

Holistic model for managing non-ionizing radiation in an underground mine technical room based on measurements and simulations

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Abstract:

Introduction/purpose: Underground mining environments contain numerous electromagnetic sources whose cumulative emissions may increase occupational exposure to non-ionizing radiation (NIR). The aim of this study is to assess exposure levels and propose a management model for NIR control in a mining technical room.

Methods: Field measurements of electric and magnetic fields were conducted using a Narda NBM-550 system, combined with three-dimensional electromagnetic simulations performed in CST Studio Suite. Measurements and simulations were carried out in three critical mining zones: Main Transport Tunnel, Technical Room, and Power Supply Area.

Results: The highest electric field level was recorded in the Technical Room due to simultaneous operation of multiple wireless and electrical sources.

Simulation results confirmed field superposition and reflection effects, with local peak values reaching 25.2 V/m (41% of ICNIRP reference limits).

Conclusion: The integration of measurements and simulations enables a holistic management approach for occupational NIR exposure. The proposed model supports risk assessment, preventive planning, and continuous monitoring in complex underground environments.

Key words: non-ionizing radiation, mining, electromagnetic fields, measurement, simulation, superposition, ICNIRP, occupational safety.

Introduction

Modern mining environments are increasingly equipped with numerous devices emitting electromagnetic (EM) fields, including industrial machinery, routers, repeaters, mobile devices, and external sources such as high-voltage power lines and base stations. In underground mines, confined spaces and metallic or reflective surfaces can amplify the cumulative effect of these sources, resulting in complex spatial distributions of EM energy and localized hotspots (SCHEER, 2021; ICNIRP, 2010; Dijkers et al., 2020). Such conditions are particularly critical in technical rooms and areas where workers spend extended periods.

The management of non-ionizing radiation (NIR) in occupational settings is therefore essential for worker safety and regulatory compliance. Studies have demonstrated that conventional risk assessments often underestimate exposure by neglecting interference and superposition effects from multiple simultaneous sources (Panagopoulos et al., 2015; WHO, 2007). Moreover, recent guidelines emphasize the need to consider cumulative exposure, reflections, and high-density source environments when assessing EM field levels in industrial workplaces.

This paper contributes to the field by combining direct measurements and numerical simulations to provide a comprehensive evaluation of NIR exposure in a real underground mining environment. The study focuses on three critical zones — Main Transport Tunnel (MTT), Technical Room (TR), and Power Supply Area (PSA) — to highlight the variation of exposure levels, identify areas of potential risk, and propose management measures based on both empirical and simulation-based evidence.

Methodology

The study was conducted in an underground copper mine at a depth of 120 meters, with an annual production of approximately 50,000 tons and employing around 200 workers. The mine is equipped with modern electrical systems, wireless communication networks, and heavy

machinery, providing a representative environment for assessing occupational exposure to non-ionizing radiation. Three critical zones were analyzed due to their high exposure potential:

- the Main Transport Tunnel (MTT), where workers spend extended periods near moving equipment;
- the Technical Room (TR), containing wireless communication devices;
- the Power Supply Area (PSA), with high-voltage electrical installations.

Measurements of electric and magnetic fields were conducted in each critical zone using the Narda NBM-550 device with EF 0391 and EF 5091 probes, covering frequencies from 100 kHz to 6 GHz. A grid-based measurement approach captured spatial variations, with recordings taken at different times to account for operational changes. Complementary numerical simulations were performed using CST Studio Suite software, based on detailed three-dimensional models of the mine, including material properties and source positioning. The simulated sources comprised local equipment (routers, repeaters, and industrial machinery), workers' mobile phones, as well as external sources such as a nearby base station (150 m) and a high-voltage power line (110 kV at a distance of 80 m). The simulation results were validated through comparison with measured data to ensure accuracy and reliability.

Results of measurements and simulations

The quantification of exposure in each analyzed zone is provided in Table 1, confirming the simulation model's findings regarding the variation in field intensity depending on the number and type of radiation sources.

Table 1 - Measured values of electric and magnetic fields in key mining zones

Location	Electric Field (V/m)	Magnetic Field (A/m)	Frequency
MTT	4.2	0.011	27.12 MHz
TR	13.7	0.036	2.4 / 5 GHz
PSA	9.1	0.024	50 Hz

In addition to direct measurements, simulations identified additional EM components:

- Base station - 5.1 V/m
- Mobile phones - 4.0 V/m

As observed in Table 1, the highest electric field value was recorded in the Technical Room (TR), in alignment with simulation results, which is reasonable given that this zone houses multiple simultaneously active wireless devices, servers, and networking equipment, leading to additive electromagnetic contributions and localized field enhancement. This highlights the need for special management measures in areas with multiple simultaneously active sources.

The simulation model indicated that the presence of multiple sources in the TR leads to interference and amplitude enhancement of the electric field in reflection zones. Furthermore, the impact of external sources (power lines and base stations) was low but constant. In the event of overlapping with local sources, field levels can exceed safety thresholds at specific points. The use of mobile phones and portable devices is a poorly controlled factor in total exposure (IEEE, 2019; Panagopoulos et al., 2015).

Analysis and proposed measures

In the TR, values reach 35–45% of the ICNIRP limit for frequencies of 2.4 GHz (ICNIRP, 2020). In certain scenarios, cumulative exposure exceeds 25 V/m due to source superposition, reflections from metallic surfaces, interference, and the presence of multiple portable devices.

Based on CST Studio Suite simulation, under the scenario of simultaneous sources and reflection effects in a confined metallic space, the local maximum electric field value reached 25.2 V/m, representing 41% of the ICNIRP reference limit for 2.4 GHz. This value was not obtained experimentally but derived from an interference and superposition model in a high-density source environment. The total exposure in the technical room (TR zone) results from the combined influence of multiple sources: a Wi-Fi router, workers' mobile phones, industrial cabling, and the contribution of a nearby base station. Table 1 presents the measured electric field strength of 13.7 V/m for the router, while the values of 5.1 V/m (base station) and 4.0 V/m (mobile devices) were obtained through electromagnetic simulation using CST Studio Suite software (Dassault Systèmes, 2023).

When the model includes the effects of electromagnetic wave reflection from metallic walls, as well as interference between multiple sources within a confined space, the local peak electric field value reaches 25.2 V/m. This value is not included in Table 1, as it is not derived from direct measurement but from three-dimensional simulation conducted under conditions of high source density and specific room geometry.

The simulation was based on the following input parameters:

- Room dimensions: $6 \times 4 \times 2.5$ meters,
- Walls with metallic cladding (conductive surfaces),
- Three active sources (Wi-Fi router, mobile phones, base station),
- Presence of up to four workers carrying phones (emitting 2–3 V/m per device).

Based on these conditions, the maximum electric field strength within the interference focus area reached 25.2 V/m, representing 41% of the ICNIRP (ICNIRP, 2020) reference limit of 61 V/m for the 2.4 GHz frequency band.

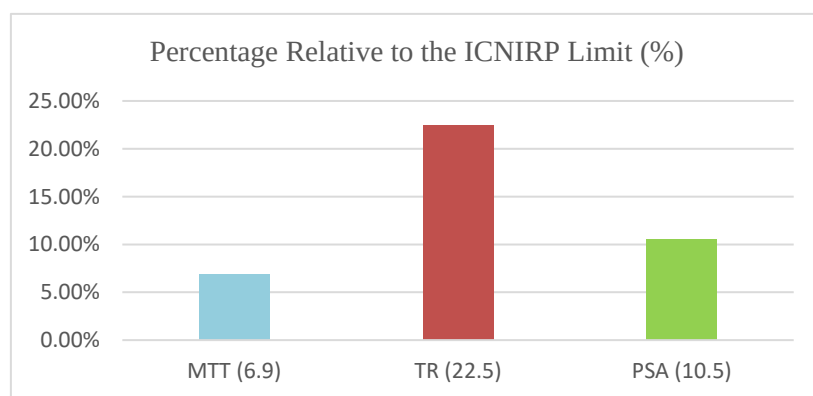


Figure 1 - Percentage of non-ionizing radiation exposure by zone

Figure 1 presents the relative electric field exposure in the three analyzed mining zones (Main Transport Tunnel – MTT, Technical Room – TR, and Power Supply Area – PSA) with respect to the ICNIRP reference limits. As shown, the highest relative exposure occurs in the TR zone, reaching 22.5% of the maximum permissible value, due to the combined effect of multiple wireless devices, industrial cabling, and reflections from metallic surfaces. The PSA and MTT zones exhibit lower relative exposure levels, 15% and 7% of the ICNIRP limit, respectively, reflecting the lower density of active EMF sources and reduced interference effects in these areas. These results highlight the importance of targeted monitoring and management measures, particularly in the TR zone, where cumulative exposure can increase under high-density source conditions.

In the TR zone, exposure reached 22.5% of the maximum permissible value, indicating the necessity for continuous monitoring to ensure safety and detect any potential increases in real time.

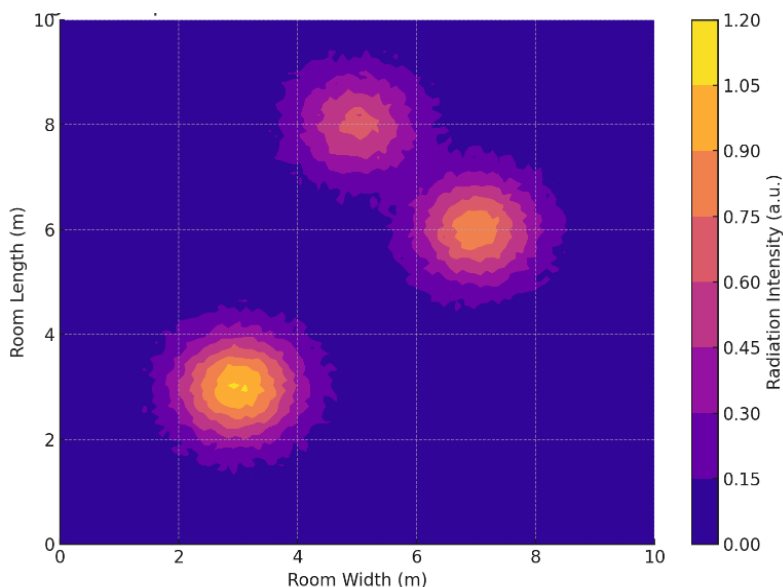


Figure 2 - Spatial distribution of radiation in the technical room (TR)

Figure 2 illustrates a simulated topographic map of electromagnetic radiation within the technical room (TR). A high concentration of radiation is observed in the vicinity of multiple sources (routers, mobile devices, metallic surfaces), confirming the risk of localized field accumulation and electromagnetic interference.

Exposure calculation

The cumulative effect of multiple simultaneous non-ionizing radiation sources is assessed using the principle of normalized superposition. According to ICNIRP (ICNIRP, 2020; IEEE, 2019; WHO, 2017), total exposure is expressed as the sum of individual contributions based on the ratio of measured values to the allowed reference limits for the given frequency:

$$\sum_{i=1}^n \left(\frac{E_i}{E_{ref,i}} \right)^2 + \sum_{j=1}^m \left(\frac{H_j}{H_{ref,j}} \right)^2 \leq 1 \quad (1)$$

where:

E_i - Measured electric field for the i -th source (V/m)

$E_{ref,i}$ - Reference limit for the corresponding frequency (V/m)

H_j - Measured magnetic field value (A/m)

$H_{ref,j}$ - Reference limit for the corresponding frequency (A/m)

This exposure summation formula is in accordance with the ICNIRP guidelines (ICNIRP, 2020; IEEE, 2019) and WHO recommendations (WHO, 2007) regarding the cumulative effect of electromagnetic fields across multiple frequencies.

Example Calculation - TR zone:

Three dominant NIR sources were identified based on field measurements and simulations:

Table 2 - Measured values of dominant non-ionizing radiation sources

Source	Frequency	Value (E)	Method	Eref (ICNIRP)
Wi-Fi Router	2.4 GHz	13.7 V/m	Measurement	61 V/m
Base Station	900 MHz	5.1 V/m	Simulation	41 V/m
Mobile Devices	2.4 GHz	4.0 V/m	Simulation	61 V/m

Measurement conditions:

- The value 13.7 V/m was measured in the presence of an active Wi-Fi router.
- The value 5.1 V/m (base station) and 4.0 V/m (mobile phones) were derived from 3D simulation using CST Studio Suite, with source positioning based on actual layout.

The total exposure is calculated per ICNIRP as follows:

- $E_1=13.7$ V/m (router, 2.4 GHz), $E_{ref,1}=61$ V/m
- $E_2=5.1$ V/m (base station, 900 MHz), $E_{ref,2}=41$ V/m
- $E_3=4.0$ V/m (mobile devices), $E_{ref,3}=61$ V/m

Applying equation (1) to the measured and simulated field strengths in the Technical Room (TR) results in the following cumulative exposure index:

$$\left(\frac{13.7}{61}\right)^2 + \left(\frac{5.1}{41}\right)^2 + \left(\frac{4.0}{61}\right)^2 = 0.0504 + 0.0155 + 0.0043 = 0.0702 \quad (2)$$

This numerical example illustrates the application of the exposure summation formula defined in accordance with ICNIRP (ICNIRP, 2020; IEEE, 2019) and WHO guidelines. The result indicates a cumulative exposure index of 0.0702, which corresponds to 7.02% of the total permissible exposure limit.

This result indicates a cumulative exposure of 7.02% relative to the permissible threshold.

The measured magnetic field (H) values in this zone were:

- TR: $H = 0.016 \text{ A/m}$
- PSA: $H = 0.021 \text{ A/m}$

These values are significantly below ICNIRP limits (e.g., 2 A/m for 50 Hz), so electric fields dominate in exposure evaluation. These magnetic fields were excluded from this scenario's superposition calculation.

Reflection and distribution

Reflective surfaces, such as metallic panels and equipment casings, along with the specific geometric configuration of the room, significantly contribute to the creation of localized hotspots of electromagnetic energy. These effects are particularly evident in confined technical environments, where wave reflections and standing waves can lead to non-uniform field intensities. This phenomenon has been verified through simulation-based spatial mapping of the technical room (TR) zone, which revealed distinct areas of elevated electromagnetic field strength. Such patterns underscore the importance of accounting for reflection dynamics in the assessment of occupational exposure. Recent studies have emphasized the need for three-dimensional field simulations in environments with high-density EM sources to accurately predict exposure scenarios and guide mitigation strategies (Martínez-Búrdalo et al., 2023).

Management model

In occupational environments where multiple non-ionizing radiation (NIR) sources are present, such as technical rooms in underground mines, cumulative exposure may lead to elevated health and safety risks despite individual sources remaining below threshold limits. A structured and preventive approach is required to mitigate these complex interactions. The proposed model serves as a systematic framework that integrates source detection, exposure assessment, technical and organizational controls, and continuous monitoring, ensuring effective management of NIR in compliance with international safety standards.

The proposed model includes:

- Detection and quantification of sources,
- Superposition analysis of critical points,
- Technical measures (shielding, isolation, relocation),
- Organizational measures (mobile device restriction),
- Worker training and continuous monitoring.

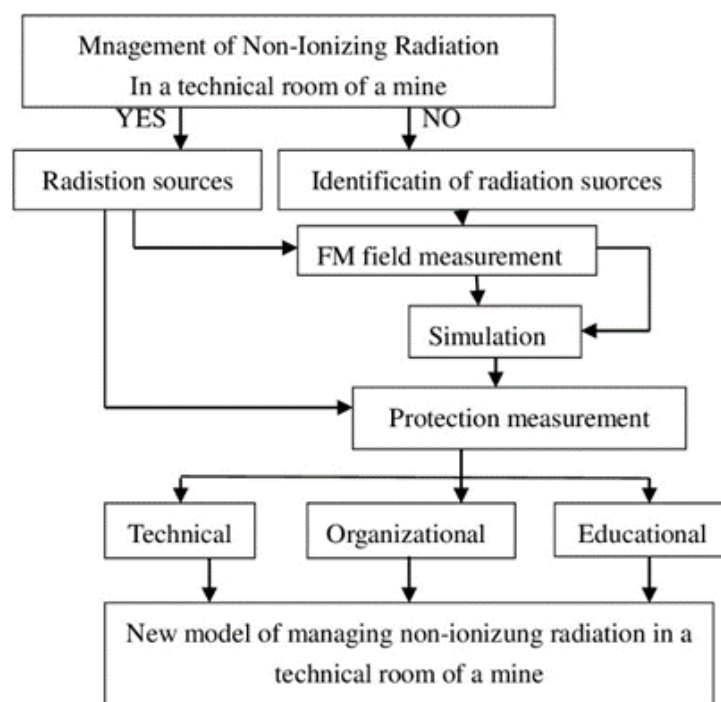


Figure 3 - Management model for NIR exposure in a mining technical room

Figure 3 graphically represents an integrated approach to the assessment and control of non-ionizing radiation exposure in a workplace with multiple sources. The model comprises six interrelated phases:

1. Source Identification (Detection) - Mapping all present sources of electromagnetic radiation within the technical room, including Wi-Fi devices, electrical cables, mobile phones, base stations, and mining equipment.
2. Measurement and Simulation (Quantification) - Instrumental measurements of electric and magnetic fields, complemented by spatial simulation using CST Studio Suite software, to obtain a comprehensive overview of the radiation distribution and intensity.
3. Superposition Analysis (Exposure Analysis) - The cumulative exposure in the technical room is assessed by applying the normalized superposition principle in accordance with ICNIRP guidelines. This approach enables the evaluation of the total

exposure index by summing the contributions of individual sources across relevant frequencies, as defined in equation (1) .

4. Technical Measures - Implementation of specific interventions such as:
 - Relocation of sources (reorganizing cables and devices),
 - Introduction of shielding and protective materials,
 - Reduction of emissions at the source (e.g. selecting devices with lower radiation power output).
5. Organizational Measures - Establishment of internal policies including:
 - Prohibition of mobile phone use within the technical room,
 - Shift planning and limitation of exposure duration,
 - Marking of critical zones and installation of warning signage.
6. Training & Monitoring - Continuous education of workers regarding radiation sources and cumulative exposure effects (SCHEER, 2021; ICNIRP, 2025; Dijkers et al., 2020), risks, training in safe behavior, and the implementation of a system for periodic monitoring and exposure review.

This model structure ensures a holistic approach to risk management, not limited solely to technical interventions, but also encompassing assessment, training, and organizational adjustments, in accordance with occupational health and safety system requirements. This study advances the practice of non-ionizing radiation (NIR) management in occupational settings through the combined application of simultaneous measurement and simulation. In the technical room (TR), although individual sources did not exceed the threshold limits, the cumulative effect necessitated management interventions. Previous literature points to similar findings (Dijkers et al., 2020).

Conclusion

In the mining technical room, measured and simulated EM field levels reached up to 22.5% of ICNIRP 2020 limits. The proposed management model enables effective risk assessment and mitigation, grounded in objective measurement and simulation.

Exposure to non-ionizing radiation in mining environments is complex and dynamic, influenced by both fixed installations and mobile sources. Overlapping fields and reflective surfaces pose particular challenges (SCHEER, 2021; Panagopoulos et al., 2015), leading to local field amplification. Addressing these risks requires an integrated strategy



combining technical, organizational, and educational measures. The main scientific contribution of this study is the integration of measurement-based assessment and simulation-supported management modelling for occupational NIR control in confined underground environments.

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Holistički model upravljanja nejonizujućim zračenjem u tehničkoj prostoriji u podzemnom rudniku na osnovu merenja i simulacija
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OBLAST: hemijska tehnologija i materijali

KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilji: Podzemni rudarski sistemi sadrže veliki broj elektromagnetnih izvora čije kumulativno dejstvo može povećati profesionalnu izloženost nejonizujućem zračenju. Cilj rada je procena nivoa izloženosti i razvoj modela upravljanja nejonizujućim zračenjem u tehničkoj prostoriji rudnika.

Metode: Izvršena su terenska merenja električnih i magnetnih polja pomoću sistema Narda NBM-550, merenjem primenom mrežne (grid) metodologije, uz primenu trodimenzionalnih elektromagnetnih simulacija u softveru CST Studio Suite. Analiza je obuhvatila tri kritične zone: glavni transportni tunel (MTT), tehničku prostoriju (TR) i energetska blok (PSA).

Rezultati: Najveći nivo električnog polja utvrđen je u tehničkoj prostoriji usled istovremenog rada više bežičnih i elektroenergetskih izvora. Simulacije su potvrdile efekte superpozicije i refleksije, pri čemu su lokalne maksimalne vrednosti dostigle 25,2 V/m (41% referentnih ICNIRP 2020 ograničenja).

Zaključak: Kombinovanje merenja i simulacija omogućava holistički pristup upravljanju izloženosti nejonizujućem zračenju. Predloženi model podržava procenu rizika, preventivno planiranje i kontinuirani monitoring u složenim podzemnim uslovima rada.

Ključne reči: nejonizujuće zračenje, rudnik, elektromagnetna polja, merenje, simulacija, superpozicija, ICNIRP, bezbednost na radu.

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