Indonesian Journal of Electrical Engineering and Computer Science
Vol. 25, No. 2, February 2022, pp. 796~804
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v25.i2.pp796-804

A review on techniques and modelling methodologies used for checking electromagnetic interference in integrated circuits

Tamana Baba, Nurul Arfah Che Mustapha, Nurul Fadzlin Hasbullah
Department of Electrical and Computer Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, Selangor, Malaysia

Article Info

Article history:

Received Jun 26, 2021
Revised Dec 4, 2021
Accepted Dec 20, 2021

Keywords:

Automotive
Electromagnetic compatibility
Electromagnetic interference
Integrated circuits
Modelling

ABSTRACT

The proper function of the integrated circuit (IC) in an inhibiting electromagnetic environment has always been a serious concern throughout the decades of revolution in the world of electronics, from disjunct devices to today's integrated circuit technology, where billions of transistors are combined on a single chip. The automotive industry and smart vehicles in particular, are confronting design issues such as being prone to electromagnetic interference (EMI). Electronic control devices calculate incorrect outputs because of EMI and sensors give misleading values which can prove fatal in case of automotives. In this paper, the authors have non exhaustively tried to review research work concerned with the investigation of EMI in ICs and prediction of this EMI using various modelling methodologies and measurement setups.

Corresponding Author:

Tamana Baba
Department of Electrical and Computer Engineering, International Islamic University of Malaysia
Jalan Gombak, 53100 Kuala Lumpur, Malaysia
Email: mehrajudinbaba5@gmail.com

1. INTRODUCTION

An integrated circuit (IC) is a small wafer, typically made of silicon, that can carry transistors, resistors, and capacitors anywhere from hundreds to millions [1]. Electromagnetic interference (EMI) is a disruption caused by an external source that will affect an electrical circuit through electromagnetic induction, radiation, conduction, or electrostatic coupling as shown in Figure 1 [2]. In the radio frequency spectrum, it is also known as radio frequency interference (RFI) [3]. Any device is electromagnetic compatible, if it functions without error and it also does not affect the operation of other devices in its intended electromagnetic environment [4].

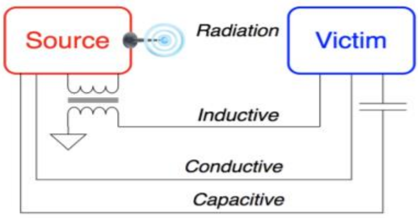

Figure 1. Path for EMI [2]

Electromagnetic compatibility (EMC) can be categorized in two directions: electromagnetic emission, which can disrupt the working of other systems and electromagnetic susceptibility, which basically describes how efficiently our system will work if it is subjected to disturbances from other systems [5]. The circuit's performance may be harmed or possibly shut down because of the disruption. EMC compliance is becoming more important as the number of ICs on electronic modules in the automotive industry grows [6]. Preventing EMI faults within a vehicle drives this EMC. Failure to do so could result in financial loss and, in the worst-case scenario, human life [7]. EMC therefore plays a major role in the design of automotive electronics, as shown by the broad body of work on this subject [8]-[14]. Research shows that the confidence level of first time passing an EMI test is easily raised from 35% to 80% if proper and upfront EMC design guidelines are followed [15]. Therefore, it becomes important to check the EMC from the IC level before the overall prototype is ready.

In this paper, main types of EMC issues encountered in ICs are briefly discussed in section 2 and an overview of most popular modelling techniques for ICs is presented in section 3. The standard EMC measurement methods have been explained briefly in section 4. Some most used EMI shielding techniques are discussed briely in section 5. Various modelling tools and experimental approaches used over the years for checking EMI in ICs have been reviewed and some of the strengths and weaknesses have been compared in section 6. Finally, in section 7, discussion is provided and conclusion is drawn.

2. EMC IN ICs

ICs play a critical role in an electronic system's EMC. Generally, ICs are both the ultimate source of interference-causing signals and the victim. The proper operation of an IC in an obstructive electromagnetic environment has always been a serious challenge. EMC problems in an IC can be generally classified into two types namely Intra chip EMC and Externally coupled EMC.

2.1. Intra chip EMC

When electromagnetic disruption from one portion of the IC interfere with the operation of other components of the same IC, this is referred to as intra chip EMC [16]. Intra chip interferences are commonly divided into two categories: Crosstalk and simultaneous switching noise, both of which constitute signal integrity (SI) concerns [17]. In electronics, Signal Integrity refers to the signal's ability to perform without being harmed [18]. The ratio of the accidental voltage emerging across the load in the victim circuit to the signal voltage in the source circuit is the general definition of crosstalk between two circuits. Simultaneous switching noise, on the other hand, is a usual impedance coupling difficulty that occurs when many circuits in an IC share the same power distribution bus [19].

2.2. Externally coupled EMC

Before devices are used in an actual product, intra-chip EMC issues are usually rectified. However, noise coupled in or out of the chip packaging can cause EMC difficulties in semiconductor devices that have no intra-chip concerns. Externally coupled EMC difficulties are developed when the ICs electromagnetic noise upsets off-chip devices or circuits, or when electromagnetic commotion from other devices disrupts the ICs operation. Conducted coupling, electric field coupling, magnetic field coupling, and radiated field coupling are all examples of externally coupled EMI [20], [21].

3. EMC MODELS

In electronic equipment, ICs are often the main source of disruption [22]. Several studies have been documented explaining the sensitivity of ICs to EMI, as these are usually the most sensitive too [23], [24]. Standards like the international special committee on radio interference (CISPR) 25 [25] for emissions and the International Organization for Standardisation (ISO) 11452 [26] for EMI susceptibility describe EMC test setups for the electronic systems used in automotive Industry. In recent years, electronic device designers have expressed a strong desire for easy and accurate measurement methods focusing on ICs.

The I/O buffer information specification (IBIS) working group made the first major contribution to standard EMC modelling by introducing a standard for defining the electrical efficiency of IC I/O structures. IBIS initially concentrated solely on signal integrity (SI) issues at the I/O level, with no knowledge about noise inside the IC core [27]. However, EMC was also considered for I/Os beginning with version 4.1.

In 1997, the "Union Technique de l'Electricite" (UTE), a French standardization committee, paid attention to component EMC modelling and created ICEM, a generic model for prediction of parasitic emissions in ICs [28]. ICEM debuted as a novel IEC proposal standard IEC 62014-3 [29] in 2002. Simultaneously, IEC 62404 [30] was adopted as the Japanese proposal known as I/O interface model for IC (IMIC). Table 1 summarises the most widely used EMC modelling techniques.

Table 1. Modelling techniques for ICs

Method	Simulation	Advantage	Drawback
IBIS [31]	Signal Integrity EMI	Not very Complex. Non confidential Data. Accurate I/O and package modelling.	Limited to 1 Ghz. Good Accuracy.
ICEM [32]	Conducted and Radiated Emissions	Not Complex. Non confidential Data.	Limited to 1 Ghz. Medium Accuracy.
IMIC [33]	Conducted and Radiated Emissions	Not Complex. Non confidential Data.	Limited to 1 Ghz. Medium Accuracy.

4. MEASUREMENT METHODS FOR EMC PREDICTION

The International Electro-Technical Commission has issued two standards: One for electromagnetic radiated and conducted emissions (IEC 61967) and the other for electromagnetic immunity (IEC 62132). The emission standard has 6 parts while the immunity standard has 5 parts as shown in the Table 2. TEM cell stands for transverse electromagnetic mode cell. GTEM or Gigahertz cell is the high frequency variant of TEM cell. Both are utilised to measure an ICs EME as well as its immunity to electromagnetic fields [34]. The surface scan method is another norm [35]. Using the surface scan technique, particular probes coupled to a receiver estimate the amplitude and phase of a particular section of the EM field generated by the IC.

IEC 61967-4 describes another method for measuring the conducted electromagnetic emission (EME) of ICs by using a 1Ω resistive probe to measure RF current and a 150Ω coupling network to measure RF voltage [36].The workbench faraday cage is another technique for conducting RF immunity and emission quantifications in a small space without the need for large anechoic chamber [37]. Magnetic probe method is another standard for emission measurement [38]. It specifies a procedure for measuring RF currents on the pins of an IC using a miniature magnetic probe and non-contact current calculation [39]. Bulk current injection (BCI) and direct power injection (DPI) are two popular immunity measurement methods. Bulk current injection’s measurement theory is based on reproducing the induced current that EM fields coupled on a system’s wires could produce in the real world [40]. On the other hand, DPI is a technique for determining how immune the IC is to conducted RF disturbances. Immunity measurements are guaranteed to be repeatable and correlated using this approach [41].

Table 2. Measurement standards of Electromagnetic immunity and emissions

S.NO	Emission		Immunity	
	Standard	Description	Standard	Description
1.	IEC 61967-1	Definitions	IEC 62132-1	Definitions
2.	IEC 61967-2	TEM/G-TEM cell [34]	IEC 62132-2	TEM cell [34]
3.	IEC 61967-3	Surface scan method [35]	IEC 62132-3	Bulk current injection (BCI) [36]
4.	IEC 61967-4	1Ω/150Ω method [37]	IEC 62132-4	Direct RF injection (DPI) [38]
5.	IEC 61967-5	Workbench faraday cage [39]	IEC 62132-5	Workbench faraday cage [39]
6.	IEC 61967-6	Magnetic probe method [40]	-	-

5. SOME COMMON WAYS TO REDUCE EMI

Aside from the EMI measurement techniques mentioned above, there are some of the most common structures used for electromagnetic shielding. A faraday cage was one of the earliest electromagnetic (EM) shields. The electrons in the walls of a faraday cage deploy in a way that neutralizes the electric field on the other side of the wall when an electric field is incident on them [37]. In addition to this, the space between each panel of a foldable shield can operate as a prow for EMI radiation in scenarios where foldable shields are used. In such circumstances, the joints and hinges should be tightly fastened to prevent any possible emission. To assure this, EMI shielding gaskets are used.

Differential mode (DM) and common mode (CM) noise make up most of the conducted emission noise. Filtering the generated CM and DM noises out of the system with EMI filters is a standard means of dealing with them. Because CM and DM noise signals require distinct filtering procedures, a noise separator is typically employed to differenciate these two undesired signals. Filters are added to the circuit once they have been separated. Electromagnetic absorbers are utilised in a variety of applications, including health monitoring, military, and radar cross section reduction, among others. These are also commonly employed in EMI/EMC technology. The reflection coefficient is the most significant metric to consider while developing and studying these absorbers. If a transmission line equivalent model is employed to examine the performance of an absorber, then the reflection coefficient R, is obtained by (1).

$$R = 20\log\frac{Z_i - 1}{Z_i + 1} \quad (1)$$

Where Z_i is the normalized input impedance [42].

6. REVIEW ON VARIOUS METHODOLOGIES USED IN RECENT WORKS TO PREDICT EMI

From the past few decades, a lot of work has been done in the field of EMC evaluation of ICs. Extraction of EMC models of ICs has been carried out extensively. Both modelling and experimental techniques have evolved and improvised over time. The EMC difficulties linked to direct and radiated emissions from high-speed ICs are discussed in [43]. Circuital and electromagnetic models are used to assess these emissions. Based on the integrated circuit emission model template (ICEM), an analogous circuit model is constructed to represent the IC and the influence of its loads. Figure 2 depicts the entire circuit as being formed of four primary subparts: the first is internal activity, IA which represents the core and I/O buffers, the second explains the package, and the third relates to the printed circuit board (PCB). The last subpart replicates a buffer that exchanges data with the IC via a generic load. In terms of radiated emission, an EM model formulated on the superposition of fields produced in the far field region by loop currents flowing towards the IC and package pins is proposed.

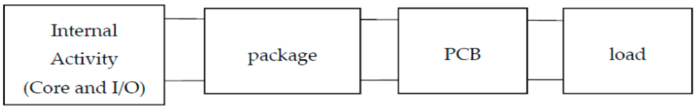

Figure 2. Circuit model conceptual diagram, based on [43]

A model-based simulation technique for characterization of immunity at system level at a premature design stage is presented which comprised of a hybrid 3D full wave, transmission line and circuit solver methodology and models for all components including ICs [44]. The bulk current injection (BCI) failure for a simple PCB comprised of a p-nitrophenol (PNP) transistor IC, namely 2SA1576 is predicted. An integrated circuit immunity model (ICIM) used for modelling the immunity of an IC is generated. Then this ICIM is used and a BCI simulation is performed. The BCI setup is simulated using method of moments (MOM). A the effects of various parameters like the number of winding turns, the width of coils on the S-Parameters of current injection probes are discussed [45]. The performance of a current injection probe is characterized with S-Parameters which could be measured using a vector network analyzer (VNA). It is reported that the insertion losses are found to decrease in low frequencies when the number of coils turns in the probe are increased showing the enhancement of the coupling effect of the probe. At high frequencies, the skin effect comes to play and insertion losses increase. To improve the probe bandwidth, it is suggested to reduce the number of turns of the coil winding.

The IC stripline technique is a new technique that could be utilized for calculating radiated emission falling in the sweep up to 3 GHz. The micro stripline approach is considered in [46] as well as its shortcomings in terms of characterisation of small package encapsulated ICs are highlighted. A novel EM guiding design that demonstrates an improved coupling with the Dalian University of Technology (DUT) in the 800 MHz-3 GHz frequency range is proposed to solve such problems. A test structure circuit model based on lumped elements that enables the use of SPICE-like simulators for circuit analysis is suggested. Contrasting the scattering parameters that were acquired from simulations with those resulting from measurements performed on a real test structure constructed and produced for this purpose, the model has been validated. A new way of modelling the DUT through EM simulations in the IC stripline has been proposed in [47]. The author has proposed the dimensions of an open version IC stripline and DUT as depicted in Figure 3.

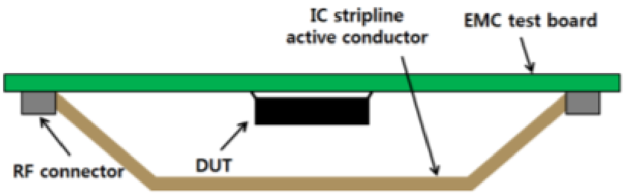

Figure 3. Simplified open version of IC stripline [47]

The S-Parameter results of 3D EM solver are looked at and an analogous lumped element circuit model is introduced and its exactitude is compared to 3D simulation. DUT is a quad flat package (QFP) with dimensions 10×10×2.1 mm. All the simulations as well as the IC stripline structure are simulated using 3D EM solver. Hwang *et al.* [47] has followed the methodology but improvised model proposed in [48] which was a single LCT model. The author has added a new parameter for modelling the capacitance between the middle active conductor and ground. Mutual inductance and coupling capacitance are used to model the EM coupling between active conductor and DUT. Compared to the previous model, more specific results could be obtained from the distributed lumped element model.

Heuvelman *et al.* [49] this concept is extended and applied to wire bonded ball grid array (BGA) IC and the modelling methodology is validated with test structures. The measurement set ups to calculate the radiated emission from reference antenna structures as well as from the real IC are used. For the simulation set up, first a representative of 3D model based on finite element method (FEM) utilizing the IC stripline dimensions is made. The DUT is then placed in the 3D model of the IC stripline. The S-Parameter model in addition with the transistor level circuit model of the I/O and load is used to configure the wire bonded BGA and IC stripline. The radiation emission spectrum is then determined using a commercially available simulation tool. Comparison between simulation and measurement results of various S-Parameters were made and found to be in excellent agreement.

The electromagnetic emissions (EME) are studied by a simulation method using a Gallium Nitride high electron mobility transistor power amplifier IC chip [50]. For simulation of 3-D IC layout, a simulation model has been suggested by introducing a high-frequency structure simulator with a Keysight advance design system (ADS). Experiments are used to verify the effects of the simulated EME. The EME for the IC chip is reduced using this simulation process, which uses a response surface methodology. In consequence, small improvements in the IC layout have been found to have a major impact on the EME.

The EMI susceptibility tests for ICs can be somewhat accurate based on the package size and shape. For example, an IC encapsulated in tiny package may show high immunity to EMI, whereas the same IC encapsulated in larger packages may show a lower immunity. The micro stripline method is studied and a new structure for coupling between the EM guiding structure and the IC terminal is proposed [51]. The DUT is organised on a test board which is used to provide the nominal signals to the DUT and collect a portion of EMI dispersed through the stripline. The preliminary design which is carried out as per the guideline has an aim to escalate the stripline to trace coupling in the range 0.7 to 4 GHz and when the DUT and its holder are put on the stripline, voltage standing wave ratio (VSWR) was observed to be below 1.25.

Novel disturbance generator models were developed to form part of a virtual EMC lab [52]. Current simulation models concentrate primarily on the IEC61000-4-2 discharged [53]-[54]. The scope varies and the primary focus is only to replicate the disturbance as defined in the specification. However, detailed and precise models over a wide range of load conditions have been implemented and tested in [52]. The study also highlights some of the inaccuracies of the standards, showing that different pass/fail EMC results can result from the use of different test equipment.

The EMI that an IC is subjected to when installed in real applications are not confined to be continuous wave (CW) or amplitude modulated. Strangely, this topic has not received as much attention as it deserves. However in [55], the author focuses on this aspect, addressing the problem from victim's perspective (DUT) and covering all possible EMI induced failures by using a two-tone interference. An IC passing an immunity test such as the DPI could fail in practical applications with much lower levels of power than the ones it could withstand in the test. A solution of using two tone interferences which has a frequency deviation lower than the bandwidth of the circuit is put forward. A method to foretell and interpret the EMI spectrum from time-domain waveforms is suggested in [56]. The technique is built based on formulated operating principle of the spectrum analyzer and the specifications of EMI standards.

The current proficiency and power rating of power converters could greatly improve by the parallelization of silicon carbide (SiC) metal-oxide semiconductor field-effect transistors (MOSFETs). However, modelling EMI in a power module with parallel-connected SiC MOSFETs (PMPSM) is complicated by the the inductive coupling effect of parasitic inductance between the paralleled branches. First an EMI source generation mathematical modelling approach for PMPSM is proposed which identifies the coupling difference in multi switch in parallel conditions [57]. The inductive coupling of parallel-connected switches can also be used to compute the interference quantity. Following that, a common mode (CM) propagation mathematical modelling approach for PMPSM is proposed, which is based on the inductive coupling theory, which discovered the suppressed effect of parasitic inductances between parallel switches on high-frequency CM interference.

A unique CMOS miller operational amplifier (OpAmp) with excellent EMI immunity is proposed In [58]. The first-order quadratic mathematical model is used to build the proposed amplifier. The modelling equations in this study were constructed using typical mixed-mode CMOS technology. The goal of the suggested modelling in this paper is to create a first-order symbolic expression that incorporates the body effect and CLM for the output offset voltage. The suggested modelling is an important tool for comparing different architectures and gaining a better knowledge of the design aspects that affect the output offset voltage.

The effects of conducted emissions from ICs are studied and noise models are developed [59]. For noise-model building, both IBIS-based and measurement methods are investigated. The noise source model created for a test IC is used in system-level simulations, and the measured far field radiation is checked through measurements. The model's ability to characterise the conducted emissions from an IC I/O pin is demonstrated by the agreement between the simulated and measured performance. IBIS models have been used in [60] for noise extraction in ICs for conducted emission modelling. Total voltage is extracted from the IBIS model and correlated with a particular structural S-Parameter using this method. The IBIS model and the S-Parameter are used in ADS software to determine total voltage. The far field radiation is obtained after simulation. The simplicity of this method for both linear and nonlinear I/O buffer circuits is its biggest ascendancy.

IBIS models have also been used in [61] to perform Signal Integrity analysis of a high speed, low power analog to digital converter IC MAX11129 from maxim integrated. IC designers have always been concerned with signal integrity. It is responsible for several other silicon failures as well as IC redesign considerations [62]. Baba *et al.* [61] have carried out the signal integrity analysis of the IC by importing the IBIS model of the IC into ADS. The mismatch between the signals at the driver pin and the load pin has been checked. Some initial mismatch has been discovered, which has been linked to DUT signal integrity problems. To prevent reflections, it has been proposed that lines be properly terminated, and crosstalk between adjacent traces be reduced to a minimum.

Equivalent models of ICs can be used for the EMC analysis. Sufficient information about the IC is required for the construction of these models. For cases where this information is not available to the designers, a mathematical modelling technique has been proposed in [63]. The feature of the near and far electromagnetic fields coupling of the IC, as derived via near field scanning, are analyzed using a dipole moment model in [63]. In addition, the study shows an array of electric and magnetic dipole moments that were utilized to duplicate field distributions in the scanning plane above the IC. Table 3 presents a comparison of various methods used in the recent works.

Table 3. Comparison of different methods used in previous literature

Authors	Method Used	Strengths	Limits
[43]	Conducted emission modelling based on ICEM and radiated emission model based on superposition of fields.	Contribution of direct emission from ICs is highlighted which is usually hidden by indirect emissions coming from PCB.	The experimental setup for finding conducted and radiated emissions accounts for an uncertainty of around ±2.5 dB on the considered frequency range.
[44]	Bulk current injection and simulation using MOM.	BCI is popular for its simplicity and cost effectiveness	The performance of the injection probe and hence the results of the test are dependent on the bundle length and terminating impedance.
[45]	Using matching components to enhance performance of BCI probe.	High current injection and high coupling density of magnetic field lines.	Adding parallel resistances to improve frequency selection can cause more losses.
[47]	DUT has been modelled in an open version IC stripline.	The model presented can be used for rapid analysis for EMC of ICs.	Manufacture and measurement of IC stripline method is different for different types of ICs.
[49]	Modelling using IC stripline method has been extended and a representative model based on FEM is used.	Radiated emissions from DUT as well as from antenna structures are determined.	Coupling varies from case to case between the IC and the stripline. Therefore, 2 samples of the same IC encapsulated in 2 striplines can show different results.
[51]	Microstrip line technique is used and a new coupling structure has been proposed between IC and the guiding structure of EM.	Coupling structure that takes care of dependence of EMC of an IC on impedances seen at the PCB level loading and dependence of coupling on stripline has been proposed.	Maintaining regulated impedance through the design is extremely important when transmission lines are routed in a high-speed design.
[55]	Two tone interference effects are checked.	Methods of making IC withstand real environment interferences are proposed.	The setup is a bit complicated with the requirement of an additional RF source and a combiner.
[59]	IBIS model is used to extract noise sources from the IC.	IBIS model for ICs is readily available as compared to SPICE models.	The set up is only for conducted emissions and not for conducted immunity.

7. DISCUSSION AND CONCLUSION

EMI and EMC of ICs has been a hot topic of interest over the years. This research reviews a good number of recent publications made in this field. In this paper all the important aspects of IC EMI/EMC are briefly explained and recent work in this field is non-exhaustively summarised. Upon analysis, it can be realised that apart from the measurement methods avaible for EMI measurement, it can be extremely beneficial to use modelling methodologies if some knowledge about the IC is available. In addition, the measurement test setup for EMI detection is highly complex and costly with limited applications making modelling methodologies even more desirable. Early electrical simulators such as SPICE simulation tools, were created to simulate electronic system susceptibility to EMI. However, it is hampered by practical realities such as different simulators, undocumented simplifications, simulation speed, model availability, and vendor's reluctance to offer the SPICE model of I/O structure to the public. IBIS is the first significant development as far as IC modelling is considered. Initially IBIS was only concerned about SI analysis in an IC. However, EMC was also considered for I/Os beginning of version 4.1. The ICEM was developed to accurately account for the internal operation of ICs. The restrictions of this model as far as the overall operating frequencies are considered can be overcome by using a distributed model to account for the effects of the loads and transmission lines on the PCB. Thus, every approach has its own benefits and choosing a measurement, or a modelling approach based on the priorities of the designer is appropriate until a technique that can very accurately consider all the aspects of the DUT can be derived.

ACKNOWLEDGEMENTS

This paper is funded by Ministry of Higher Education Malaysia through the Research Centre, International Islamic University Malaysia under the Fundamental Research Grant Scheme For Research Acculturation Of Early Career Researchers–FRGS-RACER/1/2019/TK08/UIAM//1.

REFERENCES

[1] K. Shamsi, M. Li, T. Meade, Z. Zhao, D. Z. Pan, and Y. Jin, "AppSAT: Approximately deobfuscating integrated circuits," *Proc. 2017 IEEE Int. Symp. Hardw. Oriented Secur. Trust. HOST 2017*, pp. 95–100, Jun. 2017, doi: 10.1109/HST.2017.7951805.

[2] A. Richelli, L. Colalongo, and Z. M. Kovacs-Vajna, "Analog ICs for Automotive under EMI Attack," *2019 AEIT Int. Annu. Conf. AEIT 2019*, Sep. 2019, doi: 10.23919/AEIT.2019.8893327.

[3] D. D. L. Chung, "Materials for electromagnetic interference shielding," *Mater. Chem. Phys.*, vol. 255, p. 123587, Nov. 2020, doi: 10.1016/J.MATCHEMPHYS.2020.123587.

[4] C. B. Khadse, M. A. Chaudhari, and V. B. Borghate, "Electromagnetic Compatibility Estimator Using Scaled Conjugate Gradient Backpropagation Based Artificial Neural Network," *IEEE Trans. Ind. Informatics*, vol. 13, no. 3, pp. 1036–1045, Jun. 2017, doi: 10.1109/TII.2016.2605623.

[5] A. Tsukioka *et al.*, "Simulation techniques for EMC compliant design of automotive IC Chips and modules," *2017 Int. Symp. Electromagn. Compat. - EMC Eur. 2017, EMC Eur. 2017*, Nov. 2017, doi: 10.1109/EMCEUROPE.2017.8094691.

[6] Q. Han, J. Lei, L. Zeng, Y. Tang, J. Liu, and L. Chen, "EMC Test for Connected Vehicles and Communication Terminals," *IEEE Intell. Veh. Symp. Proc.*, vol. 2018-June, pp. 55–60, Oct. 2018, doi: 10.1109/IVS.2018.8500418.

[7] T. H. Hubing, "Autonomous Vehicles Will Transform the Field of Automotive EMC," *2018 IEEE Symp. Electromagn. Compat. Signal Integr. Power Integrity, EMC, SI PI 2018*, Oct. 2018, doi: 10.1109/EMCSI.2018.8495279.

[8] H. Afewerki, C. Lautensack, N. Böttcher, and I. Kallfass, "Design Approach and Analysis of a MOSFET with Monolithic Integrated EMI Snubber for Low Voltage Automotive Applications," in *2017 International Symposium on Electromagnetic Compatibility - EMC EUROPE 2017, EMC Europe 2017*, Nov. 2017, doi: 10.1109/EMCEurope.2017.8094734.

[9] Y. S. Kim, H. Lee, H. Soo Lee, and B. Jin Choi, "Verification of EMI Limit by Means of a Receiver Sensitivity Through Interference in Case of Occurring from Vehicle Electric Parts in the ITS Frequency Band (5.86-5.93 GHz)," in *IEEE International Symposium on Electromagnetic Compatibility*, Oct. 2018, vol. 2018-August, pp. 57–59, doi: 10.1109/EMCEurope.2018.8485114.

[10] Y. Qu, W. Shu, and J. S. Chang, "A Low-EMI, High-Reliability PWM-Based Dual-Phase LED Driver for Automotive Lighting," *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 6, no. 3, pp. 1179–1189, Sep. 2018, doi: 10.1109/JESTPE.2018.2812902.

[11] D. Pissoort, A. Degraeve, and K. Armstrong, "EMI Risk Management: A necessity for safe and reliable electronic systems!," *5th IEEE Int. Conf. Consum. Electron. - Berlin, ICCE-Berlin 2015*, Jan. 2016, pp. 208–210, doi: 10.1109/ICCE-BERLIN.2015.7391236.

[12] A. Amaducci, "Design of a wide bandwidth active filter for common mode EMI suppression in automotive systems," in *IEEE International Symposium on Electromagnetic Compatibility*, Oct. 2017, pp. 612–618, doi: 10.1109/ISEMC.2017.8077941.

[13] G. Braglia, S. Barmada, and A. Duffy, "Simulations and experiments for EMC compliance in automotive environment," *2016 IEEE/ACES Int. Conf. Wirel. Inf. Technol. ICWITS 2016 Syst. Appl. Comput. Electromagn. ACES 2016 - Proc.*, May 2016, doi: 10.1109/ROPACES.2016.7465367.

[14] S. Matsushima, T. Matsushima, T. Hisakado, and O. Wada, "Trends of EMC standards for automotive network devices and communication quality of ethernet in relation to parameters of pulse disturbances," *IEEE Electromagn. Compat. Mag.*, vol. 7, no. 1, pp. 46–50, Jan. 2018, doi: 10.1109/MEMC.0.8339542.

[15] T. Baba, N. A. Che Mustapha, and N. F. Hasbullah, "Driving Ethically towards an Autonomous Future," in *Proceedings of the 4th International Conference on Engineering Professional Ethics and Education 2021 (ICEPEE'21) Redesigning Teaching and Learning towards Sustainable Education 22-23 JUNE 2021 KUALA LUMPUR, MALAYSIA*, 2021, pp. 9–14.

[16] M. Yamaguchi, P. Fan, S. Tanaka, S. Muroga, and M. Nagata, "Analysis of intra-chip degital noise coupling path in fully LTE compliant RF receiver test chip," *IEEE Int. Symp. Electromagn. Compat.*, vol. 2015-Septmber, pp. 1007–1011, Sep. 2015, doi: 10.1109/ISEMC.2015.7256304.

[17] J. Wang, C. Xu, S. Zhong, S. Bai, J. J. Lee, and D. H. Kim, "Differential Via Designs for Crosstalk Reduction in High-Speed PCBs," *2020 IEEE Int. Symp. Electromagn. Compat. Signal/Power Integrity, EMCSI 2020*, pp. 145–149, Jul. 2020, doi: 10.1109/EMCSI38923.2020.9191558.

[18] H. C. Zhang, T. J. Cui, Q. Zhang, Y. Fan, and X. Fu, "Breaking the Challenge of Signal Integrity Using Time-Domain Spoof Surface Plasmon Polaritons," *ACS Photonics*, vol. 2, no. 9, pp. 1333–1340, Aug. 2015, doi: 10.1021/ACSPHOTONICS.5B00316.

[19] S. Kim, Y. Kim, K. Cho, J. Song, and J. Kim, "Design and Measurement of a Novel On-Interposer Active Power Distribution Network for Efficient Simultaneous Switching Noise Suppression in 2.5-D/3-D IC," *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 9, no. 2, pp. 317–328, Feb. 2019, doi: 10.1109/TCPMT.2018.2841045.

[20] C. Junping *et al.*, "Electromagnetic susceptibility analysis of FPGA based on conducted coupling of power supply network," *High Power Laser Part. Beams, 2019,* vol. 31, no. 02, pp. 023202-, Feb. 2019, doi: 10.11884/HPLPB201931.180322.

[21] J. Yao, Y. Li, S. Wang, X. Huang, and X. Lyu, "Modeling and Reduction of Radiated EMI in a GaN IC-Based Active Clamp Flyback Adapter," *IEEE Trans. Power Electron.*, vol. 36, no. 5, pp. 5440–5449, May 2021, doi: 10.1109/TPEL.2020.3032644.

[22] F. Fiori, "EMI susceptibility: The achilles' heel of smart power ICs," *IEEE Electromagn. Compat. Mag.*, vol. 4, no. 2, pp. 101–105, Apr. 2015, doi: 10.1109/MEMC.2015.7204059.

[23] J. M. Redoute and A. Richelli, "A methodological approach to EMI resistant analog integrated circuit design," *IEEE Electromagn. Compat. Mag.*, vol. 4, no. 2, pp. 92–100, Apr. 2015, doi: 10.1109/MEMC.2015.7204058.

[24] E. Sicard *et al.*, "Recent advances in electromagnetic compatibility of 3D-ICS - Part II," *IEEE Electromagn. Compat. Mag.*, vol. 5, no. 1, pp. 65–74, Jan. 2016, doi: 10.1109/MEMC.2016.7477137.
[25] "CISPR 25:2016 | IEC Webstore | electromagnetic compatibility, EMC, smart city, transportation, mobility," https://webstore.iec.ch/publication/26122 (accessed Sep. 08, 2021).
[26] "ISO 11452-2:2004(en), Road vehicles — Component test methods for electrical disturbances from narrowband radiated electromagnetic energy — Part 2: Absorber-lined shielded enclosure," https://www.iso.org/obp/ui/#iso:std:iso:11452:-2:ed-2:v1:en (accessed Sep. 08, 2021).
[27] Z. Yang, "IBIS summit holds first meeting at IEEE EMC+SIPI symposium," *IEEE Electromagn. Compat. Mag.*, vol. 9, no. 3, pp. 107–110, Jul. 2020, doi: 10.1109/MEMC.2020.9241569.
[28] C. Ghfiri, A. Boyer, A. Durier, and S. Ben Dhia, "A New Methodology to Build the Internal Activity Block of ICEM-CE for Complex Integrated Circuits," *IEEE Trans. Electromagn. Compat.*, vol. 60, no. 5, pp. 1500–1509, Oct. 2018, doi: 10.1109/TEMC.2017.2767084.
[29] "IEC TR 62014-3:2002 | IEC Webstore," https://webstore.iec.ch/publication/6296 (accessed Sep. 08, 2021).
[30] "IEC TS 62404:2007 | IEC Webstore," https://webstore.iec.ch/publication/6989 (accessed Sep. 08, 2021).
[31] W. Dghais and M. Alam, "IBIS and Mpilog Modelling Frameworks for Signal Integrity Simulation," *Lect. Notes Networks Syst.*, vol. 29, pp. 15–44, 2018, doi: 10.1007/978-3-319-72215-3_2.
[32] S. Serpaud, C. Ghfiri, A. Boyer, and A. Durier, "Proposal for combined conducted and radiated emission modelling for Integrated Circuit," *Proc. 2017 11th Int. Work. Electromagn. Compat. Integr. Circuits, EMCCompo 2017*, pp. 172–177, Jul. 2017, doi: 10.1109/EMCCOMPO.2017.7998105.
[33] X. Hao, S. Xie, and Z. Chen, "A Parametric Conducted Emission Modeling Method of a Switching Model Power Supply (SMPS) Chip by a Developed Vector Fitting Algorithm," *Electron. 2019*, vol. 8, no. 7, p. 725, Jun. 2019, doi: 10.3390/ELECTRONICS8070725.
[34] W. Fang *et al.*, "Extracting the Electromagnetic Radiated Emission Source of an Integrated Circuit by Rotating the Test Board in a TEM Cell Measurement," *IEEE Trans. Electromagn. Compat.*, vol. 61, no. 3, pp. 833–841, Jun. 2019, doi: 10.1109/TEMC.2018.2836698.
[35] S. Bauer, O. Biro, G. Koczka, A. Gleinser, G. Winkler, and B. Deutschmann, "Time domain FEM computational approach for calibration of surface scan method," *2018 IEEE Int. Symp. Electromagn. Compat. 2018 IEEE Asia-Pacific Symp. Electromagn. Compat. EMC/APEMC 2018*, pp. 866–871, Jun. 2018, doi: 10.1109/ISEMC.2018.8393905.
[36] O. Aiello and P. Crovetti, "Characterization of the Susceptibility to EMI of a BMS IC for Electric Vehicles by Direct Power and Bulk Current Injection," *IEEE Lett. Electromagn. Compat. Pract. Appl.*, vol. 3, no. 3, pp. 101–107, Jun. 2021, doi: 10.1109/LEMCPA.2021.3085765.
[37] M. Rotigni, M. Merlo, M. Cordoni, P. Colombo, and V. Liberali, "Conducted emissions in a 40 nm CMOS test chip: The role of the ESD protections," *Proc. 2017 11th Int. Work. Electromagn. Compat. Integr. Circuits, EMCCompo 2017*, pp. 156–161, Jul. 2017, doi: 10.1109/EMCCOMPO.2017.7998102.
[38] D. Krolak, J. Plojhar, and P. Horsky, "An Automotive Low-Power EMC Robust Brokaw Bandgap Voltage Reference," *IEEE Trans. Electromagn. Compat.*, vol. 62, no. 5, pp. 2277–2284, Oct. 2020, doi: 10.1109/TEMC.2019.2958926.
[39] N. Munic, M. N. Stevanovic, A. Djordjevic, and A. Kovacevic, "Evaluation of radiating-source parameters by measurements in Faraday cages and sparse processing," *Measurement*, vol. 104, pp. 105–116, Jul. 2017, doi: 10.1016/J.MEASUREMENT.2017.03.008.
[40] Z. Yan, J. Wang, W. Zhang, Y. Wang, and J. Fan, "A Simple Miniature Ultrawideband Magnetic Field Probe Design for Magnetic Near-Field Measurements," *IEEE Trans. Antennas Propag.*, vol. 64, no. 12, pp. 5459–5465, Dec. 2016, doi: 10.1109/TAP.2016.2606556.
[41] O. Trabelsi, L. Sauvage, and J. L. Danger, "Characterization at logical level of magnetic injection probes," *2019 Jt. Int. Symp. Electromagn. Compat. Sapporo Asia-Pacific Int. Symp. Electromagn. Compat. EMC Sapporo/APEMC 2019*, pp. 625–628, Jun. 2019, doi: 10.23919/EMCTOKYO.2019.8893692.
[42] P. Mathur and S. Raman, "Electromagnetic Interference (EMI): Measurement and Reduction Techniques Progress and Challenges in Developing Electromagnetic Interference Materials Electromagnetic Interference (EMI): Measurement and Reduction Techniques," *Artic. J. Electron. Mater.*, 2020, doi: 10.1007/s11664-020-07979-1.
[43] D. Capriglione, A. G. Chiariello, and A. Maffucci, "Accurate Models for Evaluating the Direct Conducted and Radiated Emissions from Integrated Circuits," *Appl. Sci. 2018*, vol. 8, no. 4, p. 477, Mar. 2018, doi: 10.3390/APP8040477.
[44] B. P. Nayak, S. Ramesh, S. Rajeev, A. Devi, T. Tsuda, and D. Gope, "Model-Based System-Level EMI/EMC Simulation for BCI Pass-Fail Prediction | IEEE Journals & Magazine | IEEE Xplore," *IEEE Lett. Electromagn. Compat. Pract. Appl.*, vol. 2, no. 2, pp. 28–33, Mar. 2020, doi: 10.1109/LEMCPA.2020.2979227.
[45] Y. Zhang, Z. Yan, J. Wang, W. Liu, Z. Ning, and Z. Min, "The Research of Bulk Current Injection Probe Used for ICs Electromagnetic Immunity Measurement," *EMC COMPO 2019 - 2019 12th Int. Work. Electromagn. Compat. Integr. Circuits*, pp. 135–137, Oct. 2019, doi: 10.1109/EMCCOMPO.2019.8919952.
[46] M. Perotti and F. Fiori, "A test structure for the EMC characterization of small integrated circuits," *IEEE Trans. Instrum. Meas.*, vol. 67, no. 6, pp. 1461–1469, Jun. 2018, doi: 10.1109/TIM.2018.2800238.
[47] J. Hwang, W. Jung, and S. Kim, "Coupling analysis and equivalent circuit model of the IC stripline method," *2015 Asia-Pacific Int. Symp. Electromagn. Compat. APEMC 2015*, pp. 650–653, Aug. 2015, doi: 10.1109/APEMC.2015.7175299.
[48] H. Kang, W. Jung, K. Kim, H. H. Park, and S. Kim, "Equivalent circuit model of the IC-Stripline coupling to IC package," *2014 18th IEEE Work. Signal Power Integrity, SPI 2014 - Proc.*, 2014, doi: 10.1109/SAPIW.2014.6844556.
[49] W. Heuvelman *et al.*, "Simulation Methodology of Radiated Emission for IC Stripline Measurements," *IEEE Int. Symp. Electromagn. Compat.*, vol. 2018-August, pp. 366–370, Oct. 2018, doi: 10.1109/EMCEUROPE.2018.8485082.
[50] V. Sangwan, D. Kapoor, C. M. Tan, C. H. Lin, and H. C. Chiu, "High-frequency electromagnetic simulation and optimization for GaN-HEMT power amplifier IC," *IEEE Trans. Electromagn. Compat.*, vol. 61, no. 2, pp. 564–571, Apr. 2019, doi: 10.1109/TEMC.2018.2820202.
[51] F. Fiori and M. Perotti, "On the use of the IC stripline to evaluate the susceptibility to EMI of small integrated circuits," *IEEE Int. Symp. Electromagn. Compat.*, vol. 2016-November, pp. 306–309, Nov. 2016, doi: 10.1109/EMCEUROPE.2016.7739253.
[52] C. Leveugle and T. Weyl, "Implementation methodology of industrial and automotive ESD, EFT and surge generator models which predict EMC robustness on ICs and systems," *Electr. Overstress/Electrostatic Disch. Symp. Proc.*, Oct. 2017, doi: 10.23919/EOSESD.2017.8073453.
[53] T. Steinecke, M. Unger, S. Scheier, S. Frei, J. Bacmaga, and A. Baric, "System-ESD validation of a microcontroller with external RC-filter," *EMC COMPO 2013 Proc. - 9th Int. Work. Electromagn. Compat. Integr. Circuits*, pp. 196–201, 2013, doi: 10.1109/EMCCOMPO.2013.6735200.
[54] S. Kale and P. N. Kondekar, "Impact of underlap channel and body thickness on the performance of DG-MOSFET with Si3N4 spacer," *2014 IEEE Int. Conf. Electron Devices Solid-State Circuits, EDSSC 2014*, Mar. 2014, doi: 10.1109/EDSSC.2014.7061237.

[55] F. Fiori and M. B. Aimonetto, "Measurement of the susceptibility to EMI of ICs with two-tone interference," *2018 IEEE Int. Symp. Electromagn. Compat. 2018 IEEE Asia-Pacific Symp. Electromagn. Compat. EMC/APEMC 2018*, pp. 292–296, Jun. 2018, doi: 10.1109/ISEMC.2018.8393785.

[56] L. Yang, S. Wang, H. Zhao, and Y. Zhi, "Prediction and analysis of EMI spectrum based on the operating principle of EMC spectrum analyzers," *IEEE Trans. Power Electron.*, vol. 35, no. 1, pp. 263–275, Jan. 2020, doi: 10.1109/TPEL.2019.2914468.

[57] X. Chen, W. Chen, X. Yang, Y. Ren, and L. Qiao, "Common-Mode EMI Mathematical Modeling Based on Inductive Coupling Theory in a Power Module with Parallel-Connected SiC MOSFETs," *IEEE Trans. Power Electron.*, vol. 36, no. 6, pp. 6644–6661, Jun. 2021, doi: 10.1109/TPEL.2020.3046658.

[58] S. Boyapati, J. M. Redoute, and M. Shojaei Baghini, "Design of A Novel Highly EMI-Immune CMOS Miller OpAmp Considering Channel Length Modulation," *IEEE Trans. Circuits Syst. I Regul. Pap.*, vol. 64, no. 10, pp. 2679–2690, Oct. 2017, doi: 10.1109/TCSI.2017.2697912.

[59] S. Jin, Y. Zhang, Y. Zhou, Y. Bai, X. Yu, and J. Fan, "Conducted-emission modeling for a high-speed ECL clock buffer," *IEEE Int. Symp. Electromagn. Compat.*, vol. 2014-September, no. September, pp. 594–599, Sep. 2014, doi: 10.1109/ISEMC.2014.6899040.

[60] T. Baba, N. A. Che Mustapha, and N. F. Hasbullah, "Noise Sources Extraction for Conducted Emission Modeling of IC's using IBIS Models," *In 2021 8th International Conference on Computer and Communication Engineering (ICCCE)*, pp. 299–303, Jul. 2021, doi: 10.1109/ICCCE50029.2021.9467148.

[61] T. Baba, N. A. C. Mustapha, and N. F. Hasbullah, "Signal Integrity Analysis and Noise Source extraction of Integrated Circuits using IBIS Models," *2021 IEEE Reg. Symp. Micro Nanoelectron.*, pp. 80–83, Aug. 2021, doi: 10.1109/RSM52397.2021.9511571.

[62] T. Song, C. Liu, Y. Peng, and S. K. Lim, "Full-Chip Signal Integrity Analysis and Optimization of 3-D ICs," *IEEE Trans. Very Large Scale Integr. Syst.*, vol. 24, no. 5, pp. 1636–1648, May 2016, doi: 10.1109/TVLSI.2015.2471098.

[63] A. V. Bashkirov, I. V. Ostroumov, V. V. Glotov, T. S. Glotova, S. N. Panychev, and S. Y. Beletskaya, "Mathematical Model for Analysis of near and Far Field Characteristics based on Equivalent Transformation," *2020 Int. Multi-Conference Ind. Eng. Mod. Technol. FarEastCon 2020*, Oct. 2020, doi: 10.1109/FAREASTCON50210.2020.9271219.

BIOGRAPHIES OF AUTHORS

Tamana Baba completed her Bachelor of Technology in Electronics and communication Engineering, from Islamic University of Science and Technology Kashmir. Currently, she is working as a Research Assistant with the Department of Elec. & Comp. Engineering in International Islamic University Malaysia IIUM. Her research interests include Electromagnetic Interference, Integrated Circuits, Smart vehicles, and semiconductor devices. Currently, she is working on the critical prediction modelling for integrated circuits (ICs) electromagnetic compatibility (EMC) in smart automotive industry. She can be contacted at email: mehrajudinbaba5@gmail.com.

Nurul Arfah Che Mustapha received her B. Eng. Electronics-Computer and Information Engineering and M. Sc. (Electronics Engineering) degrees from the International Islamic University Malaysia (IIUM). In 2017, she received her Ph.D. in Engineering from IIUM. She worked as a graduate research assistant from 2009 to 2016 and obtained an IIUM Fellowship for her Ph.D. between 2011 and 2015. Nurul Arfah is currently employed as an Assistant Professor in the Electrical and Computer Engineering Department of the International Islamic University Malaysia's Kulliyyah of Engineering (IIUM). CMOS, VLSI circuit design, Energy Harvesting and Wireless Sensor Networks, and capacitive sensor signal processing are among her research interests. She can be contacted at email: nurularfah@iium.edu.my.

Nurul Fadzlin Hasbullah is a Professor in the Faculty of Engineering's Department of Electrical and Computer Engineering. In 2001, she earned a Bachelor of Engineering with First Class Honours from Cardiff University in Wales. She then spent a year as an integrated chip design engineer at Malaysia Microelectronics Solution in Cyberjaya before returning to academics as a tutor at the University Tenaga Nasional in Bangi, Malaysia. She became an Assistant Lecturer at International Islamic University Malaysia in 2003. In 2010, she received her Ph.D. from the University of Sheffield in the United Kingdom, where she studied the electrical and optical properties of quantum dot laser systems. Her research focuses on semiconductor device characterisation, optical detectors, and radiation hard devices. She can be contacted at email: nfadzlinh@iium.edu.my.