Research article

Spectral density constraints on wireless communication

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ABSTRACT

Environmental exposure to man-made electromagnetic field (EMF) has been rising as modern technologies have grown and changes in social behavior have generated more synthetic sources. For safety of human health, EMF levels need to be regulated. The level of EMF should be well below levels where there might be harm, hence we do not expect to see any health effects at these levels. Current regulations fail to place a strict limit on EMF in situations where multiple nearby devices transmit simultaneously. The way these regulations are expressed needs great care because it will have an effect on the design of wireless communication systems. In this paper, it is argued that transmitted power constraints on wireless communication devices should be expressed in a different way, namely that devices should limit the EMF spectral density that they generate to the difference between the maximum allowed, by the standard, and the amount currently present, as measured by the device, in the spectral region where it is active. Note that the limit on EMF should be expressed in terms of its *EMF spectral density* rather than as a total EMF over each of a series of separate bands. If all devices limit their own EMF spectral density, in the spectral region where they are active, in such a way that total EMF spectral density is below the regulated limit in that region, then it is certain that the aggregate EMF spectral density will be below the regulated limit at all frequencies.

1. Introduction

Constraints on transmitted power and on the electrical and magnetic field strength due to transmission exist currently in documents prepared and published by several international standards organizations [1, 2, 3, 4]. Some of these regulations are explicitly formulated for the purpose of avoiding possible harmful effects on health [5, 6], and others are formulated as technical restrictions on the use of electromagnetic spectrum, for communication [7], without explicitly acknowledging the potential for harm to be caused.

Currently power constraints are expressed as if devices share spectrum by never using the same frequency at the same time as a nearby device. However, efficient use of spectrum over time forces wireless protocols to use the same spectrum at the same time as nearby devices [8]. Under these circumstances, if many users cluster together, the health impact of their wireless communication will be cumulative. The total EMF spectral density (Electro-magnetic field spectral density, in V/m/Hz), of all nearby devices, is what needs to be regulated, for the health of those in the vicinity of these devices.

Furthermore, if the regulatory constraint continues to be expressed in terms of the transmitted power of each device it becomes possible to subvert the intention of this constraint by using a collection of devices which share the same spectrum, and all transmit at the same time. This goes against the spirit of the regulations on wireless communication, or, looking at the problem a little differently, shows that regulations on transmitted power should be expressed differently to avoid this type of abuse.

Consider, for example, a bus with 20 passengers with their mobile phones and other devices. All of the devices in the bus are permitted to transmit, or receive, signals simultaneously. If they are all using the same protocol, for example 802.11n, it is possible that simultaneous transmission will be inhibited but there is no reason to presume that all MAC protocols inhibit simultaneous transmission. In fact, in future [9], simultaneous transmission could be the best way for these devices to share spectrum. Each person in the bus could be exposed to 20 devices' signals at the same time. If there are 200 devices, each person may be exposed to 200 simultaneous signals. In effect, the aggregate signal is unregulated. We need a way to express the regulation on EMF to be

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enforced, even when there are many devices simultaneously active in the same location.

In order for such regulations to be expressed in a convenient and clear manner, since we cannot anticipate the full range of ways in which spectrum is sub-divided by devices, it is logical that the regulated constraint should be expressed in EMF spectral density V/m/Hz, or total transmitted power spectral density W/Hz, or total received power spectral density W/m^2/Hz. These three approaches are all possible, and under reasonable assumptions might be regarded as equivalent. However, in order to express the central problem most clearly, the quantity which should be regulated should be total EMF spectral density (for both the device which is regulated and nearby independent devices) for *all* frequencies, expressed in V/m/Hz.

The fact that *total* EMF (or received power), due to all nearby transmitting devices, is what needs to be regulated is acknowledged, implicitly, in [10]. However, it seems unrealistic to impose this constraint on the entire range of electromagnetic spectrum, from 1 Hz to 300 GHz. When electromagnetic spectrum is used for communication, efficient use requires that power is distributed across frequencies as a density, rather than at discrete frequencies. Therefore, if a regulation is imposed on the spectral density of transmitted power, or EMF, it is not limit the efficiency of communication. Research into techniques for efficient use of spectrum without focused use of specific frequency ranges is a topic in its own right which has been studied in [11]. By expressing regulations in terms of a spectral density, we can avoid the need for communicating devices to make use of narrowly selective spectra when limiting transmitted power. It is necessary, and appropriate, for all devices to be aware of other devices transmitting in the same range of frequencies, but it is not necessary to be aware of devices transmitting in disjoint ranges of frequencies. This observation enables a practical, and realizable, but fundamentally more rigorous approach to regulating spectrum use to be expressed.

2. Current EMF exposure limits

EMF exposure is not a new phenomenon. EMF exists everywhere in our surroundings quite naturally, and in particular both natural and artificial light are forms of EMF [12]. In [13], EMF is generated by mobile-phones and their base stations, 802.11 devices, microwave ovens, computer screens, telecommunications devices, broadcast facilities and any similar transmitters. This radiation reaches the body of any human in its path, so that part of its power is reflected away from the body, and another part is absorbed, and a third part passes through [10, 14].

In wireless communication, the number of mobile phones used has overtaken the population in advanced countries since 2007, with the percentage of devices very close to 90% in those countries. Many new applications have lead to smart phones and tablet devices needing to receive and/or transmit data frequently and at a high rate [15].

The public exposure to EMF is regulated by means of a collection of voluntary and formal standards. The study [16] reviewed guidelines and exposure limits on electric and magnetic fields. The guidelines are prepared by international standards bodies which are aiming to avoid risks to health resulting from short or long term exposure, adopting a large margin of safety. The most important of the standards on exposure to EMF is [1, 14]. Table 1 summarizes this standard and three others [2, 3, 4]. Columns 4 and 5 of this table are explained in Subsection 2.2, below.

All of these standards are expressed as limits on total EMF, or on total magnetic field, in each of a series of spectral bands. In the most complete standard ([1, 14]), there are 7 such separate bands, and the limit on EMF in each band is separately specified. Since, under most circumstances, EMF is proportional to magnetic field, and conversely, This study confines its attention to the expression of standards in terms of EMF.

The sources of the standards in Table 1 are shown in Table 2.

2.1. Electromagnetic radiation effects on health

The study [17] has reported that health effects of exposure to radio-frequency electromagnetic fields (RF EMF) are a serious concern not only from the users of smart-devices or people who live next to the base stations, but also from government and non-government organizations which are responsible for public health. Other studies [18, 19, 20] also have indicated that RF EMF affects not just human health but also animal and plant health.

Numerous epidemiological and clinical studies underline that the review and evaluation of potential health risks of exposure to EMF includes several uncertainties [16, 21, 22, 23]. They found a weak relationship between exposure to radiation and harmful human health effects.

The following organizations: the World Health Organization (WHO) agency of the United Nations, the National Institute for Environmental Health Sciences (NIEHS) of the United States, the Radiation Protection Committee (RPC) of Canada, the National Radiological Protection Board (NRPB) of the United Kingdom, the Swedish Radiation Safety Authority (SRSA) and the European Union's Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) have undertaken assessments of epidemiological and laboratory research [16, 23]. None of them reported that long-term exposure to low-levels of EMF has caused any adverse human health effects.

The study of human health effects due to exposure to EMF [24] concluded that short and long-term exposure levels to electrical and magnetic field are generally less than the safety limit values specified by international standards. On the other hand, the meta-study [25] of the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) referred to some studies which presented evidence that biological systems are affected by exposure to EMF, at intensity levels which occur in practice, associated with frequencies in the range from 100 kHz to 300 GHz, which are within the scope of international standards.

2.2. EMF spectral density

The power spectral density (PSD) is a measure of signal power density as a function of frequency [26]. The concept of spectral density is often used in communication systems analysis and design. The power spectral density shows how the power of a time series or signal is distributed over a range of frequencies. The PSD can be calculated from the Fourier transform of the signal. If the original signal is measured in Watts, the PSD will be expressed Watts/Hz.

The concept of spectral density is not limited to power. Any quantity which varies with time also has a Fourier transform which expresses how this quantity varies with frequency, and if this Fourier transform has a density, it will be expressed in terms of the original quantity per Hz. Since EMF is a function of time, this research can apply the Fourier transform to it, and thereby obtain an *EMF spectral density*, which identifies the EMF per Hz, in V/m/Hz. Columns 4 and 5 of Table 1, titled *EMF spectral density (V/m/Hz)* and *EMF spectral density (V/m/logHz)* have been *inferred* from the standards by assuming that instead of the EMF existing as a small number of discrete components, it is spread continuously in the range of frequencies which is relevant, in each row. In the cases where the original standard does not vary with frequency, within a row, in Column 4 the power spectral density is assumed to be uniform in V/m/Hz, and in Column 5, it is assumed to be uniform in V/m/logHz. Throughout this paper "log" denotes logarithm to the base 10.

In the cases where the original standard is a constraint which varies with f, the standard for EMF spectral density in Column 4 is chosen so that the functional form is the same as in the original standard and imposing the same total limit on power, assuming that the EMF is spread over frequencies separated by 1 Hz. In these cases, where the constraint depends on f, the formula in Column 5 is obtained by converting the spectral density constraint in Column 4 to a constraint expressed in

Table 1
EMF exposure limit standards.

Standard	Frequency range	Electric field strength (V/m)	EMF spectral density (V/m/Hz)	EMF spectral density (V/m/logHz)
ICNIRP	Up to 1 Hz	–	–	–
	1-8 Hz	10000	1428.57	11074
	8-25 Hz	10000	588.23	20202
	0.025-0.8 kHz	$250/f$	$0.32/f$	0.139
	0.8-3 kHz	$250/f$	$0.11/f$	0.0478
	3-150 kHz	87	0.00059	51.21
	0.15-1 MHz	87	0.0001	105.58
	1-10 MHz	$87/f^{\frac{1}{2}}$	$0.00001/f^{\frac{1}{2}}$	$0.00000435f^{\frac{1}{2}}$
	10-400 MHz	28	0.00000007	17.48
	400-2000 MHz	$1.375f^{\frac{1}{2}}$	$0.000000000086f^{\frac{1}{2}}$	$0.000000000037f^{\frac{3}{2}}$
	2-300 GHz	61	0.00000000002	28.03
IEEE	0.003-0.1 MHz	614	0.00633	403.15
	0.1-3.0 MHz	614	0.00021	415.71
	3-30 MHz	$1842/f$	$0.00007/f$	0.00003
	30-100 MHz	61.4	0.0000009	117.40
	100-300 MHz	61.4	0.0000003	128.72
	300-3000 MHz	–	–	–
	3000-15000 MHz	–	–	–
	15000-300000 MHz	–	–	–
FCC	0.3-3.0 MHz	614	0.00023	614
	3.0-30 MHz	$1842/f$	$0.00007/f$	0.00003
	30-300 MHz	61.4	0.000000023	61.40
	300-1500 MHz	–	–	–
	1500-100,000 MHz	–	–	–
ACGIH	30-100 kHz	1842	0.0263	3522
	100 kHz-1 MHz	1842	0.002	1842
	1-30 MHz	$1842/f$	$0.000063/f$	0.000027
	30-100 MHz	61.4	0.0000009	117.40
	100 MHz-300 MHz	61.4	0.0000003	128.72
	300 MHz-3 GHz	–	–	–
	3-30 GHz	–	–	–
	30-300 GHz	–	–	–

Note: f, in columns 3, 4 and 5, denotes frequency, in Hz.

Table 2
Sources for EMF exposure limit standards.

Organization	Source
ICNIRP	[1], Table 7
IEEE	[2], Table 1, part A
FCC	[3], Appendix A
ACGIH	[4], Table 15.1

V/m/logHz (by multiplying by $f/\ln 10$). Column 4 of Table 1 is plotted in Fig. 1 and Column 5 is plotted in Fig. 2. These figures also include plots the EMF spectral density due to WiFi, and 5 G, which will be generated when WiFi, or 5 G devices are transmitting at the full power allowed under national regulations, as guided by the WiFi standard. This is explained in more detail in Subsection 2.4. A closeup view, focusing on the frequency range 10^9 to 10^{10} is shown in Fig. 3. In addition, Figs. 1, 2, and 3 include *proposed* limits on spectral density, which are further discussed in the next subsection.

2.3. Spectral density constraints

Figs. 1 and 2 suggest that instead, or as well, as existing EMF standards, limits on EMF spectral density could be introduced. To be more specific, it is suggested that a *technical limit* on EMF spectral density is introduced somewhere in the range from 100 to 1000 V/m/logHz. All except very low power devices should ensure that the EMF spectral density generated by their own, and other nearby devices is below this level (i.e. some number, yet to be specified, between 100 and 1000 V/m/logHz) at all times, in the range of frequencies where they generate EMF. We do not expect to see any health effects at these levels. Nevertheless, the way these regulations are expressed needs great care
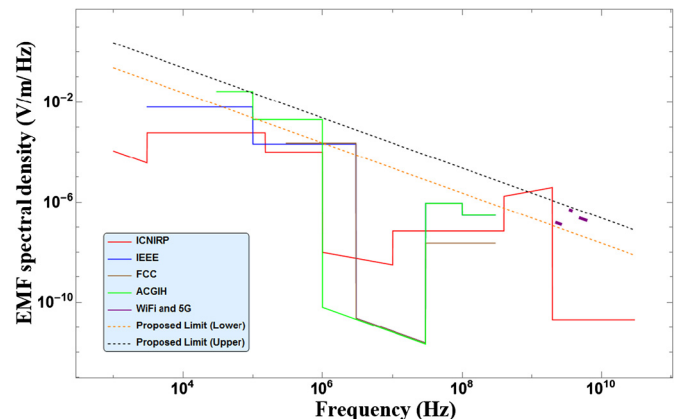

Fig. 1. EMF exposure limit for human body in (V/m/logHz).

because the way they are expressed will have an effect on the design of wireless communication systems.

Allocation of spectrum to technologies is currently evolving and changing quite rapidly and is likely to continue to change for the foreseeable future as new uses of spectrum are proposed and old ones cease to have a valid claim. However, regulations on exposure to radiation are formulated in order to protect those exposed to potentially dangerous radiation. Our understanding of the effects of radiation will also evolve and improve over time, which may lead to changes in regulated limits, also. However, the proposed limits should be based on possible risks to health rather than on current usage of spectrum.
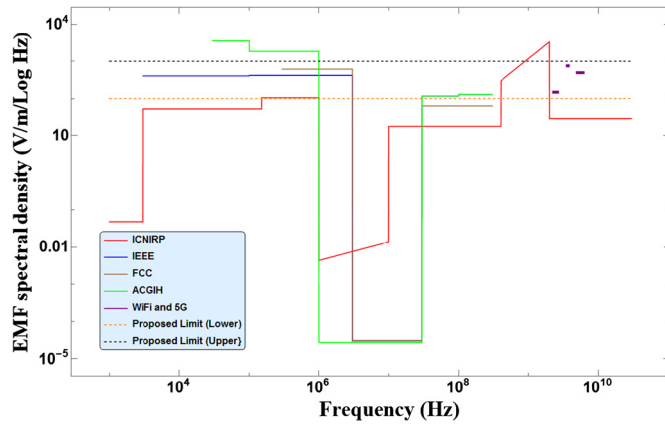
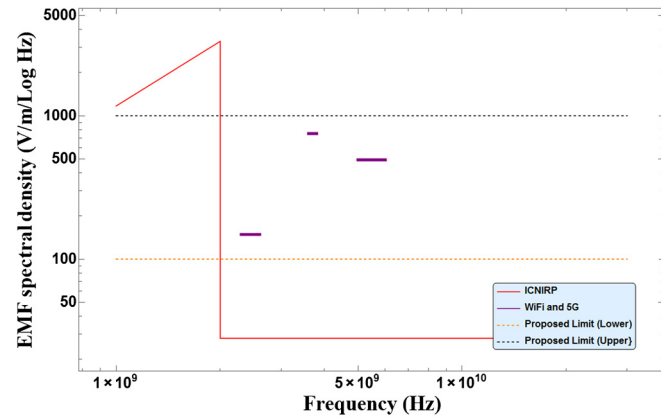**Fig. 2.** EMF exposure limit for human body in (V/m/logHz).

Fig. 3. EMF spectral density of WiFi and 5 G in the range 10^9 to 10^{10} in (V/m/logHz).

2.4. EMF due to WiFi and mobile transmission

In this subsection, we present an example in which the regulated limit on the magnitude of the EMF of a wireless signal transmitted in the 2.45 GHz, or the 5 GHz band, or by a fifth generation mobile communication (5 G) device, is estimated.

The magnitude of the far-field EMF of a wireless signal transmitted from a Hertzian dipole antenna is [27]:

$$E_\theta = \frac{\beta I l \sin\theta}{4\pi r} \sqrt{\frac{\mu}{\epsilon}}. \tag{1}$$

The parameter l is the length of the antenna; μ is the permeability of the medium, which for a vacuum is $4\pi \times 10^{-7}/m$ (and also approximately for the earth's atmosphere); ϵ is the permittivity of the medium, which for a vacuum (and approximately also for air) is 8.85419×10^{-12} F/m; I is the current through the antenna; θ is the angle between the dipole antenna and the line to the receiver, which is assumed to be $\frac{\pi}{2}$ because this produces the strongest field; β is the phase constant which is $\frac{2\pi}{\lambda}$, where λ is the wavelength of the radiation; and, finally, r is the distance from the dipole to the receiver.

Power radiated (P_{rad}) by a wireless access point is not explicitly limited by the WiFi standard [8] however a power limitation of either 10 mW, or 100 mW is implied. National regulation bodies have often adopted the lower of these two standards [3], i.e. $P_{\mathrm{rad}} = 10^{-2}$ W. Since $P_{\mathrm{rad}} = R_{\mathrm{rad}} * I^2$, where $R_{\mathrm{rad}} = 50\ \Omega$ [27], $I = \sqrt{P_{\mathrm{rad}}/R_{\mathrm{rad}}}$. All of the calculations for the field strength and field strength spectral density in any particular range of frequencies, and for any power, are carried out by the script shown in Fig. 4. This script has been used to complete the calculations for three important cases, WiFi 2.4 GHz, WiFi 5 GHz, and 5 G 3.6 GHz, and the results are shown in Fig. 5.

```
fieldstrength = function(freq,R,P,frange) {
  C = 3 * 10^8
  lambda = C / freq
  beta  = 2 * pi /lambda
  I = sqrt (P /R)
  ell = lambda/4
  theta = pi /2 # [so sin theta = 1]
  r  =  2 * lambda
  mu   = 4 *pi* 10^(-7)
  eps = 8.85419* 10^(-12)

  fstrength =(beta * I * ell * sin(theta)) *
↪   sqrt(mu/eps)/(4 * pi * r)
  fsperHz = fstrength/frange
  fsperlogHz = fstrength/(log10((freq+frange)/freq))
  c(fstrength,beta,fsperHz,fsperlogHz)

  cat ("lambda = ",lambda,"beta =", beta, "I =",I ,"ell
↪   =",ell
      ,"r =",r,"fstrength =",fstrength,"fsperHz =",
      fsperHz,"fsperlogHz =",fsperlogHz, "\n")
}
```

Fig. 4. Script for calculation of the EMF and EMF density for WiFi and 5 G.

```
> R_2.45GHz=fieldstrength(2.4*10^9,50,0.01,1*10^8)

lambda =  0.125 beta = 50.26548 I = 0.01414214
ell = 0.03125 r = 0.25 fstrength = 2.663885
fsperHz = 2.663885e-08 fsperlogHz = 150.2578


        # EMF of 5 GHz frequency band

> R_5GHz=fieldstrength(5*10^9,50,0.01,15*10^7)

lambda =  0.06 beta = 104.7198 I = 0.01414214
ell = 0.015 r = 0.12 fstrength = 5.549761
fsperHz = 3.699841e-08 fsperlogHz = 432.3178


        #  EMF of 5 G

R_5G=fieldstrength(3.6*10^9,50,0.2,5*10^8)

lambda =  0.08333333 beta = 75.39822 I = 0.06324555
ell = 0.02083333 r = 0.1666667 fstrength = 17.86989
fsperHz = 3.573977e-08 fsperlogHz = 316.3856
```

Fig. 5. Calculations of the EMF and EMF density for WiFi 2.45 GHz, wifi 5 GHz, and 5 G.

In the case of 5 G (fifth generation mobile communication), operating at 3.6 GHz, the script shown in Fig. 4 is still applicable, with power level 23 dBm (200 mW) [28, 29] and the results for EMF and EMF spectral density are also shown in Fig. 5 and Table 3.

It should be kept in mind that mobile phones do not operate at full power unless conditions require it, and also they are used less frequently than WiFi devices. Measurements of the EMF generated by a wireless access point situated in a typical work environment have found that

Table 3
Parameters of the far-field EMF, at distance 2λ, of a wireless signal transmitted from a Hertzian dipole antenna.

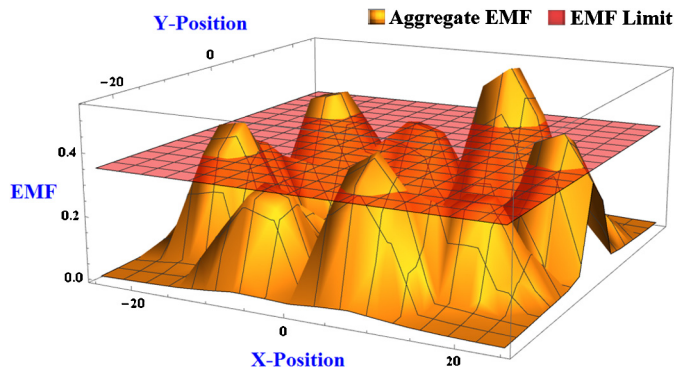| Parameters	WiFi 2.45 GHz	WiFi 5 GHz	5 G
l	0.031 m	0.015 m	0.021 m
I	0.014 A	0.014 A	0.063 A
β	50.27	104.72	75.40
λ	0.125 m	0.060 m	0.083 m
r	0.25 m	0.12 m	0.17 m
EMF	2.664 V/m	5.550 V/m	17.870 V/m
EMF/m/Hz	2.664×10^{-8}	3.700×10^{-8}	3.574×10^{-8}
EMF/m/logHz	150.258	432.318	316.386

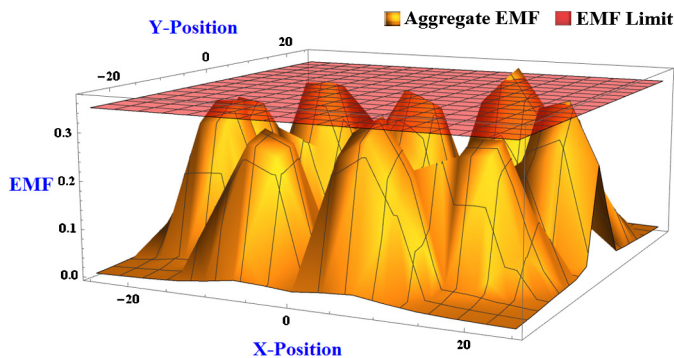**Fig. 6.** The aggregate EMF due to several nearby transmitters.

Fig. 7. The aggregate EMF when devices measure ambient EMF and limit the total.

it has a magnitude in the range 0.5 to 5 V/m [powerwatch], which is consistent with the preceding estimates.

The aggregate EMF due to several nearby transmitters, assuming each transmitter limits its own power independently, without concern for ambient EMF, is plotted in Fig. 6. This figure shows a typical situation of several devices inside the same building or vehicle which are using the same spectrum. Each device transmits at the same time. The EMF intensity is higher than that of a single transmitter because it is the aggregate effect of all the transmitting devices.

Now suppose that all devices sense and measure the EMF in the region where they are active. The resulting aggregate EMF, with the same configuration of devices as previously, is shown in Fig. 7. In this case, the regulated limit on aggregate EMF is respected. This approach is therefore safer. Mathematica code which calculates the aggregate EMF as shown in Figs. 6 and 7, is provided in [30].

2.5. Safety interpretation

A spectral density constraint is significantly different from a total power limit constraint, or a power limit on each of a sequence of bands. Spectral density can only be fully accurately measured by an infinite-
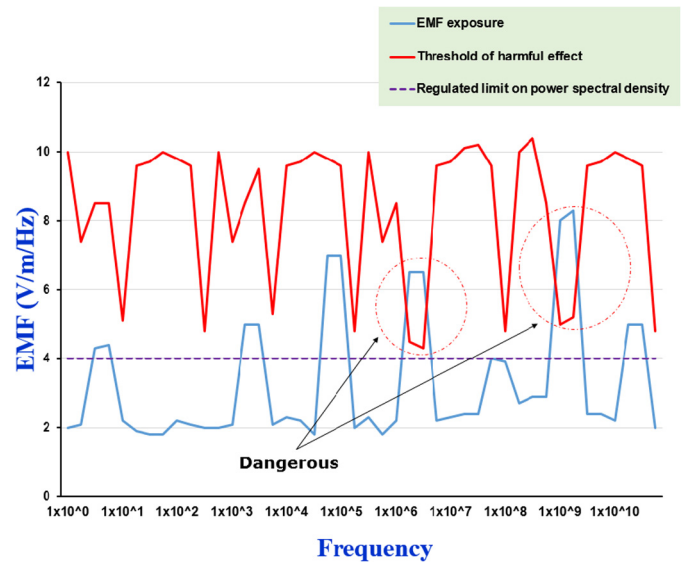

Fig. 8. Threshold of harm, EMF exposure, and propose uniform limit on power spectral density

duration sample, which cannot ever be completed. However, a spectral density measured over a finite time interval (e.g. a few seconds in duration) is also a logical interpretation of the concept of spectral density. Although this is not strictly the spectral density, a constraint based on this concept of spectral density is still significantly different from a constraint based on total EMF or total power overall, or total EMF or total power in a sequence of bands.

If biological response to EMF varies significantly with frequency, and if this variation cannot, or has not yet, been measured, it is safer to limit EMF spectral density uniformly than to limit total power in a band, because no individual frequency will be used with a significant amount of power, and hence the "dangerous" frequencies then not be used at levels where harm might occur. There are some frequencies which have traditionally been used widely and consistently, and for which, therefore, strong evidence exists concerning the unlikeness that harmful effects due to these frequencies needs to be avoided. If a spectral density constraint is imposed, as suggested in Section 2.3, an exception for a small number of such frequencies may be required.

Many devices already sense and measure the EMF in the region of spectrum where they are active. Therefore there is no additional cost for them to be required to make such measurements. On the other hand, expecting devices to measure EMF in other regions of spectrum would be costly and unnecessary so long as the regulated limits are expressed as suggested in this chapter, i.e. as limits on spectral density.

There may be some devices which generate sufficiently low EMF that regulations on their operation could omit the need for measurement of ambient EMF, although in such cases it should be a requirement that their deployment should never be in such large numbers that the regulation on ambient EMF might be breached by their aggregate contribution.

Suppose the threshold of harm caused by EMF, as a function of frequency, is not uniform, but is instead highly variable across frequencies, as shown in red in Fig. 8. Suppose, in addition, that the exposure to EMF, as a function of frequency, also varies randomly, as shown in blue in this figure. Under these circumstances there is a significant probability that there are some frequencies where the exposure to EMF exceeds the harm threshold. It will therefore be safer to limit EMF intensity as uniformly as possible, as depicted by the dashed line in this figure.

The simplest model of harm caused by EMF is to assume that it is proportional to the total absorbed energy, irrespective of frequency, or the intensity with which it is delivered. However, existing standards are not so irresponsible to accept this simple concept. Limits are placed on

power, not total absorbed energy. Harm can be caused by quite small amounts of energy if delivered in a very short space of time.

By placing a limit on power, rather than total absorbed energy, the *intensity over time* with which energy is delivered is restricted. Likewise, we should aim to restrict *intensity over space* and *intensity over frequencies*. Just as it can be dangerous to deliver a moderate amount of energy over a very short time, it may also be dangerous to deliver a moderate amount of energy over a very small range of frequencies, or a small region in space.

It therefore seems unwise, until we have more experimental data concerning the human response to EMF over different frequencies, to *assume a uniform additive model of harm due to EMF over different frequencies is correct.*

3. Conclusion

Power constraints on wireless devices should be expressed in a different way: devices should actively seek to limit total EMF spectral density, in V/m/Hz, due to their own transmission and the existing activity of other devices. Our recommendation is to use constraints on EMF spectral density, rather than (or as well as) on aggregate EMF over several large spectral ranges. EMF spectral density constraints can be used to express limits for health reasons or for technical reasons, or both. For consistency and simplicity, these constraints can be uniform across all frequencies when expressed in V/m/logHz. By the Shannon-Hartley theorem, for any maximum total power constraint, a uniform distribution of power over spectrum achieves optimal throughput, for the given power, so imposing a regulated limit on EMF spectral density does not inhibit efficient use of spectrum.

The best way to adjust transmission power from devices using wireless transmission will probably be different for 802.11 devices than for mobile cellular devices. In the former case the shared protocol for device access will have an additional constraint to take into account, while in the cellular mobile case the spectrum management undertaken by the base-station, in coordination with all the devices in its cell, will need to be adjusted. We have suggested above, already, that such changes do not need to reduce spectral efficiency, however this is a topic which needs to be investigated in its own right, is therefore a subject for future research.

Declarations

Author contribution statement

Mohammad Kaisb Layous Alhasnawi & Ronald G. Addie: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Shahab Abdulla & David Fatseas: Analyzed and interpreted the data; Wrote the paper.

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