IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 8, 2016, accepted August 1, 2016, date of publication August 17, 2016, date of current version November 18, 2016.

Digital Object Identifier 10.1109/ACCESS.2016.2601145

Exposure to RF EMF From Array Antennas in 5G Mobile Communication Equipment

BJÖRN THORS[1], DAVIDE COLOMBI[1], ZHINONG YING[2], (Senior Member, IEEE), THOMAS BOLIN[2], AND CHRISTER TÖRNEVIK[1], (Member, IEEE)

[1]Ericsson Research, Ericsson AB, SE-16480 Stockholm, Sweden
[2]Network Technology Laboratory, Research and Technology, Sony Mobile Communications AB, SE-221 88 Lund, Sweden

Corresponding author: B. Thors (bjorn.thors@ericsson.com)

ABSTRACT In this paper, radio-frequency (RF) electromagnetic field (EMF) exposure evaluations are conducted in the frequency range 10–60 GHz for array antennas intended for user equipment (UE) and low-power radio base stations in 5G mobile communication systems. A systematic study based on numerical power density simulations considering effects of frequency, array size, array topology, distance to exposed part of human body, and beam steering range is presented whereby the maximum transmitted power to comply with RF EMF exposure limits specified by the International Commission on Non-Ionizing Radiation Protection, the US Federal Communications Commission, and the Institute of Electrical and Electronics Engineers is determined. The maximum transmitted power is related to the maximum equivalent isotropically radiated power to highlight the relevance of the output power restrictions for a communication channel. A comparison between the simulation and measurement data is provided for a canonical monopole antenna. For small distances, with the antennas transmitting directly toward the human body, it is found that the maximum transmitted power is significantly below the UE power levels used in existing third and fourth generation mobile communication systems. Results for other conceivable exposure scenarios based on technical solutions that could allow for larger output power levels are also discussed. The obtained results constitute valuable information for the design of future mobile communication systems and for the standardization of EMF compliance assessment procedures of 5G devices and equipment.

INDEX TERMS 5G mobile communication, antenna arrays, beam steering, mobile device, mobile user equipment, radio base station, RF EMF exposure.

I. INTRODUCTION

The total amount of mobile traffic is expected to increase dramatically in the coming years [1]. The next generation of wireless access systems (5G), set for commercial availability around 2020 [2], is expected to constitute a key enabler for the larger system capacity and higher data rates of the future. Various research activities are currently ongoing to lay the foundation for this new technology, see e.g. [3], [4], which apart from mobile broadband will involve a range of different use cases and challenging requirements on latency, security, reliability, availability, energy performance, and device cost [5]. In terms of spectrum, 5G systems will need to be able to operate over a very wide frequency range from below 1 GHz up to and including millimeter wave (mmW) frequencies [1]. The available spectrum above 10 GHz will be a key component to fulfill long-term traffic demands and to enable the very wide transmission bandwidths needed to provide the desired multi-Gbps data rates in an efficient manner [5].

Products emitting radio-frequency (RF) electromagnetic fields (EMF) need to be designed and tested to comply with relevant regulatory requirements and limits on human exposure to EMF [6]–[9]. The most widely adopted exposure limits worldwide are the guidelines specified by the International Commission on Non-Ionizing Radiation (ICNIRP) [7] in 1998. In the US, exposure limits specified by the Federal Communications Commission (FCC) are applicable [9]. The exposure limits published by the IEEE [10], [11] are of a more recent date but has so far not been adopted in any national regulations.

For the frequencies used by existing second, third, and fourth generation (2G, 3G, and 4G) mobile communication systems, basic restrictions on RF EMF exposure are specified in terms of the specific absorption rate (*SAR*) to prevent, with wide safety margins, from established adverse health effects associated with excessive localized tissue heating and whole-body heat stress [7], [9], [10]. At higher frequencies, the absorption in the human tissue becomes more superficial and the basic restrictions changes from SAR to incident power density (S). The transition frequency where this change in exposure metric takes place is 3 GHz, 6 GHz, and 10 GHz for the IEEE, FCC and ICNIRP exposure guidelines, respectively. A literature review of what is required to ensure safety of emerging 5G technologies with respect to RF EMF exposure was presented in [12].

A fundamental property to consider when designing a mobile communication system is the transmit power to be used by the base station and user equipment (UE). For frequencies below 3 GHz, research on RF EMF exposure from base stations and UEs has been going on for more than 20 years resulting in a solid scientific understanding and well-defined and standardized exposure assessment procedures see e.g. [13]–[15]. Until recently, less attention has been paid to frequencies above 6 GHz. With the upcoming standardization of 5G radio access technologies this has started to change as there is a clear need to define the corresponding system boundaries and develop RF EMF exposure assessment methods.

In [16], the implication of the changing basic restriction from SAR to power density was investigated in terms of the maximum possible transmitted power (P_{max}) from a device (canonical dipole) used in close proximity to the human body. It was shown that the existing exposure limits will lead to a non-physical discontinuity of several dB in P_{max} as the transition is made from SAR to power density based basic restrictions. As a consequence, to be compliant with applicable exposure limits at frequencies above 6 GHz, P_{max} might have to be several dB below the power levels used for current cellular technologies [16]. In a follow-up letter [17], the increase in skin temperature due to RF exposure from the same source, when transmitting at the maximum allowable power to be compliant with these limits, was investigated. The maximum steady state temperature increase was found to display a similar discrepancy. Among the relevant U.S. (FCC) and international exposure limits, IEEE C95.1-2005 [10] was found to provide the most consistent level of protection against thermal hazards of exposure over the frequency range 6 - 60 GHz [17].

To improve the link budget and compensate for the worsened propagation conditions with an increased free space path loss at the higher frequencies it is desirable to make use of array antennas for both UEs and base stations. In [18], the RF EMF exposure for phased arrays intended for mobile devices and transmitting at 15 GHz and 28 GHz was investigated. The study considered effects of a progressive phase shift between the antenna elements but was restricted to the FCC exposure limits [9]. Until now, no systematic study on EMF exposure for phased arrays transmitting above 10 GHz has been presented where effects of frequency range, array size, scan angle, distance to human body, and all major exposure standards are considered. It is the aim of this paper to fill this gap and provide valuable information for the design and standardization of future mobile communication systems.

A method description including the considered RF EMF exposure limits is provided in Section II. The results are presented and discussed in Section III and Section IV, respectively. Finally, some conclusions are provided in Section V.

II. METHOD

A. RF EMF EXPOSURE LIMITS AND LIMITS ON MAXIMUM EQUIVALENT ISOTROPICALLY RADIATED POWER (EIRP)

Between 10 GHz – 300 GHz, the ICNIRP exposure guidelines [7] specify a maximum power density of 10 W/m^2 for the general public taken as an average over any 20 cm^2 of exposed area. In addition, the spatial maximum power density averaged over any 1 cm^2 shall not exceed 200 W/m^2.

The uncontrolled power density exposure limit for FCC between 6 GHz to 100 GHz is also 10 W/m^2, which in general is to be considered as a spatial peak value [8], [9]. Spatial peak is not a well-defined quantity, however, and the obtained result will depend on the exposure assessment method. For measurements, an average over the probe dimensions will be obtained and for computations a sufficient sampling density is required. In a recent Notice of Proposed Rulemaking (FCC 15-138) [19], the FCC stipulates that spatial peak is to be interpreted as an average over any 1 cm^2 in the shape of a square for frequencies above 6 GHz. Although this interpretation of spatial peak power density has not yet formally made its way into the FCC regulations, in this work a 1 cm^2 averaging area was assumed to be consistent with FCC 15-138 [19]. In [19], the FCC also stipulates a maximum peak EIRP, $EIRP_{lim}$, of 20 W for mobile[1] devices.

Between 3 GHz to 100 GHz, the IEEE general public basic restriction on power density is 10 W/m^2 [10]. In the frequency range between 3 GHz to 30 GHz, the power density is to be spatially averaged over any contiguous area corresponding to 100λ^2 where λ is the free space wavelength of the RF field. Above 30 GHz, the averaging is to be conducted over any contiguous area of 100 cm^2 [11]. In addition, IEEE also specifies maximum spatial peak power densities of $18.56 f^{0.699}$ W/m^2 and 200 W/m^2 at frequencies between 3 GHz and 30 GHz and above 30 GHz, respectively, where f shall be taken as the frequency in GHz. No averaging area or spatial sampling density is specified by the IEEE for the spatial peak power density limits. In this work the spatial peak power density was assessed using a minimum spatial sampling density of four samples per wavelength.

A summary of the RF EMF exposure limits, S_{lim}, is provided in Table 1. For convenience, the spatially averaged power densities were for all RF exposure limits determined

[1]The U.S. FCC distinguishes between mobile and portable devices [9]. A mobile device is defined as a transmitter designed to be used in other than fixed locations and to generally be used in such a way that a separation distance of at least 20 centimeters is normally maintained between the radiating structures and the body of the user or nearby persons. A portable device is defined as a transmitter whose radiating structures are designed to be used within 20 centimeters of the body of the user. For certification of medium range RBS, local area RBS, and home RBS [25], RF EMF exposure assessments are normally conducted according to the requirements for mobile exposure.

TABLE 1. General public/Uncontrolled basic restrictions on power density, S_{lim}, as defined by ICNIRP [7], FCC [8], [9], [19] and IEEE [10], [11]. The parentheses behind the power density limits indicate the applicable averaging area. Absence of averaging area implies spatial peak power density.

(λ = WAVELENGTH IN FREE SPACE, f = FREQUENCY IN GHz).

	ICNIRP	FCC	IEEE	
f (GHz)	10 – 300	6 - 100	3 - 30	30 - 100
S_{lim} (W/m^2)	10 (20 cm^2) 200 (1 cm^2)	10 (1 cm^2)	10 (100λ^2) $18.56f^{0.699}$	10 (100 cm^2) 200

assuming square-shaped averaging areas.

B. POWER DENSITY AND MAXIMUM TRANSMITTED POWER

For each distance d from the face of the array, the maximum spatially averaged power density over any square-shaped averaging area, A_{av}, is determined as the real power, P, flowing through A_{av} according to

$$S(x = d, A_{av}) = \max_{y,z}\left(\frac{P(d,y,z)}{A_{av}}\right) = \max_{y,z}\left(\frac{\frac{1}{2}\int_A \Re\left(\boldsymbol{E}(d,y,z) \times \boldsymbol{H}^*(d,y,z)\right)\cdot\hat{\boldsymbol{x}}\mathrm{d}S}{A_{av}}\right) \quad (1)$$

where $\Re$, $\boldsymbol{E}$, $\boldsymbol{H}$ and $*$ denote the real part, the electric and magnetic fields and the complex conjugate, respectively. The definition of the coordinate system employed and the averaging area is illustrated in Figure 1 together with a square-shaped array antenna.

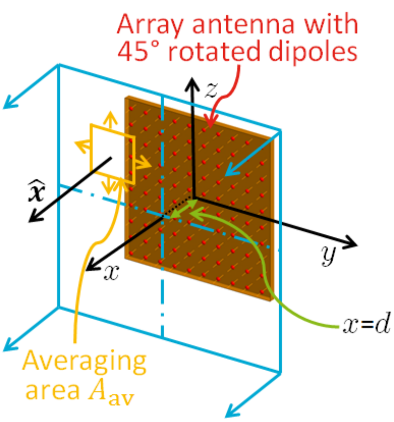


FIGURE 1. Square-shaped array antenna and definition of area over which the power density is averaged.

For large array antennas, a characteristic feature is that the maximum exposure may occur at some distance away from the face of the array due to the focusing of energy, see Section III. From an EMF compliance assessment point of view, this implies that the maximum transmitted power must be determined considering a range of distances. In this work, compliance with the exposure limits has been assessed considering distances in the range 0.5 cm – 50 cm.

In Section III, when results are presented for a certain distance, it is understood that compliance with the exposure limits is ensured for all distances larger than or equal to this distance. In particular, results are presented for distances d = 0.5 cm and d = 20 cm. The smallest distance is of relevance for portable devices, *i.e.* UEs used in close proximity of the body. The larger distance is of relevance for mobile devices (*e.g.* laptops or wireless routers) and low-power RBS.[2]

During the simulations and measurements, the power density was scaled to a transmitted power, P_{tr}, of 1 W. The maximum transmitted power, $P_{tr,max}$, and the maximum EIRP, $EIRP_{max}$, to comply with the limits in Table 1 for distances $x \geq d$ were determined according to

$$P_{tr,max}(A_{av}, f, N) = \min\left\{\begin{array}{l}\dfrac{S_{lim}}{\max\limits_{x\geq d,\beta_y}\left(S\left(x,\beta_y,A_{av},f,N\right)\right)}P_{tr}\\ \dfrac{EIRP_{lim}}{G(N)}\end{array}\right. \quad (2)$$

$$EIRP_{max}(A_{av}, f, N) = P_{tr,max}(A_{av}, f, N)\,G(N), \quad (3)$$

where G, N^2 and β_y denote the maximum antenna gain, the number of antenna elements in the considered square-shaped arrays, and the progressive phase shift to consider effects of beam scanning in the xy-plane, see Section II-C.

C. NUMERICAL SIMULATIONS

Numerical simulations were conducted using the commercial electromagnetic solver FEKO (Altair, Stellenbosch, South Africa) based on the Method of Moments (MoM) [20]. Square-shaped ground-plane backed dipole arrays with an inter-element distance of $\lambda/2$ were considered. The dipoles were rotated 45° from the z-axis as indicated in Figure 1 and the length of the dipoles was $\lambda/2$. Around the edge of the ground plane, a wall of height $\lambda/5$ was situated. All parts of the antenna were made of metal and simulated as perfectly electrically conducting objects. Arrays with $N \times N$ elements, with $N \in [2\ 10]$, were considered for frequencies $f \in [10\text{ GHz } 60\text{ GHz}]$. To investigate the effects of beam scanning, a progressive phase shift $\beta_y \in \left[0\ \pi/\sqrt{2}\right]$ was used. For the selected inter-element distance and the ideal case of no coupling among the antenna elements this would correspond to an azimuthal scan range of $\alpha \in [0°\ 45°]$.

The antenna ground plane was meshed using triangles with a maximum edge length of $\lambda/12$. The dipoles were modeled as thin wires with a maximum wire segment length of $\lambda/12$ and an equivalent radius of $\lambda/1000$ [21].

[2]For low-power RBS, compliance with RF EMF exposure limits is normally achieved during installation by making sure that the general public do not have access to a region in the vicinity of the antenna where the exposure limits may be exceeded (*i.e.* within the compliance boundary). The results on maximum transmitted power presented in this paper shall for these type of products be interpreted as the power level that would result in the specified compliance distance d. Larger power levels are possible to use if larger compliance boundaries are considered during installation of the low-power RBS.

To assess the maximum exposure, with the arrays transmitting directly towards a human body, the electric and magnetic fields were determined in a volume in front of the antenna from $x = 0$ m to $x = 0.5$ m with the extent in the y- and z-directions chosen to circumscribe both the face of the array and the location of maximum power density for the maximum considered scan angle. A minimum sampling density of four samples per wavelength was used.

The array sizes investigated were chosen arbitrarily to span a large parameter space of relevance for several different applications. For a particular application, however, only a subset of the considered domain may be relevant.

D. REFERENCE ANTENNA AND MEASUREMENTS SET-UP

To verify the numerical simulations, measurements were conducted on a 15 GHz monopole prototype antenna manufactured by Sony Mobile Communications (Lund, Sweden). The prototype antenna had a gain of 2 dBi and a vertical half-power beamwidth of 80 degrees. The measurements were conducted using a DASY 5 near-field scanner together with an isotropic E-field probe EF3DV3 (SPEAG, Zurich, Switzerland). The probe was calibrated for measurements at 15 GHz using the free-space standard-field method [22] and a PE9854/SF-10 horn antenna (Pasternack, Irvine, CA) with a nominal gain of 10 dBi. Eccosorb AN-79 RF absorbing material (Randolph, MA) was used to minimize reflections towards the measurement area from all relevant mechanical structures present in the anechoic measurement chamber. Measured results on plane-wave equivalent power density, $S_{PW,E}$, were compared with FEKO simulations based on a CAD-file of the monopole antenna.

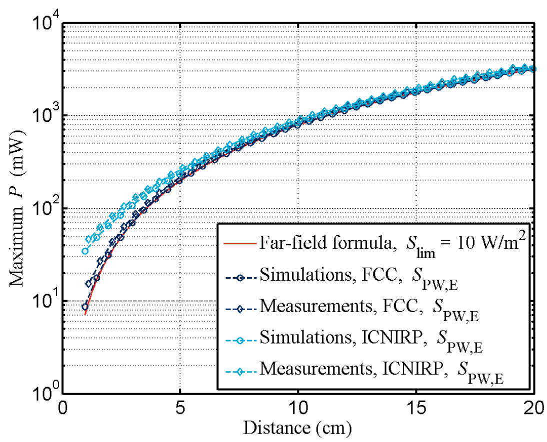


FIGURE 2. Comparison between simulated and measured results in terms of maximum transmitted power to comply with the ICNIRP and FCC limits in Table 1 for a monopole antenna transmitting at 15 GHz.

III. RESULTS

A. REFERENCE ANTENNA MEASUREMENTS

A comparison between simulated and measured plane-wave equivalent power density results is presented in Figure 2 in terms of the maximum transmitted power to comply with the ICNIRP and FCC limits. Shown also are results obtained using the spherical far-field formula [15] to comply with a spatial peak power density of 10 W/m^2. The agreement between the simulations and measurements is excellent. The spatially averaged results over 1 cm^2 also agree very well with the spatial peak results obtained using the far-field formula.

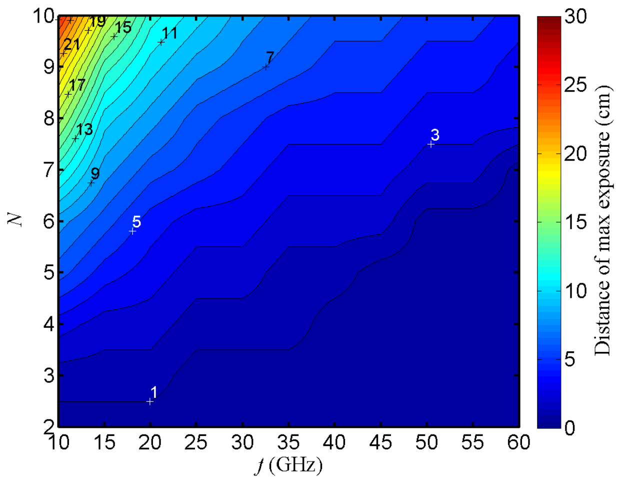


FIGURE 3. Distance of maximum exposure as function of frequency and array size for the 1 cm^2 spatial averaging area employed in FCC 15-138 [19].

B. POWER DENSITY SIMULATION RESULTS

In Figure 3, a plot of the distance of maximum exposure is provided as function of frequency and array size for the 1 cm^2 spatial averaging area employed in FCC 15-138 [19]. The obtained results illustrate that for large array antennas the maximum exposure may occur some distance away from the face of the array. Similar behaviors are also observed for other averaging areas (not shown) with the largest distance of maximum exposure obtained for the lowest frequency and largest antenna arrays considered.

The maximum transmitted power to be compliant with the ICNIRP, FCC, and IEEE limits in Table 1 with $d = 0.5$ cm has been determined and the results are provided in Figure 4 – Figure 6. The white dashed lines in Figure 4 and Figure 5 correspond to antenna arrays with areas, A, equal to the main averaging areas, A_{av}, for the ICNIRP (20 cm^2) and FCC (1 cm^2) exposure limits. Due to the short distance, d, compared with the extent of the averaging area, in the region to the right of the white dashed line in Figure 4 almost all power will pass through A_{av}. As a consequence, the maximum transmitted power in this area approaches 13 dBm (20 mW), *cf.* Table 1. For the IEEE results in Figure 6, the averaging area is larger than the array area for all considered arrays.

In general, as the physical array size is increased the transmitted power is distributed over a larger area which for a small distance d translates to a larger maximum transmitted power. The FCC exposure limits results in a lower maximum transmitted power than the ICNIRP and IEEE exposure limits. For lower frequencies and larger arrays, the IEEE exposure limits

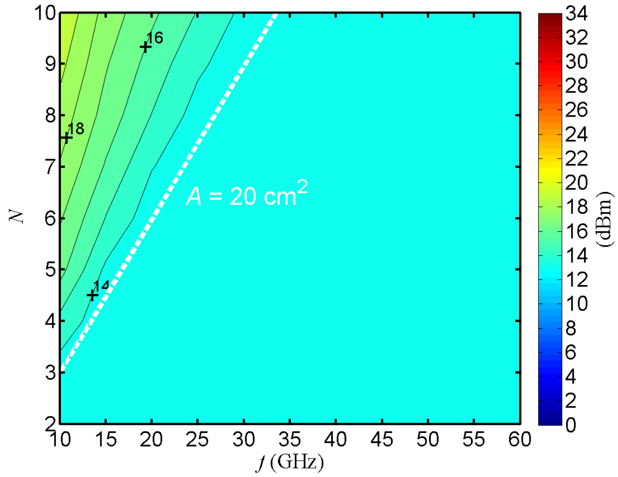


FIGURE 4. Maximum transmitted power to be compliant with the ICNIRP RF EMF exposure limit [7] for $d = 0.5$ cm.

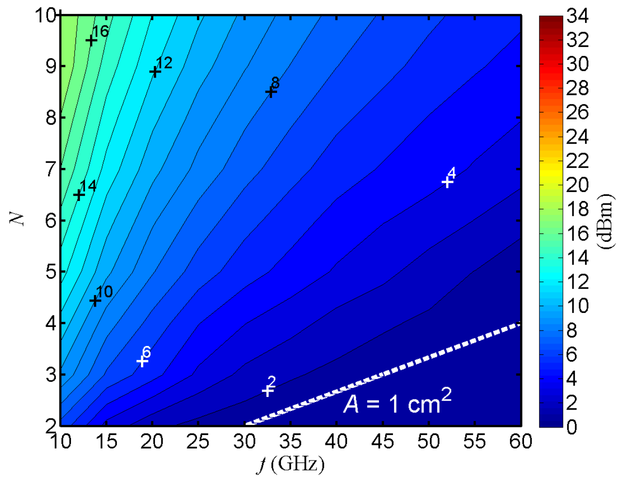


FIGURE 5. Maximum transmitted power to be compliant with the FCC RF EMF exposure limits [8], [9], [19] for $d = 0.5$ cm.

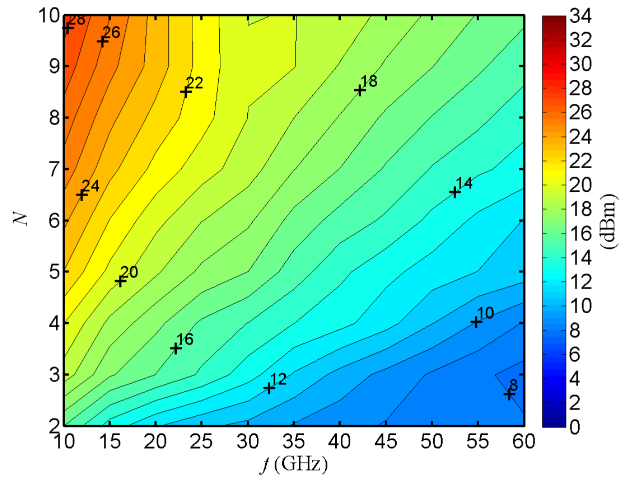


FIGURE 6. Maximum transmitted power to be compliant with the IEEE RF EMF exposure limit [10], [11] for $d = 0.5$ cm.

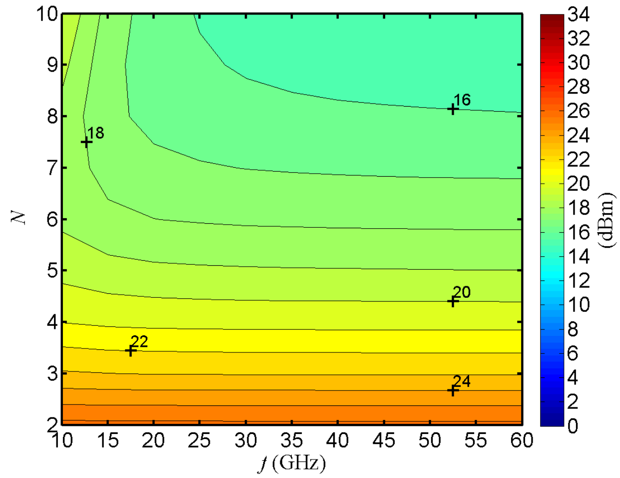


FIGURE 7. Maximum transmitted power to be compliant with the ICNIRP RF EMF exposure limit [7] for $d = 20$ cm .

results in a larger maximum transmitted power compared with the ICNIRP exposure limits. For higher frequencies and smaller arrays the opposite is true, which is explained by the fact that in this region the maximum transmitted power for the IEEE limits is determined by the spatial peak power density.

Results on maximum transmitted power to be compliant with the ICNIRP, FCC, and IEEE limits in Table 1 for $d = 20$ cm are provided in Figure 7 – Figure 9. For the smallest arrays investigated, the maximum transmitted power for the ICNIRP and FCC exposure limits is similar since far-field conditions apply and the difference between power density averaged over 1 cm^2 and 20 cm^2 is very small. In this region, the maximum transmitted power is approximately inversely proportional to the antenna gain, which for the considered square-shaped arrays is independent of the frequency. As a consequence, the largest maximum transmitted power levels in Figures 7 and 8 display a frequency independent behavior and are obtained for the array with the fewest number of elements. For the IEEE limits, the side of the averaging area at the lower frequencies is not small compared with the distance, d, which explains why the horizontal behavior of the contour lines is not maintained as the frequency is reduced. The vertical contour lines in Figure 9 for frequencies below 30 GHz indicate that, in this region, most of the transmitted power will flow through the averaging area independent of the array size.

For a communication system employing array antennas it is important to relate maximum transmitted power levels to maximum EIRP determined according to Equation (3). As an example, the maximum EIRP to be compliant with the ICNIRP exposure limits for $d = 0.5$ cm is provided in Figure 10. Since the physical array size scales with frequency, the maximum antenna gain is frequency independent. Thus, the variation in maximum EIRP versus frequency reflects the frequency dependency of the maximum transmitted power, *cf.* Figure 4. According to Figure 4, in a large part of the analyzed

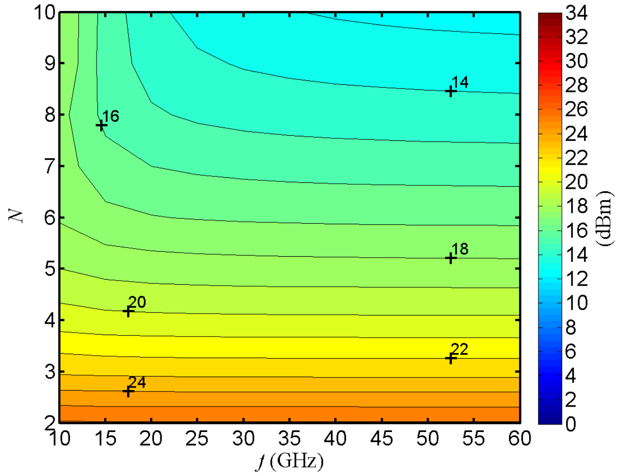


FIGURE 8. **Maximum transmitted power to be compliant with the FCC RF EMF exposure limits [8], [9], [19] for $d = 20$ cm.**

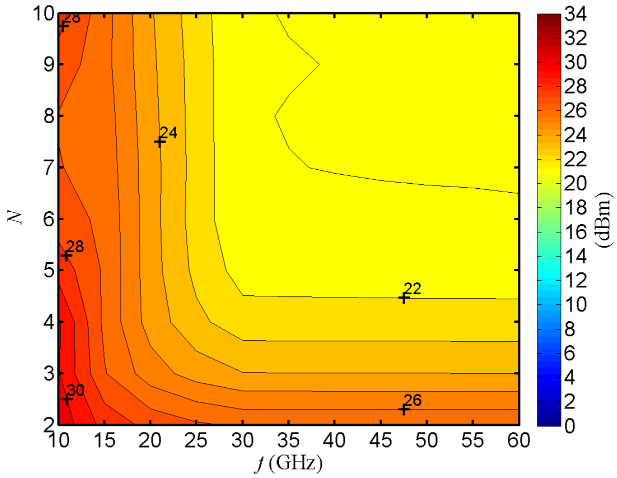


FIGURE 9. **Maximum transmitted power to be compliant with the IEEE RF EMF exposure limit [10], [11] for $d = 20$ cm.**

parameter space the maximum transmitted power is constant. The variation in maximum EIRP in this region, as observed in Figure 10, corresponds to the variation in maximum gain as function of array size. Plots of the maximum EIRP for the exposure limits and distances analyzed in Figures 5-9 are provided in Appendix A.

A summary of the results on maximum transmitted power and maximum EIRP to comply with the different exposure limits is provided in Table 2.

IV. DISCUSSION

The purpose with the numerical study presented above was to provide an indication of the maximum transmitted power levels and maximum EIRP for array antennas to be used in future 5G mobile communication systems in order to comply with all major RF EMF exposure standards. This was accomplished by investigating a wide parameter space of relevance for both UEs and low-power RBS for a maximum exposure scenario with the arrays transmitting directly towards the human body.

In the analysis, ground-plane backed arrays with canonical dipole elements were considered. For comparable arrays with other antenna elements, a similar behavior is expected with exposure levels of the same order of magnitude.

The results in Table 2 constitute a summary of the obtained results for the considered parameter space. For a particular application, where only a subset of the considered frequency range and/or array size is of interest, the reader is referred to the results in Figure 4 – Figure 10 and Figure 13 – Figure 17.

For $d = 0.5$ cm, the smallest arrays and highest frequencies considered, the IEEE limits result in a significantly lower maximum transmitted power level compared with the ICNIRP limits. This is a consequence of the maximum transmitted power being determined by the spatial peak power density for the IEEE limits in this region. As pointed out in Section II, spatial peak is not a well-defined quantity and will

TABLE 2. **Summary of maximum transmitted power and maximum EIRP to comply with the ICNIRP [7], FCC [8], [9], [19], and IEEE [10], [11] RF EMF exposure limits.**

	f (GHz)	Array area (cm²) 2 × 2 – 10 × 10 elements	Maximum transmitted power (dBm)			Maximum EIRP (dBm)		
			ICNIRP	FCC	IEEE	ICNIRP	FCC	IEEE
Portable[1] applications ($d = 0.5$ cm)	10	9.0 – 230	13 – 20	7 – 18	16 – 28	24 – 45	18 – 43	27 – 53
	20	2.3 – 56	13 – 16	2 – 13	12 – 24	24 – 41	13 – 38	23 – 49
	30	1.0 – 25	13 – 14	1 – 10	11 – 20	24 – 39	12 – 35	22 – 45
	40	0.56 – 14	13	1 – 8	9 – 20	24 – 38	12 – 33	20 – 45
	50	0.36 – 9.0	13	1 – 6	9 – 18	24 – 38	12 – 31	20 – 43
Mobile[2] applications ($d = 20$ cm)	10	9.0 – 230	20 – 26	18 – 26	27 – 31	37 – 45	37 – 43	42 – 53
	20	2.3 – 56	16 – 26	14 – 26	24 – 28	37 – 41	37 – 39	39 – 49
	30	1.0 – 25	16 – 26	13 – 26	21 – 27	37 – 41	37 – 38	38 – 46
	40	0.56 – 14	15 – 26	13 – 26	21 – 27	37 – 40	37 – 38	38 – 46
	50	0.36 – 9.0	15 – 26	13 – 26	21 – 27	37 – 40	37 – 38	38 – 46

[1] FCC terminology used to denote devices intended to be used at a distance of less than 20 cm from the human body.
[2] FCC terminology used to denote devices intended to be used at a distance of 20 cm or more from the human body.

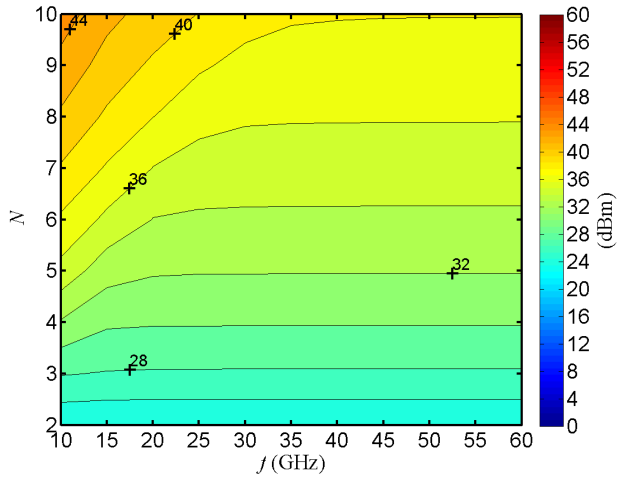


FIGURE 10. Maximum EIRP to be compliant with the ICNIRP RF EMF exposure limit [7] for $d = 0.5$ cm.

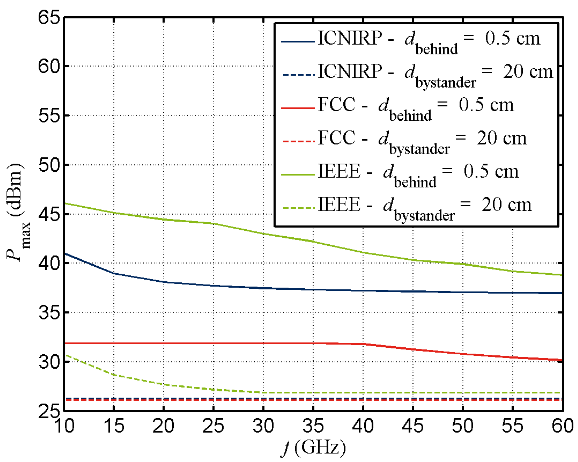


FIGURE 11. Maximum transmitted power to be compliant with all major RF exposure standards for a 2 × 2 array antenna with the exposure directed away from the human body (d_{behind} = 0.5 cm, $d_{bystander}$ = 20 cm).

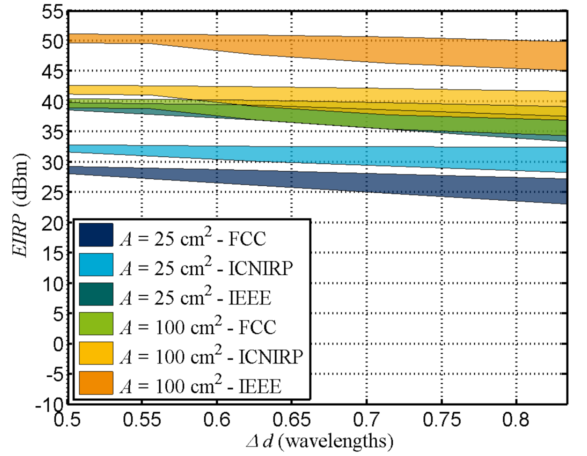


FIGURE 12. Spread of maximum EIRP as function of inter-element separation distance for arrays of area A, transmitting at 15 GHz with a progressive phase shift $\beta_y \in [0\ \pi/\sqrt{2}]$, to be compliant with all major exposure standards for $d = 0.5$ cm For the smaller array area ($A = 25$ cm^2), the considered inter-element separation distance corresponds to arrays with 5 × 5 to 3 × 3 elements. For the larger array area ($A = 100$ cm^2), the considered inter-element separation distance corresponds to arrays with 10 × 10 to 6 × 6 elements.

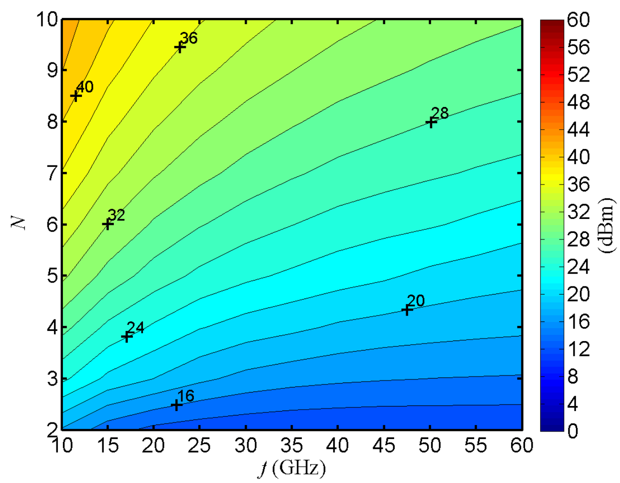


FIGURE 13. Maximum EIRP to be compliant with the FCC RF EMF exposure limits [8], [9], [19] for $d = 0.5$ cm.

depend on the assessment method. If the same definition of spatial peak power density had been adopted for the IEEE limits as for the FCC limits, i.e. if a 1 cm^2 averaging area had been used, the maximum transmitted power in the lower right corner of Figure 6 would have been 13 dBm (20 mW) and consistent with the ICNIRP limits.

The results in this paper have been obtained for array antennas with an inter-element spacing $\Delta d = \lambda/2$. This choice of inter-element spacing allows for a wide scan range without the introduction of grating lobes. A drawback with too dense element spacing is that the devices become more expensive as the cost scales with the number of transceivers. On the other hand, too wide inter-element spacing will introduce grating lobes that will reduce the EIRP and possibly increase the interference in the system. An illustration of this possible trade-off is provided in Figure 12, where the spread of maximum EIRP to be compliant with the major exposure standards for $d = 0.5$ cm is given as function of inter-element distance. The spread in maximum EIRP corresponds to the considered ideal scan range $\alpha \in [0° \ 45°]$, see Section II-C. For $\Delta d = \lambda/2$ no grating lobes will propagate. Here, the obtained spread in EIRP corresponds to a reduced gain as the arrays are scanned from broadside. As expected, the spread gets wider with an increasing inter-element separation distance illustrating the impact of propagating grating lobes, which becomes larger as the scan angle increases from broadside.

For devices intended to be used in the immediate vicinity of the human body, the ICNIRP and FCC exposure limits results in a maximum transmitted power significantly below what is specified today for existing mobile communication

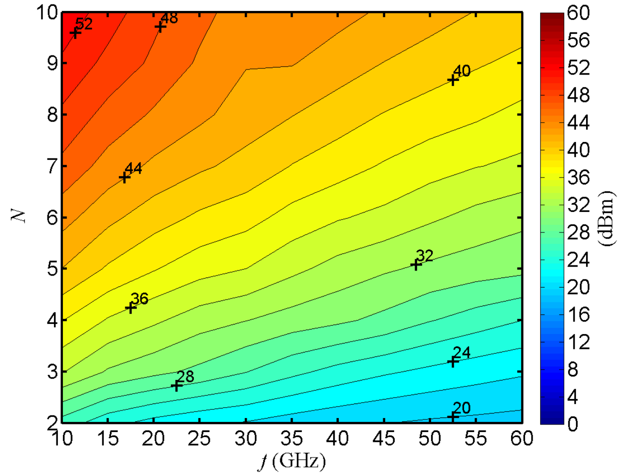


FIGURE 14. Maximum EIRP to be compliant with the IEEE RF EMF exposure limit [10], [11] for $d = 0.5$ cm.

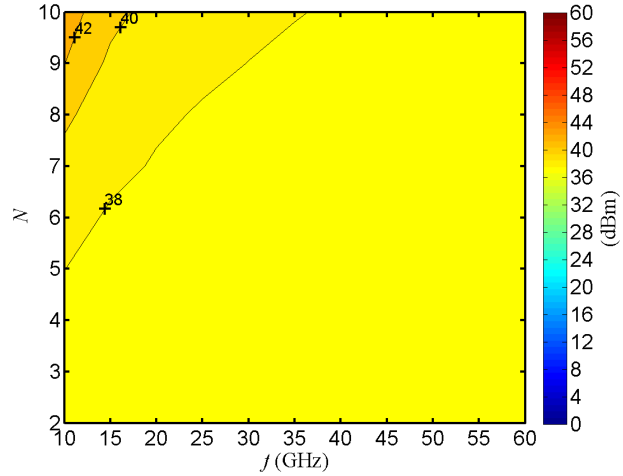


FIGURE 16. Maximum EIRP to be compliant with the FCC RF EMF exposure limits [8], [9], [19] for $d = 20$ cm.

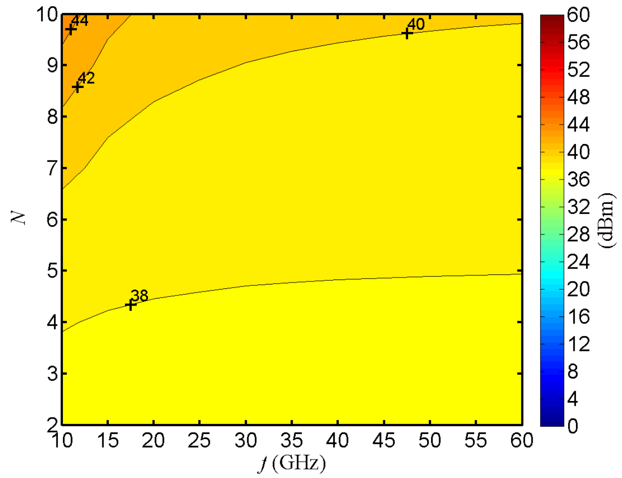


FIGURE 15. Maximum EIRP to be compliant with the ICNIRP RF EMF exposure limit [7] for $d = 20$ cm.

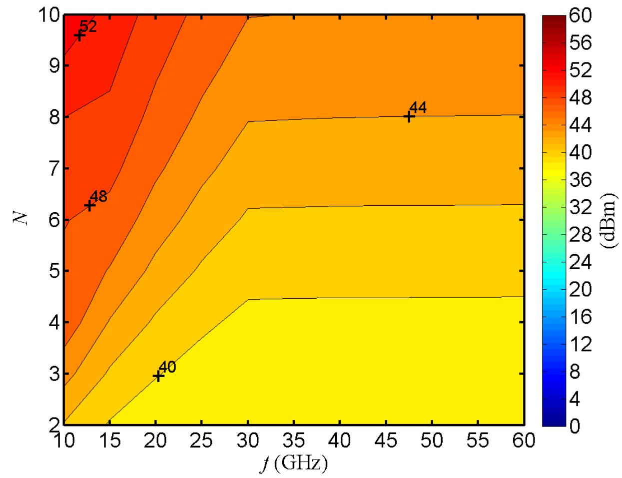


FIGURE 17. Maximum EIRP to be compliant with the IEEE RF EMF exposure limit [10], [11] for $d = 20$ cm.

technologies, e.g. 23 dBm and 24 dBm for Long Term Evolution (LTE) [23] and WCDMA [24], respectively. This is in-line with the findings in [16] where a single dipole element was considered. To circumvent these problems, and also to improve the link budget by reducing body losses, it is conceivable that technical solutions are employed whereby the transmitted energy is always directed away from the human body. A reasonable EMF compliance assessment procedure would then be based on evaluations of the exposure behind the array antenna, at a certain distance, d_{behind}, plus an evaluation of the exposure for bystanders at a distance, $d_{\text{bystander}}$, in front of the array. As an example, Figure 11 shows the maximum transmitted power for a 2×2 array antenna with the exposure directed away from the human body assuming $d_{\text{behind}} = 0.5$cm and $d_{\text{bystander}} = 20$cm. The maximum transmitted power is in this case given by the bystander exposure and is found to be in the range 26 dBm – 30 dBm for the different exposure standards and frequencies investigated.

V. CONCLUSIONS

In this paper, a study to investigate the maximum transmitted power and maximum EIRP to comply with all major RF EMF exposure standards has been presented for array antennas intended for user equipment and low-power radio base stations in 5G mobile communication systems. Effects of frequency, array size, distance to human body, scan range and array topology have been considered. The obtained results constitute valuable input to the design of future mobile communication systems employing array antennas with beam-forming capabilities.

For devices intended to be used in the immediate vicinity of the human body (portable devices) and exposure scenarios where the transmitted energy is directed towards the body, the FCC exposure limits are more restrictive than the ICNIRP and IEEE limits. In general, the ICNIRP exposure limits are more restrictive than the IEEE limits with the exception of high frequencies and small arrays where the IEEE limit on spatial peak power density will lead to a lower maximum transmitted power. In order to allow larger power levels, technical solutions, whereby the transmitted energy is always directed away from the human body, are conceivable.

For mobile devices[1] very similar results are obtained for the FCC and ICNIRP limits as the difference between the spatially averaged power density over 1 cm^2 and 20 cm^2 is small in a large part of the parameter space where far-field conditions apply.

Depending on the applicable RF EMF exposure standard, quite large variations in maximum transmitted power levels and maximum EIRP may be expected for UE to be used in future mobile communication systems. This inconsistency will lead to different pre-requisites for different markets. Furthermore, for UE intended to be used in close proximity of the body, the ICNIRP and FCC exposure limits results in a maximum transmitted power significantly below what is specified today for existing mobile communication technologies. If not resolved, these findings may have a large negative impact on the performance and cost of future mobile communication systems. A global harmonization of the RF EMF exposure limits for frequencies above 6 GHz is desirable with a similar margin of safety as for frequencies below 6 GHz to protect from established adverse health effects.

APPENDIX

The maximum EIRP to be compliant with the FCC and IEEE RF EMF exposure limits for $d = 0.5$ cm are provided in Figure 13 and Figure 14 The corresponding results for $d = 20$ cm, and the ICNIRP, FCC and IEEE RF EMF exposure limits, are given in Figures 15-17.

REFERENCES

[1] Ericsson. (Nov. 2015). *Ericsson Mobility Report—On the Pulse of the Networked Society. Ericsson AB*. [Online]. Available: http://www.ericsson.com/res/docs/2015/mobility-report/ericsson-mobility-report-nov-2015.pdf

[2] Ericsson. (Jan. 2015). *5G Systems. Ericsson AB. Uen 284 23-3244*. [Online]. Available: http://www.ericsson.com/res/docs/whitepapers/what-is-a-5g-system.pdf

[3] *The 5G Infrastructure Public Private Partnership: The Next Generation of Communication Networks and Services*. accessed on (Jun. 08, 2016). [Online]. Available: https://5g-ppp.eu/wp-content/uploads/2015/02/5G-Vision-Brochure-v1.pdf

[4] *METIS II Project*. accessed on (Jun. 08, 2016). [Online]. Available: https://metis-ii.5g-ppp.eu/

[5] Ericsson. (Feb. 2015). *5G Radio Access. Ericsson AB. Uen 284 23-3204*. [Online]. Available: http://www.ericsson.com/res/docs/whitepapers/wp-5g.pdf

[6] *Council Recommendations of 12 July 1999 on the Limitation of Exposure of the General Public to Electromagnetic Fields (0 Hz to 300 GHz)*,'' document 1999/519/EC, Off. J. Eur. Communities, Jul. 1999.

[7] ICNIRP, ''Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz),'' *Health Phys.*, vol. 74, no. 4, pp. 494–522, Apr. 1998.

[8] *FCC, Code of Federal Regulations CFR Title 47, Part 1.1310, Radiofrequency Radiation Exposure Limits*, Federal Commun. Commission, Washington, DC, USA, Aug. 1997.

[9] R. F. Cleveland, Jr., D. M. Sylvar, and J. L. Ulcek, *OET Bulletin 65*, ''Evaluating compliance with FCC guidelines for human exposure to radiofrequency electromagnetic fields,'' Washington, DC, USA: FCC, Aug. 1997.

[10] *IEEE Standard for Safety Levels With Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*, IEEE Standard C95.1-2005, 2005.

[11] *IEEE Standard for Safety Levels With Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz. Amendment 1: Specifies Ceiling Limits for Induced and Contact Current, Clarifies Distinctions Between Localized Exposure and Spatial Peak Power Density*, IEEE Standard C95.1a-2010, 2010.

[12] T. Wu, T. S. Rappaport, and C. M. Collins, ''Safe for generations to come: Considerations of safety for millimeter waves in wireless communications,'' *IEEE Microw. Mag.*, vol. 16, no. 2, pp. 65–84, Mar. 2015.

[13] *Human Exposure to Radio Frequency Fields From Hand-Held and Body-Mounted Wireless Communication Devices—Human Models, Instrumentation, and Procedures—Part 2: Procedure to Determine the Specific Absorption Rate (SAR) for Wireless Communication Devices Used in Close Proximity to the Human Body (Frequency Range of 30 MHz to 6 GHz)*, IEC Standard IEC 62209-2, 2010.

[14] *Basic Standard for the Calculation and Measurement of Electromagnetic Field Strength and SAR Related to Human Exposure From Radio Base Stations and Fixed Terminal Stations for Wireless Telecommunication Systems (110 MHz–40 GHz)*, CENELEC Standard CENELEC EN 50383, Aug. 2010.

[15] *Determination of RF Field Strength and SAR in the Vicinity of Radio Communication Base Stations for the Purpose of Evaluating Human Exposure*, IEC Standard IEC 62232, May 2011.

[16] D. Colombi, B. Thors, and C. Törnevik, ''Implications of EMF exposure limits on output power levels for 5G devices above 6 GHz,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 1247–1249, 2015.

[17] K. Foster and D. Colombi, ''Thermal response of tissue to RF exposure from canonical dipoles at frequencies for future mobile communication systems,'' *IEEE Antennas Wireless Propag. Lett.*, to be published.

[18] K. Zhao, Z. Ying, and S. He, ''EMF exposure study concerning mmWave phased array in mobile devices for 5G communication,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1132–1135, 2016.

[19] FCC. (Oct. 2015). *Notice of Proposed Rulemaking*. [Online]. Available: https://apps.fcc.gov/edocs_public/attachmatch/FCC-15-138A1.pdf

[20] R. F. Harrington, *Field Computation by Moment Methods*. New York, NY, USA: Oxford Univ. Press, 1993.

[21] *FEKO User's Manual*, Altair Eng. GmbH, Hamburg, Germany, May 2014.

[22] *IEEE Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields With Respect to Human Exposure to Such Fields, 100 kHz–300 GHz*, IEEE Standard C95.3-2002, Dec. 2002.

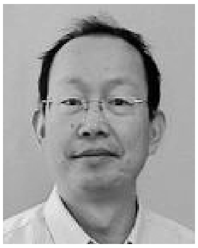
[23] *Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) Radio Transmission and Reception (Release 13)*, document 3GPP Std. TS 36.101 V13.3.0, 3rd Generat. Partnership Project, Mar. 2016.

[24] *Technical Specification Group Radio Access Network; User Equipment (UE) Radio Transmission and Reception (FDD) (Release 13)*, standard TS 25.101 V13.2.0, 3rd Generat. Partnership Project, Mar. 2016.

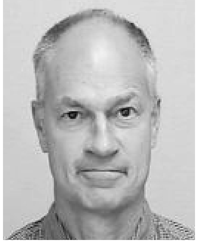
[25] *Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) Radio Transmission and Reception (Release 13)*, document 3GPP Std. TS 36.104 V13.3.0, 3rd Generat. Partnership Project, Mar. 2016.

BJÖRN THORS received the M.Sc. degree in engineering physics from Uppsala University, Sweden, in 1996, and the Ph.D. degree in electromagnetic theory from the Royal Institute of Technology (KTH), Stockholm, Sweden, in 2003. From 2003 to 2005, he was a Research Associate with KTH. Since 2005, he has been with Ericsson Research, Stockholm, where he has been involved in research and standardization related to radio frequency exposure from wireless communication equipment.

DAVIDE COLOMBI received the M.Sc. degree in telecommunication engineering (*summa cum laude*) from the Politecnico di Milano, Italy, in 2009. Since 2009, he has been with Ericsson Research, Stockholm, Sweden, where he has been involved in research and standardization related to radio frequency exposure from wireless communication equipment.



ZHINONG YING (SM'–) is currently a Principle Engineer in antenna technology with the Network Research Laboratory with Technology Office, Sony Mobile Communications AB, Lund, Sweden. Since 2013, he has been a Distinguished Engineer with the Sony Group. He joined Ericsson in 1995 and he became a Senior Specialist in 1997 and an Expert in 2003. He served as a TPC Co-Chairman in the International Symposium on Antenna Technology, in 2007. He has been a Guest Professor with the Joint Research Centre, Royal Institute of Technology, Sweden and Zhejiang University, China, since 2001. He was a member of Scientific Board of the Antenna Centre of Excellent Program in European 6th frame from 2004 to 2007. His main research interests include small antennas, broad and multi-band antenna, multi-channel antenna (MIMO) system, antenna for body area network, antenna and propagation in fifth generation mobile network, including massive MIMO and mm wave, near-field and human body effects and measurement techniques. He has authored or co-authored over 120 papers in various journal, conference and industry publications. He holds over 130 patents in the antenna and new generation wireless network areas. He has contributed several book chapters, including *Mobile Antenna Handbook* third edition edited H. Fujimoto and *Handbook of Antenna Technologies* edited by Z. N. Chen. He received the Best Invention Award at Ericsson Mobile in 1996.



THOMAS BOLIN received the M.Sc. in applied physics and the Electrical Engineering degree from Linköping University, Sweden, in 1979. From 1979 to 1983, he was an RF-Engineer with ITT Standard Radio and Telefon AB, Stockholm, where he was involved in 1 kW HF PA design. From 1983 to 2001, he held a technical management position with Ericsson Mobile Communications, Lund, Sweden, where he was involved in RF and antenna product development but also OTA measurement technology development for mobile handsets. From 2001 to 2011, he held the technical management position with Sony Ericsson Mobile Communications, Lund. Since 2011, he has been with Sony Mobile Communications, Lund, where he was involved in antenna research and standardization. He assisted in development of cm-wave antenna arrays (15-30 GHz) for 5G.

CHRISTER TÖRNEVIK (M'98) received the M.Sc. degree in applied physics from the Linköping University, Linköping, Sweden, in 1986, and the Licentiate degree in materials science from the Royal Institute of Technology, Stockholm, Sweden, in 1991. He joined Ericsson in 1991. Since 1993, he has been involved in research activities related to radio frequency exposure from wireless communication equipment. He is currently the Head of Sustainability Research with Ericsson Research and responsible for electromagnetic fields and health within the Ericsson Group. From 2003 to 2005, he was the Chairman of the Board of the Mobile Manufacturers Forum, where he is currently the Secretary of the Board. Since 2006, he has been the Chairman of the Technical Committee on electromagnetic fields with the Swedish Electrotechnical Standardization Organization, SEK, and he has as an expert contributed to the development of several CENELEC, IEC, and the IEEE standards on the assessment of RF exposure from wireless equipment.