Engineering Proceedings

Proceedings

Modelling the Influence of the 2.4 GHz Electromagnetic Field on the User of a Wearable Internet of Things (IoT) Device for Monitoring Hazards in the Work Environment †

Patryk Zradziński [1],*, Jolanta Karpowicz [1], Krzysztof Gryz [1], Leszek Morzyński [2], Rafał Młyński [2], Adam Swidziński [2], Konrad Godziszewski [3] and Victoria Ramos [4]

[1] Laboratory of Electromagnetic Hazards, Central Institute for Labour Protection—National Research Institute (CIOP-PIB), Czerniakowska 16, 00-701 Warszawa, Poland; jokar@ciop.pl (J.K.); krgry@ciop.pl (K.G.)
[2] Department of Vibroacoustic Hazards, Central Institute for Labour Protection—National Research Institute (CIOP-PIB), Czerniakowska 16, 00-701 Warszawa, Poland; lmorzyns@ciop.pl (L.M.); rmlynski@ciop.pl (R.M.); adswi@ciop.pl (A.S.)
[3] Institute of Radioelectronics and Multimedia Technology, Warsaw University of Technology, Nowowiejska 15/19, 00-665 Warszawa, Poland; K.Godziszewski@ire.pw.edu.pl
[4] Telemedicine and e-Health Research Unit, Instituto de Salud Carlos III, 28025 Madrid, Spain; vramos@isciii.es
* Correspondence:Correspondence: pazra@ciop.pl; Tel.: +48-22-623-3225

† Presented at the 7th Electronic Conference on Sensors and Applications, 15–30 November 2020; Available online: https://ecsa-7.sciforum.net/.

Published: 15 November 2020

Abstract: The aim was to test the hypothesis that it is an insignificant influence on humans from the absorption of an 2.4 GHz electromagnetic field (EMF) emitted by wearable IoT devices (using MIFA for Wi-Fi and Bluetooth technologies) for monitoring hazards in the work environment. To quantify problem, the specific energy absorption rate (SAR) was calculated in a multi-layer ellipsoidal model of the IoT device user's head exposed to EMF from MIFA attached to a headband or to a helmet. SAR values may be significant when a modelled IoT wearable device is attached to a headband, but not to a helmet.

Keywords: biomedical engineering; environmental engineering; numerical simulations; radiofrequency sensor; occupational exposure; public health; specific energy absorption rate (SAR); wearables; Wireless Sensor Networks (WSN)

1. Introduction

In the Internet of Things (IoT) systems, each device has the ability to collect and then transfer data between them via wired or wireless networks using an electromagnetic field (EMF) from the radio waves frequency band. Depending on the required range and data transfer rate of wireless connectivity, different technologies may be applied: Wi-Fi (Wireless Fidelity), Bluetooth, ZigBee, LoRa (Long Range), RFID (RadioFrequency IDentification) and four to five generations of mobile communication systems (4G–5G) as well as LTE (Long Term Evolution) [1].

A Wireless Sensor Network (WSN) can be used for example to monitor harmful factors in the work environment and can help efforts to reduce the resulting hazards to workers' health or used in e-health applications [2–4]. In such applications, the protected person often has to be equipped with a wearable device, either a sensor or an actuator, necessary to assess the monitored parameters or evaluate the hazards, or aimed at reducing it. They usually come in the form of small wireless devices located on or in the vicinity of the body (such as bands, in the form of a watch, pendant or stitched into clothing).

Bluetooth and Wi-Fi 2G operate in the 2.4 GHz unlicensed industrial, scientific, and medical (ISM) frequency band and enable communications under the IEEE 802.15.1-2005 or the family of IEEE 802.11 standards. The direct biophysical effect of exposure to EMF of frequency exceeding 100 MHz is a thermal load in exposed tissue, characterised by the specific energy absorption rate (SAR) and expressed in watts per kilogram (W/kg). Because wearable IoT devices are often used near to the body, it is necessary to evaluate the SAR values from their EMF influence on the user's body.

The aim of this study was to evaluate the absorption in the user's head of an EMF emitted by a wearable IoT devices applicable for example in various WSNs used for hazards monitoring or reduction in the work environment developed by CIOP-PIB, in order to test the hypothesis that they have an insignificant influence on humans.

2. Materials and Methods

2.1. Numerical model of EMF Source

Considered WSNs developed by CIOP-PIB consist of specific type wearable devices able to perform Wi-Fi or Bluetooth connections [5,6]. Wearable devices are worn by workers and used to alert them about any hazards or to inform them of the necessary safety measures in the monitored area, for example to alert workers using hearing protectors against approaching vehicles. The heart of wearable devices in various considered applications is the commercial radio module ESP-WROOM-32.

The modelled EMF source used in considered ESP-WROOM-32 radiofrequency module (RF module) was the omnidirectional MIFA (Meandered Inverted-F Antenna). The MIFA was designed to operate at (2400–2483.5) MHz and supporting Wi-Fi 2G and Bluetooth LE communication technologies. The numerical model of the MIFA was an antenna with the outer dimensions of 15.3 × 5.9 mm and ground of 18.0 × 19.0 mm placed on a substrate of 18.0 × 25.5 mm. Copper with a thickness of 0.035 mm, an electric conductivity of 5.813×10^7 S/m and a relative permittivity of 1 was used for the antenna and ground; FR-4 (glass-reinforced epoxy laminate material) with a thickness of 0.7 mm, an electric conductivity of 3.8×10^{-3} S/m and a relative permittivity of 4 was used as the substrate. The numerical model of described MIFA was validated by laboratory tests of the undisturbed (in free space) reflection coefficient S11 parameter: measured using Agilent PNA-X N5242A vector network analyser and simulated.

2.2. Exposure Scenarios

The investigations covered exposure scenarios with the RF module located at the side of the head: (1) on the headband with the antenna plane at a distance of 2 mm from the head, or (2) attached to a helmet of the type that is required, for example, in an industrial environment, with an antenna plane at a distance of 20 mm from the head. High-Density Polyethylene (HDPE) with thickness of 2 mm, an electric conductivity of 5.0×10^{-4} S/m and a relative permittivity of 2.25 was used for the helmet.

2.3. Numerical Model of the Head

Due to the considered exposure scenarios in which the RF module is located close to the head, the study was limited only to the numerical model of a head. The head was modelled as a multi-layer ellipsoid with dimensions corresponding to the dimensions of the 50th percentile male head of the Polish population, for more details see [7]. The model includes layers with dielectric parameters @ 2450 MHz frequency adopted from the IT'IS (Information Technologies in Society) Foundation Database of Tissue Properties corresponding to the: skin with an electric conductivity of 1.464 S/m and a relative permittivity of 38.0; subcutaneous adipose tissue (SAT)/fat tissue (0.268 S/m and 10.8); bone (skull bones) (0.394 S/m and 11.4) and internal part corresponding to brain grey matter (1.808

S/m and 48.9) [8]. The thicknesses of particular tissue layers were the median values of people: 4 mm for skin, 2 mm for SAT/fat and 9 mm for skull bone [9].

2.4. Numerical simulations

Numerical simulations were carried out by Sim4Life software (Zurich Med Tech, Switzerland) using a finite-difference time-domain solver (FDTD). The finest resolution used in the investigations was 0.005 mm, set for the antenna, and 1 mm (1/15 of the wavelength in tissues @ 2.45 GHz), set for model of the head. The uncertainty of numerical simulations was estimated as not exceeding ±20% (K = 1), within the range compliant with state-of-art in the field [10].

3. Results and Discussion

The results of experimental validation showed a sufficient agreement of the obtained centre frequency (RF module matching frequency)—with a difference of 1.3% between measurement and simulations (2.400 GHz—measurements; 2.432 GHz—simulations).

Table 1 shows the results of the numerical simulations of SAR values related to EMF exposure near the ESP-WROOM-32 RF module evaluated at an input power to MIFA of 100 mW at a frequency of 2.45 GHz (analysed with respect to continuous exposure—the worst-case exposure scenario with respect to the rules of evaluating thermal load from human exposure to EMF).

Table 1. SAR values in the head of the user of a ESP-WROOM-32 RF module equipped with MIFA, for an input power to the antenna of 100 mW @ 2.45 GHz.

Exposure Scenario	WHSAR, [1] W/kg	SAR10g, [2] W/kg	EIRP., [3] mW
RF module on the headband	0.035	4.0	6.1
RF module on the helmet	0.005	0.4	350

[1] WHSAR—SAR evaluated as averaged over the entire exposed head; [2] SAR10g—maximum local SAR averaged over 10g of mass of any continuous tissue; [3] EIRP—equivalent isotropically radiated power.

The obtained results show up to 10-times higher values of SAR in the case of the RF module located in the headband in comparison to its location on the helmet. Furthermore, in this exposure case, for an input power to the antenna over 50 mW, SAR10g values may exceed limits for the general public (2 W/kg). It was observed that antenna performance drops dramatically when it is located very close to tissues (only 6.1 mW EIRP @ 100 mW of input power to antenna, compared to 350 mW when used on the helmet).

According to ETSI EN 300 328 V2.1.1:2017-058 for transmission systems operating in the 2.4 GHz ISM band, the limit of EIRP is equal to 100 mW (Wi-Fi 2G, Bluetooth class 1) [11]. For this level of power in the case of an RF module located on headband, the values of SAR10g may be 32-times and 6-times higher than the limits for the general public (2 W/kg) and occupational exposure (10 W/kg) respectively. In fact, these values are unlikely to occur due to the technically limited input power to the analysed MIFA antenna.

The analysed frequency band (2.4 GHz—ISM) is very close to frequency bands used by LTE: 2100 (1920–1980 MHz uplink; 2110–2170 MHz downlink), 2300 (2305–2315 MHz uplink; 2350–2360 downlink) or 2600 (2500–2570 MHz uplink; 2620–2690 MHz downlink) MHz. The limit of EIRP for LTE devices is 200 mW (ETSI TS 136 101 V15.9.0 (2020-02) [12]. The obtained results of SAR values near the analysed MIFA @ 2.45 GHz may also be used to roughly estimate the SAR values for mentioned LTE frequency bands, which may have an EIRP up to twice as high as for presented values obtained for Wi-Fi 2G and Bluetooth.

4. Conclusions

The results of this work show that the absorption in the user's head of an EMF emitted by a wearable IoT device using MIFA, applied for example to alert workers against hazards in the work environment, may have a significant influence on humans when used directly on the head. The location of the MIFA on a helmet may sufficiently reduce the level of the IoT device user's exposure to EMF. This requires further research, taking into account more sophisticated models of wearable IoT devices (apart from the RF module, including also e.g., housing and battery), users' bodies and exposure scenarios.

Author Contributions: Conceptualization, P.Z., J.K., K.G. (Krzysztof Gryz), L.M., R.M. and V.R.; methodology, P.Z., K.G. (Krzysztof Gryz) and K.G. (Konrad Godziszewski); validation, P.Z. and K.G. (Konrad Godziszewski); formal analysis, P.Z., J.K. and L.M.; investigation, P.Z., J.K., K.G. (Krzysztof Gryz), V.R., L.M., R.M., K.G. (Konrad Godziszewski) and A.S.; resources, K.G. (Krzysztof Gryz), L.M. and A.S.; data curation, P.Z. and K.G. (Konrad Godziszewski); writing—original draft preparation, L.M., P.Z., J.K. and V.R.; writing—review and editing, L.M., P.Z. and J.K.; visualization, P.Z.; supervision, J.K.; project administration, P.Z., L.M., R.M. and V.R. All authors have read and agreed to the published version of the manuscript.

Funding: Results of a research tasks (II.PB.15, 2.G.04, 2.G.05) carried out within the National Programme "Improvement of safety and working conditions" partly supported in Poland in 2017–2022—within the scope of research and development—by the Ministry of Science and Higher Education/National Centre for Research and Development and within the scope of state services—by the Ministry of Family, Labor, and Social Policy (CIOP-PIB is the Programme's main co-ordinator) and the project 'Electromagnetic Characterisation in Smart Environments of Healthcare and their involvement in Personnel. Occupational and Environmental Health' (PI14CIII/00056) funding from Sub-Directorate-General for Research Assessment and Promotion in Spain (Instituto de Salud Carlos III) and as part of the research activity of the Warsaw University of Technology.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Vermesan, O.; Friess, P. *Digitising the Industry. Internet of Things Connecting the Physical, Digital and Virtual Worlds*; River Publishers: Gistrup, Denmark, 2016.
2. Morzyński, L. Wireless Sensor Networks, In *Occupational Noise and Workplace Acoustics—Advances in Measurement and Assessment Techniques*; Pleban, D., Ed.; CRC Press: Boca Raton, USA, 2021; pp. 83–121.
3. Bangotra, D.K.; Singh, Y.; Selwal, A.; Kumar, N.; Singh, P.K.; Hong, W.C. An Intelligent Opportunistic Routing Algorithm for Wireless Sensor Networks and Its Application Towards e-Healthcare. *Sensors* **2020**, *20*, 3887.
4. Ramos, V.; Trillo, A.; Suarez, O.; Febles, V.M.; Frenandez-Aldecoa, J.C.; Rabassa, L.E.; Suarez, S.D.; Karpowicz, J.; Hernandez, J.A. Electromagnetic Characterization for UHF-RFID Fixed based reader in Smart healthcare environments. In Proceedings of the International Symposium on Electromagnetic Compatibility EMC EUROPE 2020. Virtual Conference, 23–25 September.
5. Morzyński, L. IoT-based system for monitoring and limiting exposure to noise, vibration and other harmful factors in the working environment. In *Proceedings of the Inter-Noise, Madrid, Spain, 16–19 June 2019*; Institute of Noise Control Engineering: Reston, VA, USA, 2019; pp. 4734–4739.
6. Morzyński, L.; Młyński, R.; Kozłowski, E. Koncepcja systemu ostrzegania pracowników stosujących ochronniki słuchu przed zbliżającym się pojazdem [Concept of the system warning hearing protectors-using employees against the approaching vehicle]. *Bezpieczeństwo Pracy Nauka Prakt.* **2020**, *3*, 16–19.
7. Zradziński, P. Evaluation of the inter-person variability of hazards to the users of BAHA hearing implants caused by exposure to a low frequency magnetic field. *Int. J. Radiat Biol.* **2018**, *4*, 1–8.
8. Hasgall, PA.; Di Gennaro, F.; Baumgartner, C.; Neufeld, E.; Lloyd, B.; Gosselin, MC.; Payne, D.; Klingenböck, A.; Kuster, N. IT'IS Database for thermal and electromagnetic parameters of biological tissues. Version 4.0, May 15, 2018.
9. Zradziński, P.; Karpowicz, J.; Gryz, K.; Leszko, W. Evaluation of hazards caused by magnetic field emitted from magnetotherapy applicator to the users of bone conduction hearing prostheses. *Med. Pr.* **2017**, *68*, 469–477.
10. International Electrotechnical Commission (IEC)/Institute of Electrical and Electronics Engineers (IEEE) 62704-1:2017. *Determining the Peak Spatial-Average Specific Ab-Sorption Rate (SAR) in the Human Body from Wireless Communications Devices, 30 MHz to 6 GHz—Part 1: General Requirements for Using the Finite-Dierence Time-Domain (FDTD) Method for SAR Calculations*; IEC: Geneva, Switzerland, 2017.

11. European Telecommunications Standards Institute (ETSI) EN 302–328 v2.1.1 (2016-11). *Wideband Transmission Systems; Data Transmission Equipment Operating in the 2,4 GHz ISM Band and Using Wide Band Modulation Techniques*; Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU; ETSI: Sophia-Antipolis, France, 2016.
12. European Telecommunications Standards Institute (ETSI) TS 136 101 V15.9.0 (2020-02). LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (3GPP TS 36.101 version 15.9.0 Release 15); ETSI: Sophia-Antipolis, France, 2020.