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The impact of RF-EMF exposure limits stricter than the ICNIRP or IEEE guidelines on 4G and 5G mobile network deployment

ITU-T K-series Recommendations – Supplement 14

ITU-T

Supplement 14 to ITU-T K-series Recommendations

The impact of RF-EMF exposure limits stricter than the ICNIRP or IEEE guidelines on 4G and 5G mobile network deployment

Summary

Radio frequency electromagnetic field (RF-EMF) exposure limits have become a critical concern for further deployment of wireless networks, especially in countries, regions and even specific cities where RF-EMF limits are significantly stricter than the International Commission for Non-Ionizing Radiation Protection (ICNIRP) or Institute of Electrical and Electronics Engineers (IEEE) guidelines.

This problem currently affects several countries, such as China, India, Poland, Russia, Italy and Switzerland, regions of Belgium or cities such as Paris.

Supplement 14 to the ITU-T K-series of Recommendations provides an overview of some of the challenges faced by countries, regions and cities that are about to deploy 4G or 5G infrastructures. It provides information on a simulation carried out in Poland of the impact of RF-EMF limits as an example of a wider phenomenon, applicable to several other countries that have set limits stricter than those contained in the ICNIRP or IEEE guidelines.

The results of the simulation indicate that, where RF-EMF limits are stricter than ICNIRP or IEEE guidelines, the network capacity buildout (both 4G and 5G) might be severely constrained and prevent growing data traffic demand and the launching of new services on existing mobile networks being addressed.

History

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The impact of RF-EMF exposure limits stricter than the ICNIRP or IEEE guidelines on 4G and 5G mobile network deployment

1 Scope

This Supplement discusses the impact on mobile networks of radio frequency electromagnetic field (RF-EMF) exposure limits that are more restrictive than those of the ICNIRP [b-ICNIRP 1998] or IEEE [b-IEEE C95.1] guidelines. This Supplement investigates the impact on 4G and 5G deployment and suggests that there is an urgent need to begin a process to harmonize EMF standards worldwide. In this regard, note that the World Health Organization (WHO) has commenced a process of harmonization of EMF standards worldwide [b-WHO EMF].

2 References

[ITU-T K.52]	Recommendation ITU-T K.52 (2018), *Guidance on complying with limits for human exposure to electromagnetic fields*.
[ITU-T K.70]	Recommendation ITU-T K.70 (2018), *Mitigation techniques to limit human exposure to EMFs in the vicinity of radiocommunication stations.*
[ITU-T K.91]	Recommendation ITU-T K.91 (2018), *Guidance for assessment, evaluation and monitoring of human exposure to radio frequency electromagnetic fields*.

3 Definitions

3.1 Terms defined elsewhere

This Supplement uses the following terms defined elsewhere:

3.1.1 antenna [ITU-T K.70].

3.1.2 electromagnetic field (EMF) [ITU-T K.91].

3.1.3 exposure [ITU-T K.52].

3.1.4 exposure level [ITU-T K.52].

3.1.5 exposure limits [ITU-T K.70].

3.1.6 power density (*S*) [ITU-T K.52].

3.1.7 radio frequency (RF) [ITU-T K.70].

3.2 Terms defined in this Supplement

None.

4 Abbreviations and acronyms

This Supplement uses the following abbreviations and acronyms:

AR/VR	Augmented Reality/Virtual Reality
CAGR	Compound Annual Growth Rate
eMBB	extreme Mobile Broadband
EMF	Electromagnetic Field

FDD	Frequency Division Duplexing
FWA	Fixed Wireless Access
MIMO	Multiple Input and Multiple Output
PDL	Power Density Limit
RF	Radio Frequency

5 Conventions

None.

6 International guideline-based EMF exposure limit harmonization worldwide

6.1 Current status of EMF exposure limits worldwide

International RF-EMF exposure guidelines refer to the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [b-ICNIRP 1998], or of the Institute of Electrical and Electronics Engineers (IEEE) [b-IEEE C95.1]. At the time of publication, these limits are under review [b-ICNIRP].

Whilst most countries have adopted these scientifically based RF-EMF guidelines, a small group of countries, regions or even cities within the same country, especially in Europe (e.g., Poland, Russia, Italy, Switzerland, the city of Paris and regions of Belgium), use limits that are 10 to 100 times lower. Limits below the [b-ICNIRP 1998] guidelines are not limited to Europe; however, China and India, among others, have also adopted limits below [b-ICNIRP 1998] guidelines. In addition, some countries (e.g., Poland and Italy) apply a very strict measurement methodology, resulting in even stricter RF-EMF requirements. Worldwide limits may be consulted in [b-WHO GHO].

Because disparities in standards around the world have caused increasing public anxiety about exposure from the introduction of new technologies, WHO has commenced a process of harmonization of EMF standards worldwide [b-WHO EMF].

6.2 Impact of the more restrictive RF-EMF exposure limits on existing networks

[b-GSMA 2014] concluded that EMF exposure limits stricter than the [b-ICNIRP 1998] guidelines were a strong limiting factor for the deployment of 4G networks.

The strict power density limits (PDLs) result in "waste of spectrum" and "less flexibility in the network deployment" [b-GSMA 2014, p. 11], i.e., access to and optimal location of sites. Other consequences were reduced coverage, reduced opportunities for site sharing and an increased number of sites needed to deliver the same level of service.

Based on the findings, this report:

– called on the European Commission to promote good practice by member states through harmonization of RF-EMF exposure limit policies based on international guidelines;
– called on member states to follow the European Council Recommendation 1999/519/EC [b-EC 1999] and the latest Scientific Committee on Emerging and Newly Identified Health Risks opinion [b-SCENIHR] that exposure limit policies should be based on the international guidelines;
– called on the European Commission and member states to adopt evidence-based policies that enable the deployment of mobile broadband and other wireless technologies.

As of today, the EMF exposure limits have been harmonized neither globally, nor on a European level. The consequences described in paragraph 2 still apply. Going forward, strict EMF exposure limits in a number of countries will further harm future network deployments, in particular 5G, as shown in analyses outlined in this Supplement.

6.3 RF-EMF exposure limits below the ICNIRP or IEEE guidelines further restrict upcoming 5G network deployment

EMF exposure limits that are more strict than the [b-ICNIRP 1998] or [b-IEEE C95.1] guidelines negatively affect all potential levers to enhance the wireless infrastructure and deployment of 5G: *spectrum*, *technology* (determining the spectral efficiency) and *network topology* (number of sites and sectors). The capacity of a wireless site is a direct function of the width of spectrum (in megahertz) combined with the spectral efficiency (in bits per second per hertz) and with the number of sectors on the site.

For example, the unfavourable effects of different EMF exposure limits on network rollout, i.e., deployment of spectrum, technology and sites, have been simulated in Poland. The results are shown in clauses 6.3.1 to 6.3.3, which also serve as an illustrative example for other countries with PDLs stricter than the [b-ICNIRP 1998] or [b-IEEE C95.1] guidelines, e.g., Russia, India, China, Italy, the city of Paris, Switzerland and regions of Belgium.

6.3.1 Lever 1: Spectrum cannot be fully deployed

Additional radio frequencies, e.g., 60 MHz (frequency division duplexing (FDD) – 2 × 30 MHz) in the 700 MHz spectrum band, 100 MHz in the 2 300 MHz band and 400 MHz in the 3.4-3.8 GHz spectrum range have or will become available for 4G and 5G mobile communications in the near future. This would double the available spectrum and capacity in mobile networks, for example as shown in Figure 1 for the case of Poland.

However, deploying additional spectrum and consequently increasing the transmitted power on an existing site increases the EMF exposure and hence the power density levels. In dense urban areas and urban areas [b-BCG], where distances between antennas and people are short, the strict Polish EMF exposure limits do not allow mobile network operators to use the additional spectrum on most sites. In dense urban areas, some of the current spectrum can no longer be used and is wasted.

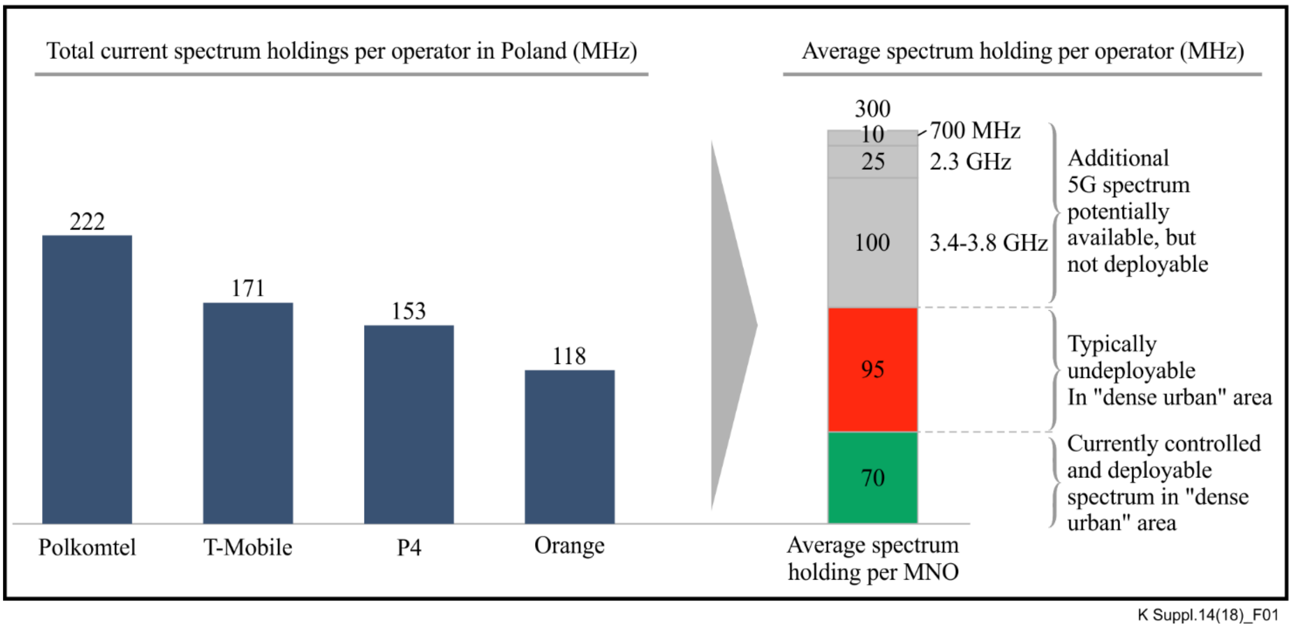

Figure 1 – Average spectrum holding (source: Office of Electronic Communications, Poland)

Large blocks of spectrum are critical for the deployment of 5G technology and thereby increasing speed and capacity. For example, harmonizing the Polish EMF exposure limits in line with [b-ICNIRP 1998] guidelines would remove the spectrum roadblock. All the current spectrum plus spectrum bands available in the near future could effectively be used by mobile network operators, including critical dense urban and urban areas; see Figure 2. Deploying new spectrum is an effective and efficient way of adding capacity to mobile networks quickly, before large capacity gaps can even occur.

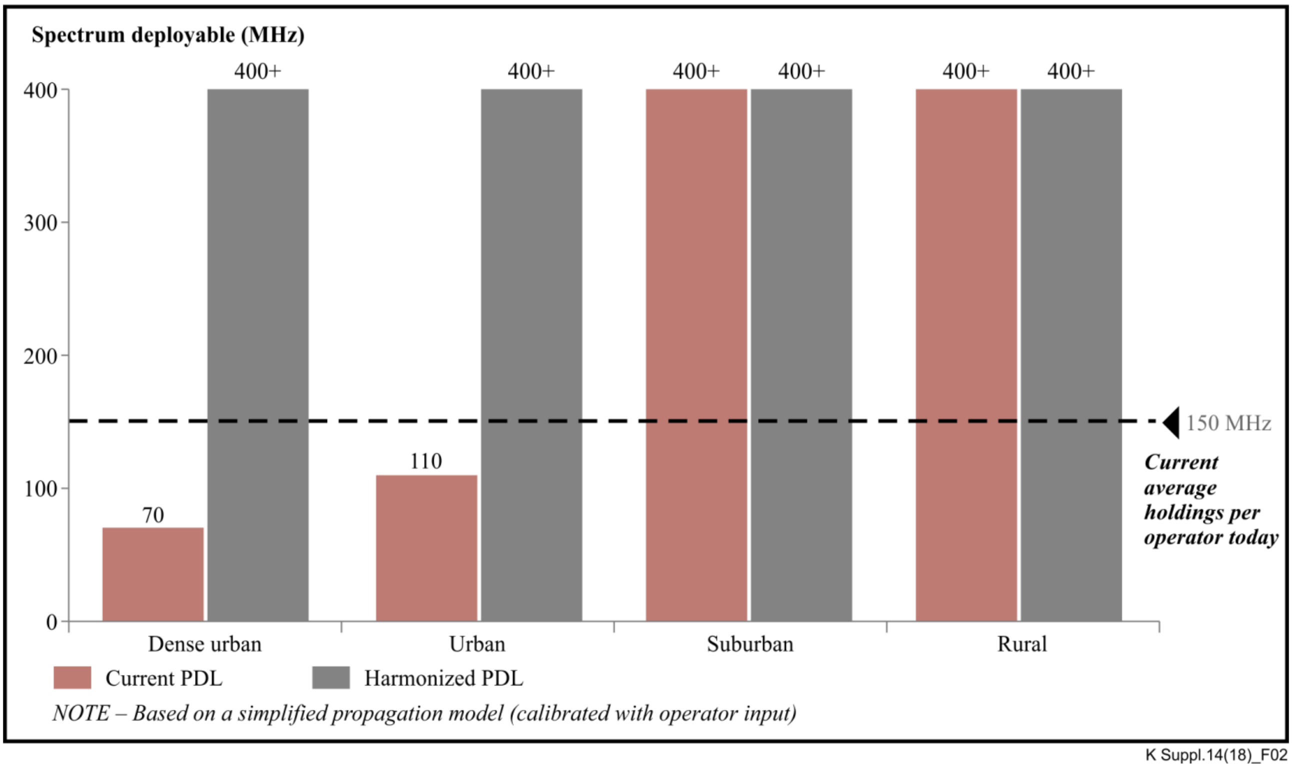

Figure 2 – Spectrum deployable on average with current and harmonized power density limits (source: adapted from Polish mobile network operators [b-BCG])

6.3.2 Lever 2: Technology innovation is restricted

New antenna technologies, such as massive multiple input and multiple output (MIMO) and beamforming, or small cells are a key element of future 5G mobile networks.

EMF exposure limits below [b-ICNIRP 1998] or [b-IEEE C95.1] guidelines (as shown in the case of Poland), do not in most cases allow mobile network operators to fully leverage these new technologies.

– Applying beamforming, i.e., further narrowing an antenna beam, would easily exceed the current EMF exposure limits.

– Deploying small cells in hot spot areas is not feasible, as the current EMF exposure limits prevent the placement of a large number of small cells due to the short distance between antenna and people; see Figure 3.

Both technology examples, beamforming and small cells, would be essential to provide more capacity in dense urban and urban areas.

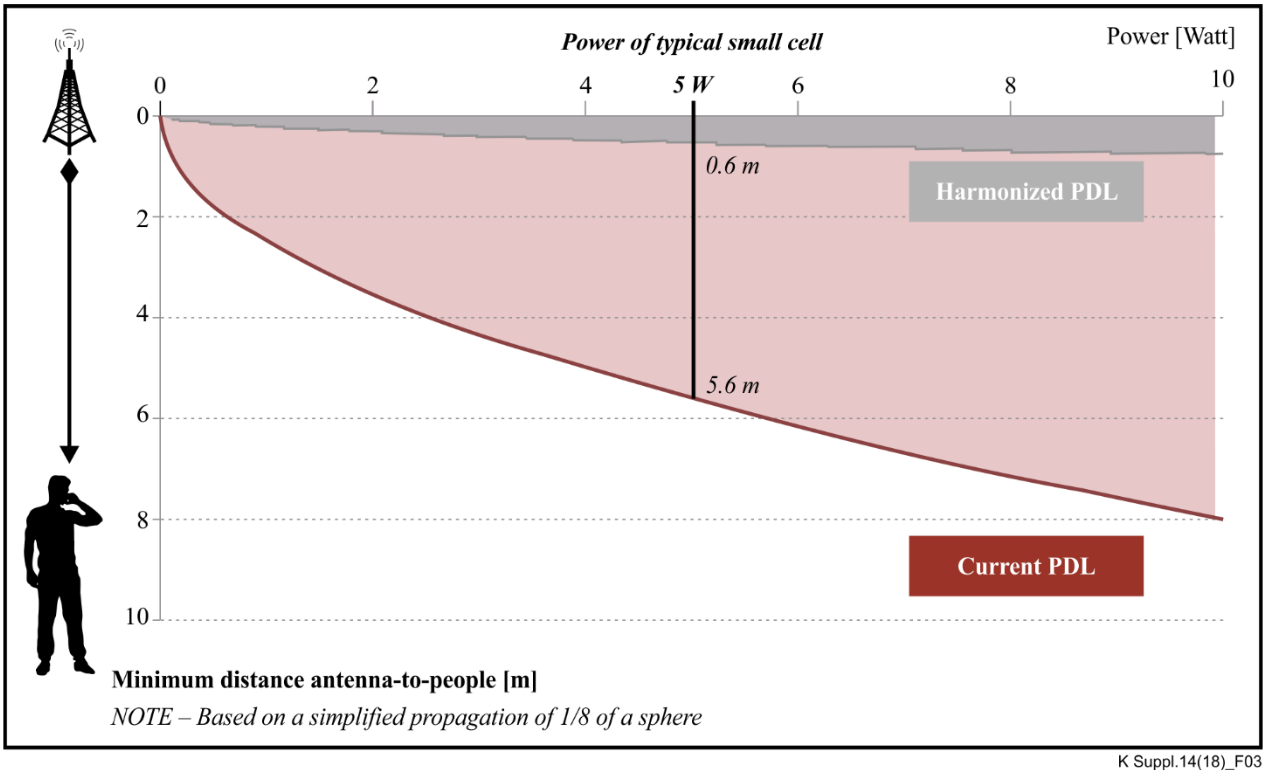

Figure 3 – Minimum distance antenna-to-people (source: [b-BCG])

6.3.3 Lever 3: Possibility to densify site grid is limited

Densifying the mobile network grid by adding new sites would be the third, but most expensive and time-consuming, lever to increase capacity in mobile networks. In order to cope with the data traffic explosion and assuming that spectrum and technology levers cannot be exploited, mobile network operators would have to have 3.5-fold the number of sites in urban areas by 2025 and almost sevenfold the number of sites in dense urban areas by 2025; see Figure 4.

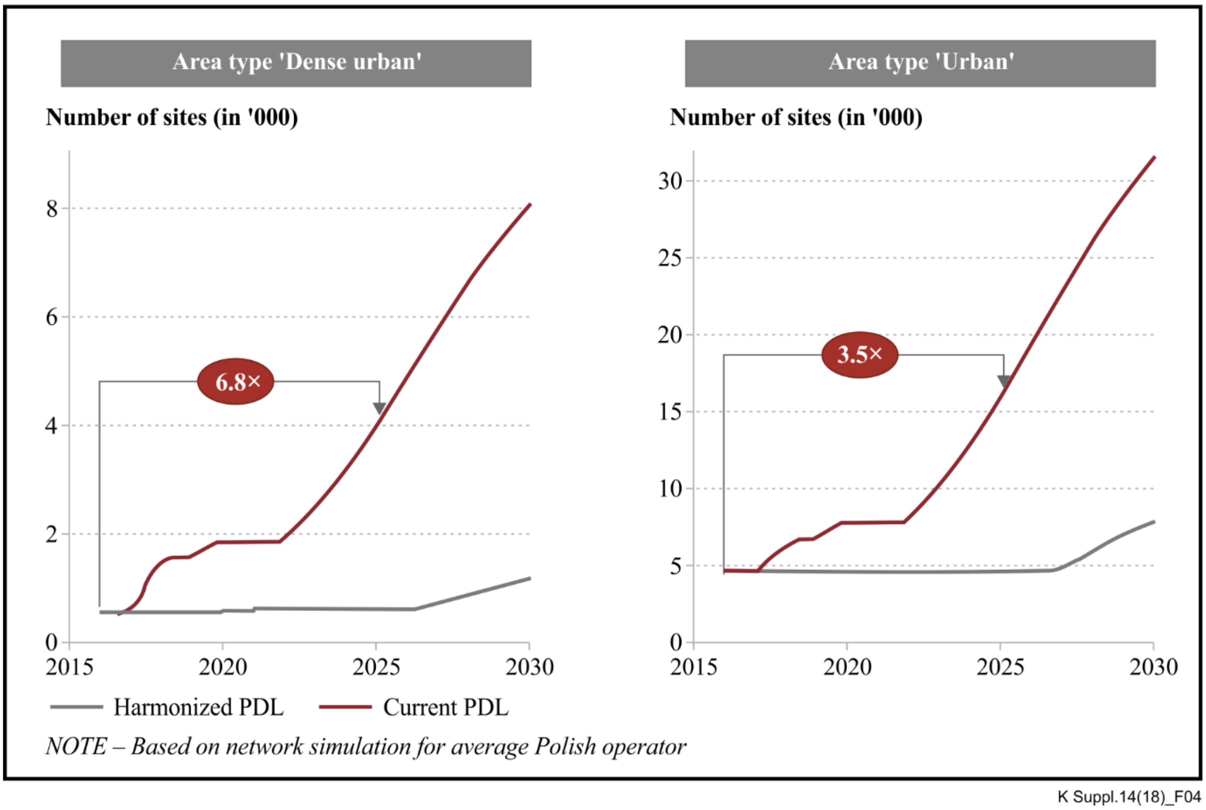

Figure 4 – Site evolution in dense urban and urban areas (source: [b-BCG])

These might become very unrealistic targets because mobile network operators are already struggling to commission new sites in urban and dense urban areas. Furthermore, already dense network grids with low site-to-site and site-to-building distances prevent mobile operators from densifying within the current EMF exposure limits. Similar issues might also be faced by other countries, such as Italy, where a new market entrant is rolling out a fourth wireless infrastructure and may be struggling with available power budgets.

6.4 Future customer experience will suffer and true 5G is not possible

Given the limitations for deployment of new spectrum, technology and the very restricted growth of a number of sites (assumption: 20% additional sites compared to the status quo), as a result of the strict EMF exposure limits, the gap between capacity supply and data traffic demand will grow very quickly. Polish data traffic growth is projected to have a compound annual growth rate (CAGR) of 36% until 2020, 29% until 2025 and 15% until 2030 (24× network data traffic in 2030 versus 2016).

In the example of Poland, in 2020, it is projected that 22% of available total mobile data traffic demand cannot be served (of which 31% of urban traffic demand and 63% of dense urban traffic demand remain unserved). In 2025, this number would increase to 41% and in 2030 to up to 56%. In dense urban and urban areas with almost half of the Polish population, the numbers are even more dramatic; see Figure 5.

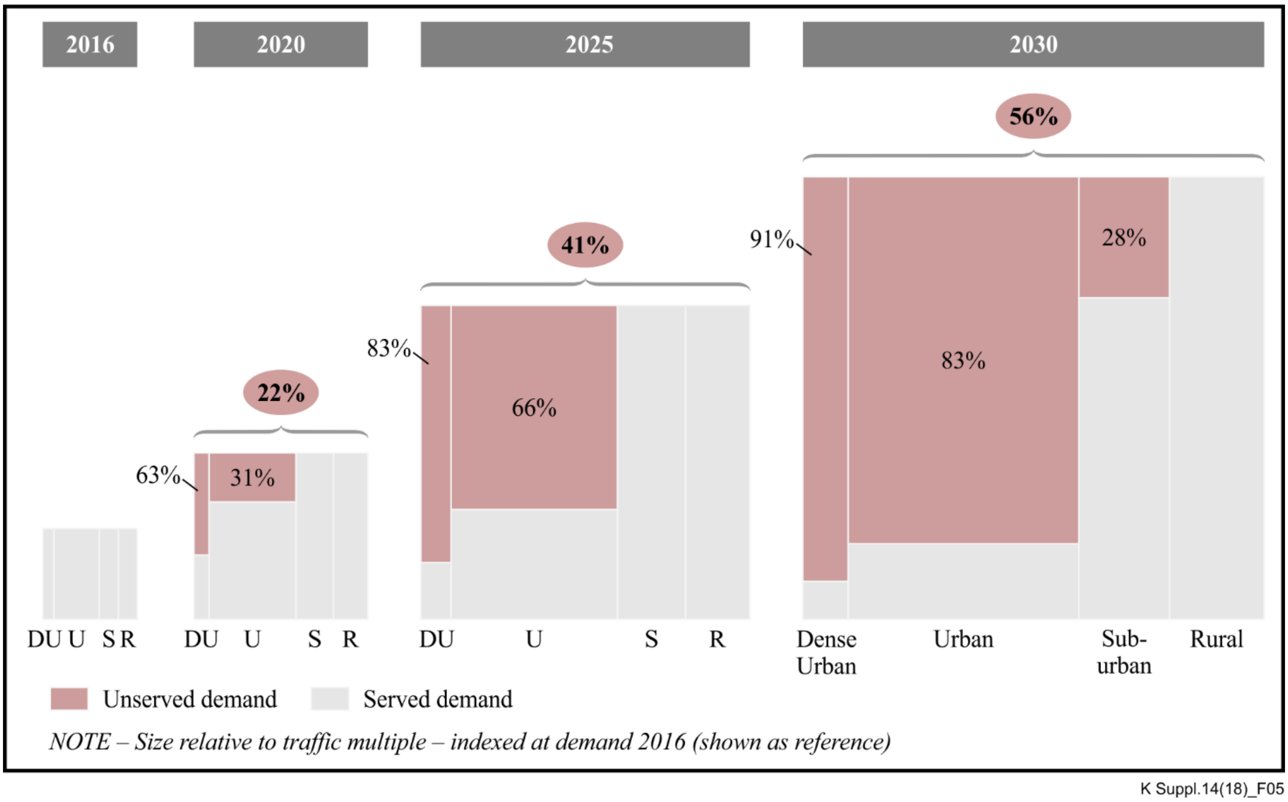

Figure 5 – Share of unserved data traffic (source [b-BCG])

Future 5G use cases that require high bandwidths, such as extreme mobile broadband (eMBB), augmented reality/virtual reality (AR/VR) or 5G fixed wireless access (FWA), would be very difficult to implement in such a scenario. The capacity gap would further create severe bottlenecks in the mobile radio access network and negatively affect latency, thus inhibiting future low-latency 5G use cases, such as mission-critical emergency services or autonomous drone delivery.

6.5 Comparison of measurements of the exposure levels in countries with different limits

The real exposure levels, based on the measurements made in Poland and France performed by the independent bodies responsible for environmental protection are presented. The measurements cover areas of both countries and are available for the years from 2015 to 2017.

6.5.1 Exposure limits in France and in Poland

Table 1 lists the limits of RF EMF exposure for the general public in the frequency ranges used by mobile communication and broadcasting.

Table 1 – Reference levels for the general public

	Exposure limits (general public), V/m	
Frequency	Poland	France [b-ICNIRP 1998]
10 MHz – 400 MHz	7	28
400 MHz – 2 GHz	7	28-61
2 GHz – 10 GHz	7	61

It should be noted that the exposure limits in Poland are much more restrictive than those in France in all frequency ranges used by radiocommunication services.

6.5.2 Comparison of the results of measurements

Table 2 lists the results of measurements for France [b-ANFR 2017], [b-ANFR 2018] and for Poland [b-GIOS 2017], [b-GIOS 2018]. In Poland, the results are given as means of measured values; for France, as median values. These values are determined differently, but the difference is slight and for the purposes of this Supplement may be neglected.

Table 2 – Results of measurements of the electric field strength in Poland and France

	Poland (mean)			**France (median)**		
Year	2015	2016	2017	2015	2016	2017
Number of measurements	2 161	2 161	2 161	3 577	2 993	2 591
Rural [V/m]	0.21	0.22	0.21	0.23	0.24	0.25
Urban/dense urban [V/m]	0.30/0.50	0.33/0.53	0.39/0.55	0.40/-	0.41/-	0.40/-

The number of measurements in both cases is similar and the measurements cover areas of whole countries and different types of the environment. Even if arithmetic means and median values are compared, the results of the measurements are very similar for both countries. It is understandable, because the same mobile systems and the same type of equipment are used worldwide, including both countries considered. Also, the stage of the development of the mobile infrastructure and the use of the mobile systems are similar.

The much more restrictive exposure limits do not mean better protection of the general public.

6.5.3 Consideration of compliance distances in the vicinity of a base station

The exposure level in an area around a typical base station is considered. In Table 3, the electrical parameters of this mobile base station operating in the 800 MHz, 900 MHz, 1 800 MHz, 2 100 MHz and 2 600 MHz frequency bands, all installed on the same antenna tower, are presented.

Table 3 – Parameters of the mobile base station

	800 MHz	**900 MHz**	**1 800 MHz**	**2 100 MHz**	**2 600 MHz**
Antenna type	Kathrein 80010892	Kathrein 80010892	Kathrein 80010892	Kathrein 80010892	Kathrein 80010892
Antenna height	15 m	15 m	15 m	15 m	15 m
Electrical downtilt	5°	5°	2°	2°	2°
Transmitter power	60 W	60 W	60 W	60 W	60 W
Equivalent isotropically radiated power	1 950 W	2 340 W	1 870 W	2 110 W	1 890 W

In Figure 6, the total exposure level at a height 9 m above the terrain level is presented as a function of the distance to the antenna tower. The calculations were made using EMF-estimator software (see Appendix I of [ITU-T K.70]. The red curve represents the total RF EMF exposure for the Polish limits, the blue curve represents the results for WHO/ICNIRP exposure limits.

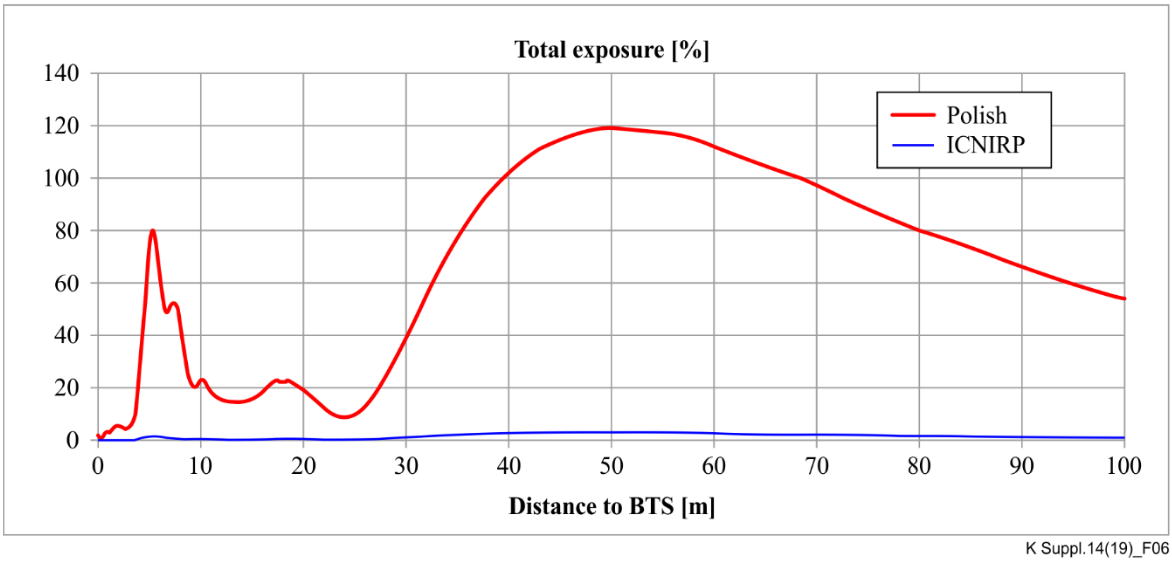

Figure 6 – Total RF EMF exposure as a function of distance to the antenna tower, 9 m above terrain level; Polish exposure limits (red curve), WHO/INIRP exposure limits (blue curve)

For Polish exposure limits, the areas accessible to people are not valid for distances between 39 m and 68 m from the antenna tower. This means that if in this range of distances there are buildings with height about 9 m, then the base station does not comply with Polish regulations. This also means that there is no space for additional emissions like 5G in the immediate future.

For WHO/ICNIRP exposure limits, there is no limitation concerning areas accessible to people – at least for buildings with heights up to 9 m – such a base station is compliant with regulations concerning RF EMF exposure limits. Additionally, there is a lot of room for additional emissions, like 5G, as total current exposure level is only 5% of the available exposure limit.

This example shows that the construction of the transmitting network under very restrictive exposure limits is much more difficult than under WHO/ICNIRP exposure limits. For such restrictive exposure limits, the implementation of 5G systems will be very difficult or even impossible.

6.5.4 Consideration of the measurement method for compliance

The calculation method for measured electric field values in areas around a typical base station is considered. Each country is responsible for constituting their own regulations concerning protection against EMF; Poland has established a very strict approach based on a one-time maximum measured value. Moreover, in many cases, local authorities responsible for regulating EMF power density levels in the environment require measurement uncertainty to be included in the final measurement result, making it the real worst-case scenario. Other countries usually calculate the arithmetic mean value, which is a more likely real-life scenario, which reflects actual exposure of the public to EMF. The example of these two different methods is presented in Table 4.

Table 4 – Comparison of average and maximum values of measurement results

Base station	Number of measurement points	Average value [V/m]	Maximum value [V/m]	Max-to-Lim[a] ratio [%]
BS 1	66	2.20	6.12	87
BS 2	107	2.25	6.33	90
BS 3	54	2.32	6.71	96
BS 4	37	2.39	4.62	66
BS 5	33	2.60	6.50	93
[a] Polish exposure limit is set to 7 V/m.				

It is clear that implementation of any additional transmitters, including 5G is impossible when using a one-time, maximum value as a measurement result. This kind of approach is an ultimate blocking point for 5G rollout.

7 Conclusion

Investigation shows that in the next 3 years up to 63% of mobile data traffic demands will not be served in countries, regions and even specific cities where RF-EMF limits are significantly stricter than the [b-ICNIRP 1998] or [b-IEEE C95.1] guidelines. This hinders countries from taking into consideration new trends to shape smarter and more sustainable societies worldwide. This also affects their ability to achieve the UNDP Sustainable Development Goals [b-UNDP SDGs].

From the analysis carried out in this Supplement, it should be noted that RF-EMF exposure limits should be harmonized worldwide. A framework for harmonization of RF-EMF standards is being developed by WHO to encourage the development of exposure limits and other control measures that provide the same level of health protection to all people.

Harmonizing the RF-EMF exposure limits should also take into consideration measurement methodologies (e.g., daily average versus maximum) and locations (e.g., indoor versus outdoor) and national compliance assessment standards should be harmonized with ITU Recommendations and IEC International Standards.

Appendix I

Modelling methodology and key input assumptions

I.1 Modelling methodology

The simulation presented in this Supplement is based on a general model of the impact of RF-EMF limits on network capacity. The [b-Hata] radio propagation model was used to simulate the relationship between RF-EMF exposure limit, coverage and capacity.

All-specific inputs were provided by the Polish Chamber of Information Technology and Telecommunications and the four Polish mobile network operators. The simulation was based on actual wireless assets (i.e., detailed infrastructure inventory per site level with respective technology and spectrum configurations) of the operators. Forecast data traffic determines the network capacity buildout (e.g., new sites, site upgrades and small cells) required.

The simulation model compares mobile data traffic demand with supply in each year and triggers appropriate network capacity upgrades. The capacity of a mobile network is a direct function of the width of spectrum (in megahertz) combined with the spectral efficiency (in bits per second per hertz) then with the number of sites and sectors.

The simulation assumes varied spectrum and network rollout strategies for (dense) urban, suburban, and rural area types. For example, small cells are rolled out only in (dense) urban areas, but not in suburban and rural areas.

Network capacity upgrades are modelled each year in order of cost efficiency (i.e., the least costly upgrades are realized first: new carriers and spectrum bands, antenna upgrades, new sites, new small cells). Capacity extension is only performed if RF-EMF exposure limits allow for it.

The capacity build-out was simulated for different scenarios of RF-EMF exposure limits: current Polish RF-EMF exposure limit versus [b-ICNIRP 1998] guidelines.

I.2 Key input assumptions used in the model

Mobile data traffic forecast in Poland is derived from [b-CISCO].[1] Traffic growth was extrapolated until 2030, using a conservative growth assumption of declining annual growth rate; see Figure I.1. Another report estimated annual data traffic growth in mega-cities (e.g., London, Paris) will be ~35% between 2017 and 2025, leading to a mean estimated traffic consumption of ≥30 Gbyte/month in 2025 [b-GSMA 2018]. The forecasts for the entire population of Poland are in line with these projections.

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1 Polish data traffic growth with a CAGR of 36% until 2020, 29% until 2025, and 15% until 2030 (24× network data traffic in 2030 versus 2016).

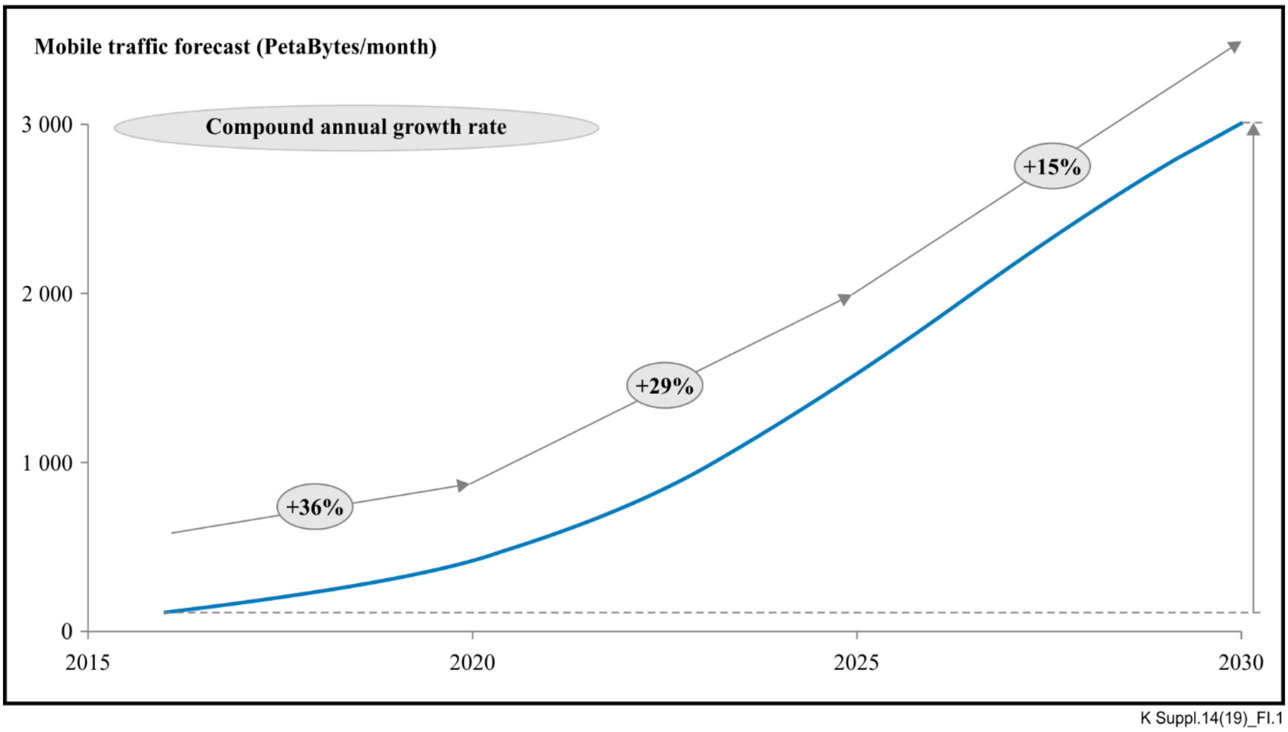

Figure I.1 – Polish mobile traffic increase until 2030

Downlink site capacity is based on mean effective data rates (per 5 MHz and sector). A mean of three sectors per site was applied to all area types. Sectorization (e.g., upgrading from three to six sectors) is not modelled in the simulation. Table I.1 shows assumed average effective data rates.

Table I.1 – Assumed average effective data rates

Radio access technology	3G		4G				
Spectrum band (MHz)	900	2 100	800	900	1 800	2 100	2 600
Assumed MIMO	1 × 1		2 × 2				
Average effective data rate (Mbit/s per 5 MHz and sector)	4.7	4.9	8.0				

As additional radio frequencies will likely become available for 4G and 5G mobile communications in the near future, the availability of such spectrum bands and bandwidths for wireless use are assumed from 2021 onwards. For simulation purposes, the additional spectrum was (almost) evenly allocated amongst the operators. Spectrum refarming and phase-out of legacy radio access technology is considered in the simulation. Table I.2 shows assumed additional radio frequencies for wireless use.

Table I.2 – Assumed additional radio frequencies for wireless use

Spectrum band	Availability	Mobile network operator 1	Mobile network operator 2	Mobile network operator 3	Mobile network operator 4
700 MHz	2021	2 × 10 MHz	2 × 10 MHz	2 × 5 MHz	2 × 5 MHz
2 300 MHz	2021	1 × 25 MHz	1 × 25 MHz	1 × 25 MHz	1 × 25 MHz
3.x GHz	2021	1 × 75 MHz	1 × 75 MHz	1 × 75 MHz	1 × 75 MHz

New technologies such as MIMO (4 × 4 or massive MIMO) or beamforming increase the spectral efficiency; see Table I.3. We did not assume any additional gains of 5G beyond antenna technology.

Table I.3 – Assumed spectral efficiency

Antenna technology	Spectral efficiency (index = 100)
2 × 2 MIMO	100
4 × 4 MIMO (deployed on bands below 2.6 GHz)	150
64 × 64 Massive MIMO (deployed on bands at 2.6 GHz and higher)	300

Bibliography

[b-ITU-T K.100] Recommendation ITU-T K.100 (2019), *Measurement of radio frequency electromagnetic fields to determine compliance with human exposure limits when a base station is put into service*.

[b-ITU-T K.121] Recommendation ITU-T K.121 (2016), *Guidance on the environmental management for compliance with radio frequency EMF limits for radiocommunication base stations*.

[b-IEC 62232] IEC 62232:2017, *Determination of RF field strength, power density and SAR in the vicinity of radiocommunication base stations for the purpose of evaluating human exposure*.

[b-IEC/TR 62669] IEC/TR 62669:2019, *Case studies supporting IEC 62232 – Determination of RF field strength, power density and SAR in the vicinity of radiocommunication base stations for the purpose of evaluating human exposure*.

[b-ANFR 2017] Agence Nationale des Fréquences (2017). *Étude de l'exposition du public aux ondes radioélectriques*: *Analyse des résultats de mesures d'exposition du public aux ondes électromagnétiques réalisées en 2016 dans le cadre du dispositif national de surveillance.* [Study of public exposure to radio waves: Analysis of the results of measurements of exposure of the public to electromagnetic waves carried out in 2016 as part of the national monitoring system]. Paris: ANFR. 17 pp. Available [viewed 2019-11-01] at: https://www.anfr.fr/fileadmin/mediatheque/documents/expace/Analyse_mesures_2016_VF_9oct.pdf

[b-ANFR 2018] Agence Nationale des Fréquences (2018). *Etude de l'exposition du public aux ondes radioélectriques: Analyse des résultats de mesures d'exposition du public aux ondes électromagnétiques réalisées en 2017 dans le cadre du dispositif national de surveillance.* [Study of public exposure to radio waves: Analysis of the results of measurements of exposure of the public to electromagnetic waves carried out in 2017 as part of the national monitoring system], Paris: ANFR. 20 pp. Available [viewed 2019-11-01] at: https://www.anfr.fr/fileadmin/mediatheque/documents/expace/20180919-Analyse-mesures-2017.pdf .

[b-BCG] Steiger, M., Schicht, R., Bernold, H. (2018), *Wpływ limitów gęstości mocy (PDL – power density limits) na łączność bezprzewodową: Czy Polsce grożą opóźnienia w rozwoju 5G?* [Effects of strict power density limits (PDL) in wireless communication]. Warsaw: Boston Consulting Group. 27 pp. Available [viewed 2019-10-31] at: http://image-src.bcg.com/Images/Effects-Polish-Power-Density-Limits_tcm78-196349.pdf

[b-CISCO] CISCO (Internet). *VNI mobile forecast highlights tool*. Polish data traffic growth with a CAGR of 36% until 2020, 29% until 2025, and 15% until 2030 (24x network data traffic in 2030 versus 2016).

[b-EC 1999] Publications Office of the European Union. Council Recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz): (1999/519/EC). *Official Journal of the European Communities* 1999, **L199**, pp. 59-70. Available [viewed 2019-10-31] at: https://op.europa.eu/en/publication-detail/-/publication/9509b04f-1df0-4221-bfa2-c7af77975556/language-en

[b-GIOS 2017] Główny Inspektorat Ochrony Środowiska (2017). *Ocena poziomu pól elektromagnetycznych w środowisku za lata 2014-2016 – w oparciu o wyniki pomiarów Wojewódzkich Inspektoratów Ochrony Środowiska* [Assessment of the RF EMF exposure in environment in 2014-2016 – based on the results of measurements made by Regional Inspectorate of Environmental Protection]. Warsaw: Chief Inspectorate of Environmental Protection. 29 pp. Available [viewed 2019-11-04] at: http://www.gios.gov.pl/images/dokumenty/pms/monitoring_pol_elektormagnetycznych/Ocena_poziomu_pol_elektromagnetycznych_za_lata_2014-2016.pdf

[b-GIOS 2018] Główny Inspektorat Ochrony Środowiska (2018). *Ocena poziomu pól elektromagnetycznych w środowisku w roku 2017 – w oparciu o wyniki pomiarów Wojewódzkich Inspektoratów Ochrony Środowiska* [Assessment of the RF EMF exposure in environment in 2017 – based on the results of measurements made by Regional Inspectorate of Environmental Protection]. Warsaw: Chief Inspectorate of Environmental Protection. 29 pp. Available [viewed 2019-11-04] at: http://www.gios.gov.pl/images/dokumenty/pms/monitoring_pol_elektormagnetycznych/Ocena_poziomu_pol_elektromagnetycznych_w_srodowisku_w_roku_2017.pdf

[b-GSMA 2014] GSM Association (2014), *Arbitrary radio frequency exposure limits: Impact on 4G network deployment – Case studies: Brussels, Italy, Lithuania, Paris and Poland*. London: Global System for Mobile Communications Association. 20 pp. Available [viewed 2019-10-31] at: https://www.gsma.com/publicpolicy/wp-content/uploads/2014/03/Arbitrary-Radio-Frequencyexposure-limits_Impact-on-4G-networks-deployment_WEB.pdf

[b-GSMA 2018] GSM Association (2018), *Delivering the digital revolution: Will mobile infrastructure keep up with rising demand?* London: Global System for Mobile Communications Association. 28 pp. Available [viewed 2019-11-11] at: https://www.gsma.com/publicpolicy/wp-content/uploads/2018/02/GSMA_DigitalTransformation_Delivering-the-Digital-Revolution.pdf

[b-ICNIRP 1998] International Commission on Non-Ionizing Radiation Protection (1998). Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). *Health Physics*. 1998, **74**(4), pp. 494-522. Available [viewed 2019-10-30] at:https://www.icnirp.org/cms/upload/publications/ICNIRPemfgdl.pdf

[b-ICNIRP 2009] International Commission on Non-Ionizing Radiation Protection (2009). *ICNIRP Statement on the "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)".* http://www.icnirp.org/cms/upload/publications/ICNIRPStatementEMF.pdf

[b-ICNIRP] International Commission for Non-Ionizing Radiation Protection (Internet). *High frequency fields: Revision of the guidelines on high frequency up to 300 GHz*. Available [viewed 2019-10-30] from: http://www.icnirp.org/en/activities/work-plan/details/work-plan-hf.html

[b-IEEE C95.1] IEEE C95.1-2019, *IEEE standard for safety levels with respect to human exposure to electric, magnetic, and electromagnetic fields, 0 kHz to 300 GHz*. Available [viewed 2019-10-30] from: https://standards.ieee.org/standard/C95_1-2019.html

[b-SCENIHR] Scientific Committee on Emerging and Newly Identified Health Risks (2015). *Opinion on potential health effects of exposure to electromagnetic fields (EMF)* Brussels: European Commission. 288 pp. Available [viewed 2019-10-30] at: https://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_041.pdf?utm_campaign=Issue%20520_14_Feb_5_.htm&utm_medium=email&utm_source=Eloqua&elq=ff829fb495774e20b5f511bf0ff99663&elqCampaignId=1200

[b-UNDP SDG] United Nations Development Programme (2019). *Sustainable Development Goals*. Available [viewed 2019-11-01] at: https://www.undp.org/content/undp/en/home/sustainable-development-goals.html

[b-WHO EMF] World Health Organization (Internet). *Electromagnetic fields (EMF): Standards and guidelines*. Available [viewed 2019-10-30] at: http://www.who.int/peh-emf/standards/en/

[b-WHO GHO] World Health Organization (Internet). *Global Health Observatory data repository: Exposure limits for radio-frequency fields (public) – Data by country*. Available [viewed 2019-10-31] at: http://apps.who.int/gho/data/node.main.EMFLIMITSPUBLICRADIOFREQUENCY?lang=e

[b-Hata] Hata, M. (1980). Empirical formula for propagation loss in land mobile radio services. *IEEE Transactions on Vehicular Technology*. **VT-29**, pp. 317–25.

[b-Törnevik] Törnevik, C. (2017), *Impact of EMF limits on 5G network roll-out*, ITU Workshop on 5G, EMF & Health, Warsaw, December 5. Available [viewed 2019-11-02] at: https://www.itu.int/en/itu-t/workshops-and-seminars/20171205/documents/s3_christer_tornevik.pdf

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