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Assessment of Electromagnetic Field Exposure from Multiple Sources Simultaneously in the High-Frequency Range Based on Safety Standards

Vanvisa Chutchavong and Pongsathorn Aroonmitr*†

School of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand
(Tel: +66-2-329-8000; E-mail: vanvisa.ch@kmitl.ac.th; *Corresponding author: 66016063@kmitl.ac.th)

Abstract: This study presents a method for evaluating electromagnetic field (EMF) exposure from multiple sources operating simultaneously across a wide range of frequencies, based on the guidelines defined by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) in its 2020 publication. The proposed approach adopts the normalized exposure ratio, which combines the exposure values from all relevant sources and frequency bands. A key issue addressed in this study is the lack of standardized measurement methods for absorbed power density (S_{ab}) in high-frequency bands above 10 GHz, despite the existence of defined exposure limits. A comparison reveals that the difference between the limits for S_{ab} and incident power density (S_{inc}) for the general public is relatively small when compared to the gap between the general public and occupational exposure limits. Therefore, the use of S_{inc} is proposed as a temporary surrogate for S_{ab} in frequency ranges where direct measurement is not yet feasible. This approach enables comprehensive exposure assessment from multiple sources under both near-field and far-field conditions. It also serves as a practical alternative while S_{ab} measurement techniques for high-frequency applications such as 5G, WiGig, and next-generation wireless technologies are still under development.

Keywords: EMF Exposure, SAR, APD, IPD, Safety Standards.

1. INTRODUCTION

In an era of rapid advancement in wireless communication technologies including 5G systems, IoT devices, and millimeter-wave (mmWave) frequencies electromagnetic fields (EMF) have increasingly permeated daily human life at unprecedented levels. Nearly all types of radiocommunication equipment from mobile phones to home network devices are sources of EMF emissions, and in many cases, individuals may be exposed to multiple sources simultaneously.

To protect human health from potentially harmful EMF exposure, international organizations such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP) have developed safety guidelines. The 1998 version of the ICNIRP guidelines [1] was widely accepted and adopted in countries such as Thailand, Indonesia, and the Philippines. Later, in 2020, the guidelines were updated to reflect modern technological contexts, expanding the applicable frequency range from 100 kHz to 300 GHz and transitioning from Specific Absorption Rate (SAR) as the primary exposure metric to using Absorbed Power Density (S_{ab}) and Incident Power Density (S_{inc}) for higher frequency ranges such as those above 6 GHz [2]. Countries such as Germany, Japan, and Switzerland have already adopted the new standard.

Despite these updates, a critical technical limitation remains particularly regarding the measurement of SAR, which according to the IEC/IEEE 62209-1528 standard is only applicable within the 4 MHz to 10 GHz frequency range [3]. Consequently, there is currently no standardized method for evaluating SAR at frequencies above 10 GHz, a range now commonly used in 5G and high-speed wireless systems. This creates a significant gap in safety assessments for EMF exposure at higher frequencies.

† Pongsathorn Aroonmitr is the presenter of this paper.

Recent studies have investigated alternative approaches for evaluating EMF exposure in high-frequency ranges where SAR measurement is not feasible. For instance, one study demonstrated that substituting SAR with S_{inc} at 6 GHz leads to discontinuities in the maximum allowable power transmission levels between frequency bands below and above 6 GHz. SAR is more stringent in close proximity (e.g., $\leq 0.1\lambda$), whereas S_{inc} becomes more stringent as the distance increases (e.g., $\geq 0.2\lambda$), with differences of up to 6 dB observed in certain cases [4].

Similarly, another study examined SAR, S_{inc}, and S_{ab} exposure metrics for user equipment (UE) operating at 6 and 10 GHz. The results showed that S_{inc} could not accurately substitute for S_{ab} in the near-field region, especially at distances of 4-10 mm. The findings support the ICNIRP 2020 recommendation [2] that S_{inc} should not be used for near-field assessments. The study also proposed empirical formulas to estimate S_{ab} from SAR values with low average error (less than 0.3 dB). However, practical limitations remain, particularly for systems operating above 10 GHz where SAR measurements are not standardized [5].

Another investigation proposed refined criteria for applying S_{inc} in near-field evaluations at quasi-millimeter wave frequencies. The study pointed out that the conventional threshold of $\lambda/2\pi$ used to distinguish between reactive near-field and far-field regions may not be suitable in practice. Instead, an alternative criterion was proposed to better reflect the relationship between S_{inc} and S_{ab} in real-world test scenarios [6].

These findings emphasize the necessity for an evaluation approach that can integrate exposure contributions from multiple sources and across multiple frequency ranges simultaneously especially in the high-frequency domain where SAR-based measurements are limited. Such an approach should ensure that assessments remain comprehensive and aligned with contemporary safety standards.

To address this issue, the author proposes using S_{inc} as a substitute for SAR in high-frequency assessments, particularly from 6 GHz to 300 GHz. ICNIRP 2020 specifies clear limits for S_{inc}, such as averaging over 4 cm^2 for frequencies between 6-30 GHz and 1 cm^2 for frequencies above 30 GHz. Additionally, the use of a normalized exposure sum, where the cumulative exposure ratio does not exceed unity, is recommended for evaluating simultaneous multi-source exposure.

As a result, it can be formulated to comprehensively assess EMF exposure from multiple sources across all frequency ranges, based on ICNIRP 2020 principles. This offers a practical solution for exposure evaluation in scenarios where SAR measurements are not directly applicable particularly in high-frequency environments that are increasingly vital to the infrastructure of future wireless communication systems.

2. EXPOSURE LIMITS

2.1 Electromagnetic Field Exposure Limits

To evaluate EMF exposure from multiple sources occurring simultaneously, the approach in this study follows the safety guidelines outlined by ICNIRP 2020. These guidelines categorize exposed individuals into two main groups: the general public and occupational workers. Occupational exposure refers to individuals operating under controlled conditions, such as technical personnel at base stations or within engineering environments. In contrast, the general public includes individuals without specialized technical knowledge and are considered at greater risk from EMF exposure, thus requiring stricter protective limits.

For the general public, the average SAR is limited to no more than 4 W/kg for the frequency range from 100 kHz to below 6 GHz. For localized exposure at frequencies from 6 GHz to 300 GHz, the S_{ab} must not exceed 20 W/m^2. In comparison, occupational exposure is subject to higher limits: the SAR must not exceed 20 W/kg, and the localized S_{ab} must not exceed 100 W/m^2, as illustrated in Figure 1.

Radiocommunication devices with components that emit EMF in close proximity to the head or less than 20 cm. from the body during normal operation such as portable, handheld, and body-worn devices must be designed and regulated to comply with the respective exposure limits for each user group. This ensures that such devices do not pose health hazards during near-field exposure scenarios.

For radiocommunication equipment installed in vehicles, or for equipment that can be relocated between usage sites including fixed stations and base stations where EMF-emitting components are positioned at least 20 cm^2 away from the body or are permanently installed and designed to radiate over a wide area, the exposure is evaluated based on electric field strength or S_{inc}. The specific limits for S_{inc} are defined in accordance with the ICNIRP guidelines and are shown in Figure 2. The differences between the dosimetric approaches using S_{ab} and S_{inc} are compared in Figure 3.

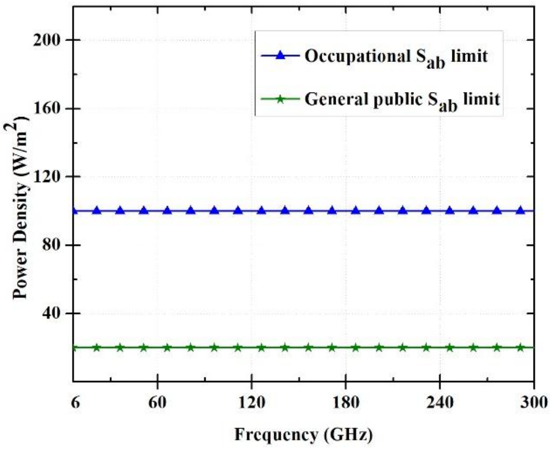

Fig.1 S_{ab} limit at 6 GHz to 300 GHz

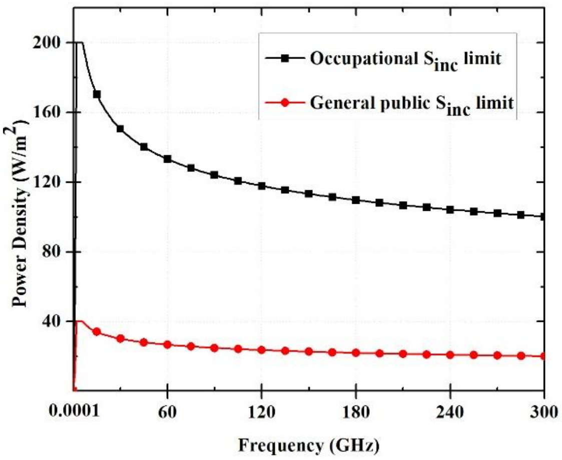

Fig.2 S_{inc} limit at 100 kHz to 300 GHz

2.2 Electromagnetic Field Exposure Limits from Simultaneous Multiple Sources

Exposure to EMF from multiple sources simultaneously at various frequencies is highly probable in real-world environments. For example, users may operate mobile phones in areas where Wi-Fi, Bluetooth, and base station signals are present at the same time. Therefore, exposure assessment must account for the combined effects from all active sources rather than evaluating each source in isolation.

According to the ICNIRP 2020 guidelines, the cumulative exposure from multiple EMF sources must be evaluated using a normalized exposure ratio, where the sum of the exposure values divided by their respective limits across different frequencies must not exceed 1. This ensures that total exposure remains within safe levels over any 6 min. averaging period within the frequency range of 100 kHz to 300 GHz.

For radiocommunication devices with EMF-emitting components located close to the head or less than 20 centimeters from the body during normal use, the exposure can be assessed using (1). This equation expresses the total normalized exposure sum across three frequency bands based on different dosimetric quantities. For frequencies from 100 kHz to 6 GHz, SAR is used. For the 6 GHz to 30 GHz range, S_{ab} averaged over 4 cm^2 is applied. For frequencies above 30 GHz, the assessment takes the maximum ratio between S_{ab} averaged over 4 cm^2 and 1 cm^2 compared to their respective limits (BR). The sum across all three frequency regions must not exceed 1 to be considered safe.

$$1 \geq \sum_{i=100\,kHz}^{6\,GHz} \frac{SAR_i}{SAR_{BR}} + \sum_{i>6\,GHz}^{30\,GHz} \frac{S_{ab,4cm,i}}{S_{ab,4cm,BR}} + \sum_{i>30\,GHz}^{300\,GHz} MAX\left\{\left(\frac{S_{ab,4cm,i}}{S_{ab,4cm,BR}}\right), \left(\frac{S_{ab,1cm,i}}{S_{ab,1cm,BR}}\right)\right\} \quad (1)$$

where SAR_i is the SAR value, SAR_{BR} is the SAR limit, $S_{ab,4cm,i}$ is the averaged SAR value over the body surface of 4 cm^2, $S_{ab,4cm,BR}$ is the averaged SAR limit over the body surface of 4 cm^2, $S_{ab,1cm,i}$ is the averaged SAR value over the body surface of 1 cm^2 and $S_{ab,1cm,BR}$ is the averaged SAR limit over the body surface of 1 cm^2

For radiocommunication equipment with EMF-emitting components located at least 20 cm^2 away from the body, or permanently installed systems with wide-area radiation patterns, the exposure assessment follows (2). In this case, for the frequency range of >6 GHz to 30 GHz, S_{inc} averaged over 4 cm^2 is compared against the corresponding reference level (RL). For frequencies above 30 GHz, the maximum of the ratios of S_{inc} averaged over 4 cm^2 and 1 cm^2 to their respective limits is used. The total must not exceed 1, as specified in (2).

$$1 \geq \sum_{i=100\,kHz}^{30\,MHz} MAX\left\{\left(\frac{E_{inc,i}}{E_{inc,RL,i}}\right)^2, \left(\frac{H_{inc,i}}{H_{inc,RL,i}}\right)^2\right\} + \sum_{i>30\,MHz}^{2\,GHz} MAX\left\{\left(\frac{E_{inc,i}}{E_{inc,RL,i}}\right)^2, \left(\frac{H_{inc,i}}{H_{inc,RL,i}}\right)^2, \left(\frac{S_{inc,i}}{S_{inc,RL,i}}\right)\right\} + \sum_{i>2\,GHz}^{6\,GHz} \left(\frac{S_{inc,i}}{S_{inc,RL,i}}\right) + \sum_{i>6\,GHz}^{30\,GHz} \left(\frac{S_{inc,4cm,i}}{S_{inc,4cm,RL,i}}\right) + \sum_{i>30\,GHz}^{300\,GHz} MAX\left\{\left(\frac{S_{inc,4cm,i}}{S_{inc,4cm,RL,i}}\right), \left(\frac{S_{inc,1cm,i}}{S_{inc,1cm,RL,i}}\right)\right\} \quad (2)$$

where $E_{inc,i}$ is the incident electric field strength, $E_{inc,RL,i}$ is the limit of incident electric field strength, $H_{inc,i}$ is the incident magnetic field strength, $H_{inc,RL,i}$ is the limit of incident magnetic field strength, $S_{inc,i}$ is the incident power density, $S_{inc,RL,i}$ is the limit of incident power density, $S_{inc,4cm,i}$ is the average incident power density over 4 cm^2, $S_{inc,4cm,RL,i}$ is the limit of incident power density over 4 cm^2, $S_{inc,1cm,i}$ is the average incident power density over 1 cm^2 and $S_{inc,1cm,RL,i}$ is the limit of incident power density over 4 cm^2

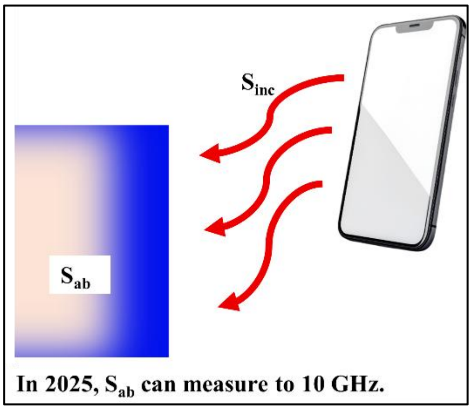

Fig.3 The dosimetric approaches using S_{ab} and S_{inc}

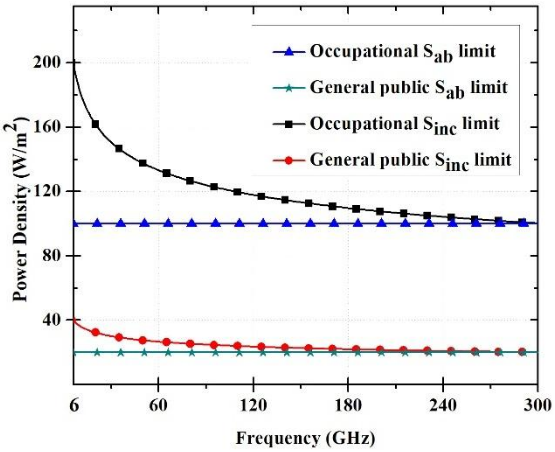

Fig.4 Comparison of limitations S_{ab} Vs S_{inc} at 6 GHz to 300 GHz

3. METHODOLOGY AND ANALYSIS

The evaluation of EMF exposure from multiple sources occurring simultaneously requires the use of the normalized exposure ratio approach. This method involves summing the exposure values from all frequency bands and sources and comparing them against the corresponding exposure limits defined by ICNIRP 2020. The exposure quantities used in the assessment differ depending on the distance between the source and the human body. In near-field conditions, SAR or S_{ab} is applied, while in far-field conditions, S_{inc} is used.

According to the ICNIRP 2020 guidelines, the localized exposure limits for S_{ab} and S_{inc} for the general public differ by approximately a factor of two. For example, the S_{ab} limit is 20 W/m^2, while the S_{inc} limit can reach up to 40 W/m^2 at 6 GHz. In contrast, the occupational exposure limits are about five times higher than those for the general public. S_{ab} for occupational exposure is 100 W/m^2, while for the general public it is 20 W/m^2. This observation indicates that the general public's S_{inc} values remain within the S_{ab} limit defined for occupational exposure, implying an acceptable level of safety under practical conditions, as illustrated in Figure 4.

This numerical comparison supports the feasibility of using S_{inc} as a temporary substitute for S_{ab} in situations where no standard method exists for S_{ab} measurement, especially in frequency ranges above 10 GHz. In such cases where instruments and standardized procedures are not yet available, this approach offers a reasonable and technically grounded alternative.

At present, there is no established method for measuring S_{ab} in high-frequency bands, particularly those above 10 GHz that are increasingly used in modern wireless systems such as 5G, WiGig, and other short-range high-speed technologies. Although ICNIRP 2020 defines the S_{ab} limits, the lack of practical measurement procedures limits their implementation in current exposure assessments.

To address this limitation, the author proposes a new evaluation approach that combines the concepts from (1) and (2) into a unified framework referred to as (3). Enables the assessment of EMF exposure from multiple sources operating simultaneously across a broad range of frequencies by using SAR or S_{ab} where measurement is feasible and S_{inc} where it is not.

$$1 \geq \sum_{i=100\,kHz}^{6\,GHz} \frac{SAR_i}{SAR_{BR}} + \sum_{i>6\,GHz}^{30\,GHz} \left(\frac{S_{inc,4cm,i}}{S_{inc,4cm,RL,i}} \right) + \sum_{i>30\,GHz}^{300\,GHz} MAX \left\{ \left(\frac{S_{inc,4cm,i}}{S_{inc,4cm,RL,i}} \right), \left(\frac{S_{inc,1cm,i}}{S_{inc,1cm,RL,i}} \right) \right\} \quad (3)$$

(3) is formulated to integrate exposure levels based on frequency range and device configuration, whether close to or away from the body. This allows for a more flexible and comprehensive model for EMF exposure assessment. Once S_{ab} measurement methods for high-frequency ranges are developed and standardized, (1) can be reinstated as the primary tool for evaluation without conflict.

4. NUMERICAL SIMULATION RESULTS

To validate the effectiveness and practicality of the proposed evaluation method (3), a numerical simulation was conducted to estimate EMF exposure from multiple sources operating at various frequency bands. The chosen frequencies were 2.4 GHz, 3.6 GHz, 5 GHz, 28 GHz, and 60 GHz, representing typical bands used in contemporary wireless systems such as Wi-Fi, 5G, mmWave, and WiGig, respectively. The SAR values were set to 0.4 W/kg at 2.4 GHz and 5 GHz, and 0.5 W/kg at 3.6 GHz, with an SAR limit of 4 W/kg for those frequencies. For the higher bands (28 GHz and 60 GHz), the average incident power density over 4 cm² was set to 10 W/m², against a reference limit of 20 W/m². The simulation results are summarized in Table 1, under the ICNIRP 2020 general public exposure limits.

Table 1 Numerical Simulation of EMF Exposure from Multiple Sources

Frequency (GHz)	Measured Exposure	Limit Exposure	Normalized Exposure Ratio
2.4	0.4 W/kg	4 W/kg	0.1
3.6	0.5 W/kg	4 W/kg	0.125
5	0.4 W/kg	4 W/kg	0.1
28	10 W/m²	20 W/m²	0.5
60	10 W/m²	20 W/m²	0.5
Total	-	-	1.425
* Exposure levels calculated according to the proposed (3)			

The simulation results indicate that the normalized exposure ratio for each individual source ranges from 0.1 to 0.5. When Equation (3) is not applied considering only the 2.4 GHz, 3.6 GHz, and 5 GHz bands the cumulative normalized exposure ratio across those sources is approximately 0.425, which falls below the safety threshold of 1. However, once Equation (3) is used to include the higher-frequency bands at 28 GHz and 60 GHz, the total normalized exposure ratio from all sources rises to about 1.425, exceeding the ICNIRP safety limit of 1, even though each individual band remains within its own limit. This finding demonstrates that simultaneous exposure to multiple EMF sources can push cumulative exposure levels beyond acceptable safety standards. Consequently, additional protective measures such as reducing transmission power or managing the spatial arrangement of devices are necessary to ensure compliance with safety regulations.

This numerical simulation confirms the suitability and practical applicability of (3) for assessing total EMF exposure, emphasizing the value of the proposed methodology in real-world scenarios. It should be noted that while (3) provides a comprehensive and practical method for evaluating EMF exposure, certain limitations exist in practical applications. For instance, complexities in electromagnetic propagation environments, variability in antenna configurations, and variations in human proximity could influence the accuracy of exposure assessments. Consequently, users should apply (3) with consideration of these practical constraints, and further specific studies or measurements may be needed in complex scenarios.

5. CONCLUSION

This study proposed a method for evaluating human exposure to EMFs from multiple sources operating simultaneously across various frequency ranges. The assessment was based on the normalized exposure ratio concept defined by ICNIRP 2020, which considers cumulative exposure across all applicable sources and frequency bands. A key challenge addressed in this work was the lack of standardized measurement methods for S_{ab} in high-frequency ranges above 10 GHz, despite the availability of established exposure limits.

To overcome this limitation, the author proposed the use of S_{inc} as a temporary substitute for S_{ab} in frequency ranges where direct S_{ab} measurement is not feasible. A new combined equation, referred to as (3), was developed by integrating the evaluation principles of (1) and (2). This approach enables practical and comprehensive assessment of simultaneous exposure from multiple RF sources in both near-field and far-field scenarios.

The approach proposed in this study can be applied as a supporting tool for designing safety measures or as a supplementary criterion in verifying the compliance of radiocommunication equipment operating in environments with multiple EMF sources. This is especially relevant for emerging high-frequency wireless systems such as 5G networks and short-range communication devices. However, (3) should be further validated through simulations or experimental measurements to confirm its accuracy and applicability in real-world scenarios, particularly when standardized methods for measuring S_{ab} in high-frequency bands become available in the future.

Future research should focus on the development and standardization of S_{ab} measurement techniques at frequencies above 10 GHz. Additionally, extensive experimental validation under various realistic environmental conditions will further strengthen the applicability and reliability of the proposed methodology.

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