

LOW ELECTROMAGNETIC FIELD EXPOSURE WIRELESS DEVICES

FUNDAMENTALS AND RECENT ADVANCES

EDITED BY

MASOOD UR REHMAN
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Fundamentals and Recent Advances

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*I dedicate this effort to my parents, Khalil Ur Rehman and Ilfaz Begum;
my siblings, Habib, Waheed, Tahera;
my wife, Faiza;
and my son, Musaab.*

Masood Ur Rehman

*I dedicate this effort to my parents, Jamshed Iqbal and Nuzhut Jamshed;
my siblings, Laiba, Maliha, Mariam;
and my wife, Aqsa Tariq.*

Muhammad Ali Jamshed

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Preface

The past decade has seen a huge upsurge in the demand of wireless devices that are expected to cross the 29.4 billion mark by 2030. This increase is fueled by the advances in wearables, portables, flexible electronics, and other wireless technologies facilitating communication, transportation, and navigation needs of billions of users around the world in the wake of Internet of Things and 5G/6G. These rising numbers, along with ever-growing data requirements, necessitate a growth in the capacity of wireless communication networks by almost 1000 times. Part of this capacity enhancement will be made possible by increasing the number of access points (APs). These developments are ultimately resulting in added electromagnetic field (EMF) exposure sources in the environment.

EMF exposure has been deemed prone to inflict adverse health and safety effects on the users. The World Health Organization (WHO) has classified these EMF radiations as possibly carcinogenic to humans and has an ongoing project to assess potential health effects of exposure to EMF in the general and working population. The Federal Communications Commission (FCC) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) have, therefore, imposed strict safety standards for device operation. Consequently, EMF exposure characterization warranting strict adherence to these safety regulations is a vital design parameter for wireless devices to ensure the safety of the users.

The current developments and expected future growth of the wireless systems are also mounting concerns regarding users' safety and possible health consequences of EMF exposure to modern wireless technologies, such as millimeter-wave (mmWave) communications, massive multiple-input multiple-output (MIMO), and beamforming. It necessitates deeper investigations on health risk assessments and requires a comprehensive reference dealing with this fundamental and paramount issue suggesting some novel directions for updating the EMF exposure evaluation framework.

A dedicated book tackling this important issue is seldom available. Therefore, this volume will not only fill this gap but also educate the reader on most important aspects of designing energy efficient and low EMF wireless devices laying foundation for future advancements. A multidisciplinary approach based on artificial intelligence (AI) and new multiplexing technologies like non-orthogonal multiple access (NOMA) is adopted to devise efficient mechanisms and techniques realizing low EMF solutions through integration of antenna design, system modeling, and signal processing.

Both software and hardware solutions to minimize EMF exposure covering state-of-the-art and advanced topics are discussed. EMF evaluation tools and numerical assessment methods for conventional as well as future wireless systems' enablers such as mmWave technologies are detailed as also is EMF reduction through radio resource allocation, energy conservation, EMF-aware antenna design, backscatter communication, and MIMO. Moreover, a comprehensive account of validation studies as well as the modeling and selection of dielectric properties for all the age groups are utilized to provide sufficient background and highlight recent advancements. The book is concluded by highlighting potential future directions of research and implementation for energy-efficient and low EMF user proximity wireless devices. The book covers a wide variety of subject categories and would, therefore, benefit a larger readership in the scientific community.

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1

Electromagnetic Field Exposure: Fundamentals and Key Practices

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1.1 Introduction

In the past, significant research efforts have been devoted to first understanding how EM field (EMF) exposure affects humans [1–3] and, then, to create tools for measuring exposure and defining exposure metrics [4–6]; these measuring techniques and metrics can be used to establish exposure recommendations [7]. Indeed, the health impact of EMF, magnetic field (MF), and electrical field (EF) is currently being contested in studies and among the general public, particularly for children [8]. Wireless communication (e.g. the cellular system) has grown so rapidly in recent decades that it is now one of the most major sources of EMF exposure in the general environment (see Figure 1.1). Similarly to other sources of EMF exposure, measures and recommendations have been created in wireless communication throughout the last decades [10] to restrict exposure and, thereafter, enhance approaches to minimize it [11]. In the future generation of communication networks, the exponential increases in both multimedia traffic and connected devices will necessitate a rise in the number of access points (APs) (e.g. base stations) to meet demand. As a result of the rising number of wireless devices and APs, the level of EMF exposure will increase. Similarly, the widespread use of mmWave spectrum in 5G, which will have carrier frequencies over 24 GHz, is anticipated to have an effect on exposure since it would necessitate a high density of APs [12]. Recent research in [13–16] has revealed that exposure at these frequencies may pose some health risks.

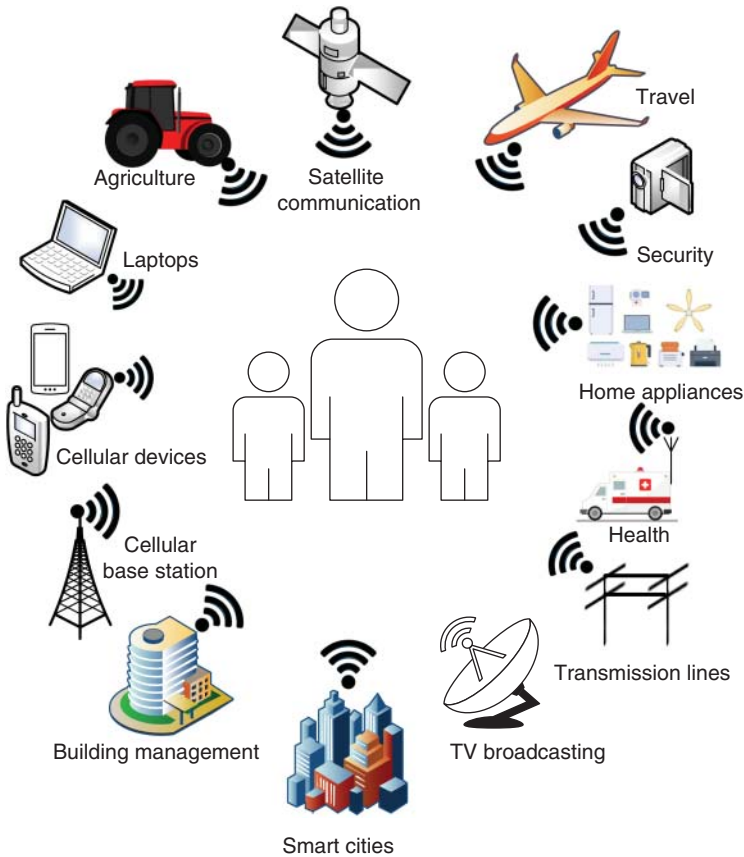


Figure 1.1 Common EMF exposure sources generally present in the environment [9].

The chapter’s structure and key topics of discussion are summarized as follows:

1. Section 1.2 covers the existing techniques for assessing EMF exposure in various circumstances, i.e. the EMF assessment framework, and includes information on the metrics most typically used for measuring EMF exposure in communication. First, research projects relating to the EMF exposure assessment frameworks are provided; the majority of these studies outline their EMF exposure evaluation mechanism, examine the reasons of exposure, and then recommend solutions to minimize it. Second, different categories of exposure metrics are reviewed, where each category of metrics is explained vis-à-vis its target scenario(s). Third, generic metrics are presented, which are developed by integrating measurements from several categories.

2. Section 1.3 explains and illustrates how the various available EMF metrics have been utilized for restricting (i.e. creating standards) or lowering exposure.
3. Finally, Section 1.4 concludes the chapter.

1.2 EMF Metric and Evaluation Framework

A significant amount of work has been carried out in recent years for evaluating the EMF exposure in various scenarios, using different measurement systems and tools, to assess the potential risks emanating from EMF radiations in wireless communications and mitigate their effects (through guidelines and EMF-aware reduction techniques). As a result, EMF monitoring has gained relevance in wireless networks over the last decade [17], given that ambient RF-EMF exposure does not remain constant over time owing to environmental changes and variations in the number of active users (as well as the nature of their device usage). For example, the *moniT* (acronym for electromagnetic radiation exposure assessment in mobile communications) project, funded by Optimus, TMN, and Vodafone [18], provided public information on population exposure to EMF from mobile communication systems in Portugal from 2004 to 2012. This project's monitoring system was built on a network of autonomous remote probing stations and a comprehensive EMF sounding program, both of which were carried out in public spaces around the country. According to the project monitoring data, the EMF values of mobile systems were below the required threshold. Another EMF assessment and monitoring effort was the *SEMONT* project, which was implemented and utilized for real-time EMF exposure evaluation. Monitoring findings indicated that possible exposure was well below the permissible level set by Serbian legislation for the general population [19]. Their approach was then utilized to quantify the exposure produced by GSM when fluctuations in traffic circumstances were considered [20]. According to RF exposure assessments, exposure levels tend to grow with rising urbanization [21]. Meanwhile, the exposure survey assessment in [22] discovered that exposure levels in Europe are not exceeding the recommended levels, but exposure from wireless communication devices has increased significantly over the last years, accounting for more than 60% of total exposure.

In addition to these monitoring initiatives, other projects, such as the monitoring and control activities relating to electromagnetic fields in the RF range (*MONICEM*) and low EMF exposure future network (*LEXNET*) projects, have established new EMF assessment metrics that may be used to reduce the overall level of EMF exposure. For example, in *MONICEM*, which was supported by both the inter-University center for the study of interactions between electromagnetic fields and biosystems (*ICEmB*) and the institute for environmental protection and research (*ISPRA*), it was discovered that services such as cellular base

stations, wireless networks, and so on create large amounts of EMF radiations, much over the natural limitations. The project created an environmental impact indicator (FIAE) based on the EMF derived from a generic source [23]. Similarly, in the LEXNET project, which was funded by the European Commission, a new realistic metric known as the exposure index (EI) [24] was developed to quantify the degree of EMF exposure to people in the environment. Using this criterion, the research established innovative strategies for lowering (by at least 50%) human exposure to electromagnetic (EM) radiation generated by wireless communication while maintaining quality of service (QoS) [25]. The metrics created in MONICEM or LEXNET are intended for assessing or realistically modeling EMF exposure across vast geographical regions while accounting for various forms of EMF radiations. These more general measurements or assessment frameworks sometimes rely on or combine existing measures created for more particular contexts. For example, consider the EI created by LEXNET, which includes in its definition the specific absorption rate (SAR) and power density (PD), both of which are typical metrics for measuring the EMF exposure of wireless communication devices and equipment. In the following sections, we will first go through the most often used metrics in wireless communications for analyzing EMF exposure in various circumstances, and then describe how some of them may be combined to generate more general metrics.

1.2.1 EMF Exposure Factors

As a byproduct of its transmission, each device delivering information to another device creates EMF exposure to users or persons in wireless communications. In general, the total exposure at any location in a given region under observation is the sum of the radiations emitted by all transmitting devices in the vicinity (accounting for both the active and passive exposures). The severity of the exposure is determined by four major criteria, which are discussed in the following.

1.2.1.1 Transmit Antenna Regions

Transmitting antennas typically have two radiating regions: near field and far field, with the near field region further classified as reactive and radiated near field dependent on the distance and frequency of the radiating antenna. The reactive near field lies in the immediate proximity of the antenna, where the electric and MF are 90° out of phase, making the reactive effect more dominating. The radiating near field, also known as the Fresnel area, is the space between the reactive near and far fields. In this area, the radiating impact of the antenna begins to outweigh the reactive effect. The far field area, on the other hand, is further away from the antenna and has the electric and MF in phase. It should be noted that each zone is determined by specific boundary criteria, which are further specified

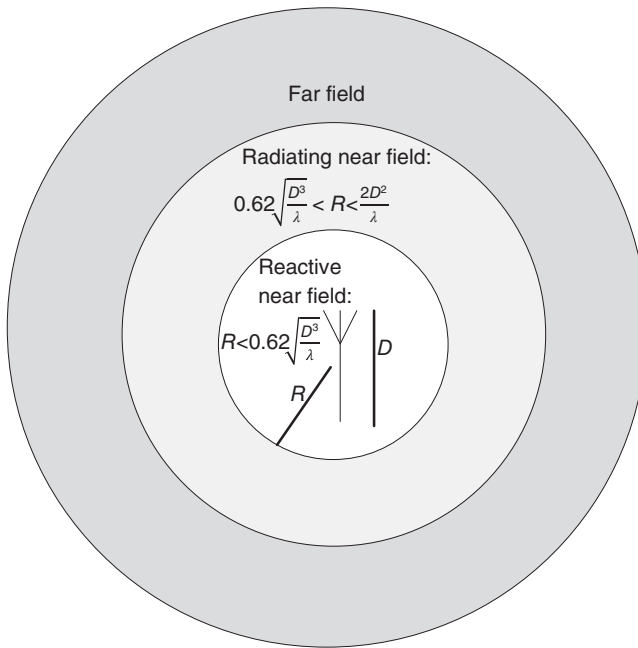


Figure 1.2 Antenna field areas are depicted [26].

in Figure 1.2. In Figure 1.2, D denotes the diameter of the antenna, R the radius of each zone, and λ the wavelength of an EM wave. The impact of the near field on EMF exposure is more significant in the uplink scenario, when the antenna(s) of a user mobile device radiate(s) to send data to an access point (AP) and most of the antenna(s) dissipated energy can easily be absorbed by the user body/head (given the user body/presence head's in the near field region) [27]. The influence of the radiated EMF, on the other hand, decreases with distance in the far field. It should be emphasized that active exposure normally results from near field EMF waves, whereas passive exposure typically results from far field radiations.

1.2.1.2 Transmit Antenna Characteristics

The transmitting antenna's parameters, such as transmitted power, antenna gain, directivity, effective aperture, polarization, beam width, and so on, are critical in defining the extent of exposure. The intensity of exposure is generally proportional to the intensity of the EF, which is proportional to the transmit power. For example, in [28], the EMF radiations from mobile communication antennas were examined by taking into consideration the relevance of antenna characteristics for determining exposure.

1.2.1.3 Duration of Exposure

As with any other sort of exposure, such as pollution or cigarette smoke, the longer the exposure, the greater the exposure dosage. For example, [29] has demonstrated that the duration of exposition is associated to a rise in body temperature when humans are exposed to RF radiation, which can be hazardous over time. Similarly, [30] claims that growing mobile phone usage might have negative impacts on the human reproductive system.

1.2.1.4 Electrical Properties of Biological Tissues

Variations in the dielectric characteristics of organic materials and tissues can be regarded as a significant influence in EMF exposure. Indeed, as previously stated, children absorb more radiation than adults due to differences in the dielectric characteristics of their tissues. For example, [31], which explored the changes in dielectric constant between bones and fatty regions using microwave tomography, found a relatively large deviation in dielectric constant between soft and hard tissues. Meanwhile, [32] provides a thorough experimental examination linked to the variation in dielectric constant of different biological tissues for frequencies ranging from 10 Hz to 20 GHz.

1.2.2 EMF Exposure Metrics

Several metrics have been defined throughout the years in order to analyze and predict the EMF exposure of wireless communication systems in various circumstances, depending on the numerous parameters indicated in Section 1.2.1. To the best of our knowledge, there are four primary categories of EMF metrics, namely, SAR, PD, exposure-ratio, and dosage, which may be grouped as shown in Figure 1.3.

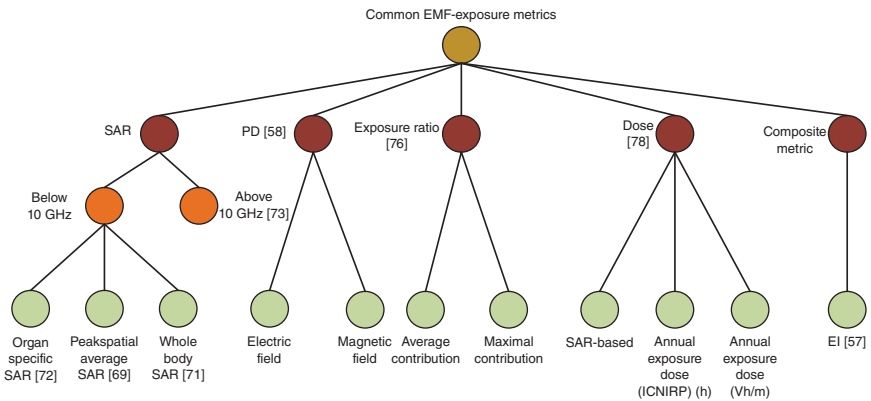


Figure 1.3 The most often used metrics for assessing EMF exposure [9].

1.2.2.1 Specific Absorption Rate

The SAR is a measure of the generated EMF inside the human body when exposed to a transmitting antenna's near field. Watts per kilogram are the units of measurement of SAR. The SAR measure is widely used by regulatory organizations throughout the world to determine exposure standards and evaluate the exposure produced by various handset [35]. Indeed, to ensure public safety, each handset maker should give the electromagnetic energy deposition within surrounding biological tissues, as measured by the SAR [36, 37]. The SAR in the near field of an antenna mounted on a wireless device can be expressed as [38];

$$\text{SAR} = \frac{\sigma \times E^2}{m_d} \text{ (W/kg)}. \quad (1.1)$$

In (1.1), σ represents the conductivity of the exposed tissue(s), E indicates the strength of the EF and m_d is the mass density of the sample under test. Figure 1.4 depicts a typical setup for measuring the SAR of a human head, in which a radio frequency (RF) radiating device (with two antenna components in our example) is positioned close to a phantom head, and a probe (receiver) is used to measure the strength of E [33]. To test SAR in the worst case scenario, the phantom head would be filled with a sugar solution that replicated the dielectric and conduction characteristics of brain tissue on average. The SAR may be further classified

Figure 1.4 A typical SAR measuring setup is depicted. Source: Jamshed et al. [9]/with permission of IEEE.

