5G Communications Systems and Radiofrequency Exposure Limits

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Abstract

The prospective rollout of 5G around the world has brought with it the requirement that 5G systems comply with limits for human exposure to radiofrequency radiation, both for handsets and for base stations. This article reviews two major international guidelines/standards for RF exposure, focusing on exposures to an individual in the far field of transmitters such as from a wireless base station. The scientific basis of the limits is described. The paper will briefly describe other "precautionary" limits adopted in some jurisdictions. While the 5G is still an evolving technology, prospective technical issues with establishing compliance of 5G base stations with regulatory limits are briefly described.

1. Introduction

An important consideration for the wireless industry in siting cellular base stations is the need to comply with local limits for human exposure to radiofrequency (RF) energy. In some respects, the radiation characteristics of 5G base stations will be considerably more complex than for present generations of wireless technology. This article briefly describes two major international sets of guidelines/standards (International Commission on Non-ionizing Radiation Protection (ICNIRP) and IEEE C95.1 Standard) for RF exposure including the latest (2019) revisions, as they would apply to emissions from 5G base stations, and briefly describe other, lower, limits in effect in some jurisdictions. We also briefly describe some of the technical challenges that industry will face in meeting exposure limits for 5G base stations. Among other differences in nomenclature, ICNIRP refers to its limits as a "guideline", while IEEE uses "standard"; the limits themselves are quite similar.

5G technology is still evolving, and basic operating parameters including frequency bands are subject to revision. At least initially, 5G systems will operate just below the millimeter wave band (30-300 GHz) in the U.S. and elsewhere (e.g. 28 and 39 GHz in the U.S.) or close to present cellphone bands below 6 GHz (in many other countries). However, future 5G systems will almost certainly make greater use of the mm wave band, which has not heretofore been used for cellular services. The use of multiple steerable beams in 5G base stations will introduce new issues for compliance assessment for RF exposure limits.

2. ICNIRP and IEEE Exposure Limits

Worldwide, most RF exposure limits are based on limits developed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1], or the IEEE International Committee on Electromagnetic Safety, which develops the IEEE standard C95.1 [2]. The current ICNIRP guidelines [1] were approved in 1998, while the current version of the IEEE standard (C95.1-2005) was approved in 2005 [2]. Both sets of limits were revised and updated in 2019 and the revised limits will be in effect by the time this present article appears [3], [4]. U.S. limits (those of the Federal Communications Commission (FCC)) are generally similar to IEEE and ICNIRP limits and have been in place since 1996. For detailed reviews of RF exposure limits see [5], [6]. All three sets of limits (ICNIRP, IEEE, and FCC) have separate tiers for the general public and occupational groups, with occupational limits being generally five times higher than those for the general public. We focus below on ICNIRP and IEEE limits as they would apply to a member of the general public exposed to RF signals from a cellular base station.

Both the IEEE and ICNIRP limits have evolved over many years and are based on research going back to the 1950s which by now has grown to include several thousand papers. These limits have been designed to avoid all established adverse health effects from RF exposure, which at RF frequencies relevant to wireless communications are associated with excessive heating of the body. This could be due to excessive absorption of RF energy by the body as a whole (whole body exposure) leading to excessive heat loads to the body, or excessive local exposure to RF energy, raising tissue temperature to thermally hazardous levels. Given the short energy penetration depths of mm waves into tissue (less than 0.5 mm) the limiting hazards involve heating of the skin and cornea, even though the total thermal load on the body might be physiologically minor. A considerable amount of literature exists on thermal effects from mm waves [7]–[9], chiefly involving short term exposures (a few seconds to a few minutes) but in some cases much longer exposures as well. For exposures to the public from a wireless base station, the relevant sections of the limits specify maximum power levels of radiation incident on the body. In addition, the limits specify "averaging times" and "averaging areas" over which the exposure is to be averaged (see Table 1).

Table 1 Limits for general public (lower tier) in ICNIRP and IEEE

	Frequency range	Incident power density	Averaging area	Averaging time
ICNIRP (1998)	2-10 GHz	10 W/m^2		6 min
	10-300 GHz	10 W/m^2 (200 W/m^2)	20 cm^2 (1 cm^2)	Decrease from 6 min to 10 s
IEEE (2005)	Whole Body Exposure			
	5-30 GHz	10 W/m^2	100 λ^2 *	Decrease from 30 min to 5 min
	30-100 GHz	10 W/m^2	100 cm^2	Decrease from 5 min to 2.8 min
	100-300 GHz	Increase from 10 W/m^2 to 100 W/m^2	100 cm^2	Decrease from 2.8 min to 10 s
	Local Exposure			
	3-30 GHz	Increase from 40 W/m^2 to 200 W/m^2	peak	Decrease from 30 min to 5 min
	30-300 GHz	200 W/m^2		Decrease from 5 min to 10 s
ICNIRP (2019)	Whole Body Exposure			
	2-300 GHz	10 W/m^2		30 min
	Local Exposure			
	6-300 GHz	Decrease from 40 W/m^2 to 20 W/m^2	4 cm^2	6 min
	30-300 GHz	Decrease from 60 W/m^2 to 40 W/m^2	1 cm^2	6 min
IEEE C95.1 (2019)	Whole Body Exposure			
	2-300 GHz	10 W/m^2		30 min
	Local Exposure			
	6-300 GHz	Decrease from 40 W/m^2 to 20 W/m^2	4 cm^2	6 min
	30-300 GHz	Decrease from 60 W/m^2 to 40 W/m^2	1 cm^2	6 min

* λ means the free space wavelength

The latest (2019) revisions of both the IEEE and ICNIRP standard/guideline [3], [4] for local exposures above 6 GHz were set with the aid of extensive thermal modeling [5], [10]–[12] using a combination of analytical and computational approaches using detailed image-based models of the body. This modeling was supported by experimental data where available. Figure 1 shows the incident power density defined as reference levels in ICNIRP and IEEE. In both sets of standards/guidelines, separate limits apply for whole body and local exposure. For occupational exposures, the limits for local exposure are intended to limit skin temperature increases in a continually exposed person to about 2-3 ºC. Limits for whole body exposure are equivalent to less than one-half of the basal metabolic rate of an adult human, a negligible thermal burden. Limits for a member of the public are a factor of 5 lower. Needless to say, RF exposures to a member of the public from wireless base stations or other environmental sources of RF exposure under normal exposure conditions would be far below thermally hazardous levels.

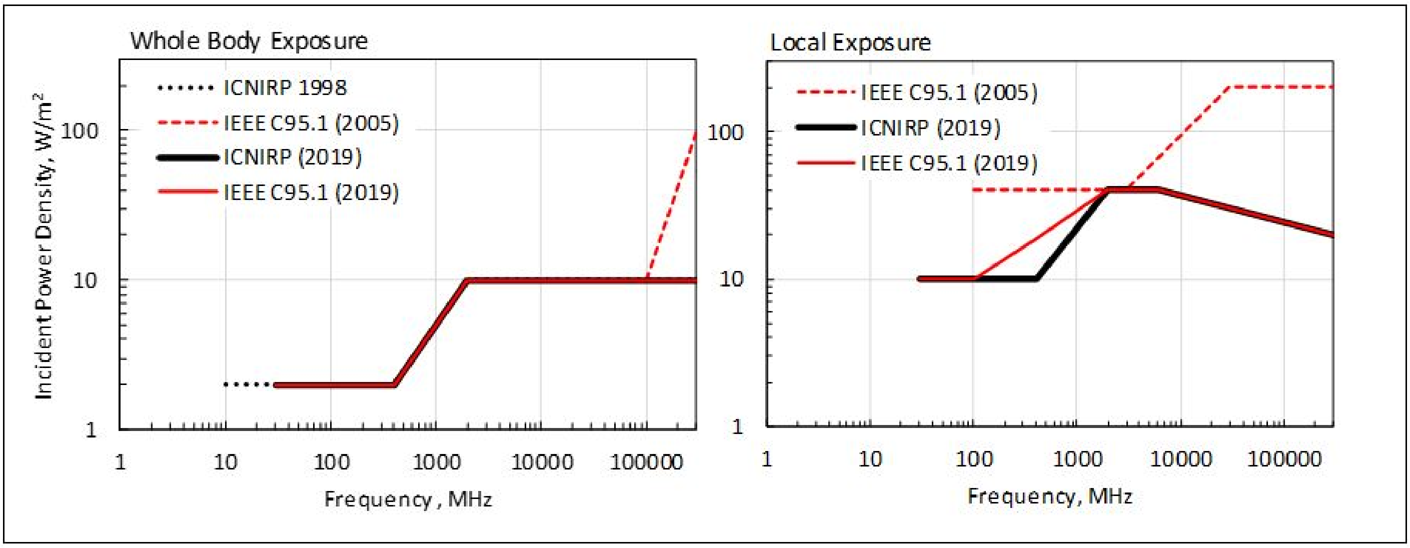

Figure 1 Exposure reference levels for general public in ICNIRP and IEEE.

While the possibility of "nonthermal" or not heat-related hazards at exposure levels below the current exposure limits has been a matter of public (and to some extent scientific) controversy, neither committee that developed the ICNIRP and IEEE limits considered any such hazards to be established, based on their reviews of the scientific literature and reviews of health agencies (e.g. a draft Technical Document by WHO and the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR)) [13]. There also appear to be no advisories by health agencies about hazards from low-level exposures. The bioeffects literature for mm waves is, however, quite scattered. The 300 laboratory and human studies in the literature report many biological effects of mm wave exposure in a variety of biological preparations [14]. However, the studies vary greatly in quality, exposure level, and relevance to health and few have been independently replicated. In many cases it is not clear whether effects may simply be due to heating of the sample by the RF exposure. In addition, there is little data on thermal response of skin to RF exposure for periods more than a minute or so, which would be expected to vary somewhat among different individuals. In brief, extensive research has yielded reliable information about thermal hazards of mm waves and no clear evidence for "nonthermal" hazards from mm waves, but there are also considerable gaps in the literature that need to be addressed.

3, Precautionary limits

A few jurisdictions (including some cities) have established "precautionary" RF exposure limits that are considerably below ICNIRP or IEEE limits, typically in response to citizens' concerns. Such measures in general aim to be "safe rather than sorry", as opposed to avoiding any identified hazard [6]. Some revisions are simply arbitrary reductions from ICNIRP or IEEE limits on precautionary grounds. India, for example, has set limits for RF exposure from wireless base stations (but not, apparently, from broadcast or other transmitters) to 10% of ICNIRP limits. Wallonia, a region in southern Belgium, has adopted what is probably the lowest limit in Europe, 3 V/m "per antenna" over an unspecified frequency range in areas accessible to the public (0.5% of the ICNIRP limit at 900 MHz). The limits are reduced to 0.6 V/m in schools, day care centers, and hospitals (0.02% of ICNIRP guidelines expressed in terms of incident power density). Russia and some Eastern European countries also have RF exposure limits far below ICNIRP, in part an inheritance from Soviet-era regulations.

4. Meeting the Limits

Ultimately, wireless carriers are going to have to comply with local regulatory limits, typically through a combination of engineering analysis and on-site measurements (although some countries such as Italy and Poland impose stricter measurement methodologies than accepted elsewhere for compliance assessment). A major complication with 5G base stations is the use of multiple, independently steerable mm wave beams transmitted from multiple input-multiple output (MIMO) antennas (for a review see [15]). Individual mm wave beams will follow individual subscribers as they move about, providing them with satisfactory service in a difficult propagation environment for mm waves. This will create a complex time varying signal in the environment of the base station. In a worse-than-worst-case scenario, multiple beams can impact on the same area raising the exposure, although that is not an intended or realistic scenario [16]. This approach, since it directs signals towards users, is likely also to reduce the time-average RF exposure at locations away from users.

In assessing potential exposures from cellular antennas, a useful concept is the compliance distance, which is the distance from the antenna beyond which the RF signal will fall below specified limits. For example, Ericcson researcher Törnevik presented sample calculations based on two Ericsson base station transmitters for 5G [17]. Assuming maximum possible transmitted power for an Ericsson AIR 5121 small cell transmitter with 8 beams transmitting a total of 1 W and TDD (Time Division Duplex) operation, he calculated the compliance distance relative to ICNIRP limits for the general public to be 1.5 m, assuming maximum power in all beam directions. Such a small cell might be installed atop a 6-10 m tall utility pole by the side of a street in a community, and a compliance distance of 1.5 m could be accommodated easily by installing the cell a suitable distance from nearby buildings and preventing access of personnel from the immediate vicinity of the antennas. By contrast, the exclusion distance from a 5G transmitter operating at 3.5 GHz transmitting a total of 200 W using an array of 64 antennas is 25 m. Such a cell might typically be located on a rooftop, and compliance could also be achieved but care must be needed about the nearby buildings. "ICNIRP limit compliance not an issue for normal installations – although [a] larger exclusion zone [is required] than for 3G/4G", Törnevik concludes in [17].

Much greater problems, however, are likely to occur in jurisdictions where RF exposure limits are significantly below IEEE or ICNIRP limits. A hundred-fold reduction in limits below ICNIRP would mean a tenfold increase in the exclusion distance. A carrier could reduce the number of transmitting elements in a MIMO array, which would reduce peak "worse-than-worst case" exposures but also reduce the capacity of the station, perhaps to uneconomic levels. It would also, most likely, require installation of more base stations. In countries with relatively very low exposure limits (e.g. Poland) this may effectively prevent the rollout of 5G services [18].

One approach, yet to be accepted by regulators, would be to adopt a statistical approach to compliance assessment [19], to provide a more realistic assessment of time-averaged exposures from MIMO base station antennas. Such time-averaged exposures would comply with IEEE and ICNIRP requirements for time-averaging but be less conservative than unrealistic "worse-than-worst-case" peak exposure calculations.

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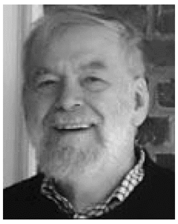

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