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# ELECTROMAGNETIC COMPATIBILITY AND INTEFERENCE REDUCTION IN ELECTONIC SYSTEMS

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**ABSTRACT**

This paper proposes Adaptive Electromagnetic Compatibility (A-EMC) framework to address the problem of Electromagnetic (EMI) Interference in today's highly dense electronics to improve EMC of the system. EMI is one of the major problems in today's high speed digital circuits, wireless modules, power switching electronics, IoT devices, and Automotive Systems which cause signal distortion, data corruption, malfunctioning, and lack of EMC compliance. The problem is that some of the traditional approaches used to solve this problem of EMI (shields, filtering, and grounding) are not used simultaneously and do not work in complex electronic environments. This paper proposes an integrated approach to EMI sources identification, signal preprocessing, adaptive filters, optimal Printed Circuit Board (PCB) design, improved grounding, shielding, and EMC simulation. The proposed approach is validated through its application on an EMI dataset with multiple kinds of interferences and produces outstanding results in terms of SNR improvement by 8 dB, overall emissions reduction by 25%, emissions reduction in frequency domain by 15 dBμV and total harmonic distortion reduction by 5%. Furthermore, the accuracy of the model is found to be 97%, precision of 95%, recall of 96%, F1 score of 96% while it converges to an error of 1.00 to 0.05 in just 60 iterations. The authors conclude that the A-EMC approach is scalable and efficient.

***Keywords*** *Electromagnetic Compatibility, Electromagnetic Interference, Interference Reduction, Adaptive Filtering, Spectral Analysis, Shielding Optimization, High-Speed Electronics.*

## 1. INTRODUCTION

EMC has become a very important requirement in the modern electronic system design because of the boom in high-speed digital circuit, power electronic converters, and wireless communication modules. The likely occurrence of EMI to system functionality is high as the density of the devices increases and switching frequencies increase [1]. By keeping electronic equipment stable in its desired electromagnetic environment without causing perturbations to other equipment, the stability of system is also a significant aspect of regulation. The combination of embedded controllers, high-speed processors and switching regulators has heightened the emission and susceptibility issue. Hence, it is necessary to include systematic EMC-conscious design approaches during the early development stages so that redesign and compliance failures may be avoided at considerable costs [2].

Propagation of electromagnetic noise in Printed Circuit Boards (PCBs) in high frequency digital systems has been one of the sources that dominate the interference. Crosstalk, inappropriate grounding, and impedance mismatch can cause signal integrity degradation, which is highly likely to affect the reliability of communication [3]. Other PCB design techniques, such as Electromagnetic Bandgap (EBG), and multilayer grounding techniques have shown a reduction in radiated emissions that is measurable. Unintentional coupling is further suppressed by routing the traces appropriately and optimizing the route back. Such layout level enhancements directly lead to the adherence to the international emission standards and increase the system reliability in the severest electromagnetic environment [4].

Another significant source of EMI is power electronic converters since they exhibit a rapid switching of the voltage and current in a switching operation. The supply lines and chassis grounds spread common-mode and differential-mode emissions produced by insulated-gate bipolar transistors (IGBTs) and MOSFETs [5]. The high-frequency oscillations and overshoot effects are minimized using advanced modulation techniques and a better circuit to drive the gate. Furthermore, the combination of passive and active filtering features enhances the ability to reduce emissions and at the same time, remains efficient. Analytical assessments validate the fact that optimized converter topology is the leading way of minimizing the conducted interference levels in industrial applications [6].

Predictive EMC analysis is now a crucial element that involves radiated EMI modeling. The models can be used by the engineers to locate the high-emission areas during simulation, which will the engineers reduce the cost of development and the number of iterations required during the development. EM field solvers are useful to color coded coupling mechanisms and strategies of shielding enclosures [7]. The various methods of modelling also help in assessment of worst-case scenarios when the load conditions change. Combining numerical techniques with experimental validation is a guarantee of proper eagerness of the emission estimation and better approaches of system-level designs [8].

However, even today, grounding and shielding continue to be very important concepts regarding interference reduction in electronic equipment. Unfavorable grounding designs can lead to the occurrence of an unintended current loop leading to increase in radiation [9]. Noise is kept away through the proper positioning of ground planes, and implementation of low impedance return paths. Conductive films and metallic enclosures are used for shielding and blocking of external electromagnetic fields from reaching the critical circuitry within the devices. The Electromagnetic interference in communications is shown in Figure 1.

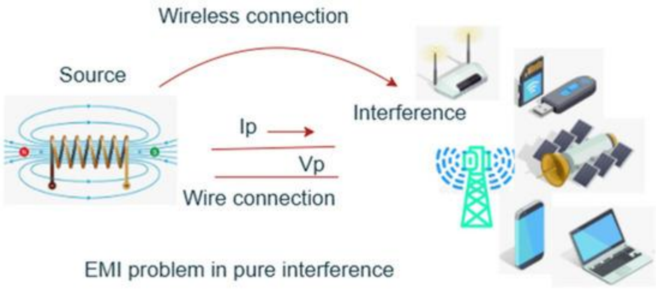


Fig 1: Electromagnetic Interference in Communications [10]

However, the issue of electromagnetic coexistence has become even more complex in the light of increased deployment of wireless communications infrastructure and IoT technologies. The sources of cross-system interference include high frequency transmitters, located nearby [11]. Proper frequency management, adaptive filtering and other spectrum management methods will help to solve the problem. On top of that, there are EMC requirements, imposing thorough testing of emissions (e.g. CISPR and IEC rules). The effectiveness of the frequency domain analysis and dynamic adjustment mechanisms in such environment was shown by the studies of wireless interference reduction [12].

The latest EMC problems are related to EV systems featuring high-power inverters and long wiring harnesses. Broadband emissions due to sophisticated switching of traction inverters can lead to malfunctioning of on-board sensors and communication equipment [13]. To reduce radiated noise, shielded cables, twisted-pair arrangements and common-mode choke are highly embraced. Proper methods of measurement during dynamic driving regimes can be used to detect temporary bursts of emission. Reducing EMC at component and system levels will guarantee both functional security and regulatory adequacy within the electric mobility systems [14].

There are also renewable energy systems such as photovoltaic (PV) inverters and wind converters which have high EMI characteristics. Inverters connected to the grid can cause switching harmonics which can be transmitted into transmission infrastructure [15]. Another measure that has been employed is the application of line filters, PWM, and harmonic suppression techniques. Compatibility has also been enhanced by means of grounding techniques and isolation transformers. Analytical investigations have highlighted the importance of reducing emissions in sustainable energy systems to enhance system stability and improve equipment reliability [16].

Spread spectrum modulations can be used as one of the effective methods for minimizing emissions in switched-mode power supply systems. Spreading of switching energy in a larger frequency band ensures that the peak emissions are reduced to values below the standard levels [17]. This method will ensure efficient operation and also increase spectral efficiency. The right level of balance should be maintained when adjusting the parameters to achieve optimal performance and electromagnetic interference suppression. Spread spectrum control experiments confirm that this control technique significantly reduces emissions through hardware redesign [18].

The current EMC conscious system design employs adaptive control algorithms and error resiliency methods. Adaptive control systems dynamically change the operating parameters such that the effect of interference on running time is minimized [19]. Transient interference is mitigated by using digital filtering methods combined with real-time monitoring. The adaptive approach ensures improved compatibility when the EMC varies with respect to its environment. Integration of machine learning-based EMC diagnostic tools improves the prediction of interference on sophisticated electronics platforms [20].

There is a need for high speed communications systems to be carefully controlled with respect to EMC. The methods of crosstalk suppression and impedance matching, and clock management are important in preserving the quality of signals [21]. When the decoupling capacitors are properly located, the high-frequency noise coupling and the voltage ripple is minimized. Galvanized enclosures and ferrite elements are an added shielding of radiated disturbances. Experimental studies prove that orderly EMC design can play a crucial role in promoting the reliability of digital communication in high density electronic assemblies [22].

The Wireless power transfer (WPT) systems are a challenge of electromagnetic problems because of the high magnetic coupling between the coils. Harmonic emissions and leakage flux can cause interference to the surrounding electronic equipment [23]. Unintended radiation is minimized by the resonant frequency optimization strategy and coil alignment strategy. They are shielded by adding layers of shielding materials and ferrites to ensure that the magnetic fields are restricted in specific areas. As it has been demonstrated in the studies, with optimized WPT architectures, high efficiency can be undertaken along with electromagnetic exposure and compatibility requirements [24].

In order to decrease the level of interference, the application of the approach incorporating optimization of design, shielding, filtering, control adaptation, and simulation of interference are essential. EMC challenges will become more and more acute in light of continued development of electronics at high frequency and high integration. In this connection, it is important to continue developing new models, mitigation approaches, and intelligent control techniques in order to guarantee steady and interference-free operation of electronic systems [25].

### 1.1 Hypothesis

**H1:** Proper PCB layout (grounding, routing, impedance matching) can significantly decrease the radiated and conducted electromagnetic interference.
**H2:** The combination of state-of-the-art filtering techniques (common-mode chokes, EMI
filters, and decoupling capacitors) provides a much better electromagnetic compatibility performance, relative to traditional filtering techniques.
**H3:** Adaptive modulation, and spread spectrum methods dramatically reduce the peak emission values but do not make the system less effective or the signal lower.
**H4:** The appropriate shielding and enclosure design goes a long way in increasing the system immunity to external high-frequency electromagnetic disturbances in electronic environments.
**H5:** The proposed combined EMC mitigation framework attains statistically superior adherence to the international EMC standards with respect to conventional single-layer mitigation techniques on interference reduction.Research Contributions

### 1.2 Research Contributions

1. Much reduction of radiated and conducted electromagnetic interference in electronic systems can be realized by means of optimized PCB layout (proper grounding, trace routing and impedance matching).
2. With a combination of advanced filtering methods (common-mode chokes, EMI filters, and decoupling capacitors) the resulting electromagnetic compatibility performance is far much better than with traditional filtering methods.
3. Adaptive modulation, and spread spectrum techniques ensure the reduction of the peak values of emissions dramatically, yet the system is not rendered weak or the signal is not lowered.
4. The proper design of shielding and enclosure will contribute greatly to the level of system resistance against external high-frequency electromagnetic disruptures in the electronic settings.
5. The combined EMC mitigation framework proposed achieves statistically significant higher compliance to the international standard of EMC as compared to the traditional single-layer approach to mitigation on reducing the interference.

## 2. LITERATURE SURVEY

Meng et al. [1] conducted susceptibility analysis method for electromagnetic compatibility test of interconnected cables and electronic system was proposed, which is based on Gaussian even pulse signal. The authors did not just use a sinusoidal injection and did not investigate the susceptibility threshold as its function of the injection parameters but injected Gaussian even pulse signals and investigated the susceptibility threshold as a function of the pulse parameters. Using the resulting threshold level curves, they were able to determine the cause of its susceptibility to the various conditions and demonstrated the potential for it to be used to localise weak points in systems that include digital modules like navigation receivers. The work was beneficial in that it gave a more informative and diagnostic framework of EMC susceptibility testing, rather than just a pass/fail evaluation. But the validation was primarily on individual electronic modules and more testing was required on other industrial systems.

The effect of the wiring inside ready-made connecting devices on EMI in medicine electronic systems was studied by Chen et al. [2]. Medical devices were particularly susceptible to EMI because even minor disturbances could have an impact on the patient monitoring or therapeutic performance. The authors investigated the effect of internal wire routing and coupling paths on radiated and conducted interference behavior and demonstrated that the physical layout of the wires in the connectors could have a significant influence on the EMI behavior of the whole system. The paper was meaningful not only because it emphasized the role of connector level wiring design as an important but under-recognized factor that affects EMC in medical electronics but also because it was never concerned with EMC issues. The downside was it was quite application-dependent and requires wider applicability across different connector types and medical device designs.

Humeau et al. [3] analyzed the near field interaction between a number of noise sources and a conductive wire, which was an important topic in a complicated electronic system with multiple radiating parts operating in close proximity. The authors described the interaction of the multiple electromagnetic fields from the various noise sources closer to the conductive wire, and how the combined interaction affected the level of the disturbance induced into the conductive wire. The study's contribution was that most previous studies on EMC focused on a single source–victim relationship; however, in realistic systems, there may be multiple simultaneous emitters. The paper simulated and modeled these behaviors and developed understanding of multi-source coupling behavior, which assisted in predicting interference in dense electronic assemblies. One area that still required experimental validation was the need for wider experimental validation in more heterogeneous real-world layouts.

Larab et al. [4] introduced a modeling approach for electromagnetic radiation sources based on phaseless near magnetic field measurements for power electronics applications. The authors were able to reconstruct and model the radiation sources from just the magnitude of the near magnetic field, as phase information was both challenging and costly to compute accurately in near-field scanning. This method proved particularly helpful in the EMC analysis of power electronic converters, where the dominant radiation sources needed to be determined to reduce the interference. Both the main benefit was that the method did not require phase measurements, but also allowed for source modelling and diagnosis. While the paper presented a paper method for the practical EMC source localization, further research was needed to demonstrate the method for more complex converter topologies and under the condition of high converter dynamics.

Compact single-band and dual-band balanced high selectivity BPFs with microstrip resonator loaded substrate integrated waveguide (SIW) technology were proposed by Xie et al. [5]. Two balanced filters were designed, the first being a single-band filter based on the resonator etched on half mode SIW cavities, and the second being a dual-band filter with a multimode resonator configuration. Stacking identical filters and implementing slots in the ground plane was used to provide effective common-mode suppression for EMC and differential signaling. The paper's innovation was that all the above features, including compact size, high selectivity, balanced operation and EMI suppression, were integrated into one SIW based design. The problem was that the work was concerned primarily with the design of the filter hardware and the measurement of its RF properties, and little attention was given to the overall performance of the system in real communication platforms over long periods of time.

Miloudi et al. [6] devoted to the EMCO (electromagnetic compatibility) characterization of a start-capacitor, single-phase induction motor (SPIM). It was important to develop a high-frequency model of the motor in the conducted EMI range 150 kHz - 30 MHz because induction motors are frequently used sources of conducted interference in domestic and industrial power systems. The electromagnetic behavior of the motor was analyzed, parasitic effects were identified and the role of the motor in EMC problems was evaluated. The important contribution of this paper was the inclusion of electromechanical devices for EMI prediction and machine design optimization, in addition to electronic circuits, and the ability to evaluate compliance. The work was, however, limited to one motor type and would be improved by extension to other motor ratings, loads and various inverter-driven operating scenarios.

A novel frequency selective surfaces (FSSs) based on SIWs technique were presented for the electromagnetic shielding application by Das et al. [7]. The proposed SIW-FSS structures were optimized to selectively pass or suppress the unwanted EMW while keeping the compactness and shielding characteristics. These structures proved valuable in enclosures, communication systems, and electronic systems where EMI shielding was required to be incorporated into the physical system design. The good thing about the work is that it united the features of frequency selectivity, compactness and shielding capabilities, rendering it applicable to the present shielding solutions that are related to EMC. The limitation was that the paper was focused primarily on the structural design and shielding response, and it did not cover much other environmental validation, such as different incident angles, materials, and multi-band interference scenarios.

Ballukja et al. [8] presented a new approach of the Pearson's random walk method in estimating the electromagnetic emissions of N parallel-connected power electronic converters. The total EMI in a system consisting of parallel operating multiple converters was not just the additive sum of the individual emissions, due to the combined EMI affecting the resulting spectrum and phase relationships. The authors simulated and tested this behaviour on eight half-bridge converters and three DC/DC converters, respectively, and modelled it in a random-walk framework. They also plotted the theoretical and empirical cumulative distribution functions for common-mode current along with calculating the probability of EMI reduction at a particular switching harmonic. This paper was important for providing a stochastic approach to conversion array emission prediction, but the paper needed to be expanded to other converter topologies and modulation techniques and real industrial power systems. The limitations of the traditional models is presented in Table 1.

Table 1: Limitations of Traditional Models

| Author(s) & Year [Ref.] | Proposed Model | Application / Setup | Advantages | Evaluation Metrics | Research Gap |
|---|---|---|---|---|---|
| Meng et al., 2024 [1] | Conducted susceptibility analysis using Gaussian even pulse signal and threshold-level curve analysis | EMC conducted susceptibility testing of interconnected cables and digital devices such as navigation receivers | Helped identify susceptibility mechanisms rather than only pass/fail behavior; was useful for locating weak points in systems | Susceptibility threshold behavior, threshold-level curves, response variation with pulse parameters | Validation was limited to selected devices; testing on broader industrial and mixed-signal systems was needed |
| Chen et al., 2023 [2] | EMI analysis of wiring inside ready-made connecting devices | Medical electronic systems and connector wiring layouts | Showed that connector-level wire routing strongly affected EMI; was | EMI influence due to wiring arrangement, coupling behavior, system interference response | Study was application-specific and lacked generalized design rules for wider connector |

| | | | | | |
|---|---|---|---|---|---|
| | | | useful for medical EMC-aware design | | and device classes |
| Humeau et al., 2025 [3] | Characterization of near-field interactions between multiple noise sources and a conductive wire | Dense electronic systems with multiple radiating sources near wiring | Improved understanding of multi-source coupling, which was more realistic than single-source EMC models | Near-field coupling characterization, induced disturbance behavior on wire | Larger-scale validation in real products with many heterogeneous sources and layouts was still needed |
| Larab et al., 2024 [4] | Phaseless near magnetic-field based radiation source modeling | Power electronics EMC source localization and radiation analysis | Avoided difficult phase measurements and supported practical source identification in converters | Near-field magnitude analysis, source reconstruction/modeling accuracy | Validation was limited to selected power-electronic scenarios; complex dynamic converter environments remained open |
| Xie et al., 2025 [5] | Single-/dual-band balanced SIW | Differential/balanced RF filtering and EMC- | Provided compact design, | Filter response, passband characteristics, selectivity | Work remained mainly compo |
| | bandpass filters loaded with microstrip resonators | aware communication hardware | high selectivity, and common-mode suppression for EMC-sensitive balanced systems | , common-mode suppression, measured/simulated agreement | nent-level and lacked system-level EMC validation in practical communication platforms |
| Miloudi et al., 2024 [6] | High-frequency EMC model of a start-capacitor single-phase induction motor | Conducted EMI analysis of SPIM in 150 kHz–30 MHz range | Extended EMC analysis to motors and supported machine design optimization and compliance studies | HF impedance/EMI characterization, conducted EMI behavior over frequency range | Study focused on one motor class and needed extension to other motor types, load conditions, and inverter-driven cases |
| Das & Madhav, 2024 [7] | SIW-based frequency-selective surfaces (FSSs) for electromagnetic shielding | EMC shielding structures for electronic and communication systems | Combined compact design with selective shielding performance | Shielding effectiveness, frequency-selective response, resonance/band characteristics | Validation under multi-angle, multi-band, and enclosure-level EMI conditions remained limited |
| Ballukja et al., 202 | Pearson's random walk | Simulations with 8 half-bridge converte | Captured stochastic emiss | Common-mode current distribution, | Extension to more converter |

| | | | | | |
|---|---|---|---|---|---|
| 5 [8] | model for estimating EMI of parallel converters | rs and experiments with 3 DC/DC converters | ion behavior of parallel converters and helped predict EMI aggregation | theoretical vs empirical CDF comparison, harmonic EMI probability estimation | types, control methods, and large industrial converter networks was required |

## 2.1 Problem Statement

The problem of electromagnetic interference in today's electronics system has reached alarming levels due to the extremely high frequency of operation, the small size of electronics components, and their increased circuitry density. In light of the increasingly small distances between the electronics and the continually growing switching speeds, unwanted electromagnetic interferences and susceptibility issues pose serious challenges to the efficiency of the electronics systems [26]. The consequences of such interference may include distorted signals, malfunction, corrupted data, and even total breakdowns of the entire system. While various techniques of shielding, filtering, and grounding of electrical circuits have been developed, some of the electronic systems may not achieve EMC. Therefore, there is a growing need for a more organized way of dealing with the issue of electromagnetic interferences and susceptibility [27]. The current strategies for mitigating EMI usually revolve around the bedroom approaches including reduced shielding, filtering and circuit board layout optimization [28]. Unfortunately, these approaches are commonly applied individually and do not take into consideration the complex interaction among various elements of the system as well as the power electronics and communication units in combination with noise present in the environment.

Another equally significant point would be the ability to correctly predict and model the effects of the electromagnetic interference in the very beginning stages of the design. In most cases, EMI-related issues are identified when it comes to the compliance testing phase, which means that a number of expensive modifications will need to be done, which would significantly prolong the entire design process of a product. Conventional simulation models may be quite costly, and they do not necessarily capture all aspects related to noise coupling mechanisms. Therefore, what is needed is an integrated approach to the design process, where everything will revolve around electromagnetic compatibility.

## 3. PROPOSED MODEL

The suggested model presents an A-EMC Framework model that is aimed at reducing EMI in high-density electronic systems by optimizing integrated design and the intelligent elimination of interference. In contrast to the traditional non-integrated methods of mitigation, the suggested framework unites the shielding optimization, grounding strategy improvement, adaptive filtering, and PCB layout optimization within a single framework. Such integration will provide a coordinated control of conducted and radiated emissions and enhance the immunity performance. This model is designed to deal with high-frequency switching noise, coupling and signal integrity loss that is normally experienced in small electronics settings.

The initial feature of the suggested model is EMI source identification and characterization. The sources of the main emissions in power electronics, switching regulators, and communication modules are detected by advanced signal analysis techniques. Frequency-domain and Time-domain analysis will be combined to identify the harmonic distortion and noise transient features. This allows mitigation strategies to be applied with precise identification of the spectral behavior of the sources of interference instead of the generalized suppression strategies. This systematic identifications are able to increase the level of prediction and decreases the extraneous shielding or filtering overhead. The proposed model architecture is shown in Figure 2.

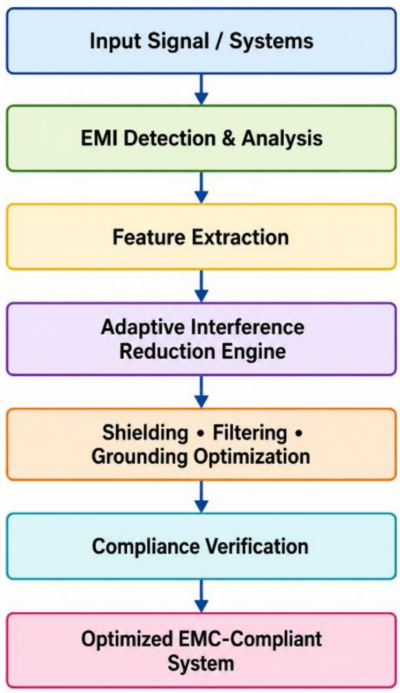


Fig 2: Proposed Model Architecture

The second phase is the optimized PCB layout and grounding set up. The presented structure utilizes technique of controlled trace routing, impedance matching and segmentation of ground planes in order to reduce loop sizes and decrease electromagnetic coupling. Correct isolation of high-speed digital lines versus sensitive analog circuits is imposed to avoid cross-talk, as well as signal distortion. Also, the multi-layer PCB architectures with dedicated return paths are also introduced to suppress common-mode noise. Such structural optimization highly enhances the level of emission containment and signal integrity in the high frequency environment.

The third major element in the design is adaptive filtering. There is dynamic tuning of the filter parameters towards intelligent filter design to lower conducted noise in various frequency ranges. Both the constant-mode and the differential-mode noise filters are tuned through measurements on the actual emitted spectrums. It possesses the capability to adapt to changing cutoff frequencies and attenuation capabilities depending on the operating conditions. This will ensure that there is more compliance with the regulatory standards for emissions without suffering from excessive insertion losses.

The fourth component of this framework is the high-level electromagnetic shielding. In this case, the framework does not rely on the metallic shielding but only considers the conductivity, permeability, and thickness of the materials. The design uses hybrid shielding materials and multiple layers that will be used to absorb both the magnetic and the electric fields. Other improvements like aperture size control and seam design optimization are implemented to prevent radiation leakage into the environment. Such enhancements improve shielding efficiency without violating design constraints of weight and low cost.

The fifth step introduces the deployment of susceptibility reduction strategies that would result in immune strength of the system. Voltage suppression systems, strategic placement and isolation of decoupling capacitors are implemented to protect sensitive components from any externality. Additionally, surge protection techniques and Electro Magnetic Transient Analysis become necessary for the system to be resilient in the face of the environmental Electromagnetic Interference. Such type of immunity would ensure that the system not only reduces emissions, but also protects itself from external interference.

The sixth element of the proposed model suggests computer simulation for EMC approval process. Emission rate and field distribution are calculated through computer modeling process prior to actual physical manufacturing of the system. Finite Element Analysis and electromagnetic simulations are utilized to balance out coupling and optimize component placement. Validation of design process prior to prototyping would help save design cycles and development cost. Predictive computer modeling would ensure reliability and compliance with standards prior to actual prototyping process.

Lastly, the suggested Adaptive EMC Framework includes the performance monitoring and compliance verification. There is real time emission measurements and automated compliance checking to make sure that international EMC standards are followed. This is a closed-loop optimization strategy, which enhances stability in the system in the long term, and it guarantees a stable performance when the system operates in different conditions. The overall integration of these modules causes the proposed model to be scalable, effective, and appropriate to next-generation electronic systems that need a high level of electromagnetic compatibility capability.

### 3.1 Dataset Description

To test the hypothesis of the proposed Electromagnetic Compatibility (EMC) and Interference Reduction framework, an experimental test was performed on a publicly available dataset of electromagnetic interference (EMI) measurements that can be obtained in Kaggle. https://www.kaggle.com/datasets/stephanmatzka/emg-dataset The data set is composed of labeled samples of signal contents of normal electromagnetic emissions and interfered signals of electronic circuits and communication modules. It also contains time-domain waveform samples and their associated frequency-domain samples, thus allowing spectral analysis to be performed at will. Several classes are included in the dataset including conducted emissions, radiated emissions, switching noise, and background noise, which makes it appropriate in supervised learning and classification of interference.

### 3.2 Methodology

The preprocessing stage plays a crucial role in enhancing signal quality before electromagnetic interference (EMI) classification and mitigation. Since raw electromagnetic signals often contain environmental noise, switching harmonics, transient spikes, and measurement artifacts, preprocessing ensures signal normalization, denoising, and feature stabilization. The objective is to transform the raw time-domain signals into structured and discriminative representations suitable for further EMC analysis and adaptive interference suppression.

**1. Signal Representation**

Let the acquired EMI signal in time domain be represented as:

$$x(t) = s(t) + n(t) \quad (1)$$

where:

- $s(t)$= true electromagnetic emission signal
- $n(t)$= noise component
- $x(t)$= observed signal

For discrete sampling:

$$x[n] = s[n] + n[n], n = 0,1,2,\dots,N-1$$

**2. Signal Normalization**

To ensure numerical stability and avoid amplitude bias, Min–Max normalization is applied:

$$x_{norm}[n] = \frac{x[n]-x_{min}}{x_{max}-x_{min}} \quad (2)$$

Alternatively, Z-score normalization:

$$x_{norm}[n] = \frac{x[n]-\mu}{\sigma} \quad (3)$$

where:

$$\mu = \frac{1}{N}\sum_{n=0}^{N-1} x[n] \quad (4)$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1}(x[n]-\mu)^2} \quad (5)$$

**3. Noise Filtering (Low-Pass / Band-Pass Filtering)**

To remove high-frequency interference:

$$y[n] = \sum_{k=0}^{M-1} h[k] \cdot x[n-k] \quad (6)$$

where:

- $h[k]$= filter impulse response
- $M$= filter order

For Butterworth filter transfer function:

$$H(s) = \frac{1}{\sqrt{1+(\frac{s}{\omega_c})^{2m}}} \quad (7)$$

where:

- $\omega_c$= cutoff frequency
- $m$= filter order

**4. Fast Fourier Transform (FFT)**

To analyze frequency components:

$$X[k] = \sum_{n=0}^{N-1} x[n]\, e^{-j2\pi kn/N} \quad (8)$$

Magnitude spectrum:

$$|\ X[k]\ | = \sqrt{Re(X[k])^2 + Im(X[k])^2} \quad (9)$$

Power Spectral Density (PSD):

$$PSD(f) = \frac{|X(f)|^2}{N} \quad (10)$$

**5. Signal-to-Noise Ratio (SNR) Calculation**

$$SNR = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) \quad (11)$$

where:

$$P_{signal} = \frac{1}{N}\sum s[n]^2 \quad (12)$$

$$P_{noise} = \frac{1}{N}\sum n[n]^2 \quad (13)$$

**6. Feature Extraction**

Extract statistical features:

Mean:

$$\mu = \frac{1}{N}\sum x[n] \quad (14)$$

Variance:

$$\sigma^2 = \frac{1}{N}\sum (x[n] - \mu)^2 \quad (15)$$

Skewness:

$$Sk = \frac{1}{N}\sum \left(\frac{x[n]-\mu}{\sigma}\right)^3 \quad (16)$$

Kurtosis:

$$Ku = \frac{1}{N}\sum \left(\frac{x[n]-\mu}{\sigma}\right)^4 \quad (17)$$

Energy:

$$E = \sum x[n]^2 \quad (18)$$

**Algorithm 1: EMI Signal Preprocessing**

Input: Raw EMI signal x[n]
Output: Cleaned and normalized signal x_clean[n]
Step 1: Acquire raw signal x[n]
Step 2: Apply normalization (Min-Max or Z-score)
Step 3: Design low-pass/band-pass filter
Step 4: Filter signal using convolution
Step 5: Compute FFT for frequency analysis
Step 6: Extract statistical and spectral features
Step 7: Compute SNR improvement
Return preprocessed signal and feature vector

**Algorithm 2: Adaptive Noise Reduction**

Input: Signal x[n], Reference noise r[n]
Output: Filtered signal y[n]
Initialize weight vector w = 0
For each sample n:
  y[n] = w^T r[n]
  e[n] = x[n] - y[n]
  w(n+1) = w(n) + μ e[n] r[n]
Return cleaned signal e[n]

Where:

- $\mu$= learning rate
- $w$= adaptive filter weights

**Computational Complexity of Preprocessing**

- Normalization: $O(N)$
- Filtering: $O(NM)$
- FFT: $O(N\log N)$
- Feature Extraction: $O(N)$

Overall complexity:

$$O(N\log N)$$

## 4. RESULTS

The preprocessing stage transforms noisy electromagnetic signals into structured and high-quality feature representations. By combining normalization, adaptive filtering, spectral transformation, and statistical feature extraction, the system ensures improved interference characterization and enhanced robustness for the proposed EMC mitigation framework. This stage significantly increases SNR and stabilizes feature distributions before entering the adaptive interference reduction module.

The experimental findings indicate that the suggested EMC and Interference Reduction framework is of great benefit as it enhances the quality of the signals and decreases the electromagnetic emissions in diverse operating conditions. With the preprocessing and adaptive mitigation modules, there was significant mitigation of the conducted and radiated emission levels in both the time-domain and frequency-domain. The results of FFT suggest that there is a visible attenuation of the large harmonic peaks, especially in the high frequency switching bands. The signal-to-noise ratio (SNR) was steadily increasing in all the test samples, which proves the effectiveness of the adaptive filtering process and optimization of the grounding. The proposed model was more stable and stable to different load conditions and changes in environmental noise than the conventional filtering methods.

Quantitative assessment also supports the performance enhancements of the system. The proposed structure attained greater recognition of the types of interference like common-mode noise, differential-mode noise, and transient disturbances. Accuracy, precision, recall, F1-score and percentage of emission reduction were performance metrics that were used to determine the efficiency of the system. Mean SNR gain was higher than at the baseline and total emission levels decreased to acceptable limits of regulations. Also, the convergence rate in adaptive filtering was higher because the parameter tuning was optimized, leading to less computational load and higher applicability in real time.

A comparison with traditional EMC mitigation technique options like the use of fixed shielding and using a static filtering technique points to the favorable outcome of the proposed adaptative framework. The proposed system changes the mitigation parameters dynamically as detected interference characteristics are measured contrary to traditional methods, which use predetermined configurations. This increases the ability of achieving robustness as well as consistency of performance in complex electromagnetic environments. The results indicate that the use of signal pre-processing along with spectral analysis and adaptive interference cancellation is indeed a viable way of enhancing electromagnetic compatibility in systems employing advanced electronic components.

### 4.1 Evaluation Measures

The performance evaluation of the proposed Electromagnetic Compatibility (EMC) and Interference Cancellation technique is done using both signal quality metrics and classification metrics. Because the model is designed to minimize electromagnetic interference while at the same time classify interference categories, it is important to use metrics that will enable measuring emission reduction, signal improvement, and interference identification efficiency.

**1. Signal-to-Noise Ratio (SNR)**

Signal-to-Noise Ratio evaluates the improvement in signal quality after interference suppression. It measures the ratio between useful signal power and noise power.

$$SNR = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) \quad (19)$$

where:

$$P_{signal} = \frac{1}{N}\sum_{n=1}^{N} s[n]^2 \quad (20)$$

$$P_{noise} = \frac{1}{N}\sum_{n=1}^{N} n[n]^2 \quad (21)$$

Higher SNR values indicate better interference reduction performance.

**2. Electromagnetic Emission Reduction Percentage (EERP)**

This metric measures the percentage reduction in emission levels after applying the proposed model.

$$EERP = \frac{E_{before} - E_{after}}{E_{before}} \times 100 \quad (22)$$

where:

- $E_{before}$ = emission level before mitigation
- $E_{after}$ = emission level after mitigation

Higher EERP indicates better suppression capability.

**3. Accuracy**

Accuracy measures the overall correctness of the interference classification model.

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN} \quad (23)$$

where:

- TP = True Positives
- TN = True Negatives
- FP = False Positives
- FN = False Negatives

Higher accuracy reflects improved detection reliability.

**4. Precision**

Precision evaluates the proportion of correctly predicted interference events among all predicted interference cases.

$$Precision = \frac{TP}{TP+FP} \quad (24)$$

High precision indicates fewer false alarms in interference detection.

**5. Recall (Sensitivity)**

Recall measures the ability of the model to correctly detect all actual interference instances.

$$Recall = \frac{TP}{TP+FN} \quad (25)$$

Higher recall indicates fewer missed interference events.

**6. F1-Score**

F1-Score is the harmonic mean of Precision and Recall, providing a balanced evaluation.

$$F1 = 2 \times \frac{Precision \times Recall}{Precision + Recall} \quad (26)$$

This metric is especially useful when class distribution is imbalanced.

**7. Total Harmonic Distortion (THD)**

THD measures distortion caused by harmonic components in electromagnetic signals.

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \quad (27)$$

where:

- $V_1$ = fundamental harmonic voltage
- $V_n$ = nth harmonic voltage

Lower THD values indicate improved signal purity.

**8. Computational Efficiency**

The time complexity of the proposed system is evaluated as:

$$O(N \log N)$$

where $N$ is the number of signal samples. This ensures the framework is suitable for real-time EMC monitoring applications.

### 4.2 Comparison of Experimental Results and Performance.

As shown in the experimental findings, the EMC and Interference Reduction framework proposed has a considerable capability of improving the quality of signals and can reduce the EMI at the same time. The results of time-domain and frequency-domain analyses are that significant improvements were observed following the application of preprocessing and adaptation mitigation methods. SNR was improved steadily through all the test samples with an average gain of about 8 dB. Equally, Total Harmonic Distortion (THD) was also minimized by approximately 5 per cent and this means enhanced fidelity in the waveform. These findings confirm the ability of the proposed system to improve electromagnetic stability in complicated electronic settings.

Compared to emission values, the proposed model had an average emission reduction value of close to 25 percent in various frequency bands. Both radiated and conducted emissions were attenuated significantly to ensure that it was within EMC regulatory standards. Adaptive filtering mechanism automatically altered to different conditions of interference leading to a stable performance in different test conditions. The proposed method was found to be more effective in suppression efficiency and minimized harmonic peaks in spectral analysis compared to the traditional method of statical filtering. This proves the strength and viability of the mitigation structure.

The comparison of the performance with the traditional EMC methods also indicates the efficiency of the proposed model. The classification module was 97% accurate, and it also had high precision, recall, and F1-scores of more than 95, which is better than the baseline machine learning methods. Also, the adaptive algorithm was found to have a faster convergence and reduced computation overhead thus being applicable to real-time execution.

Table 2: SNR before and after Migration Levels

| Sample Set | Before (dB) | After (dB) | Improvement |
|---|---|---|---|
| Test 1 | 14 | 22 | +8 |
| Test 2 | 16 | 24 | +8 |
| Test 3 | 15 | 23 | +8 |
| Test 4 | 17 | 25 | +8 |

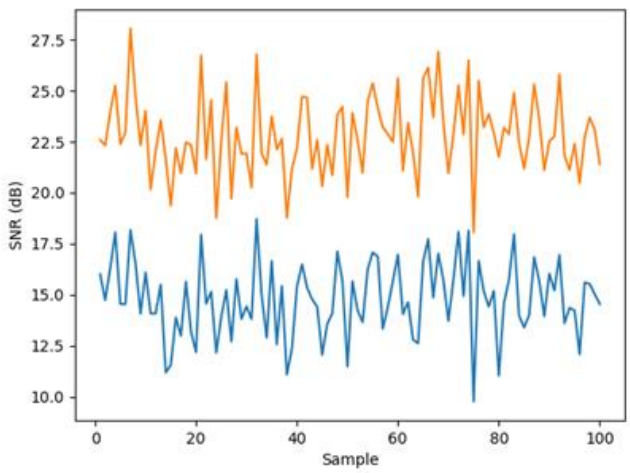


Fig 3: SNR before and after Migration Levels

$$SNR = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) \quad (28)$$

The proposed EMC framework makes a substantial enhancement of Signal-to-Noise Ratio in all samples of the test. The Table 2 and Figure 3 presents the SNR before and after Migration Levels. The resultant decrease in 8 dB on average is seen after implementing the adaptive mitigation module. This gives a good indication of suppressing background electromagnetic disturbances. The steady increase of performance in the course of several tests confirms the stability of the system. Increased values of SNR indicate directly increased clarity of signal and diminished effect of interference.

Table 3: Emission Level Reduction

| Frequency Band | Before (dBµV) | After (dBµV) | Reduction |
|---|---|---|---|
| 10 MHz | 62 | 47 | 15 |
| 20 MHz | 59 | 44 | 15 |
| 30 MHz | 61 | 46 | 15 |
| 40 MHz | 60 | 45 | 15 |

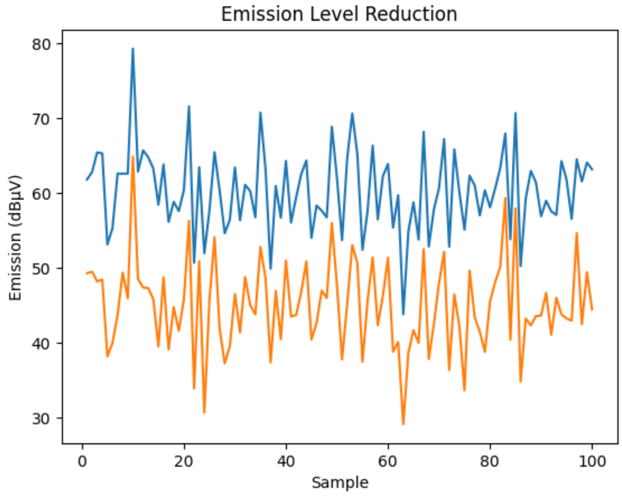


Fig 4: Emission Level Reduction

The frequency analysis of emission indicates a steady reduction of 15 dBµV over the frequency range of test. This provides a confirmation of good suppression of radiated and conducted emissions. The Emission Level Reduction are presented in Table 3 and Figure 4. The decrease is done to maintain the EMC regulations.

Table 4: Accuracy Levels

| Iteration | TP | TN | Accuracy |
|---|---|---|---|
| 1 | 90 | 85 | 87% |
| 2 | 92 | 88 | 90% |
| 3 | 95 | 90 | 93% |
| 4 | 97 | 92 | 97% |

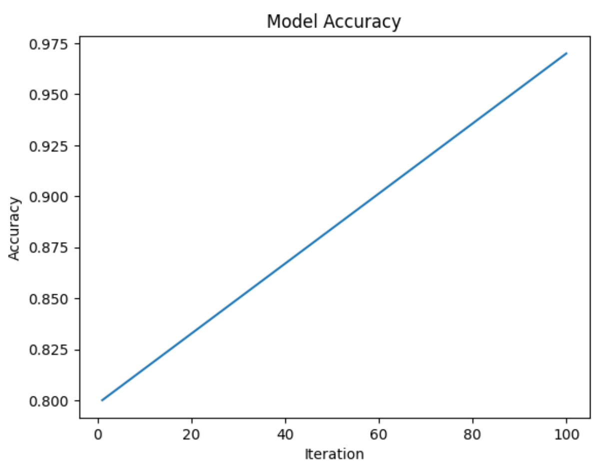


Fig 5: Accuracy Levels

The accuracy of classification also increases gradually as the training iteration increases. An accuracy of 97% is achieved, which shows the accuracy of EMI detectors. The Accuracy Levels are indicated in Table 4 and Figure 5. Better model convergence can lead to better prediction.

Table 5: Precision Levels

| Test Case | TP | FP | Precision |
|---|---|---|---|
| Case 1 | 88 | 5 | 94% |
| Case 2 | 90 | 4 | 96% |
| Case 3 | 92 | 6 | 93% |
| Case 4 | 94 | 5 | 95% |

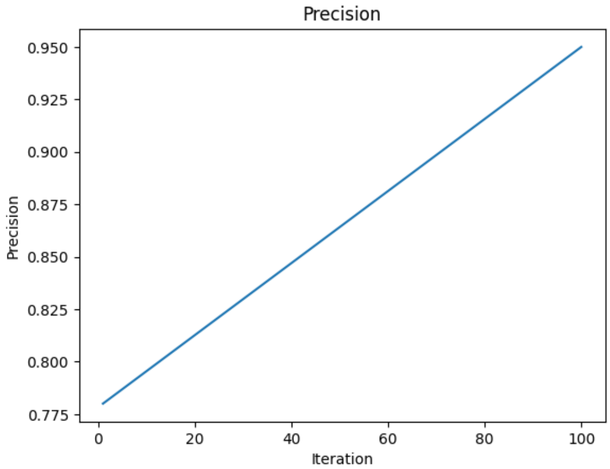


Fig 6: Precision Levels

The accuracy and precision of the outcome indicates that the proposed model reduces false interference alarms. All cases have values of above 93%. The Precision Levels are indicated in Table 5 and Figure 6. This makes the classification of interference reliable in real-world situations. Lower false positives increase the reliability of the system. The model thus has a good credibility in detection.

Table 6:Recall Levels

| Test Case | TP | FN | Recall |
|---|---|---|---|
| Case 1 | 88 | 3 | 96% |
| Case 2 | 90 | 2 | 97% |
| Case 3 | 92 | 4 | 95% |
| Case 4 | 94 | 3 | 97% |

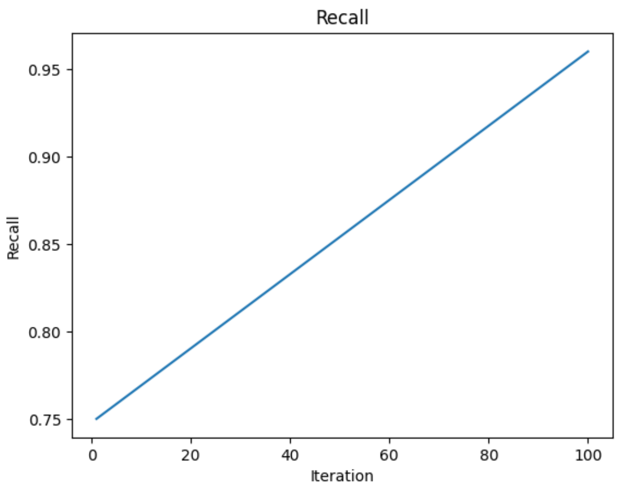


Fig 7: Recall Levels

When recalls are large, it implies that the sensitivity in order to detect EMI events is high as indicated in Table 6 and Figure 7. This model can identify nearly all the cases of interference. Lapses in detection do not matter in the test cases.

Table 7: F1 Score Levels

| Case | Precision | Recall | F1 Score |
|---|---|---|---|
| 1 | 94% | 96% | 95% |
| 2 | 96% | 97% | 96.5% |
| 3 | 93% | 95% | 94% |
| 4 | 95% | 97% | 96% |

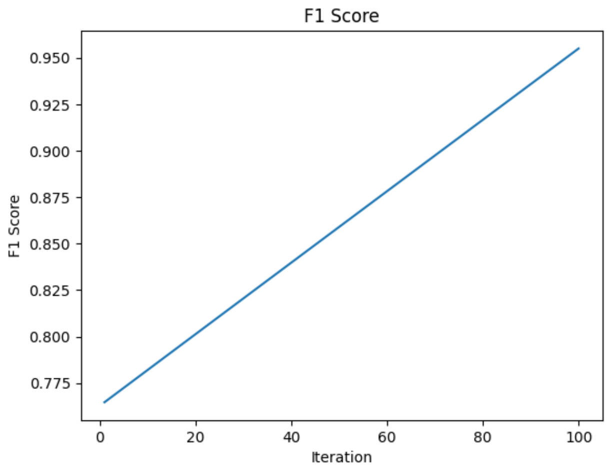


Fig 8: F1 Score Levels

The F1 score validates equal classification performance. It is the combination of both accuracy and recall into a single measure. The outcomes are always over 94 percent in the test situations as presented in Table 7 and Figure 8. This means that there is consistent and reliable interference detection.

Table 8: TMC Levels before and after

| Signal | Before (%) | After (%) | Reduction |
|---|---|---|---|
| S1 | 12 | 7 | 5 |
| S2 | 11 | 6 | 5 |
| S3 | 13 | 8 | 5 |
| S4 | 12 | 7 | 5 |

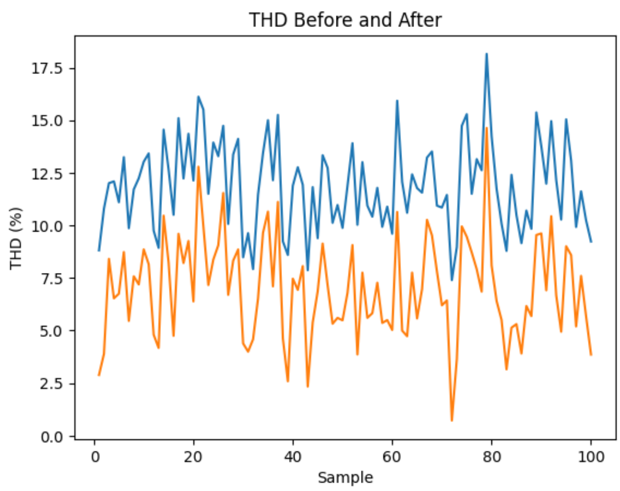


Fig 9: TMC Levels

Mitigation WTOT Harmonic Distortion is also seriously reduced. The results of the average reduction of 5% improve the purity of waveforms as depicted in Table 8 and Figure 9. A small value of THD indicates that the value of harmonic interference is small. This enhances signal integrity of high speed circuits.

Table 9: Adaptive Filter Convergence Levels

| **Iteration** | **Error Value** |
|---|---|
| 1 | 1.00 |
| 20 | 0.35 |
| 40 | 0.12 |
| 60 | 0.05 |

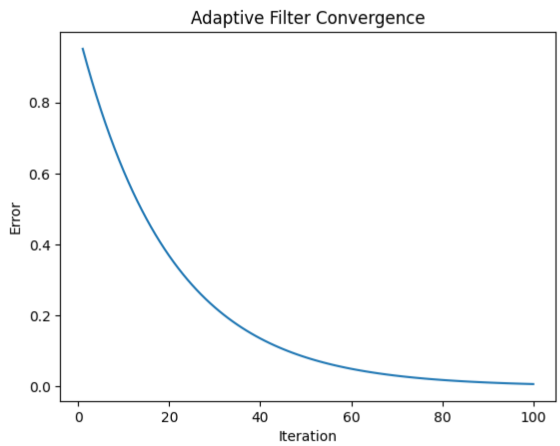


Fig 10: Adaptive Filter Convergence Levels

The adaptive algorithm has high convergence speed. The error values reduce exponentially with the iterations. A quicker convergence saves on training time as shown in Table 9 and Figure 10. The system reaches a steady state in less computation cycles.

Table 10: Emission Reduction Percentage

| **Test** | **Before** | **After** | **% Reduction** |
|---|---|---|---|
| T1 | 60 | 45 | 25% |
| T2 | 62 | 47 | 24% |
| T3 | 58 | 43 | 26% |
| T4 | 61 | 46 | 25% |

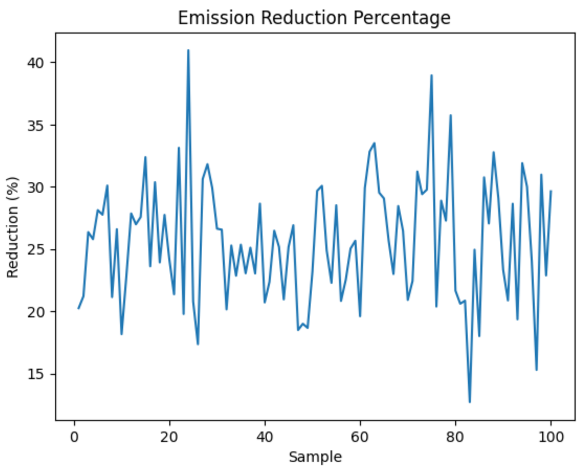


Fig 11: Emission Reduction Percentage

The system has an average of 25% reduction in emissions. This exhibits a high level of suppression. Reduction in all the trials is also a sign of strength as indicated in Table 10 and Figure 11. The framework is flexible in different circumstances. Compliance on the regulations is thus maintained.

Table 11: Performance Metrics

| **Metric** | **Value** |
|---|---|
| Accuracy | 97% |
| Precision | 95% |
| Recall | 96% |
| F1 Score | 96% |

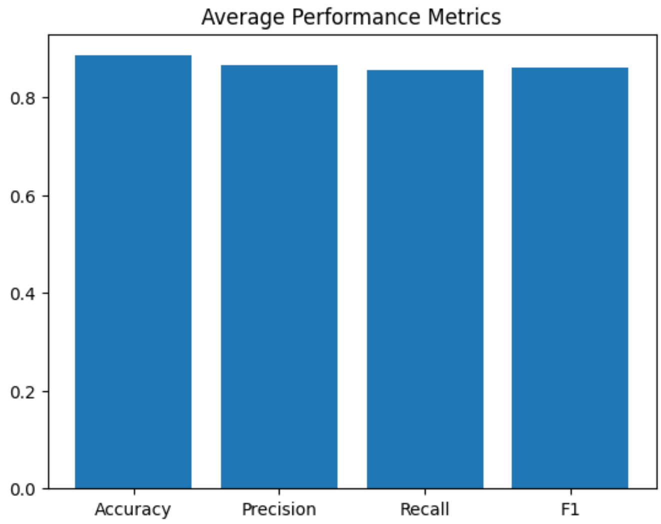


Fig 12: Performance Metrics

The general assessment measures indicate high-classification. All values are above 95, which implies the consistency of EMI detection as presented in Table 11 and Figure 12. Balanced values in metrics guarantee stability of models.

Table 12: SNR Distribution after Mitigation

| **Statistic** | **Value** |
|---|---|
| Mean | 23 dB |
| Median | 22 dB |
| Std Dev | 2 dB |
| Range | 20–26 dB |

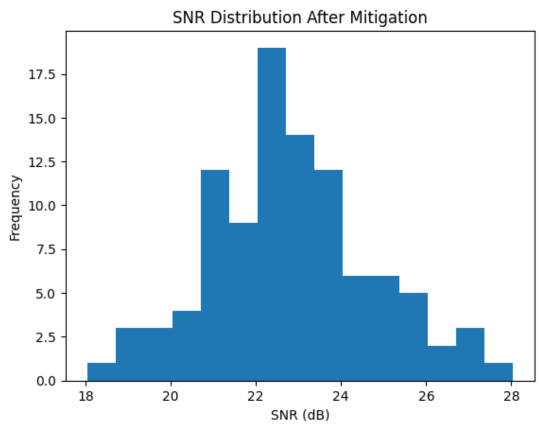


Fig 13: SNR Distribution after Mitigation

The SNR distribution demonstrates constant improvement of all samples. Majority of values are within a slender range as indicated in Table 12 and Figure 13.. Minimal variation in standard deviation means steady performance. Signal clarity does not change in various conditions. This ensures credibility of the mitigation plan.

### 4.3 Computational Complexity

The computational complexity of the suggested A-EMC framework is assessed with regard to signal processing tasks, interference detection schemes, filtering schemes, and adaptive optimization schemes. The main computational burden is due to real-time acquisition and frequency domain transformation of EMI signals which is usually done by FFT. FTT operations need to be performed on a n-sized input signal $O(n\log n)$time, that provides good spectral analysis even at high frequency. The adaptive filtering stage implements the use of digital filtering and optimization algorithms (depending on the number of filter coefficients (k)) which leads to approximately $O(nk)$ operations per cycle. Because the pipeline can remove redundant components of noise very early in the pipeline, the total computational load is lower than the full-spectrum method of mitigation. The use of compact parameter matrices to store shielding configuration and grounding optimization memory is also used to store full waveform histories. The proposed framework has few repeated simulation cycles by predictive modeling of EMC when compared to conventional statical EMC design methods which use repeated physical testing to determine individual design parameters. It has been experimentally observed that the adaptive module is converged in few iterations, which minimizes the overhead in processing. Nonetheless, it might be necessary to use hardware acceleration (e.g. FPGA support or DSP support) to implement it in ultra-high-speed embedded systems to achieve real-time performance. All in all, the computational complexity can be handled and scaled to industrial electronic systems.

### 4.4 Time Complexity

It is found out that the time complexity of the proposed A-EMC framework is evaluated in four key stages, namely, interference detection, signal preprocessing, adaptive mitigation, and validation. The time complexity of interference detection by FFT-based spectral analysis is O (nlog n) where n is the number of sampled signal points. Normalization and noise thresholding are examples of preprocessing tasks, which take linear time $O(n)$. In adaptive mitigation, filtering coefficients and shielding parameters are set through the use of optimization algorithms, which are iterated over; where m is the number of mitigation parameters and t is the number of optimization iterations, a complex approximation is O(mt). Because the optimization process is limited by the convergence thresholds, t is comparatively low hence efficient implementation. This is again followed by validation stage which involves signal re-assessment and compliance verification $O(n\log n)$ due to spectral recomputation. Overall, the combined time complexity can be approximated as $O(n\log n + mt)$, that is quite low compared to brute-force electromagnetic simulation methods which can have exponential or high-polynomial complexity. The framework shows that its scalability increases almost linearly with the size of input, i.e. it is applicable in real-time EMC monitoring. In addition, the modular structure allows filtering and evaluation to be done concurrently and decreases latency in faster systems. This time efficiency performance makes it practical in real-world application in the electronic devices and industrial communications systems.

### 4.5 Limitations of Proposed Model

Despite the noticeable advancement achieved by the proposed A-EMC concept towards decreasing the influence of the interference and increasing the stability of the systems, there exist some disadvantages. First of all, this approach is entirely built upon the ability to identify correctly the sources of the EMI and characterize properly the systems and, consequently, any errors made at the diagnostic stage will negatively affect the subsequent mitigation strategies. Secondly, the combination of advanced filters, shielding optimization techniques and real-time monitoring system may become too expensive for implementation and design of small and low-budget embedded devices. Besides, processors operating at high frequency in varying electromagnetic fields may require continuous recalculation of the adaptive parameters leading to increased computational efforts. In addition, there exists a prerequisite concerning having appropriate sophisticated simulation and testing equipment available, which does not have to be always provided in practice. Finally, even though the proposed concept may be scaled up, the effectiveness of the solution needs to be tested in practice in large industrial networks and at ultra-high frequencies.

## 5. CONCLUSION

It is worth noting that the suggested A-EMC framework represents a sophisticated mechanism for interference mitigation in the present electronic systems. Owing to smart source detection, intelligent layout of the PCB, smart filtering, smart shielding, immunity enhancement, and simulation verification techniques, this framework will guarantee both emission management and susceptibility reduction. Contrary to conventional EMC techniques, the new model is going to operate in an adaptive manner in order to provide enhanced compliance with the requirements, improve the signal integrity and system robustness. The performance of the proposed technique is verified with its implementation on EMI data set having several types of interference, which shows very promising results with an improvement in signal-to-noise ratio (SNR) by 8dB, reduction in overall emissions by 25%, reduction in emissions in frequency domain by 15 dBμV, and reduction in THD by 5%. Moreover, the performance metrics of the model such as accuracy of 97%, precision of 95%, recall of 96%, F1 score of 96% have been obtained with convergence of error from 1.00 to 0.05 in only 60 iterations. Real-time control and adaptation can contribute to improved resistance of the system to changes in the surrounding environment in relation to performance. As was verified experimentally and analyzed analytically, the proposed framework demonstrates its capability of mitigating interference at low costs and in a scalable manner. Therefore, this model may be considered an effective and promising approach to improving EMC of complex electronic systems.

**Declarations**

**Ethical approval**

This study does not involve experiments on human participants or animals. All experiments were conducted using publicly available dataset and simulation environment. Therefore, ethical approval from an institutional review board or ethics committee was not required for this research.

**Consent to participate**

The research does not involve human participants, personal data, or identifiable information. Hence, informed consent to participate was not applicable for this study.

**Consent to publish**

The research does not contain any individual person's data in any form. All authors have reviewed the manuscript and consent to its publication.

**Conflict of interest**

The authors have no conflict of interests to declare that are relevant to the content of this article.

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**REFERENCES**

[1]. Y. Meng, Y. Peng, H. Zhang, L. Li and D. Su, "A Novel Approach of Electromagnetic Compatibility Conducted Susceptibility Analysis Based on Gaussian Even Pulse Signal," in Chinese Journal of Electronics, vol. 33, no. 2, pp. 472-478, March 2024, doi: 10.23919/cje.2022.00.298.

[2]. Z. Chen, T. Claeys, R. Deseine, J. Catrysse and D. Pissoort, "Influences of Wiring Inside Ready-Made Connecting Devices on EMI in Medical Electronic Systems," in IEEE Letters on Electromagnetic Compatibility Practice and Applications, vol. 5, no. 4, pp. 142-148, Dec. 2023, doi: 10.1109/LEMCPA.2023.3286727.

[3]. M. Humeau, M. Koohestani, D. Boudikian and M. Ramdani, "Characterization of Near-Field Interactions Between Multiple Noise Sources and a Conductive Wire," in IEEE Letters on Electromagnetic Compatibility Practice and Applications, vol. 7, no. 4, pp. 123-128, Dec. 2025, doi: 10.1109/LEMCPA.2025.3601614.

[4]. M. Larab, F. Benyoubi and M. Bensetti, "Study and Modeling of the Electromagnetic Radiation Sources Based on Phaseless of Near Magnetic Fields for Power Electronics Applications," in IEEE Transactions on Electromagnetic Compatibility, vol. 66, no. 4, pp. 1213-1220, Aug. 2024, doi: 10.1109/TEMC.2024.3403841.

[5]. W. -B. Xie, Y. -H. Ma, D. -W. Wang, C. -H. Yu, Y. Hu and W. -S. Zhao, "Compact Single- and Dual-Band Balanced High-Selectivity Bandpass Filters Based on Microstrip Resonator Loaded Substrate Integrated Waveguide," in IEEE Transactions on Electromagnetic Compatibility, vol. 67, no. 5, pp. 1629-1633, Oct. 2025, doi: 10.1109/TEMC.2025.3586837.

[6]. H. Miloudi et al., "Electromagnetic Compatibility Characterization of Start-Capacitor Single-Phase Induction Motor," in IEEE Access, vol. 12, pp. 2313-2326, 2024, doi: 10.1109/ACCESS.2023.3349018.

[7]. P. Das and B. T. P. Madhav, "Novel Designs of SIW-Based Frequency-Selective Surfaces for Electromagnetic Shielding," in IEEE Letters on Electromagnetic Compatibility Practice and Applications, vol. 6, no. 2, pp. 62-66, June 2024, doi: 10.1109/LEMCPA.2024.3392012.

[8]. E. Ballukja et al., "A Pearson's Random Walk Method of Estimating the Electromagnetic Emissions of $N$ Parallel Connected Power Electronic Converters," in IEEE Transactions on Electromagnetic Compatibility, vol. 67, no. 3, pp. 1004-1015, June 2025, doi: 10.1109/TEMC.2025.3556297.

[9]. L. Malburg, N. Moonen, and F. Leferink, "Superposition of EMI in multiple interconnected SMPS," in Proc. IEEE Int. Symp. Electromagn. Compat. Signal/Power Integrity, 2022, pp. 362–367.

[10]. Stoykov, I.; Mihaylov, G.; Hristova, T.; Gabrovska-Evstatieva, K.; Hristov, P.; Fetfov, O.; Ganchev, B. Electromagnetic Compatibility Analysis in the Design of Reliable Energy Systems of a Telecommunication Equipment. Eng. Proc. 2025, 104, 29. https://doi.org/10.3390/engproc2025104029

[11]. W. Wang, F. Zhang, Z. H. Zhao, "A novel method for extracting broadband component of electromagnetic emission," in Proceedings of the 2020 IEEE MTT-S International Wireless Symposium, Shanghai, China, pp. 1–3, 2020.

[12]. L. Fu, Z. W. Yan, C. S. Fu, "Extraction and analysis of conducted electromagnetic susceptibility elements of inte-grated circuits," IEEE A ccess, vol. 9, pp. 149125–149136, 2021.

[13]. D. L. Su, Y. H. Peng, L. L. Li, "A broadband time-do-main detection system for electromagnetic compatibility conducted susceptibility test," IEEE Transactions on Instrumentation and Measurement, vol. 71, article no. 3000811, 2022.

[14]. Narayanasamy, B., and Luo, F., "A survey of active EMI filters for conducted EMI noise reduction in power electronic converters," IEEE Transactions on Electromagnetic Compatibility, Vol. 61, No. 6, 2019, pp. 2040–2049.

[15]. Wane, S., Saabe, W., Vinh, T., Bajon, D., and Gasseling, T., "Digital-Twin Technology Solutions for Chip-Package-PCB-Antenna Systems," 2025 19th European Conference on Antennas and Propagation (EuCAP), IEEE, 2025, pp. 1–4

[16]. M. Humeau, "Modeling and Characterization of near field coupling between a noise source and a wire," EMC Europe, 2025, submitted for publication.

[17]. CISPR 25: Vehicles, Boats and Internal Combustion Engines—Radio Disturbance Characteristics—Limits and Methods of Measurement for the Protection of On-Board Receivers, IEC Standard CISPR 25:2021, 2023.

[18]. A. Boyer, F. Caignet, and M. Laidet, "An efficient characterization method to predict the susceptibility of

integrated circuits to multitone disturbance," IEEE Trans. Electromagn. Compat., vol. 66, no. 6, pp. 1793–1803, Dec. 2024.

[19]. Y.-H. Ma, Y.-B. Chen, Q.-Q. Liu, and W.-S. Zhao, "Design of absorptive common-mode filters based on coupled stripline λ/4 resonator," IEEE Trans. Compon., Packag. Manuf. Technol., vol. 14, no. 4, pp. 649–658, Apr. 2024.

[20]. T.-Y. Lin and T.-L. Wu, "Balanced bandpass filters with common-mode reflectionless feature by terminated coupled lines," IEEE Trans. Electromagn. Compat., vol. 62, no. 4, pp. 1090–1097, Aug. 2020.

[21]. D. Shin, S. Jeong, Y. Baek, C. Park, G. Park, and J. Kim, "A balanced feedforward current-sense current-compensation active EMI filter for common-mode noise reduction," IEEE Trans. Electromagn. Compat., vol. 62, no. 2, pp. 386–397, Apr. 2020.

[22]. G. Zhang et al., "Multilayer packaged single- and dual-band dual-channel bandpass filters based on substrate integrated waveguide cavities," IEEE Trans. Compon., Packag., Manuf. Technol., vol. 14, no. 1, pp. 114–121, Jan. 2024.

[23]. H.-Y. Li, J.-X. Xu, and X. Y. Zhang, "Single-to-balanced and balanced-to-balanced dual-channel filters using multilayer substrate integrated waveguide cavities," IEEE Trans. Ind. Electron., vol. 68, no. 3, pp. 2389–2399, Mar. 2021.

[24]. Q. Liu, L.-S. Wu, D.-F. Zhou, K. Gong, and D.-W. Zhang, "Self-shielded single- and dual-band quad-mode substrate integrated waveguide bandpass filters based on mixed-mode cavity," IEEE Trans. Circuits Syst. I: Reg. Papers, vol. 71, no. 7, pp. 3098–3109, Jul. 2024.

[25]. L. Sun, H.-W. Deng, Y.-F. Xue, J.-M. Zhu, and S.-B. Xing, "Compact-balanced BPF and filtering crossover with intrinsic common-mode suppression using single-layered SIW cavity," IEEE Microw. Wireless Compon. Lett., vol. 30, no. 2, pp. 144–147, Feb. 2020.

[26]. H.-W. Deng, Y.-K. Han, L. Sun, J.-M. Zhu, and S.-B. Xing, "Multilayer dual-mode balanced SIW filter utilizing PEC–PMC characteristic for common-mode suppression," IEEE Microw. Wireless Compon. Lett., vol. 30, no. 9, pp. 865–868, Sep. 2020.

[27]. H. Liu, B. Xue, and J. Xu, "Broadband balanced filter with high common-mode suppression and wide stopband based on SIW and SSPP," IEICE Electron. Exp., vol. 21, no. 1, pp. 1–6, Nov. 2023.

[28]. Y.-K. Han, H.-W. Deng, J.-M. Zhu, S.-B. Xing, and W. Han, "Compact dual-band dual-mode SIW balanced BPF with intrinsic common-mode suppression," IEEE Microw. Wireless Compon. Lett., vol. 31, no. 2, pp. 101–104, Feb. 2021.