TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 69, Issue Special III, July, 2026

ELECTROMAGNETIC EXPOSURE AND IMMERSIVE TECHNOLOGIES: AN EMERGING OPERATIONAL VULNERABILITY IN MILITARY TRAINING ENVIRONMENTS

Simona MICLĂUȘ, Ionuț-Cristian ȚOPA

Abstract: *The expanding use of immersive virtual- and augmented-reality technologies in military training introduces new operational considerations beyond performance metrics. This paper investigates the electromagnetic field emissions of wireless head-mounted displays used in close proximity to the head as a potential emerging vulnerability. Near-field electric and magnetic field measurements were conducted on the Meta (Oculus) Quest 2 and Microsoft HoloLens 2 under realistic conditions. Emission levels remain well below international exposure limits. However, device-specific electromagnetic signatures and continuous near-field operation distinguish these systems from conventional wireless equipment. In demanding training environments, electromagnetic exposure may interact with visual, cognitive, and vestibular stressors, supporting the need for integrated risk assessment frameworks addressing cumulative effects in military training infrastructures.*

Keywords: *Immersive systems, wireless head-mounted displays, electromagnetic field emission, near-field exposure, VR and AR headsets emissions, Microsoft HoloLens 2, Meta (Oculus) Quest 2.*

1. INTRODUCTION

The integration of extended reality (XR) technologies—including virtual reality (VR), augmented reality (AR), and mixed reality (MR)—into military training environments has become a strategic enabler for enhanced realism, situational awareness, and decision-making under stress [1,2]. As a result, XR-based human–machine interfaces are increasingly recognized as critical emerging technologies supporting future military preparedness [2]. Alongside these operational benefits, their rapid adoption introduces new categories of risk that extend beyond traditional performance and safety metrics.

Wireless XR head-mounted displays (HMDs) are associated with well-documented human-factors challenges, including cybersickness, visual strain, and postural instability [3,4]. Prolonged exposure to immersive environments may induce physiological stress responses and transient cognitive effects influencing attention and working memory [5]. In operationally relevant training scenarios—where cognitive resilience and sensorimotor stability are essential—such effects may reduce training efficiency and operational readiness, thereby representing a potential vulnerability.

From an electromagnetic perspective, immersive HMDs rely on multiple radiofrequency (RF) sources to support wireless communication, tracking, and sensor integration. Existing studies primarily focus on compliance with exposure limits and generally report limited evidence of acute effects below established thresholds [6]. However, most assessments evaluate electromagnetic field (EMF) exposure in isolation and do not consider its interaction with cognitive load, sensory conflict, or ergonomic stressors that are intrinsic to immersive military training environments.

Empirical studies involving both civilian and military users further demonstrate that combined perceptual and ergonomic stressors—such as visual fatigue and visuo-vestibular conflict—can

influence comfort, performance, and task endurance [7]. When combined with localized near-field EMF exposure generated by wearable immersive devices operating in close proximity to the head, these factors suggest the emergence of a multidimensional operational vulnerability.

Accordingly, a focused assessment of electromagnetic emissions from wireless VR and AR HMDs is required to support risk-informed integration of immersive technologies into military training systems. The present study contributes to this objective by experimentally characterizing near-field electromagnetic emissions from representative immersive head-mounted platforms under realistic operational conditions.

2. ELECTROMAGNETIC ENVIRONMENT IN MILITARY TRAINING FACILITIES

Military training facilities operate in complex electromagnetic environments created by the simultaneous use of multiple RF and low-frequency (LF) systems. Communication, surveillance, radar, and electronic warfare equipment generate spatially and temporally variable EMF exposure scenarios that differ significantly from civilian settings. Reviews of occupational EMF exposure in military contexts indicate that personnel may be exposed to multiple RF sources concurrently, while comprehensive exposure characterization remains limited [8].

Military RF systems cover a wide frequency range, from HF and VHF communication systems to microwave-band emitters used for data transmission and sensing. Narrative and systematic reviews identify localized near-field exposure, particularly during close interaction with transmitting equipment, as a major contributor to individual exposure in military environments [9], underscoring the importance of device-specific and proximity-based assessments.

The adoption of immersive training technologies, such as VR and AR HMDs, introduces additional EMF sources located in close proximity to the user's head. These devices incorporate wireless communication modules and internal electronics that emit RF fields during operation. Due to the short separation distances, exposure characteristics differ from ambient background fields and require targeted assessment approaches [10].

Relevant electromagnetic exposures span from LF fields associated with power delivery and internal circuitry to RF fields extending into the Gigahertz range. International guidelines issued by ICNIRP and IEEE establish limits to prevent known adverse health effects but primarily address single-source exposures under controlled conditions [11,12]. Consequently, they do not explicitly consider composite exposure scenarios or localized emissions from wearable devices used in operational environments.

Accordingly, focused near-field electromagnetic measurements of VR and AR head-mounted displays provide a practical approach for characterizing localized emissions within the broader military electromagnetic environment. This perspective directly informs the methodological approach adopted in the present study, which emphasizes comparative near-field electric (E)- or magnetic (H)-field assessment across relevant frequency bands.

3. CASE STUDY: ELECTROMAGNETIC CHARACTERIZATION OF VR AND AR HEADSETS EMISSIONS

The rapid proliferation of VR and AR head-mounted displays has intensified research interest in the EMF emitted by these devices, particularly because of their close and prolonged proximity to the head and eyes [13]. Unlike conventional consumer electronics, immersive systems integrate multiple LF and RF sources—including display drivers, inertial sensors, wireless communication modules, and tracking electronics—creating complex near-field exposure scenarios [14]. Experimental studies confirm that smart glasses and VR headsets generate measurable EMF near the head, with spatial distributions influenced by device architecture and antenna placement [13]. Computational and experimental investigations

have evaluated the specific absorption rate (SAR) in cranial tissues and ocular structures, showing that wireless eyewear devices may locally modify SAR distributions even when overall exposure remains below regulatory limits [15,16]. LF magnetic field emissions have also been identified as a relevant exposure component, particularly in devices employing inside-out tracking and high-refresh-rate displays [17]. In parallel, research on wearable military and tactical networks highlights the importance of assessing cumulative EMF exposure when multiple wireless systems operate simultaneously. In [18], the authors compared human EMF exposure across different operating frequencies for on-body wearable communications, providing guidance for the design of devices within the Internet of Battlefield Things (IoBT).

From an ergonomic and human-factors perspective, recent studies indicate that users increasingly associate smart glasses with potential health concerns despite the absence of confirmed adverse biological effects at compliant exposure levels [19,20]. This perception gap emphasizes the need for transparent, device-specific exposure assessments. Existing international frameworks, including ICNIRP and CENELEC guidelines, define general compliance criteria for wireless devices operating below 6 GHz but do not explicitly address the near-field and multi-source characteristics of immersive head-mounted systems [11,21].

Although modeling, dosimetric, and laboratory investigations of VR and AR devices are available, comparative experimental data for commercially deployed systems remain limited [8]. Moreover, standardized measurement approaches tailored to immersive head-mounted displays are still evolving despite existing guidance on electromagnetic measurement and shielding effectiveness [12]. Continued device-specific measurements are therefore necessary to improve exposure characterization and support evidence-based risk assessment.

3.1 Electromagnetic emissions of headsets models Meat (Oculus) Quest 2 and Microsoft HoloLens 2

Building on the current state of research, the present case study extends the experimental investigation to representative wireless immersive systems, focusing on standalone and network-connected AR and VR head-mounted displays that rely on integrated Wi-Fi and Bluetooth radios for communication, tracking, and system operation.

Table 1 summarizes the RF emission characteristics of the two wireless immersive systems considered in this study: the Meta (Oculus) Quest 2 standalone VR headset and the Microsoft HoloLens 2 AR headset [22, 23]. Both devices integrate multiple wireless communication technologies, including Wi-Fi and Bluetooth, operating in the 2.4 GHz and 5 GHz frequency bands.

Table 1

RF emission characteristics of wireless immersive head-mounted displays used in training environments

Parameter	Microsoft HoloLens 2	Meta Quest 2 (Oculus Quest 2)
Operating Frequency – Wi-Fi 2.4 GHz	2400–2483.5 MHz, ~18.30 dBm EIRP	2400–2483.5 MHz, < 20 dBm EIRP
Operating Frequency – Wi-Fi 5 GHz	5.15–5.25 GHz, ~21.20 dBm EIRP 5.25–5.35 GHz, ~18.50 dBm EIRP 5.47–5.725 GHz, ~18.60 dBm EIRP 5.725–5.85 GHz, ~12.7 dBm EIRP	5180–5240 MHz: < 23 dBm 5260–5320 MHz: < 20 dBm 5500–5700 MHz: < 20 dBm 5745–5825 MHz: < 14 dBm
Bluetooth / GFSK Frequency	2400–2483.5 MHz, ~14.9 dBm EIRP	Bluetooth (2402–2480 MHz): < 20 dBm EIRP

The table reports the corresponding operating frequency ranges and the maximum equivalent isotropically radiated power (EIRP) values specified by the manufacturers, reflecting the upper bounds of RF emissions during active wireless operation. These parameters are particularly relevant for near-field electromagnetic exposure assessment, as the transmitting antennas are located in close

proximity to the user's head during typical use. The inclusion of both an AR and a VR wireless headset enables a comparative evaluation of RF emission profiles across different immersive system architectures while maintaining a consistent measurement framework.

The RF emission characteristics presented in Table 1 provide the technical basis for the subsequent near-field measurement campaign, enabling a preliminary experimental evaluation of electromagnetic exposure patterns associated with wireless VR and AR head-mounted displays under realistic operational conditions.

3.2 Methodology of Electric- & Magnetic-field strength measurements around the headsets models

Near-field measurements were employed as a proxy for LF and RF exposure. Although this approach does not provide regulatory SAR values for tissue energy deposition, it enables comparative evaluation of local electromagnetic emissions and potential exposure patterns in close proximity to the head.

- **Measurement setup**

Measurements were performed using a calibrated spectrum analyzer together with electric (E)- and magnetic (H)-field probes. A Near Field probe set PBS-1 (Aaronia, Germany), covering frequencies from DC to 6 GHz, and a signal and spectrum analyzer FSV 3013 (Rohde & Schwarz), operating from 10 Hz upward, were used to determine E- and H-field levels. The headsets were tested under three operational states: (a) Idle – powered on without active simulation; (b) Static display – simple visual scene without user interaction; and (c) Dynamic simulation – immersive scenario involving user movement, active Wi-Fi transmission, cloud synchronization, and simultaneous Bluetooth communication.

Measurements were acquired at predefined positions relative to the headset—frontal (eye region), lateral (temple region), and posterior (occipital region)—at distances of approximately 0.8–1 cm from the device. Background EMF levels were present in the testing facility; therefore, the 2.4 GHz band could not be evaluated. The methodology follows established EMF characterization practices for wearable devices [11], [21].

- **Head mannequin preparation**

A hollow plastic mannequin head was filled with a saline solution (7 g NaCl per liter of distilled water) to approximate the electrical conductivity of biological tissues, enabling reproducible EMF measurements without exposing human subjects. This setup was used for evaluating near-field electromagnetic emissions from wireless VR and AR head-mounted displays under realistic wearing conditions (Fig. 1) and in the position of maximum detected field level.



Fig. 1. Head mannequin filled with saline used for measurements of near-field emissions, the two headsets used in the experiment and the spectrum analyzer and electric- and magnetic-field probes.

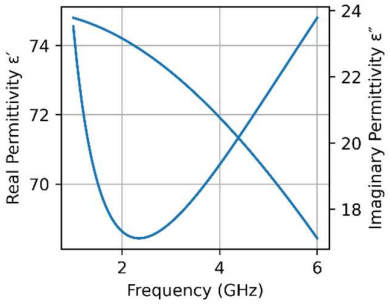


Fig. 2. Frequency dependence of the complex relative permittivity of saline water (7 g/L NaCl) in the (1–6) GHz range.

The complex permittivity (Ɛ*) of saline water was modeled using a Debye-based dispersion

model with conductivity correction, following the formulations reported in [24] and [25]. In the (1–6) GHz frequency range, a saline solution consisting of distilled water with 7 g/L NaCl exhibits a frequency-dependent Ɛ* characterized by a monotonically decreasing real part (Ɛ') and increasing dielectric losses (Ɛ") – Fig. 2.

3.3 Low frequency emissions of the headsets

Fig. 3 shows the H near-field emission spectrum measured in close proximity (≈ 1 cm) to the Meta Quest 2 VR headset at frequencies below 1.5 MHz, using the RMS detector and PBS-H4 field probe. Very pronounced discrete lines in the low range (tens–hundreds of kHz) are seen and a relatively wide broadband packet centered approximately at 1.1 MHz. The large amplitudes for H near-field may correspond to pulsed current sources. The spectrogram indicates that low lines are stable in time, which may correspond to fixed clocks or converters.

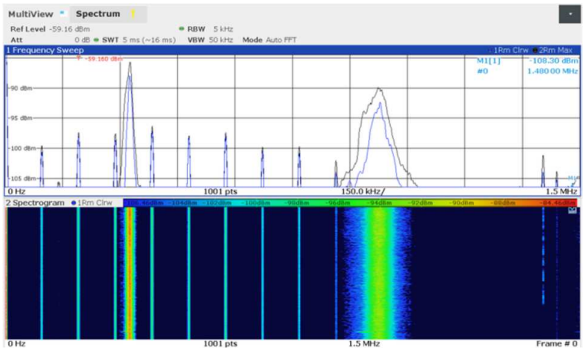


Fig. 3. Spectrum and spectrogram of the emitted power at 1 cm from the Meta Quest 2 VR headset, f<1.5MHz (RMS values, clear/write and max hold traces) when the headset is in Idle mode.

The band from ~1.1 MHz indicates a continuous activity, with slow level variation. The probable interpretation is that for frequencies < 300 kHz we see the emisions from DC/DC converters (buck/boost) or from the display power supply. In the ~ (1–1.5) MHz the broadband emission is specific to higher harmonics plus switching jitter, which is typical for modern spread-spectrum switched-mode power supply.

In Fig. 3 the levels of the two dominant components were converted to H-field strength using the conversion formula provided by the probes producer. The levels may be seen in Table 2, together with the ICNIRP maximum limits for population. These results indicate a substantial compliance margin with respect to international exposure guidelines in the low-frequency magnetic near-field domain.

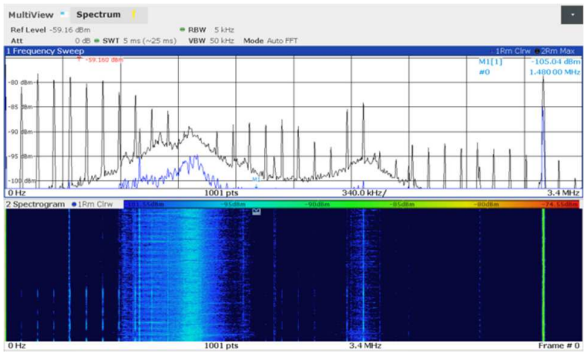


Fig. 4. Spectrum and spectrogram of the emitted power at 0.8 cm from the Meta Quest 2 VR headset, f<3.4 MHz, (RMS values, clear/write and max hold traces) when the headset is in Idle mode.

Fig. 4 corresponds to another position of the H-field probe which captured the spectrum up to 3.4 MHz. A very regular "comb" of spectral lines, evenly spaced, is observed. Also, a high broadband background is seen between ~0.5 and ~2 MHz. The spectrogram indicates by the dense light blue area a persistent activity, with no transient events, but steady-state operation. The regular spacing indicates the emission of a fundamental clock plus harmonics or a switching frequency with well-preserved multiples. This is a classic "fingerprint" of complex digital electronics. In Table 2 we inserted the H-field levels corresponding to the highest two peaks of Fig. 4: the pronounced peak at ~160 kHz with significantly higher H field level, indicating a larger effective current loop or stronger magnetic coupling and the distinct peak at 3.15 MHz suggesting the contribution of higher-order switching harmonics or additional internal subsystems becoming electromagnetically active.

Fig. 5 provides the spectrum and spectrogram measured in the proximity of the Meta Quest 2 VR headset at all the frequencies up to 10 MHz. The spectrum becomes very dense in lines and the magnetic noise floor increases with frequency. Also, there is a lack of a clear "gap" between the bands. In the spectrogram we see

very frequent vertical stripes which indicates the presence of repetitive impulse activity. No RF burst behavior appears. The images correspond to high harmonics of DC/DC and to digital coupling (buses, internal interfaces): SoC + GPU + memory + sensors functioning. Here we are not talking about point sources, but about a "complex H-field" generated by many small loops. Two emitted power peaks were chosen from the spectrum and their H-field level can be seen in Table 2.

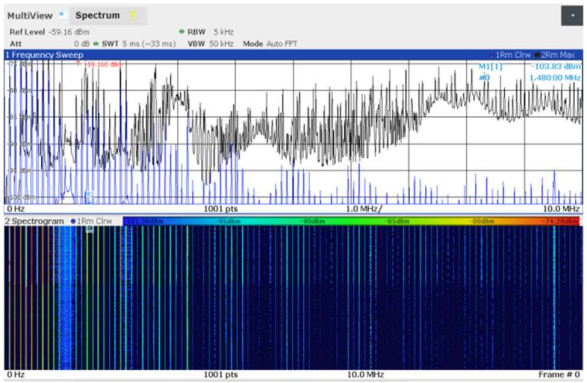


Fig. 5. Spectrum and spectrogram of the emitted power at 0.8 cm from the Meta Quest 2 VR headset, f<10 MHz, when the headset is in Idle mode.

Table 2

Examples of maximum emissions in the very low frequency range of the magnetic near field of the headsets

Peak frequency (MHz)	P_{RMS} (dB)	H (A/m)	ICNIRP Limit (A/m)	Fraction of the limit
0.325	-86	1.73×10^{-3}	0.225	0.77%
1.10	-90	3.24×10^{-4}	0.066	0.49%
0.160	-78	2.80×10^{-2}	0.456	6.1%
3.15	-78	4.50×10^{-4}	0.023	2.0%
0.83	-78	1.70×10^{-3}	0.088	1.93%

Fig. 6 emphasizes a part of the VHF range emissions, between (38-142) MHz. Here we still can observe some H-field emissions present in the near field of the Meta Quest 2 VR headset, respectively in the band (90-100) MHz. The H near-field spectrum measured in close proximity to the HoloLens 2 headset exhibits a phenomenology that is distinctly different from that observed for the Meta Quest 2. While both devices are complex, self-contained XR systems, the spectral structure and distribution of magnetic emissions indicate different internal power management architectures and current loop geometries.

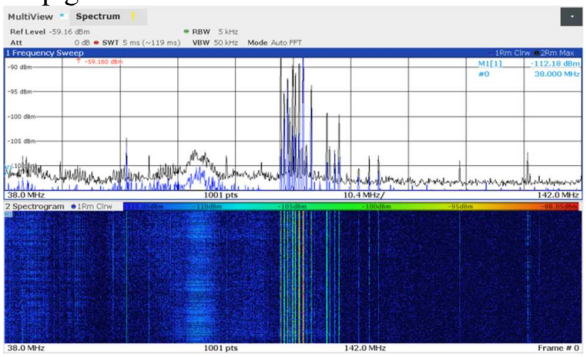
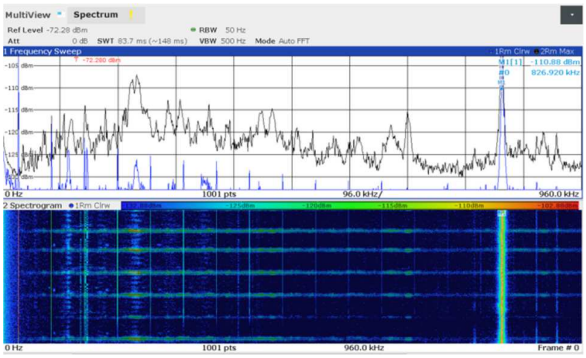
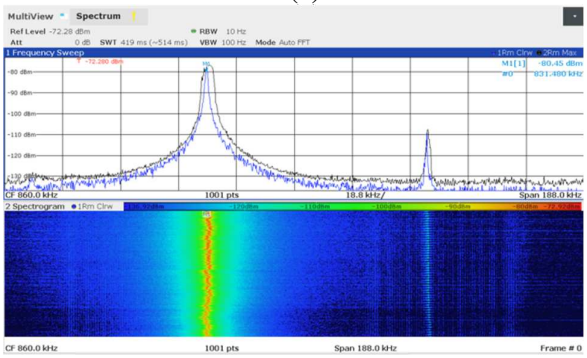


Fig. 6. Spectrum and spectrogram of the emitted power at 0.8 cm from the Meta Quest 2 VR headset, 38 MHz <f< 142 MHz, when the headset is in Idle mode.



(a)



(b)

Fig. 7. Spectrum and spectrogram values of the emitted power at 1 cm from the HoloLens 2 AR headset for the clear/write and max hold traces, when the headset is in Idle mode: a) f<960 kHz; b) 766 kHz < f < 954 kHz

In the low-frequency region (below approximately 500 kHz), the HoloLens 2 spectrum shows less pronounced discrete peaks and a comparatively smoother spectral envelope (Fig. 7a). This suggests a reduced dominance of single, strongly coupled DC/DC switching loops, potentially due to either different

converter topologies, lower instantaneous current levels, or improved spatial distribution of power regulation circuitry. The magnetic emissions in this region appear more distributed, indicating that no single converter dominates the near-field magnetic signature.

In the mid-frequency region (hundreds of kHz to a few MHz), unlike the Meta Quest 2 headset, where distinct switching-related peaks were clearly identifiable, the HoloLens 2 spectrum displays a denser but lower-amplitude structure, with multiple weaker components rather than a few dominant ones (Fig. 7b). One of the peak's frequencies is 830 kHz, and the H-field level is 1.93% of the ICNIRP safe limit (Table 2). Phenomenologically, this points to increased use of spread-spectrum modulation, stronger temporal averaging of switching events, or improved current return path management. As a result, the magnetic near-field exposure is distributed across frequency rather than concentrated at specific switching frequencies.
The corresponding spectrogram indicates stable, continuous emission patterns over time, with no evidence of burst-like or intermittent behavior. Compared to the Quest 2, the HoloLens 2 exhibits less temporal contrast between spectral components, reinforcing the interpretation of a more homogeneous internal electromagnetic activity. From a phenomenological standpoint, the HoloLens 2 appears to generate a more diffuse magnetic near-field signature, characterized by: lower peak dominance, broader spectral spreading, and reduced magnetic coupling at individual frequencies. This behavior is consistent with a device architecture optimized for continuous mixed-reality operation, where thermal, power, and electromagnetic considerations favor distributed and less impulsive current flow.

3.4 Radiofrequency emissions of the headsets

Because our measurements took place in a crowded environment (not shielded and uncontrolled), the measurements in the 2.4 GHz band were impossible to be achieved. We could identify and separate well in the background just the emissions in the 1.7 GHz and 5.2 GHz bands.

Figures 8 and 9 exemplify the emissions of Meta Quest 2 VR headset, while the E-field probe model PBS-E1 was placed at 1 cm from the headset.

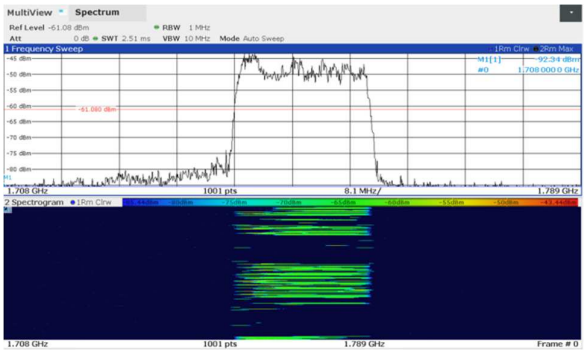


Fig. 8. Spectrum and spectrogram of a communication channel of 20 MHz centered at 1.755 GHz, in a point situated at 1 cm from Meta Quest 2 VR headset

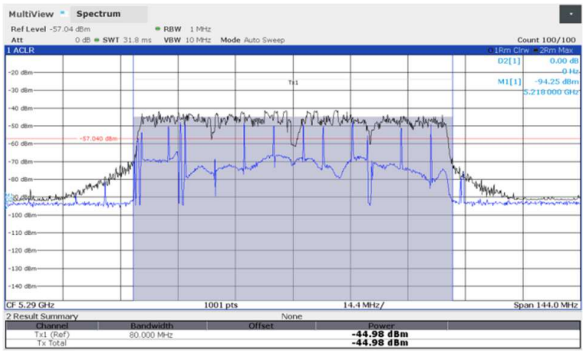


Fig. 9. Channel power measurement in a point situated at 1 cm from Meta Quest 2 VR headset: WIFI transmission centered on 5.29 GHz with a bandwidth of 80 MHz

Fig. 8 shows an intentional E-field emission centered at 1.755 GHz, with an occupied bandwidth of 20 MHz. The relatively narrow bandwidth and well-defined spectral envelope are consistent with the single communication channel operating without channel aggregation. The emission is clearly confined within the allocated band, with no significant out-of-band components visible. The corresponding spectrogram indicates the sustained transmission activity, suggesting the active communication link used. The E-field strength corresponding to this emission was 1.16 V/m, which represents approximately 1.9% of the ICNIRP general public reference level, indicating a substantial compliance margin.

Fig. 9 shows an emission centered on the 5.29 GHz, with a 80 MHz occupied bandwidth,

indicative of high-throughput wireless communication using power channel measurement. The broad, flat spectral profile is characteristic of OFDM-based WLAN transmission, consistent with performance-intensive operation. The corresponding channel power representation indicates the sustained high-duty-cycle transmission used. The E-field strength associated with the 80 MHz-wide emission was 0.49 V/m, corresponding to about 0.8% of the ICNIRP general public reference level.

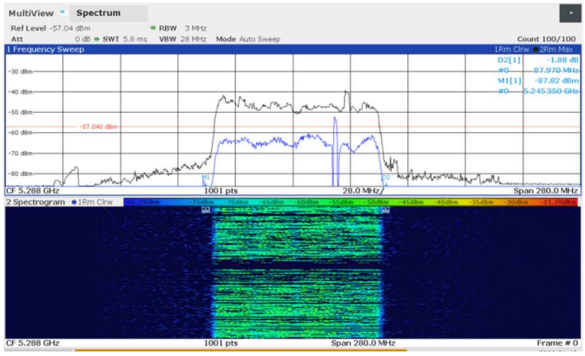


Fig. 10. Spectrum and spectrogram of a WIFI emission centered on 5.29 GHz with a bandwidth of 80 MHz, in a point situated at 1 cm from Holo Lens 2 AR headset

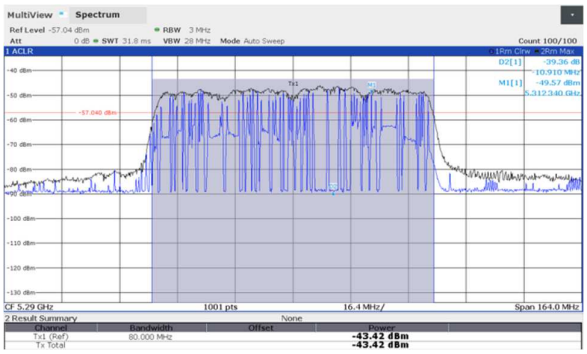


Fig. 11. Channel power measurement in a point situated at 1 cm from Holo Lens 2 AR headset: WIFI transmission centered on 5.29 GHz with a bandwidth of 80 MHz

Fig. 10 and Fig. 11 exemplify communication emissions of HoloLens 2 AR headset in the 5.2 GHz range with a bandwidth of 80 MHz, as it was captured by PBS-E1 E-field probe at 1 cm distance from the headset. Based on the channel power measurement shown in Fig. 11, the E-field level in this case was 0.58 V/m which is equivalent to 0.96% from the ICNIRP safe limit.

In all the above examples of communication emissions in the GHz range, the right settings of the analyzer were crucial for reporting precise E-field levels. The approach in the present paper took into consideration the previous expertise of one of the authors on these topics and was not technically detailed here. Separate and much more complex analysis is needed for a comprehensive view on the subject.

Although the EMF emissions from VR and AR headsets are extremely low and well below international safety limits, potential health risks may arise from the combination of multiple factors during use. Extended exposure to close-up screens can cause eye strain and visual fatigue, while the mismatch between visual motion cues and the vestibular system can trigger motion sickness or dizziness. Physical pressure from the headset and heat generated by the electronics can add to discomfort. In this context, even the minimal EMF emissions, while individually safe, may contribute to the overall sensory load, exacerbating headaches, fatigue, or minor physiological stress when combined with these other factors. Therefore, the primary concern is not EMF alone but the cumulative effect of visual, vestibular, mechanical, and EMF-related stimuli on the user's well-being.

4. CONCLUSIONS

This work demonstrates that, while the electromagnetic emissions generated by wireless VR and AR head-mounted displays remain well below international exposure limits, their deployment in military training environments introduces a subtle but non-negligible operational vulnerability. Near-field measurements performed on the Meta (Oculus) Quest 2 and Microsoft HoloLens 2 confirm substantial compliance margins across both low-frequency and radiofrequency domains. However, the proximity of multiple internal EMF sources to critical sensory organs, combined with continuous operation during immersive training scenarios, distinguishes these systems from conventional wireless devices and justifies focused exposure assessment.

The experimental results highlight device-specific electromagnetic emission patterns that reflect different internal architectures and power

management strategies. Pronounced low-frequency magnetic components and switching-related harmonics observed in the Quest 2 contrast with the more spectrally distributed and diffuse emissions measured for the HoloLens 2. From an operational perspective, such differences are relevant not because of regulatory exceedance, but because they contribute differently to the overall sensory and physiological load experienced by the user. In high-fidelity military training, even small variations in cumulative stressors may influence situational awareness, comfort, and task endurance.

Consequently, the primary vulnerability does not arise from EMF exposure in isolation, but from its potential interaction with visual, vestibular, cognitive, and thermal stressors inherent to immersive systems. In training environments characterized by prolonged use, high cognitive demand, and concurrent electromagnetic sources, this cumulative burden may affect individual performance and readiness. These findings support the need for an integrated operational risk framework that extends beyond compliance-based EMF assessment, incorporating human factors, system design, and usage scenarios to ensure the resilient and safe integration of immersive technologies into military training infrastructures.

5. REFERENCES

[1] Sayler, K. M., *Military Applications of Extended Reality*, Congressional Research Service, CRS Report IF12010, Washington, DC, 2025.

[2] Grand View Research, *Immersive Reality for Defense Market Size*, Share & Trends Analysis Report, Grand View Research Inc., ISBN 978-1-68038-999-4, San Francisco, 2025.

[3] Rebenitsch, L., Owen, C., *Review on Cybersickness in Applications and Visual Displays*, Virtual Reality, ISSN 1359-4338, 2016.

[4] Chang, E., Kim, H. T., Yoo, B., *Virtual Reality Sickness: A Review of Causes and Measurements*, International Journal of Human-Computer Interaction, ISSN 1044-7318, 2020.

[5] Zielasko, D., Rehling, B., von Dawans, B., Domes, G., *Prolonged Effects of Cybersickness on Stress and Cognitive Performance after Virtual Reality Exposure*, arXiv Preprint, 2025.

[6] Zothansiama, Z., Zosangzuali, M., Lalramdinpuii, M., Jagetia, G. C., *Impact of Radiofrequency Radiation on Human Health: A Review of Biological Effects*, Electromagnetic Biology and Medicine, ISSN 1536-8378, 2017.

[7] Frankl, D., Racz, J., Hegedus, T., *Patterns of Virtual Reality Use and Associated Symptoms Among Civilian and Military Users*, Honvédelmi Szemle, ISSN 0133-684X, 2025.

[8] Gallucci, S., Fiocchi, S., Bonato, M., Chiaramello, E., Tognola, G., Parazzini, M., *Exposure Assessment to Radiofrequency Electromagnetic Fields in Occupational Military Scenarios: A Review*, International Journal of Environmental Research and Public Health, ISSN 1660-4601, 2022.

[9] Risling, M., Günther, M., *Radio Frequency Exposure in Military Contexts: A Narrative Review of Thermal Effects and Safety Considerations*, Military Medicine, ISSN 0026-4075, 2025.

[10] World Health Organization, *Radiation: Electromagnetic Fields*, World Health Organization, Geneva, 2016.

[11] International Commission on Non-Ionizing Radiation Protection (ICNIRP), *Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz–300 GHz)*, Health Physics, ISSN 0017-9078, 2020.

[12] IEEE, *IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields (0 Hz to 300 GHz)*, IEEE C95.1-2019, IEEE, New York, 2019.

[13] Jungk, P., Wienke, M., Schiefer, C., et al., *Investigation of the Impact of Electromagnetic Fields Emitted Close to the Head by Smart Glasses*, Biomedical Engineering / Biomedizinische Technik, ISSN 0013-5585, 2022.

[14] Poulsen, J., Hansen, M. K., *Low-Frequency EMF Emissions from Head-Mounted*

Displays, Electromagnetics, ISSN 0272-6343, 2021.
[15] Lan, J. Q., Liang, X., Hong, T., Du, G. H., *On the Effects of Glasses on the SAR in Human Head Resulting from Wireless Eyewear Devices at Phone Call State*, Progress in Biophysics and Molecular Biology, ISSN 0079-6107, 2018.
[16] Cvetković, N., Krstić, D., Stanković, V., Jovanović, D., *Electric Field Distribution and SAR Inside a Human Eye Exposed to VR Glasses*, IET Microwaves, Antennas & Propagation, ISSN 1751-8725, 2018.
[17] Poungsri, P., Pechrkool, T., Pruksanubal, A., *Prediction of SAR of Electromagnetic Radiation due to Virtual Reality Headsets*, Przegląd Elektrotechniczny, ISSN 0033-2097, 2020.
[18] Nasim, I., Kim, S., *Human EMF Exposure in Wearable Networks for Internet of Battlefield Things*, Proceedings of the IEEE Military Communications Conference (MILCOM), pp. 1–6, ISBN, Norfolk, VA, USA, 2019, IEEE, New York.
[19] Pierrette, M., Perrin, N., Lux, A., Marchal, P., Klingler, A., *Smart Glasses: Environmental Perception and Perceived Health Effects*, Ergonomics, published online, 2025.
[20] Adebowale, B., *Are Smart Glasses Bad for You*?, http://medicalnewsbulletin.com/smart-glasses-ar-ai-safety/
[21] European Committee for Electrotechnical Standardization (CENELEC), *EN 62479: Assessment of the Compliance of Low-Power Wireless Devices with Human Exposure Requirements*, CENELEC, Brussels, 2010.
[22] Meta Platforms Inc., Oculus Quest 2 – *RF Exposure Report and Test Documentation*, FCC Equipment Authorization Database, https://fcc.report/FCC-ID/2AGOZ-S3A.
[23] Microsoft Corporation, *HoloLens 2 RF Exposure and EMC Test Reports*, FCC Authorization Database, https://fcc.report/company/Microsoft-Corporation.
[24] Ellison, W. J., *Permittivity of Pure Water, at Standard Atmospheric Pressure, over the Frequency Range 0–25 THz*, Journal of Physical and Chemical Reference Data, ISSN 0047-2689, 2007.
[25] Stogryn, A., *Equations for Calculating the Dielectric Constant of Saline Water*, IEEE Transactions on Microwave Theory and Techniques, ISSN 0018-9480, 1971.

Expunerea Electromagnetică și Tehnologiile Imersive: O Vulnerabilitate Operațională Emergentă în Mediile de Instruire Militară

Rezumat: Utilizarea tot mai extinsă a tehnologiilor imersive de realitate virtuală și augmentată în instruirea militară introduce noi considerente operaționale, dincolo de indicatorii tradiționali de performanță. Această lucrare investighează emisiile de câmp electromagnetic generate de dispozitive VR și AR wireless purtabile pe cap, utilizate în imediata proximitate a capului utilizatorului, cu accent pe relevanța acestora ca vulnerabilitate operațională emergentă. Măsurători în câmp apropiat ale câmpurilor electric și magnetic au fost efectuate pe două sisteme reprezentative, Meta (Oculus) Quest 2 și Microsoft HoloLens 2, în condiții operaționale realiste. Rezultatele confirmă faptul că nivelurile de emisie se situează mult sub limitele internaționale de expunere. Cu toate acestea, semnăturile electromagnetice specifice fiecărui dispozitiv și funcționarea continuă în câmp apropiat diferențiază sistemele imersive purtabile pe cap de echipamentele wireless convenționale. În medii de instruire cu solicitare ridicată, expunerea electromagnetică poate interacționa cu factori de stres vizuali, cognitivi și vestibulari, afectând potențial rezistența și gradul de pregătire al utilizatorului. Aceste rezultate susțin necesitatea unor cadre integrate de evaluare a riscurilor, care să abordeze efectele cumulative în implementarea tehnologiilor imersive în infrastructurile de instruire militară.

Simona MICLĂUȘ, Ph.D, Professor (habil.), "Nicolae Balcescu" Land Forces Academy, Communications, Information Technology, and Cyber Defense Department, miclaus@armyacademy.ro, +40 269 432 990, 3-5 Revoluției Street, Sibiu, Romania.
Ionuț-Cristian ȚOPA, Ph.D student, Eng., "Nicolae Bălcescu" Land Forces Academy, Technical Science Department, topaionutcristian@gmail.com, 3-5 Revoluției Street, Sibiu, +40-269-432 990, University of Oradea, 1 Universității Street, Oradea, Romania.