TX}^{r,c}$
Triggered network report	Percentages of UE Rx power samples for good, medium and bad radio conditions [%]	Good 36.76%	Medium 43.15%	Bad 20.09%	$\overline{DF}^{r,c}$
Cell statistics	Average voice usage in time (per 1h), all users [Erl]	36.52			$\overline{DF}^{r,c}, TD_{p,e,pos}^{DL}/T$
Cell statistics	Average data usage UL in time (per 1h), all users [Erl]	41.96			$\overline{DF}^{r,c}, \overline{TD}_{r,c,data}^{UL}$
Cell statistics	Average data (UL and DL) usage in time (per 1h), all users [Erl]	159			$TD_{p,e,pos}^{DL}/T$
Cell statistics	Average data volume UL (per 1h), all users [kbits]	3,452,109.00			$\overline{TD}_{r,c,data}^{UL}$
Measurements in the field with laboratory equipment	Recorded average field strength in the macro area excluding micro area [V/m]	0.152			$\bar{S}_{RXinc,area}^{r}$
Measurements in the field with laboratory equipment	Recorded average field strength in the micro area [V/m]	0.199			$\bar{S}_{RXinc,area}^{r}$
Source	Data	GSM macro layer			Used to calculate
Triggered network report	Avg. UE Tx power for voice service [dBm]	29.76			$\bar{P}_{TX}^{r,c}$
Triggered network report	Percentages of UE Rx power samples for good, medium and bad radio conditions [%]	Good 14.88%	Medium 61.31%	Bad 23.81%	$\overline{DF}^{r,c}$
Measurements in the field with laboratory equipment	Recorded average field strength in the macro area excluding micro area [V/m]	0.103			$\bar{S}_{RXinc,area}^{r}$
Measurements in the field with laboratory equipment	Recorded average field strength in the micro area [V/m]	0.107			$\bar{S}_{RXinc,area}^{r}$

TABLE 15. $\overline{SAR}_{actual}$ values.

Area considered	$\overline{SAR}_{actual}$ [W/kg] per scenario		$\Delta\overline{SAR}_{actual}$ with micro ON
	Micro ON	Micro OFF	
Macro area	1.38E-05	1.42E-05	-2.22%
Micro area	2.97E-06	1.93E-05	-84.60%

TABLE 16. Shares of the total $\overline{SAR}_{actual}$ per technology and uplink/downlink.

Area considered	Technology	UL/DL	Micro ON	Micro OFF
Macro area	UMTS	UL	0.10%	0.14%
		DL	1.00%	0.98%
	GSM	UL	98.36%	98.37%
		DL	0.53%	0.51%
Micro area	UMTS	UL	0.01%	0.07%
		DL	8.11%	1.21%
	GSM	UL	88.42%	98.30%
		DL	3.45%	0.42%

Compared to whole-body SAR limit of 0,08 W/kg for given frequency ranges, according to [28], which is being basis for many national regulations, we see that even the highest aggregated value presented in Table 15 is several orders of magnitude lower that the limit.

Further insight is obtained by observing the $\overline{SAR}_{actual}$ components per technology and uplink/downlink, over the micro and the macro area. Table 16 shows the percentage share of these exposure components in the overall $\overline{SAR}_{actual}$ (over micro and over macro area), whereas Table 17 shows the absolute values with the growth percentage per component.

First, GSM UL generated the major part of the $\overline{SAR}_{actual}$. This was expected considering the technology intrinsic characteristics and also due to the fact that a large number of users were actually connected to GSM, since many of them were voice-only users, using a GSM-only device or GSM-only user option on the device. The largest exposure reduction with the introduction of the micro layer was observed over the micro area for the GSM technology.

It is also clear that the DL part of the $\overline{SAR}_{actual}$ pertaining to UMTS technology was bigger than the UL part. UMTS is an interference-limited system, and its efficient power control is one of its most important features, ensuring low UE Tx power levels. Due to the presence of surrounding base stations and sectors, with up to three carriers, the UMTS DL component was dominant, in both scenarios. In the macro area, it was several times higher than the UL component. In the micro area, with the micro layer turned on, the difference between the DL and UL components was even more pronounced due to the decrease of the UL component (improved channel quality led to lower UE Tx power levels) and the increase of the DL component due to addition of the new layer.

Looking at absolute values and growth percentages (Table 17), it is obvious that the introduction of the micro layer brought huge reduction of UL exposure components.

TABLE 17. $\overline{SAR}_{actual}$ **components per technology and uplink/downlink.**

Area considered	Technology	Micro ON [W/kg]	Micro OFF [W/kg]	$\Delta\overline{SAR}_{actual}$w ith micro ON	UL/DL	Micro ON [W/kg]	Micro OFF [W/kg]	$\Delta\overline{SAR}_{actual}$with micro ON
Macro area	UMTS	1.53E-07	1.58E-07	-3.04%	UL	1.44E-08	1.93E-08	-25.68%
					DL	1.39E-07	1.39E-07	0.11%
	GSM	1.37E-05	1.40E-05	-2.21%	UL	1.36E-05	1.39E-05	-2.22%
					DL	7.35E-08	7.29E-08	0.85%
Micro area	UMTS	2.41E-07	2.47E-07	-2.33%	UL	2.89E-10	1.31E-08	-97.80%
					DL	2.41E-07	2.34E-07	3.04%
	GSM	2.73E-06	1.90E-05	-85.66%	UL	2.62E-06	1.89E-05	-86.14%
					DL	1.03E-07	8.02E-08	27.88%

UMTS UL component over the macro area decreased by 25.68%, and over the micro area by 97.80%, due to the improvement of channel quality. The UMTS DL component over the micro area increased several percent with the micro layer turned on, due to addition of another source of radiation. Over the macro area, the UMTS DL component was just somewhat higher with the addition of the new layer.

The GSM UL component over the micro area was reduced by 86.14% due to improvement of the received signal, which resulted in more than 2% decrease over the macro area. The GSM DL component over the micro area was increased by 27.88%, which was reflected over the macro area as an increase of less than 1%.

Looking per technologies, joint exposure as a sum of UL and DL components, the $\overline{SAR}_{actual}$ over the micro area decreased for both technologies. Although UMTS UL component much decreased with micro layer turned on, the DL component was dominant, so the percentage gain in joint exposure was not high (2.33% reduction in micro area). For GSM, the UL component was dominant so its significant reduction reflected strongly on joint exposure (85.66% reduction in micro area). Micro area here was a specific one, where high presence of people was expected during weekend and after working hours. If observed during these periods, with much more people in the micro area, the gain in $\overline{SAR}_{actual}$ with the introduction of the micro layer would have been even higher.

V. DISCUSSION

The above results opened several points for discussion.

First, statistical exposure calculation with measurements from the live network, even with indicated uncertainties, gives a means to compare joint exposure, on a real, actual value basis, originating from base stations and from user's devices, as well as different RATs. Such a complex calculation, accounting for so many factors, was intended to show real average SAR values for actual usage scenarios, to compare them by scenario and by exposure components, and to show how far from the limits the actual average population exposure is, marking space available for the future (4G/5G) network.

The significant reduction of the exposure in the micro area with the introduction of the micro base station was apparent, more than 84% over the micro area, with the macro base station still on. Due to growing usage of mobile technologies and devices, the exposure from user devices became a significant or even dominant factor. This is not clearly visible through current compliance procedures, as the user devices must conform to SAR limits, where SAR is measured in laboratories, while for base stations conformance with reference levels is evaluated with on-site field measurements. SAR does not capture the actual usage, as the worst case value measured is reported (the user might never use the device in that exact manner) and the relation between uplink and downlink exposure is not intuitive. The main contribution to the exposure reduction comes from GSM, again expected due to technology properties (power classes and power control). The proposed method for assessing exposure is explained and demonstrated experimentally using two scenarios in GSM and UMTS networks, but it can be used for any wireless network with the appropriate collection of data from the network. Same network data, in real time and on longer term basis, can be extracted from 4G network, so this method can be used as is to assess exposure generated by 4G network. For WLAN network, we lack user profile data, but it could be extrapolated based on data from mobile network as it is assessed in and valid for longer term, not only during measurements.

Second, the average actual SAR could be calculated more precisely on the network level with the introduction of sophisticated tools that would combine radio and application data on per-user basis (geolocation tools, probes in the core, CEM tools). The spatial distribution of users, emphasized as a key parameter for exposure assessment in systems using massive MIMO with beamforming [15], [18] could be obtained using geolocation tools but this would require high computational efforts for near-real-time assessment, however some behavioral patterns could be extracted on a longer-term basis and used in calculation as realistic data. The exact distribution of population categories, postures, environment, would still be an assumption based on external sources. Duty factor would still need to be measured externally. In our study, we conducted on-site measurements outdoors and extrapolated the values for overall (population) indoor exposure based on number of people estimated to be indoors and based on attenuation factor, as we could not perform measurements indoors. Frequency selective field measurements for the DL calculation would be hard to perform in every environment even just for the set of typical conditions, but some extrapolation based on typical environments and UE Rx measurements could be performed. Cell reports could be also improved to this end. Though the UE Rx measurements do not capture the whole field, they still give valuable data that could be used through a calibrated model to estimate incident power density. The majority of people communicate indoor, where the field measurements for the DL are generally not possible on a massive scale, for all environment and load conditions, so UE Rx measurements with extrapolation could be used. As noted in [16], network measurements represent a powerful tool, especially when using beamforming and looking for spatial distribution of power.

Further, the introduction of agents on phones (including sensors) that would collect radio and usage data or even some customer-category data, could improve the calculation and reduce the need for external sources, but the additional reporting messages from phones to the network would be needed. Software-modified phones, as suggested in [45] for collecting usage data in a study, could be combined with network tools in order to obtain the mapping of user plane data with radio parameters needed for exposure assessment. Moreover, user context information that could be used in ultra-dense networks with device-to-device communication for managing connectivity and decreasing energy consumption [46], could also be used for the purposes of assessing and further reducing EMF exposure, through means of connectivity management among other techniques [24].

Third, such estimation based on network data opens up the door for the future EMF-aware networks. Simulations and live network measurements could be used together to calibrate models, and provide a powerful tool for future EMF-aware network planning. Further, converged networks could collect data, evaluate EMF exposure on population basis and take optimization steps for decreasing it (access selection etc.) [24]. EMF exposure management could be added to Self-Optimizing Network (SON) functionalities, but near-real-time assessment and response would require processing huge amounts of data. With the rise of different wireless networks (IoT), especially those with access points within home (Wi-Fi), the in-home analytics over wireline could provide valuable data for indoor exposure assessment. The challenges of 5G exposure assessment, including massive MIMO, beamforming and new frequency bands, along with existing 2G/3G/4G network complexity, suggest that the most appropriate model for the EMF estimation would be based on statistical approach [5]. For the statistical methodology we proposed, besides the tools that would decrease uncertainties, downlink exposure would need to be modelled in order to reduce the number of on-site measurements needed for assessment. In case of beamforming in the downlink, the method for assessing the average downlink exposure based on UE Rx power would be very useful, having in mind that appropriate on-site field measurements would be complex to perform and process. Beamforming in uplink would pose a significant challenge for assessing the uplink exposure, as the beam direction and spatial distribution of radiated power would need to be modelled.

VI. CONCLUSION

The presented analysis shows that the introduction of microcells in both technologies, GSM and UMTS, led to decrease of average exposure of the population in the area of microcell use, due to the reduction of exposure originating from user devices. This decrease was remarkable for GSM technology, more than 85%, while for UMTS it was just over 2%, with the resulting total exposure reduction of over 84.6%. Joint exposure from base stations (access points) and user devices was evaluated, and the insight into these two components gave a real picture on the contribution of user devices to the overall exposure. Their non-negligible and in some cases dominant contribution is the consequence of rising usage of mobile technologies, and generally not intuitive for the general public, nor obvious regarding the compliance measurement procedures that treat the exposure from base stations and user devices separately. The exact reduction of exposure with the introduction of smaller cells depends heavily on dominant technology used, number of users in the small cell coverage area and network load, on user habits, devices and area and network topology. Moreover, usage of small cells is in line with coverage and capacity requirements.

The analysis was based on a proposed novel EMF exposure evaluation method, showing how data in an operational network, from multiple network sources, from triggered power measurement reports and cell statistics, to usage data, signaling messages and traffic inspection, can be used to assess average actual exposure of population in an area. The exposed method could be used to evaluate exposure from any wireless network in which required network data may be collected. It reveals the network potential for future EMF-awareness, i.e. near-real-time self-assessment and EMF exposure control. Usage of advanced tools and methods is proposed for mitigating the identified uncertainties.

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