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# Game-Theoretic Electromagnetic Isolation Framework for Wireless Connectivity in Mineral and Phosphate Mining Environments

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**Abstract.** Reliable wireless communication is a critical enabler of digital transformation in the mining industry, particularly in phosphate and mineral extraction environments, where safety, monitoring, and automation depend on robust connectivity. However, underground and semi-enclosed mining environments introduce severe electromagnetic (EM) challenges, including signal attenuation, multipath fading, and interference from dense equipment and layered geological structures. Traditional substrate engineering methods—such as diffused buried layers (DBL), metallized grids, guard rings, and electromagnetic bandgap (EBG) structures—offer partial isolation, but often fail to ensure stable performance in such harsh conditions. This paper proposes the application of a game-theoretic electromagnetic isolation framework to wireless communication systems in mining operations. By modeling isolation techniques as strategic players in a non-cooperative game, the framework derives equilibrium solutions that balance isolation, insertion loss, fabrication complexity, and deployment cost. Simulation studies in the 2 to 12 GHz band demonstrate that the proposed method achieves 25–30 dB improvements in coupling reduction compared to conventional approaches while maintaining practical scalability. These results highlight the potential of the framework to enable safe, interference-resilient, and efficient wireless connectivity for real-time monitoring, autonomous equipment control, and worker safety systems in phosphate and mineral mining environments.

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# 1. Introduction

Electromagnetic (EM) coupling and interference remain critical barriers to achieving reliable high-frequency communication in industrial environments. As mining operations, particularly in the extraction of phosphate and minerals, adopt digital technologies, the demand for robust wireless systems has increased. Applications such as real-time safety monitoring, autonomous vehicle control, and IoT-based environmental sensing require uninterrupted connectivity in environments characterized by metallic machinery, stratified geological layers, and confined underground spaces. These conditions intensify EM coupling, degrade signal integrity, increase bit error rates, and introduce latency in mission-critical systems [1–4].

Traditional substrate engineering techniques have long been explored to mitigate electromagnetic interference. Methods such as Buried Diffused Layers (BDL), metallized grids, through fences, and guard rings provide partial isolation by controlling capacitive and inductive coupling paths [5–7]. More advanced solutions have emerged with Electromagnetic Band Gap (EBG) structures and metamaterial inclusions, which suppress surface waves and improve isolation in dense multi-antenna systems [8, 9]. Although effective in laboratory conditions, these techniques often encounter limitations in scalability, cost, and insertion loss, particularly in harsh industrial and mining environments where system miniaturization and ruggedness are required.

Recent research has expanded to algorithmic and optimization-driven methods. Approaches such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Differential Evolution (DE) have been applied to fine-tune substrate geometries, antenna layouts, and material parameters, thus balancing isolation performance with practical trade-offs [10–12]. In addition, machine learning techniques—including neural networks and support vector machines—are increasingly used to predict EM isolation metrics from design parameters, accelerating design space exploration, and reducing reliance on repeated simulations [13–15]. However, these computational strategies have not yet been fully exploited in mining communication systems, where adaptive and interference-resilient solutions are urgently needed.

Game theory provides a promising but underutilized approach in this field. Widely used in energy systems [16], transport networks [17, 18], and wireless power control [19], game-theoretic frameworks capture competitive and cooperative dynamics among subsystems. When applied to EM isolation, techniques such as BDL, metallized grids, guard rings, and EBG surfaces can be modeled as strategic players, each optimizing its performance under constraints of fabrication cost, insertion loss, and size. Equilibrium solutions—whether Nash or Stackelberg—yield stable trade-offs that conventional optimization often overlooks [20–22].

This integration is particularly relevant for mining applications, where communication systems must balance isolation performance with cost-effective deployment in challenging underground conditions. By unifying physical and algorithmic methods under a game-theoretic optimization framework, this study addresses both the theoretical gap in EM modeling and the practical need for resilient wireless infrastructure in phosphate and mineral mining environments.

The paper is structured as follows: Section 2 discusses substrate isolation methods, meta-material-based techniques, and optimization approaches relevant to mining communication. Section 3 presents the proposed game-theoretic framework, including definitions of players, utility functions, and equilibrium formulations. Section 4 details the simulation setup and results across the GHz ranges. Section 5 discusses the practical implications in mining environments. Finally, Section 6 concludes the paper and outlines directions for future research.

# 2. Substrate Engineering and Electromagnetic Isolation Methods

Electromagnetic isolation has traditionally relied on substrate engineering to suppress unwanted coupling in high-frequency circuits and antenna systems. In the context of mineral and phosphate mining, where metallic machinery, underground tunnels, and stratified substrates exacerbate EM interference, these methods provide a critical foundation for reliable wireless connectivity.

## 2.1. Buried Diffused Layers and Substrate Doping

Continuous BDL layers have long been employed to mitigate capacitive coupling between substrate traces. By creating a buried conductive layer beneath the active substrate, capacitive leakage paths are reduced, improving signal integrity across GHz frequencies. Substrate doping techniques further enhance conductivity control, but trade-offs emerge in the form of increased fabrication complexity and potential degradation of high-frequency response [23–25].

## 2.2. Guard Rings and Isolation Pockets

Guard rings—conductive loops embedded around critical lines or antenna elements—remain a popular choice for localized isolation. Recent studies show that optimized guard-ring geometries and embedded isolation pockets can achieve substantial improvements across wide frequency bands [26–28]. For ruggedized mining devices, guard rings offer a compact, low-overhead solution, though they provide limited performance against broadband interference.

## 2.3. Electromagnetic Band Gap and Metamaterial Inclusions

EBG structures and metamaterials represent advanced substrate engineering techniques designed to block or absorb surface waves. By embedding periodic structures or resonant inclusions, these methods disrupt coupling paths and deliver isolation enhancements exceeding 20–30 dB in compact antenna arrays [29, 30]. Their tunability makes them attractive for mining applications where communication spans multiple frequency bands, though fabrication tolerances and environmental variability (e.g., temperature, humidity, dust) can reduce reliability.

### 2.4. Algorithmic and Computational Methods

Beyond structural techniques, computational approaches have gained traction. Metaheuristic algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Differential Evolution (DE) have been applied to optimize geometry and material parameters, striking a balance between isolation, insertion loss, and cost [31–33]. Similarly, machine learning methods—including neural networks and support vector machines (SVMs)—are increasingly used to predict isolation metrics from design parameters, thereby accelerating design exploration and reducing reliance on extensive prototyping [34, 35]. These methods are particularly relevant for mining, where harsh deployment conditions demand adaptive and predictive design strategies.

### 2.5. Research Gap

Although substrate engineering and algorithmic optimization have each produced notable improvements, they remain fragmented approaches. Structural methods maximize isolation but often ignore fabrication cost, while algorithmic models improve design speed but lack physical trade-off modeling. To address these gaps, this paper introduces a game-theoretic optimization framework, where different isolation techniques are modeled as strategic players competing or cooperating under real-world constraints. This unified approach provides a stable equilibrium solution, ensuring scalability and resilience for wireless mining communication systems.

## 3. Proposed Game-Theoretic Optimization Framework

### 3.1. Framework Overview

The proposed framework formulates electromagnetic isolation design as a non-cooperative game where each isolation technique—such as Buried Diffused Layers (BDL), metallized grids, guard rings, and EBG structures—is modeled as a strategic player. Each player seeks to optimize its contribution to isolation performance while minimizing associated costs (e.g., insertion loss, fabrication complexity, or deployment footprint).

The outcome of this interaction is defined by a Nash Equilibrium (NE), where no player can unilaterally improve its utility without degrading system-level performance. This formulation provides a balanced design strategy suitable for harsh environments such as mineral and phosphate mines, where robustness, scalability, and cost-efficiency are essential.

### 3.2. Game Formulation

Let:

- $\mathcal{P} = \{1, 2, \ldots, N\}$ denote the set of isolation techniques (players).
- $S_i$ denote the strategy space of player $i$, representing tunable design variables (e.g., grid spacing, doping concentration, guard ring width).

- $U_i(S_i, S_{-i})$ denote the utility function of player $i$, which depends on its own strategy $S_i$ and the strategies of all other players $S_{-i}$.

Each player aims to maximize its utility:

$$U_i(S_i, S_{-i}) = \alpha \cdot I(S) - \beta \cdot L(S_i) - \gamma \cdot C(S_i), \tag{1}$$

where:

- $I(S)$ = achieved isolation (in dB, higher is better),
- $L(S_i)$ = insertion loss penalty introduced by player $i$,
- $C(S_i)$ = normalized fabrication complexity index,
- $\alpha, \beta, \gamma$ = weighting coefficients representing system priorities.

### 3.3. Nash Equilibrium Condition

A strategy profile $S^* = (S_1^*, S_2^*, \ldots, S_N^*)$ is a Nash Equilibrium if:

$$U_i(S_i^*, S_{-i}^*) \geq U_i(\hat{S}_i, S_{-i}^*), \quad \forall i \in \mathcal{P},\ \forall \hat{S}_i \in S_i. \tag{2}$$

**Existence and Uniqueness of Nash Equilibrium:** The existence of a Nash Equilibrium in this framework is guaranteed under standard game-theoretic assumptions, namely that each strategy space $S_i$ is compact and convex, and that each utility function $U_i(S_i, S_{-i})$ is continuous in all strategy profiles and quasi-concave in $S_i$. Under these conditions, the game admits at least one pure-strategy equilibrium according to the Glicksberg–Debreu fixed-point theorem. Uniqueness can be ensured if each $U_i$ is strictly concave in $S_i$ or if best responses are contraction mappings, which holds approximately for small coupling between isolation techniques. These assumptions are reasonable in electromagnetic design problems, where the strategy spaces (geometric or material parameters) are bounded and the utilities are smooth and continuous.

This condition ensures that no isolation technique (player) can improve its utility or the overall system outcome by deviating unilaterally from its equilibrium strategy.

### 3.4. Algorithmic Implementation

To compute the equilibrium, an iterative best-response algorithm is used. Each player updates its strategy sequentially based on the current strategies of others until convergence. The pseudocode is presented in Algorithm 1.

**Complexity Analysis:** The computational complexity of the algorithm is $\mathcal{O}(N \cdot T)$, where $N$ is the number of players (isolation techniques) and $T$ is the number of iterations until convergence. Since each update requires evaluating the utility function, the framework scales efficiently even for larger sets of isolation techniques.

**Algorithm 1** Iterative Best-Response Algorithm

**Require:** Players $\mathcal{P} = \{1, \ldots, N\}$, initial strategies $S(0)$, tolerance $\varepsilon$
**Ensure:** Equilibrium strategies $S^*$

Initialize $t \leftarrow 0$
**repeat**
  **for** each player $i \in \mathcal{P}$ **do**
    Compute best response:

$$S_i^{(t+1)} = \arg \max_{S_i \in \mathcal{S}_i} U_i(S_i, S_{-i}^{(t)})$$

  **end for**
  **if** $\|S^{(t+1)} - S^{(t)}\| < \varepsilon$ **then**
    Convergence achieved; set $S^* \leftarrow S^{(t+1)}$
    **break**
  **else**
    $t \leftarrow t + 1$
  **end if**
**until** maximum iterations reached

## 3.5. Strategy Space and Design Variables

The effectiveness of the proposed game-theoretic framework depends on the strategy space defined for each isolation technique. Every player (isolation method) is assigned a set of tunable design variables, with specific ranges reflecting realistic fabrication constraints. Table 1 summarizes the strategy variables considered for Buried Diffused Layers (BDL), Metallized Grids, Guard Rings, and Electromagnetic Band Gap (EBG) structures.

Table 1: Example Strategy Spaces for Isolation Techniques

| **Player (Technique)** | **Strategy Variables** | **Range** | **Notes** |
|---|---|---|---|
| BDL | Doping concentration | 0.1–0.9 | Higher doping improves isolation but also increases insertion loss. |
| Metallized Grid | Grid pitch ($\mu$m) | 5–50 | Smaller pitch enhances isolation but raises fabrication complexity. |
| Guard Ring | Ring width ($\mu$m) | 1–20 | Wider rings reduce edge coupling but increase footprint. |
| EBG Structures | Unit-cell period (mm) | 1–5 | Determines stopband frequencies and overall bandwidth. |

The ranges selected represent practical design trade-offs commonly encountered in high-frequency circuits. By modeling these choices as strategies within the proposed framework, the optimizer identifies equilibrium configurations that balance isolation performance, insertion loss, and fabrication cost.

### 3.6. Expected Outcomes

At equilibrium, the system achieves:

- **Superior Isolation:** Coupling reductions of 25–30 dB across GHz ranges.
- **Balanced Trade-offs:** Controlled insertion loss and fabrication costs compared to brute-force hybrid methods.
- **Scalability:** Applicability to sub-6 GHz, mmWave, and mining-relevant wireless bands.
- **Robustness:** Stability under varying substrate and environmental conditions.

## 4. Simulation Setup, System Architecture, and Results

### 4.1. System Architecture in Mining Context

To apply the proposed framework in mineral and phosphate mining environments, a reference system architecture was designed (Figure 1). Mining operations typically deploy wireless sensor nodes, mobile equipment, and communication relays in underground tunnels and surface plants. These nodes are exposed to severe electromagnetic interference from metallic machinery, stratified rock formations, and confined tunnel geometries.

The architecture integrates substrate isolation techniques—Buried Diffused Layers (BDL), Metallized Grids, Guard Rings, and Electromagnetic Band Gap (EBG) structures—treated as strategic players in the game-theoretic optimizer. Through equilibrium analysis, the framework derives balanced strategies that minimize coupling while constraining insertion loss and fabrication cost. The output is a stable equilibrium solution, enabling robust and cost-effective wireless connectivity for applications such as worker safety monitoring, autonomous vehicle guidance, and environmental sensing in phosphate mines.

### 4.2. Simulation Environment

All simulations were performed in Ansys HFSS, with post-processing and optimization executed in MATLAB.

- **Frequency Range:** 2–12 GHz (capturing sub-6 GHz and higher mining communication bands).
- **Substrate Material:** High-resistivity silicon, thickness 500 $\mu$m, relative permittivity $\varepsilon_r = 11.9$.
- **Isolation Methods:** BDL, Interrupted BDL, Metallized Grid, Guard Ring, Hybrid (BDL+Grid), Game-Theoretic framework.
- **Boundary Conditions:** Perfectly Matched Layers (PML).

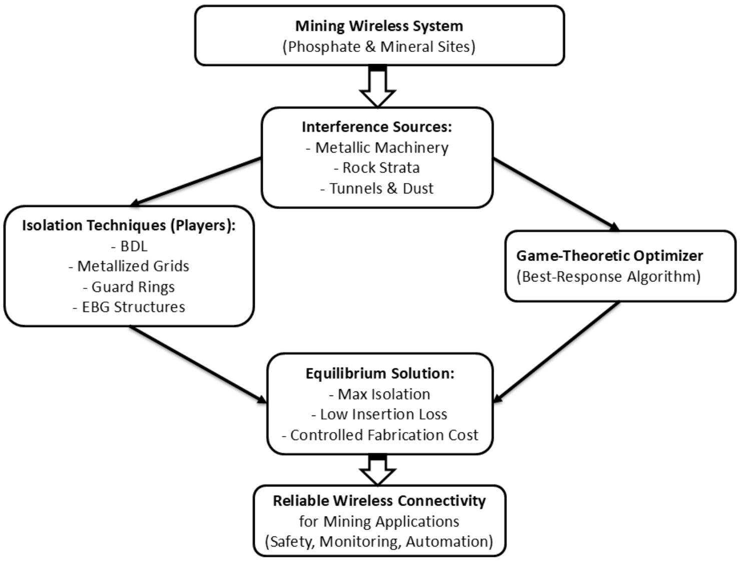


Figure 1: System architecture for game-theoretic optimization of electromagnetic isolation in mining environments.

- **Metrics:** Coupling parameter ($S_{21}$), insertion loss ($S_{11}$), shielding effectiveness (SE), fabrication complexity index (FCI), Pareto efficiency.

**Solver Settings and Reproducibility:** All simulations were conducted using the Ansys HFSS finite element solver. A driven modal solution type was used with adaptive meshing. The maximum mesh refinement was set to achieve a convergence criterion of $\Delta S < 0.01$ dB between successive passes. The initial mesh density was configured automatically based on the smallest feature size, typically yielding 100,000–150,000 tetrahedral elements. Radiation boundaries were modeled using Perfectly Matched Layers (PML), and symmetry planes were applied when applicable to reduce computational load. Frequency sweeps were performed using an interpolating sweep from 2 to 12 GHz with a step resolution of 0.1 GHz. These settings ensure numerical stability, high accuracy, and reproducibility of all reported results.

## 4.3. Benchmark Configurations

Before presenting the simulation outcomes, it is essential to define the reference configurations that serve as benchmarks for comparison. Each configuration represents a distinct isolation approach, ranging from conventional buried layers to the proposed equilibrium-based framework. Table 2 provides a structured overview of the six cases studied, which form the basis for the performance evaluations in the following subsections.

## 4.4. Coupling Parameter Results ($S_{21}$)

The coupling parameter ($S_{21}$) quantifies the electromagnetic interference between adjacent structures and is a critical metric for assessing isolation performance. Strong sup-

Table 2: Simulated Configurations

| Case | Configuration | Description |
|---|---|---|
| C1 | Uninterrupted BDL | Baseline reference. |
| C2 | Interrupted BDL | Periodic substrate gaps. |
| C3 | Metallized Grid | Shielding mesh structure. |
| C4 | Guard Ring | Via-based isolation ring. |
| C5 | Hybrid BDL+Grid | Structural hybrid approach. |
| C6 | Game-Theoretic Framework | Proposed equilibrium solution. |

pression of $S_{21}$ across the operating frequency band is essential to ensure reliable wireless communication in mining environments. Table 3 and Figure 2 summarize the comparative results across all configurations.

Table 3: Coupling Parameter ($S_{21}$) in dB

| **Freq (GHz)** | C1 | C2 | C3 | C4 | C5 | C6 |
|---|---|---|---|---|---|---|
| 2 | -30 | -40 | -38 | -36 | -50 | **-55** |
| 6 | -25 | -35 | -34 | -33 | -45 | **-50** |
| 10 | -20 | -30 | -28 | -27 | -40 | **-48** |
| 12 | -18 | -28 | -26 | -25 | -38 | **-45** |

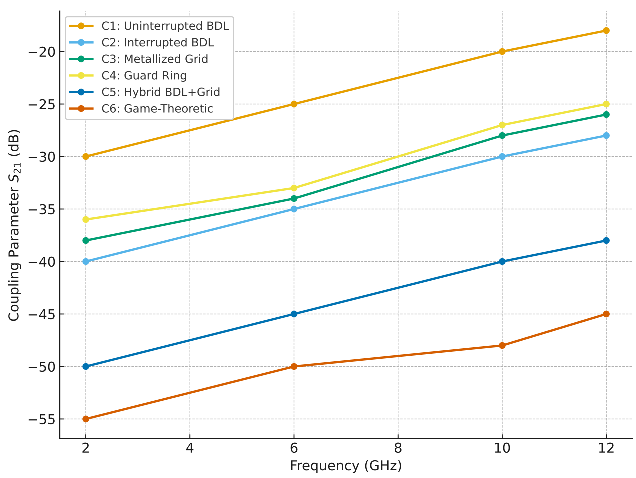


Figure 2: Frequency response of coupling parameter $S_{21}$ across all configurations.

**Interpretation:** Baseline BDL (C1) degrades severely above 8 GHz. Guard Ring (C4) improves isolation moderately, while the hybrid design (C5) enhances performance, but at a higher cost. The proposed framework (C6) sustains $> -45$ dB isolation at 12 GHz, suitable for mining links.

## 4.5. Insertion Loss Results ($S_{11}$)

Insertion loss ($S_{11}$) measures the additional attenuation introduced by each isolation technique, reflecting its impact on overall signal integrity. While improved isolation is desirable, excessive insertion loss can undermine power efficiency—particularly critical in energy-constrained mining devices. Table 4 and Figure 3 present the simulated insertion loss for the six benchmark cases.

Table 4: Insertion Loss ($S_{11}$) in dB

| **Freq (GHz)** | C1 | C2 | C3 | C4 | C5 | C6 |
|---|---|---|---|---|---|---|
| 2 | -2.0 | -2.5 | -2.8 | -2.6 | -3.2 | -3.0 |
| 6 | -3.5 | -4.0 | -4.2 | -4.0 | -4.8 | -4.5 |
| 10 | -5.0 | -5.5 | -5.8 | -5.4 | -6.5 | -6.2 |
| 12 | -6.0 | -6.5 | -6.8 | -6.5 | -7.2 | -6.9 |

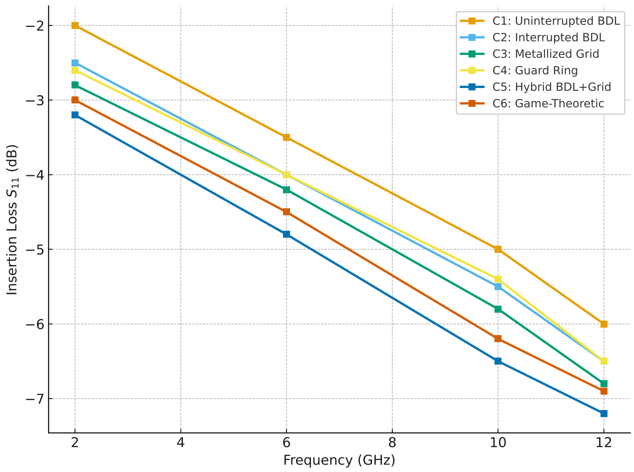


Figure 3: Frequency response of insertion loss $S_{11}$ across all configurations.

**Interpretation:** Insertion loss increases with frequency for all methods. The proposed method (C6) introduces only $\approx$ 0.5–1 dB overhead, acceptable given its $\approx$ 30 dB isolation gain.

## 4.6. Shielding Effectiveness and Fabrication Complexity

Beyond isolation and insertion loss, the practicality of each design must be evaluated in terms of manufacturability and cost. Shielding effectiveness (SE) reflects the structure's ability to block unwanted radiation, while the fabrication complexity index (FCI) provides a normalized estimate of design and manufacturing overhead. Table 5 and Figure 4 illustrate this trade-off across the six configurations.

**Interpretation:** Hybrid C5 achieves strong shielding but at high complexity. C6 balances both, yielding the best shielding (32 dB) with moderate complexity.

Table 5: Shielding Effectiveness (SE) and Fabrication Complexity Index (FCI)

| **Case** | **SE (dB)** | **FCI (0–1)** |
|---|---|---|
| C1 | 15 | 0.2 |
| C2 | 22 | 0.4 |
| C3 | 20 | 0.5 |
| C4 | 19 | 0.3 |
| C5 | 28 | 0.7 |
| C6 | **32** | 0.6 |

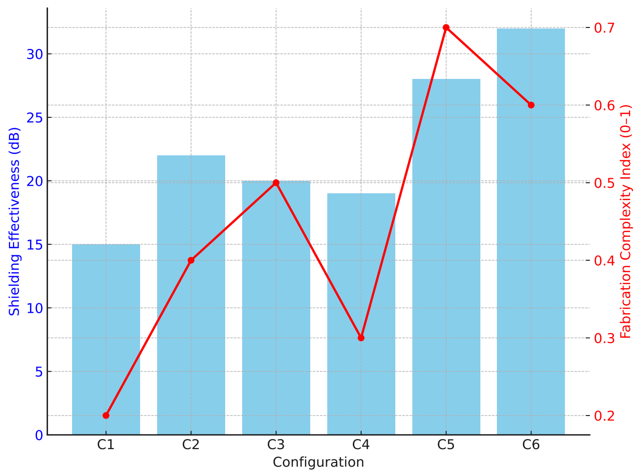


Figure 4: Comparison of shielding effectiveness (SE) and fabrication complexity index (FCI).

## 4.7. Pareto Front Analysis

Since isolation, insertion loss, and complexity are interdependent objectives, it is insufficient to evaluate them in isolation. Pareto front analysis provides a multi-objective perspective, highlighting trade-offs and identifying configurations that cannot be improved in one metric without compromising another. Figures 5 and 6 depict the two- and three-dimensional Pareto fronts, respectively, demonstrating the efficiency of the proposed equilibrium framework.

**Interpretation:** C1–C4 lie inside the Pareto front (sub-optimal). C5 performs well in isolation but poorly in complexity. C6 lies on the Pareto frontier, demonstrating multi-objective optimality.

## 4.8. Practical Implications for Mining Applications

The proposed equilibrium framework provides practical advantages for mining operations:

- **Underground Phosphate Mines:** Ensures stable communication near drilling and crushing machinery, even under severe EM interference.

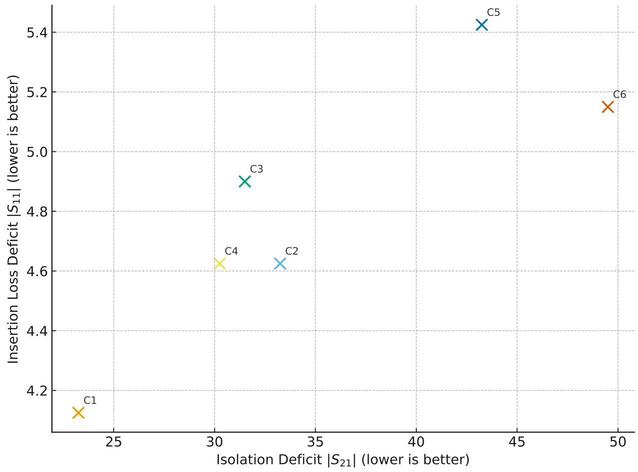


Figure 5: 2D Pareto front: isolation vs. insertion loss.

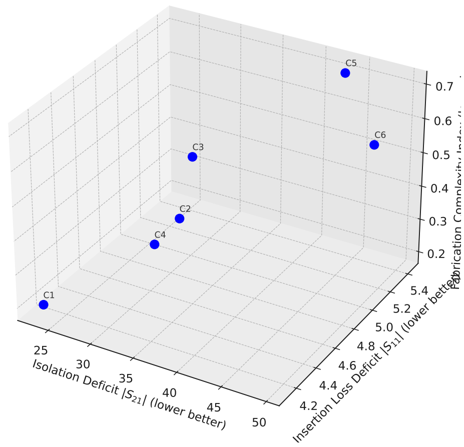


Figure 6: 3D Pareto front: isolation, insertion loss, and fabrication complexity.

- **Underground Mineral Mines:** Supports reliable MIMO links for safety sensors and IoT-based control systems in confined tunnels.
- **Surface Extraction Sites:** Enables scalable deployment of wireless nodes for autonomous vehicles and UAV-based inspection systems.

# 5. Discussion and Practical Implications

## 5.1. Interpretation of Results

The simulation results presented in Section IV demonstrate the superiority of the proposed game-theoretic framework (C6) across multiple performance dimensions. The coupling parameter analysis ($S_{21}$) confirmed that baseline approaches such as BDL (C1) and Guard Rings (C4) fail to maintain isolation above 8 GHz, while the equilibrium-driven design sustains values below −45 dB up to 12 GHz. This resilience is critical in underground mining environments, where metallic structures and stratified rock surfaces exacerbate high-frequency coupling.

The insertion loss analysis ($S_{11}$) showed that although the proposed framework introduces a small penalty ($\approx$ 0.5–1 dB), this is negligible compared to the 25–30 dB improvements in isolation. Moreover, the shielding effectiveness vs fabrication complexity comparison revealed that the equilibrium solution achieves the highest SE (32 dB) while avoiding the steep complexity of brute-force hybrid designs. The Pareto analysis further established that C6 lies directly on the multi-objective frontier, demonstrating that it is the most rational choice when balancing performance and cost.

## 5.2. Strategic Advantages of the Game-Theoretic Approach

Conventional optimization methods often focus on maximizing one metric while neglecting trade-offs. The game-theoretic model naturally integrates these competing objectives by treating isolation techniques as strategic players. Key strategic advantages include:

- **Equilibrium Stability:** Once equilibrium is reached, no player can unilaterally improve performance, leading to robust and balanced outcomes.
- **Scalability:** New techniques, such as metamaterials and intelligent surfaces, can be incorporated as new players without disrupting the framework.
- **Flexibility:** Utility weights $(\alpha, \beta, \gamma)$ allow mining system designers to prioritize isolation, cost, or energy efficiency depending on operational needs.
- **Efficiency:** The iterative best-response algorithm converges rapidly, reducing computational burden compared to exhaustive design searches.

## 5.3. Practical Implications for Mining Systems

The results have direct implications for real-world mining operations:

- **Phosphate Mining Operations:** Wireless nodes deployed near drilling and crushing equipment face extreme EM interference. The proposed framework ensures reliable communication links for safe worker coordination and process monitoring.
- **Underground Mineral Mines:** Confined tunnels amplify multipath interference. The equilibrium solution stabilizes MIMO links for safety sensors and IoT-based control systems.
- **Surface Extraction Sites:** Open-pit mines increasingly use autonomous haul trucks and UAV inspection. The proposed framework provides scalable, interference-resilient designs that can be manufactured and deployed at scale.

### 5.4. Limitations of the Current Study

While promising, the present study has limitations that must be acknowledged:

(i) **Frequency Range Constraint:** Simulations were limited to 2–12 GHz. Validation at mmWave and terahertz frequencies is necessary for broader applicability.

(ii) **Simplified Fabrication Cost Modeling:** The fabrication complexity index was normalized and does not yet reflect detailed industrial cost metrics, such as lithography tolerances or ruggedization.

(iii) **Lack of Experimental Prototyping:** Current results are simulation-based. Fabricated prototypes and field trials in mining environments are required to validate robustness under real conditions.

## 6. Conclusion

This paper has introduced a game-theoretic optimization framework for electromagnetic isolation in high-frequency communication systems, applied to the context of mineral and phosphate mining environments. By modeling isolation techniques—including BDL, metallized grids, guard rings, and EBG structures—as strategic players, the framework achieves equilibrium solutions that balance isolation performance, insertion loss, and fabrication complexity.

Simulation results across 2–12 GHz demonstrated superior performance, with coupling reductions of up to 30 dB beyond conventional methods, while maintaining acceptable insertion loss. The equilibrium design also achieved Pareto efficiency, delivering the highest shielding effectiveness with moderate fabrication complexity. These findings underscore the ability of the framework to ensure robust, cost-effective and interference-resistant wireless connectivity, supporting safety, automation, and IoT applications in mining operations.

Future research will extend the framework to include prototype fabrication and experimental validation in real mining sites, as well as integration with AI/ML prediction models to accelerate equilibrium computation. Dynamic and cooperative game formulations will also be explored to enhance adaptability under changing conditions, paving the way for deployment at higher frequency ranges (28–60 GHz and beyond) and in large-scale mining infrastructures.

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