

Evaluation of the effectiveness of error detection in the implementation of shielded enclosures

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ABSTRAKT

Diplomová práce se zaměří na analýzu efektivity EM stínících krytů implementovaných na desce plošných spojů (PCB). Hlavním cílem práce je evaluace běžně dostupných měřících technik, jako jsou semi-anechoické komory, GTEM cely, elektromagnetické skeny a další, k identifikaci potenciálních chyb v implementaci těchto krytů. Diplomová práce zahrne využití simulačních nástrojů pro predikci chování elektromagnetických polí a interakcí navržených krytů. Výstup práce bude obsahovat vyhodnocení možností odhalení jemných implementačních nedostatků pomocí existujících měřících metod a zvážení potřeby implementace inovativních přístupů pro zlepšení detekce chyb.

Klíčová slova: Stínící účinnosti, GTEM cely, board-level shielding, EMxpert, detekce chyb

ABSTRACT

The thesis will analyze the effectiveness of electromagnetic shielding enclosures implemented on a printed circuit board (PCB). The primary objective of the thesis is to evaluate commonly available measurement techniques such as semi-anechoic chambers, GTEM cells, electromagnetic diagnostics scans, and others to identify potential errors in implementing these enclosures. The thesis will use simulation tools to predict the behavior of electromagnetic fields and interactions of the designed enclosures. The work output will include an evaluation of the potential to detect subtle implementation flaws using existing measurement methods and considering the need to implement innovative approaches to improve fault detection.

Keywords: Shielding effectiveness, GTEM cell, board-level shielding, EMxpert, failures detection

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CONTENTS

INTRODUCTION	11
I THEORETICAL PART	12
1 ELECTROMAGNETIC COMPATIBILITY.....	13
1.1 ELECTROMAGNETIC SUSCEPTIBILITY	14
1.2 ELECTROMAGNETIC INTERFERENCE	14
1.3 REQUIREMENTS FOR PROPER EMC FUNCTION	15
2 EM SHIELDING.....	17
2.1 INTERACTION OF ELECTROMAGNETIC WAVES WITH SHIELDING MATERIAL	17
2.2 SHIELDING EFFECTIVENESS	18
2.3 ASPECTS DETERMINING SE	18
2.4 PHYSICAL MECHANISM SE	19
2.5 PITFALLS OF SHIELDING DESIGN FOR OVERALL SE	20
3 BLS MEASUREMENT METHODS ACCORDING TO IEEE P2716.....	21
3.1 STANDARDIZED MEASUREMENT METHODS	21
3.1.1 SAE ARP6248: Stripline Test Method to Characterize the Shielding Effectiveness of Conductive EMI Gaskets up to 40 GHz.....	21
3.1.2 Reverberation method	23
3.2 NON-STANDARDISED MEASUREMENT METHODS.....	27
4 STATE-OF-THE-ART	29
4.1 EVALUATION OF SE PLANAR SAMPLES USING DTEM CELL.....	29
4.2 INVESTIGATION OF SE IN THE NEAR FIELD AT LOW FREQUENCIES	30
4.3 EFFECT ON SE DURING SPREADING OF HYBRID YARNS IN FABRICS	30
4.4 DETERMINATION OF SE USING STRIPLINE UP TO 44 GHz.....	31
4.5 SE ON BLS AT MICROWAVE FREQUENCIES.....	31
4.6 THE BLS WAS MEASURED USING A DUAL VIRC.....	32
4.7 SIMULATION MEASUREMENTS ON PCBs.....	33
4.8 MEASUREMENTS FOR COMPARISON OF STANDARDS	34
4.9 PLANE WAVE	36
5 BOX PLOT	37
6 MEASURING TECHNOLOGY	38
6.1 GTEM CELL	38
6.2 VECTOR NETWORK ANALYZER	39
6.3 EMI TEST RECEIVER	40
6.4 SIGNAL GENERATOR.....	40

6.5	EMXPert EHX	40
II	PRACTICAL PART	41
7	EXPERIMENTAL SAMPLES.....	42
8	EXPERIMENTS.....	45
8.1	MEASUREMENT METHOD USING VNA	47
8.1.1	Results SE with original shield	48
8.1.2	Results SE with a new shield	50
8.2	MEASUREMENT METHOD USING EMI TEST RECEIVER.....	52
8.2.1	Result in SE.....	53
8.3	MEASUREMENT METHOD USING THE EMXPert	55
8.3.1	Wide frequency measurement	56
8.3.2	Narrow frequency measurement	58
8.4	OVERALL SE ASSESMENT	60
9	SIMULATION.....	61
9.1	S – PARAMETERS SIMULATION	62
9.1.1	Results of S-parameter simulation	63
9.2	ELECTRIC FIELD MAPPING SIMULATION	65
9.2.1	Results SE.....	66
9.3	NEAR FIELD SCANNING SIMULATION	68
9.3.1	Results	69
10	COMPARISON OF REAL AND SIMULATED MEASUREMENTS.....	71
10.1	COMPARISON OF THE VNA METHOD WITH S-PARAMETERS	71
10.2	COMPARISON OF THE EMI METHOD WITH ELECTRIC FIELD MAPPING	72
10.3	COMPARISON OF THE EMXPert METHOD WITH NEAR FIELD SCANNING.....	73
11	IDENTIFICATION OF SAMPLE ERRORS.....	74
11.1	MEASUREMENT METHOD USING VNA	74
11.2	MEASUREMENT METHOD USING EMI TEST RECEIVER.....	75
11.3	MEASUREMENT METHOD USING THEEMXPert	75
11.4	S- PARAMETERS SIMULATION	76
11.5	ELECTRIC FIELD MAPPING SIMULATION	77
11.6	NEAR FIELDS SCANNING SIMULATION.....	77
	CONCLUSION.....	79
	BIBLIOGRAPHY	83
	LIST OF FIGURES	88
	LIST OF TABLES	90
	LIST OF ABBREVIATIONS	91

INTRODUCTION

Electronic devices have become an integral part of every industry and everyday life. Whether it's critical systems in transportation, medical equipment or consumer electronics, their reliable operation in an increasingly dense electromagnetic environment is critical. Electromagnetic interference (EMI) can come from the device itself or from surrounding sources - from high-frequency transmitters to interference from nearby circuits. Unwanted emissions can cause malfunction, data loss or even safety hazards. At the same time, there is increasing pressure for miniaturisation and high component density on PCBs, which further increases the risk of mutual interference and makes it more difficult to achieve the required level of EMC.

Specialised test equipment is required to verify the immunity and emission characteristics of such structures. Standard equipment includes semi-anechoic chambers for complex emissions, Gigahertz Transverse Electromagnetic (GTEM) cells as a compact alternative for rapid pre-certification testing, vector network analyser (VNA) for detailed analysis of transmission parameters, EMI receivers for broadband spectral scans, and near-field scanners to visualise hot spots directly on the PCB surface. These experiments are usually complemented by numerical simulations in CST Microwave Studio or similar tools, which allow virtual reproduction of measurement conditions and study of the interaction of electromagnetic (EM) fields with the designed covers without the need for repeated physical testing.

The aim is to identify implementation errors in the design of shielding directly on the board-level shielding (BLS) and to evaluate the sensitivity of commonly used measurement methods to detect them, which include measurement techniques such as semi-anechoic chambers, GTEM cells, electromagnetic scans, and others. The thesis will analyse the shielding effectiveness (SE) of enclosures implemented on PCBs. The thesis will also use simulation tools to predict EM field behavior and the designed shields' interactions. The thesis output will consist of evaluating the ability to detect subtle implementation flaws using existing measurement methods and considering the need to implement innovative approaches to improve fault detection.

I THEORETICAL PART

1 ELECTROMAGNETIC COMPATIBILITY

EMC can be defined as the capacity of devices to operate without causing interference to one another. In essence, the functionality of these devices must be ensured in environments where other EM signals are present, and concurrently, their own emissions must not interfere with the operation of other devices. The first documented instance of this issue is believed to be from the 1960s in the USA. Initially, EMC was only addressed in the military and aerospace industries. As time progressed and technological advances were made, an increasing number of experts and other industries began to address this issue. [1]

At present, there exist precise stipulations that electrical equipment is required to meet with regard to EMC. The definition may lead to the misconception that EMC only deals with the reliability of electronic systems, but it is much more complex than that. In 1968, H. M. Schlike, a pioneering figure in the field of EMC and an independent expert in the field, made the following statement: *"It is imperative to acknowledge that while a system may possess inherent reliability, its practical value is contingent upon its EMC during operation. Reliability and electromagnetic compatibility are inseparable requirements for a system that is to function at all times and under all circumstances."* [2] In consideration of the prevailing circumstances, this assertion can be regarded as valid. [1], [2]

EMC is defined as the compatibility of technical systems and devices, with a focus on the interaction and harmony of electrical and electronic devices. EMC's original focus was on protection against radio signal interference. However, over time, the company has expanded its activities into many other industries. It is imperative to acknowledge that EMC is a discipline that prioritises the development of application and system solutions. As emphasised by scientist C. R. Paul, electromagnetic compatibility does not introduce new principles or methods; rather, it provides the specifics of general, basic applications in many areas related to principles and laws. [1], [2]

EMC testing is divided into three main parts. The initial section of the text provides a comprehensive overview of the sources of EMI, encompassing their natural and artificial origins, as well as the characteristics of their intensity. The second part of the text provides a detailed exposition of the transmission environment and electromagnetic coupling, i.e. the manner in which energy is transmitted to the interference receiver. The final section of this text focuses on the receiver itself, i.e. the device or systems affected by interference, and seeks methods to eliminate it. In essence, the process is characterised by its complexity,

which arises from the functionality of the devices in question. These devices possess the capacity to act as both transmitters and receivers of interference, thereby inducing parasitic electromagnetic coupling between them. EMC is divided into two branches: Electromagnetic interference, Electromagnetic susceptibility.[1], [2]

1.1 Electromagnetic susceptibility

Electromagnetic susceptibility (EMS) also means immunity, which means that a device can function even when it is disturbed by other signals. The present issue thus focuses on technical measures that increase the immunity of systems and devices to environmental interference. It is evident that the primary concern of resistance is the elimination of the effects of interference. In addition to real measurements, simulation environments are currently employed to verify functionality and perform tests during the development process. The presence of high immunity is indicative of a reduced risk of interference. [1], [3]

1.2 Electromagnetic interference

Electromagnetic interference (EMI) is defined as the transfer of a generated signal by an interference source to another device or system via electromagnetic coupling. Such transfer is considered undesirable as it can cause device malfunction, reduce efficiency, or in extreme cases, cause complete failure of sensitive electronic devices. Electromagnetic coupling is a pivotal factor in this context, as it facilitates the transmission of interference signals between sources and receivers that are not directly connected by an electrical conduit. EMI analysis is a process that involves the identification of sources of interference signals, the identification of unwanted paths of propagation, and the detailed characterisation of individual interference. These aspects provide the basis for accurate measurement and subsequent effective suppression of interference. EMI therefore examines not only the consequences of interference, but also its origin, so that these phenomena can be appropriately eliminated or at least reduced during the design phase of systems. The analysis incorporates both the frequency parameters of the interfering components and their time course. [3], [4]

From the perspective of practical application in engineering, the issue of EMI is closely linked to the design of PCBs. In order to reduce EMI, it is essential to implement key preventive measures. These include the following:

- appropriate board layer layout;

- the shortest possible signal paths;
- consistent separation of circuits with different frequency characteristics;
- Proper grounding. [4]

The extant literature further emphasises the necessity of applying decoupling capacitors in the power supply branches and using shielding in places where interference signals may be emitted or captured. These design measures contribute significantly to achieving the required EMC and are a standard part of the design of high-frequency electronic equipment. [4]

1.3 Requirements for proper EMC function

In order for a device to be considered to be in compliance with EMC requirements, it is essential that the emission level of the device remains below the maximum emission limit that has been specified. Furthermore, it is imperative that the device exhibits an immunity to EMI that exceeds the minimum specified value. The fundamental principle of EMC is to establish a relationship in which the emission limit is lower than the immunity limit. This enables the achievement of the requisite EMC margin. The margin size is not subject to a rigid definition and is instead determined by the discretion of the equipment manufacturer. However, an excessive margin can result in increased costs associated with implementing interference suppression measures (e.g., shielding, filtering, etc.), while a margin that is too low may lead to non-compliance with EMC testing requirements, consequently incurring additional costs for subsequent measures. [1]

The optimisation of EMC-related expenditures entails the identification of an equilibrium between investments in EMC security measures and the financial implications of addressing any potential faults that emerge. As the number of faults increases, the financial costs of resolving them also increase. The probability of equipment failure due to inadequate EMC protection is inversely proportional to the amount invested in its electromagnetic immunity. The total costs of the project therefore consist of two components – investments in EMC measures and the costs of resolving problems caused by insufficient compatibility. The optimal ratio of these elements corresponds to the point of minimum cost. The precise amount of optimal costs cannot be determined in advance and is based primarily on practical experience and technical literature. The recommended range of investment in EMC is between 2–10% of the total cost of equipment development. It has been

demonstrated that, if EMC requirements are given due consideration at the initial stage of design, the associated costs can be reduced to as low as 1%. [1]

2 EM SHIELDING

Shielding can be defined as the deliberate insertion of a conductive or otherwise functional barrier between the transmitter and receiver. The purpose of this insertion is to mechanically weaken the flow of electromagnetic energy, thereby reducing the intensity of the emitted field. A secondary consequence of this insertion is that it simultaneously increases the immunity of the protected electronics. The implementation of such a barrier can often be a subsequent process, such as the addition of a metal enclosure or the application of a thin conductive layer on a PCB. This approach is often more cost-effective and expeditious than undertaking a complete redesign of the structure. In order to protect individual components and entire devices, it is imperative that shielding covers are used only after simpler interference suppression methods have been exhausted, and that their effectiveness is verified. This verification can be achieved in two ways: either by conducting direct measurements of the attenuation achieved, or by conducting numerical calculations based on known material parameters. The material parameters in question are electrical conductivity (σ), relative permeability (μ_r), and permittivity (ϵ_r). [1], [5]

2.1 Interaction of electromagnetic waves with shielding material

The attenuation caused by the shielding barrier is described by the shielding coefficient K_s , which is defined as the ratio of the field intensity behind the obstacle to the field intensity incident, as shown in formula (1). In applications, the logarithmic form of the ratio, referred to as SE (attenuation) SE (2), (3), is generally employed, as opposed to the linear ratio. [1], [2], [3]

$$K_s = \frac{E_t}{E_i} [dB] \quad K_s = \frac{H_t}{H_i} [dB] \quad (1)$$

$$SE = 20 \cdot \log \frac{1}{|K_s|} [dB] \quad (2)$$

$$SE = 20 \cdot \log \left| \frac{E_i}{E_t} \right| [dB] \quad SE = 20 \cdot \log \left| \frac{H_i}{H_t} \right| [dB] \quad (3)$$

In the event of a plane wave impacting the enclosure, and in the absence of variation in the environment both in front of and behind the plane wave, the electric and magnetic components are found to be subject to the same characteristic impedance. Consequently, the aforementioned relationship remains applicable to both fields without modification. Deviations from this standard are only observed in the near field, or in instances where the materials at the input and output differ. Nevertheless, in such cases, the definition of the coefficient K_s can still be utilised as a basis. [1], [6]

2.2 Shielding effectiveness

SE of a shield is determined as the ratio of the intensity of the electric field E_i (or magnetic field H_i) incident on the shield to the intensity of the same field E_t (H_t) measured behind the shield. In instances where direct data on the fields is not available, the quantity can be derived from the corresponding powers P_i and P_t . In general, the SE of a given material is indicative of the amplitude of EM waves that it transmits. In the relevant literature, this indicator is sometimes erroneously confused with the term "material attenuation". However, it should be noted that the two are in fact based on the same principle. In the context of a plane wave propagating in an environment characterised by an impedance that remains constant in both the frontal and rear regions of the shield (for instance, in the context of air), the SE calculated from the electric component is equivalent to the SE derived from the magnetic component. [7]

$$SE = \left| \frac{E_i}{E_t} \right| [dB] \quad SE = \left| \frac{H_i}{H_t} \right| [dB] \quad SE = \left| \frac{P_i}{P_t} \right| [dB] \quad (4)$$

$$SE = 20 \cdot \log \left| \frac{E_i}{E_t} \right| [dB] \quad SE = 20 \cdot \log \left| \frac{H_i}{H_t} \right| [dB] \quad SE = 10 \cdot \log \left| \frac{P_i}{P_t} \right| [dB] \quad (5)$$

2.3 Aspects determining SE

The following parameters have been identified as affecting SE:

- the frequency of incoming radiation is measured and documented,
- the properties of the material used must be considered, with particular reference to its conductivity, permittivity and associated parameters,
- the thickness of the barrier, otherwise referred to as the skin depth in the given material, is of paramount importance,
- the nature of the field source is to be determined (electric component, magnetic component, plane wave, etc.),
- the distance between the source and the shield is of significance in determining whether the former is a near or far field,
- the presence of design imperfections, such as holes, gaps or geometric errors, is to be noted,

- the quality of the conductive connection between the individual parts of the cover is of paramount importance. [8]

2.4 Physical mechanism SE

The initial comprehensive model by Mr. Schelkunoff delineates a weakening plane wave traversing a shielding cover through the utilisation of a transmission line analogy. Subsequent scholars contributed to the development of this concept. Schelkunoff's theory is predicated on the assumption that the shield is located in the far field of the field source. Consequently, the total SE for a plane wave can be determined as the sum of reflection attenuation (R), absorption attenuation (A), and multiple reflection attenuation (M). The principle of electromagnetic shielding is illustrated in Figure 1. [7], [9]

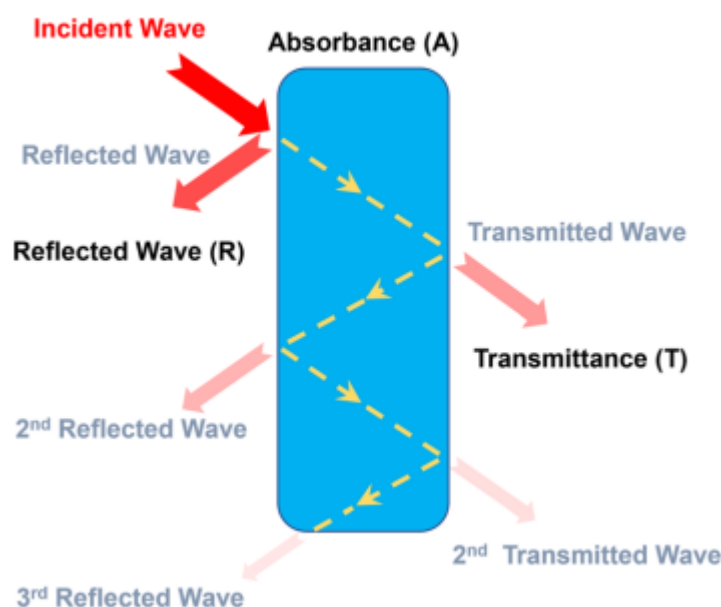


Figure 1 The principle of EM shielding. [10]

It is important to note that the shield is incapable of reflecting or absorbing all EM radiation; consequently, SE is described as the ratio of the power that passes through the barrier to the power that remains within it. EMI attenuation can be categorised into three distinct components: SE_R , SE_A , and SE_M . The calculation of these components can be achieved through the utilisation of a scattering matrix derived from S-parameters obtained from either empirical measurements or simulations. [10] In the event of the cover exhibiting higher shielding, such as approximately 15dB, the overall effectiveness is principally determined by components related to reflection and absorption. It can thus be concluded that the aforementioned relationship can be expressed by the total SE using SET (11). [12], [13]

$$R = S_{11}^2 = S_{22}^2 \quad (6)$$

$$T = S_{12}^2 = S_{21}^2 \quad (7)$$

$$A = 1 - R - T \quad (8)$$

$$SE_R = 10 \log \left(\frac{1}{1-R} \right) = 10 \log \left(\frac{1}{1-S_{11}^2} \right) \quad (9)$$

$$SE_A = 10 \log \left(\frac{1-R}{T} \right) = 10 \log \left(\frac{1-S_{11}^2}{S_{21}^2} \right) \quad (10)$$

$$SE_T = SE_A + SE_R = -20 \log(S_{21}) \quad (11)$$

2.5 Pitfalls of shielding design for overall SE

In addition to the attenuation issue, the design requirements for the enclosure's tightness must be considered. In practice, defects may occur at the point at which holes, gaps, or other inhomogeneities (leaks) appear in the material. This allows the EM field to "leak" through, thereby reducing the effectiveness of the shielding. The leaks above have been observed to behave analogously to small holes in the shield. Consequently, at low frequencies, they result in only marginal attenuation. Within the MHz range, it is possible to achieve almost maximum suppression; however, as frequency increases, a significant dispersion of values becomes evident. This is due to the action of the gaps, which begin to act as waveguides or substitute antennas. In exceptional circumstances, an attenuation of up to approximately 120 dB can be attained, provided that the conductive connection of all components within the enclosure is impeccably uninterrupted. [2]

3 BLS MEASUREMENT METHODS ACCORDING TO IEEE P2716

BLS, is a protective covering applied to PCBs with the purpose of providing shielding. While the primary function of BLS may appear to be the protection of devices against external interference or the prevention of interference being emitted into other devices, in practice, it is predominantly employed for EM isolation between the actual structure, components, and antennae installed on the board, among other applications. In the context of working with BLS, it is imperative to acknowledge that effective shielding is not solely determined by the characteristics of the enclosure itself. The method of installation, the number and dimensions of apertures, and other factors, play a pivotal role in determining the efficacy of shielding. It is evident that BLS does not constitute a fully independent shielding enclosure. Indeed, it represents only five of the six total walls of a Faraday cage. Furthermore, its electrical connection to the reference part of the cover is not perfect. A plethora of methodologies have been developed for the purpose of measuring BLS; however, it is important to note that not all of these methods are equally suitable. Consequently, results obtained through different methods can exhibit significant variations. The IEE P2716 standard; herefore, recommends, presents and generally describes which measurement procedures are suitable. The prevailing convention in the field divides measurements into two broad categories: those that are standardized and those that are non-standardized. [14]

3.1 Standardized measurement methods

Standardized techniques are defined as precise requirements stipulated in standards and technical reports. The requirements for design, calibration procedures, measurement protocols and data processing are clearly defined, ensuring reproducibility and comparability of results. [14] The methods that fall under the umbrella of standardized methods, as outlined in IEE 2716, will be described in general terms below.[14]

3.1.1 SAE ARP6248: Stripline Test Method to Characterize the Shielding

Effectiveness of Conductive EMI Gaskets up to 40 GHz

The original stripline configuration, which was developed for the purpose of EMC testing of integrated circuits, gave rise to the SAE ARP 6248 test procedure. This procedure allows the SE of conductive EMI seals to be evaluated up to a frequency of 40 GHz. This concept was further modified for the evaluation of BLS enclosures. Individual accessories are manufactured for the purpose of testing each BLS. These consist of a PCB module equipped

with a microstrip transmission line to which the measurement signal is fed, with the BLS enclosure itself mounted on this board. The entire assembly is subsequently inserted into the assembly, employing a stripline feed through the BLS. [14], [15]

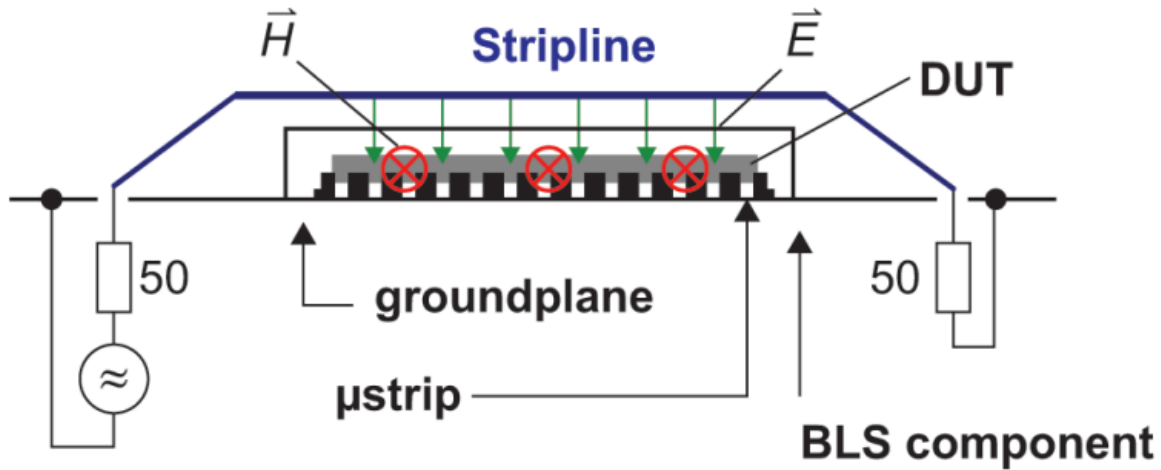


Figure 2 Wiring diagram for the Stripline method. [14]

The method of analysis employed in this study involves the monitoring of the attenuation of the coupling between the microstrip line on the PCB under test and the parent stripline conductor. The insertion of the cover reveals its SE. The arrangement functions up to 40 GHz, and the results correspond with those obtained in the reverberation chamber. The standard dimensions of a stripline are 150 mm in length, 240 mm in total length, 120 mm in width, and 25 mm in height above GND, thereby maintaining an impedance of 50 Ω . The PCB accessory measures approximately 120 mm $\times$ 300 mm, with an active area of 70 mm $\times$ 70 mm. The microstrip line is also 50 Ω and is terminated with a load. The dimensions can be adapted to the size of the cover, but it is imperative that the impedance of 50 Ω is maintained. [14], [15]

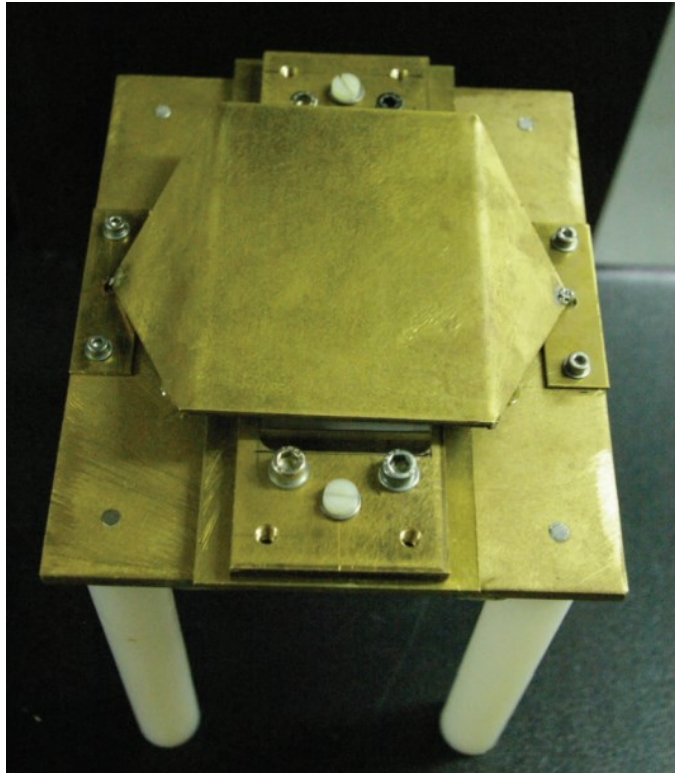


Figure 3 Stripline connection example. [14]

This method facilitates the determination of the SE for BLS located on a PCB, incorporating the influence of the board material and the method of connecting the enclosure to the GND plane. It is imperative to exercise caution and ensure that adequate isolation is maintained between incoming cabling/signals and outgoing cabling/signals. Utilising a 1 W amplifier, the dynamic range exhibited exceeded 80 dB up to 40 GHz. [14]

3.1.2 Reverberation method

The method is divided into four measurement options, each of which has its own specific design and operational requirements. The first method under consideration is the Stirred Reverberation Chamber. The apparatus under consideration is a conductive metal enclosure with a built-in mechanism (a 'rotating stirrer', frequency or source 'mixing'). The mechanism for altering the boundary conditions enables the positions to be averaged, thereby generating a homogeneous field, otherwise referred to as a 'statically uniform' EM field. This method draws inspiration from Wallace Sabina acoustic chambers, which facilitate uniform illumination of the sample from all directions and polarizations. [14]

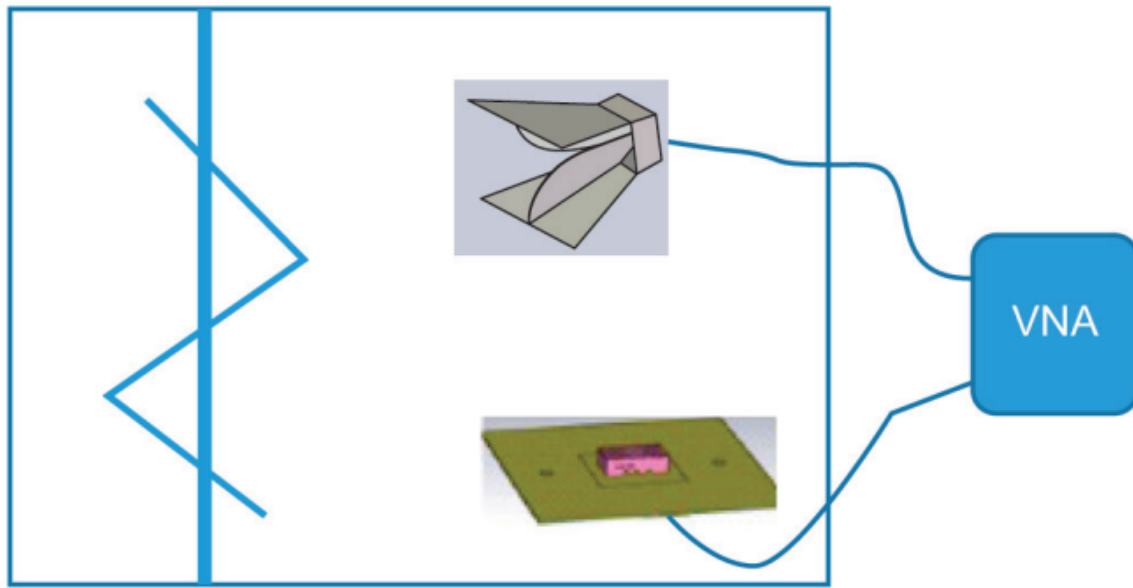


Figure 4 Stirred Reverberation Chamber – Wiring Diagram. [14]

It is evident from the aforementioned properties that reverberation chambers offer the advantage of being insensitive to the arrangement of cabling, cabinets and antennas. In contradistinction to anechoic chambers or free space, reverberation chambers generate a larger field at a given power, which can have a positive effect on the dynamic range of measurements. This is an additional advantage of reverberation chambers. Further information regarding the testing and measurement of vibrations in a reverberation chamber, including the use of SE measurements in sufficiently large spaces, i.e. several wavelengths at the lowest frequency of interest, can be found in the IEC-61000-4-21 standard. [16] Another standard that can be utilised for measurement is IEE Std 299.1™-2013, a specification which provides guidelines for enclosures ranging in size from 0.1 m to 2 m. [17] In this method, SE measurement is performed using a continuous wave (CW) that powers the antenna. Initially, the sample is measured in the absence of BLS, and subsequently with BLS (P_s). It is imperative to note that both measurements are performed under identical conditions, encompassing equivalent positions and frequencies. The SE is subsequently calculated using equation (12), where the angle brackets in the calculation represent the average of all 'stirrer' positions. [14], [15]



Figure 5 Stirred Reverberation chambre. [14]

$$SE = \frac{\langle P_u \rangle}{\langle P_s \rangle} \quad (12)$$

Nested reverberation chambers (NRCs), in contradistinction to the preceding methodology, which utilised a solitary chamber for measurement, this method employs dual interconnected chambers, thereby facilitating the measurement of external and internal parameters. An opening exists between the chambers, which is filled with the measured BLS cover, and the SE is then determined based on the energy transfer through the BLS. Each chamber is equipped with a stirrer that rotates during the measurement process, thereby ensuring the creation of a homogeneous environment. The measurement of energy transfer is facilitated by the utilisation of four antennas. The SE is then calculated from the ratio of the average power input between the outer and inner spaces, expressed in S-parameters. [14]

$$SE = 20 \log \frac{\langle |S_{41o}|^2 \rangle}{\langle |S_{41s}|^2 \rangle} \quad (13)$$

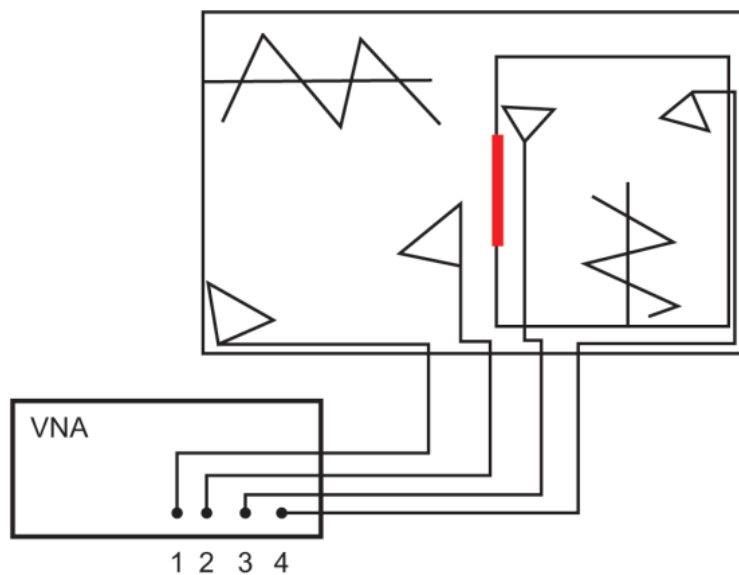


Figure 6 Wiring diagram for nested reverberation chambers.[14]

Dual reverberation chamber, this method bears a resemblance to the previous case, which also comprised two chambers. In this method, the chambers are positioned adjacent to each other and are interconnected by a BLS measuring cover. The SE is determined by the degree of energy transfer between the chambers. It is also possible to use each individual chamber for other measurements if the opening is sealed, which is why the chambers also have their own access port. The standard does not provide a precise formula for calculating the SE. [14]

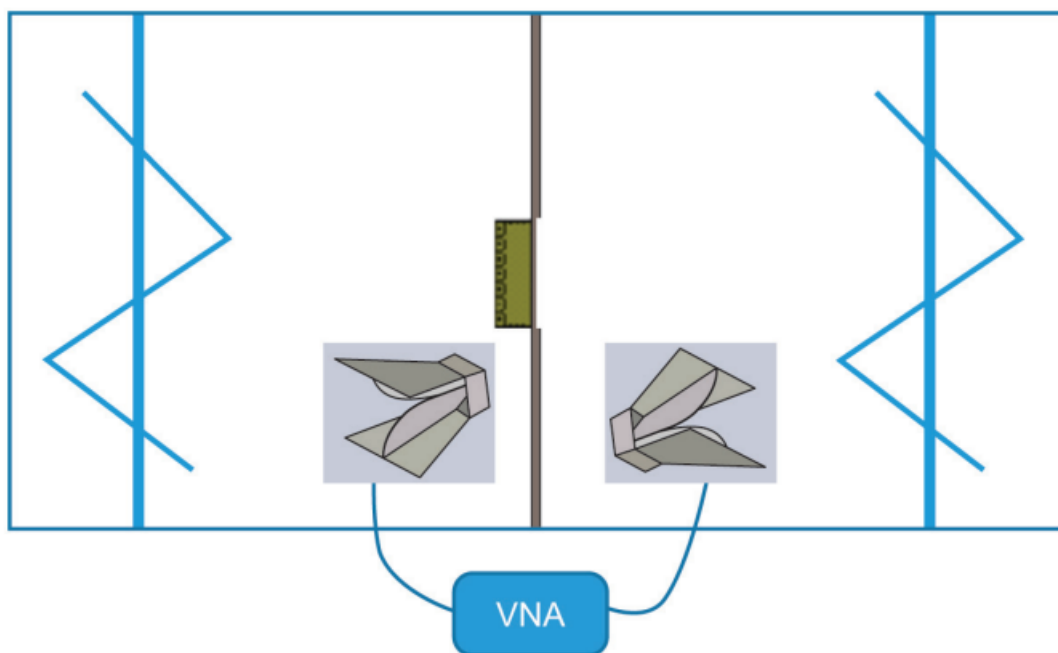


Figure 7 Dual reverberation chamber wiring diagram. [14]

Vibrating intrinsic reverberation chamber (VIRC), this method is distinguished by its marked deviation from the design principles of preceding chambers. This chamber is composed of a flexible material, and it functions as a mixer through the utilisation of its design properties, as opposed to the conventional mechanical mixer. For the purpose of SE measurements, two of these chambers are utilised, with the BLS positioned between them, and the degree of energy transfer between the chambers is employed for the calculation. In comparison with a fixed chamber of equivalent dimensions, the VIRC facilitates enhanced 'mixing' of the field due to its flexible configuration, thereby attaining reduced cut-off frequencies. The primary disadvantage associated with the material used in the construction of the chamber pertains to its service life and functionality.[14]



Figure 8 Two VIRC chambers made of flexible material, with a red mark indicating the sample location.[14]

3.2 Non-standardised measurement methods

Non-standardised techniques are alternative procedures which do not contain precisely defined requirements for measurement, preparation of measurement, calibration, etc. Consequently, it can be posited that the comparability of results with those obtained by other laboratories is not ensured. Non-standardised measurement methods include measurement in the GTEM cell. The GTEM is powered by coaxial cables with an impedance of $50\ \Omega$, and the septum is designed to maintain a surge impedance of $50\ \Omega$ along its entire length. A resistor network, also having a rating of $50\ \Omega$, is located at the extremity of the cell between

the absorbers. High-frequency absorbers are attached to the rear of the vehicle in order to absorb signals over a wide frequency range. Within the GTEM, a far-field environment is simulated, whereby the wave propagates from the input port to the absorbers. The deployment of a resistor network, in conjunction with an inner conductor and absorbers, serves to mitigate wave reflection. Depending on the measurement method, the SE can be calculated using the formulas (14) and (15). In the event of a generator/receiver being utilised for measurement purposes, formula (14) is applicable to the SE. In instances where a vector VNA, receiver is utilised for measurement purposes, formula (15) is applicable to the SE. [14]

$$SE_{dB} = 20 \log_{10} \left(\frac{V_{open}}{V_{BLS \text{ in place}}} \right) \quad (14)$$

$$SE_{dB} = 20 \log_{10} \left(\left| \frac{S_{21}}{S_{21 \text{ BLS in place}}} \right| \right) \quad (15)$$

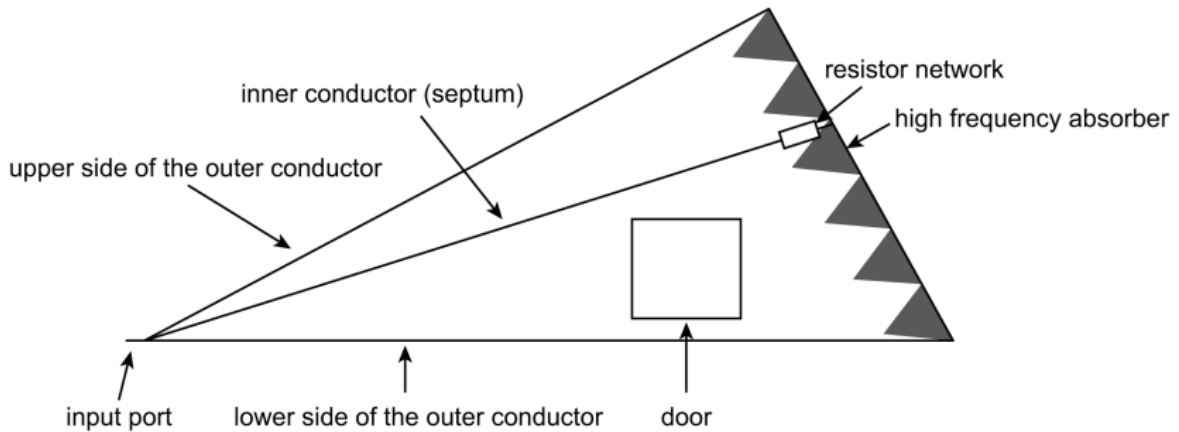


Figure 9 Description of GTEM cell.[14]

4 STATE-OF-THE-ART

The present chapter provides a comprehensive overview of the current state of research in the domain of electromagnetic shielding. The text provides a comprehensive overview of the various methods of SE measurement and their applications. The presentation will offer an overview of the range of approaches that are currently being used in studies in this field. These approaches include the use of a DTEM chamber for measurements, as well as SE evaluation in the near field and stripline measurements in the microwave band. Each study provides a different perspective on the issue and contributes to the overall picture of the current state of knowledge.

4.1 Evaluation of SE planar samples using DTEM cell

The present study is the first to address the evaluation of SE measurements using a method employing a dual transverse electromagnetic cell (DTEM cell) of planar samples. The objective of this study was to identify the factors that affect the accuracy and repeatability of the method, to analyse its sensitivity to measurement parameters, and to determine its limitations. The research was conducted utilising VNA measurement technology in conjunction with a DTEM cell, which comprises two TEM cells. The experimental procedure entailed the placement of the subject under investigation between two TEM chambers in an aperture, as illustrated in Figure 10. A series of experimental measurements were conducted on two distinct categories of materials: firstly, soft materials, including silver-coated textiles, and secondly, conductive plastics designed for use with hard materials. [18]

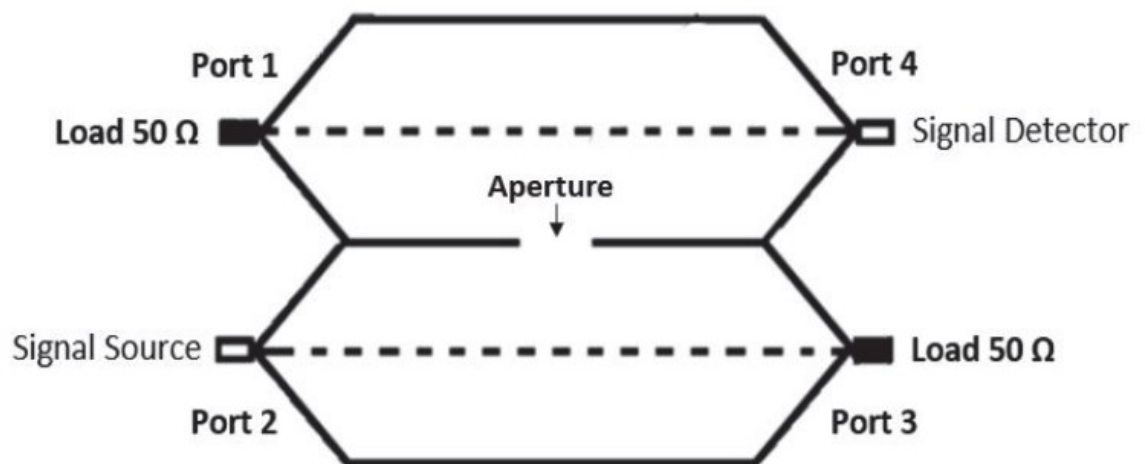


Figure 10 Wiring diagram for measurement using DTEM. [18]

The findings of the experiment demonstrated that the SE outcomes for DTEM measurements were significantly impacted by the positioning and fixation of the samples within the aperture. The correct placement and fixation of the electrodes is crucial, as this minimises energy leakage and significantly increases the measured SE values. The dimensions of the aperture also exerted an influence on the measurements. It is evident that the DTEM method is not appropriate for the estimation of SE; rather, its efficacy lies in the comparison of relative differences between analogous materials. [18]

4.2 Investigation of SE in the near field at low frequencies

The research in [19] concentrated on the evaluation of the effectiveness of EM shielding in the near field for low-frequency magnetic induction tomography (MIT) applications. A series of experimental and numerical tests were conducted using a variety of materials, including hard metal shields such as aluminium and Mu-metal, soft shields composed of ferrite powder, and combinations of these materials. The results of these tests demonstrated that metallic materials exhibit higher SE at lower frequencies, up to 13 MHz. Conversely, soft shields based on ferrite powder demonstrated a greater capacity to absorb EM radiation at higher frequencies. Furthermore, a newly designed method of partial encapsulation of the receiving coil has enabled more accurate measurement of SE by eliminating unwanted edge effects. The findings of this study are of practical significance for the selection of suitable shielding materials and the optimisation of MIT system design. [19]

4.3 Effect on SE during spreading of hybrid yarns in fabrics

The objective of the present study [20] was to evaluate the SE properties of fabrics containing metal hybrid yarns. The experiment comprised the production of yarns by combining metal and polyamide, the weaving of these yarns into single-layer and double-layer samples with differing yarn distributions, and the measurement of SE using the free space method over the range of 0.8–5.2 GHz. The findings demonstrated that the type of metal did not influence the overall SE; however, stainless steel exhibited higher absorption compared to copper or silver. The findings of the study demonstrated that two-layer fabrics exhibited significantly superior shielding performance in comparison to single-layer fabrics. Furthermore, it was established that full yarn coverage yielded the highest SE. It can thus be concluded that a two-layer structure incorporating stainless steel yarns is optimal for achieving maximum absorption and minimising reflections. [20]

4.4 Determination of SE using stripline up to 44 GHz

The present experiment is concerned with the characterisation of SE BLS using stripline measurements, as described in IEEE Standard 2716. [13], [20] The measurements were conducted over a broad frequency range, extending up to 44 GHz. The stripline method represents an adaptation of the previously standardised method for testing conductive seals, SAE ART 6248. [20], [21] The objective of the experiment was twofold: firstly, to evaluate the SE for BLS, and secondly, to analyse the influence of the sample mounting on the PCB ground plane. The experiment was conducted employing a method specifically adapted for this purpose. The microstrip line was utilised as the radiation source, with the stripline itself functioning as the receiving antenna. The PCB was then positioned in a manner that ensured its placement above an opening in the conductive board. Two types of BLS were selected for the measurements - one without holes and the other with holes. In the sample with holes, the SE was limited precisely because of the holes. At high frequencies (>10 -15 GHz), a decrease in SE was observed for all configurations, attributable to the design gap between the PCB layers. [21]



Figure 11 Sample of tested samples.[21]

4.5 SE on BLS at microwave frequencies

The present study [23] focused on quantifying the variability of SE BLS at the PCB level in microwave frequencies when installed in different metal enclosures. The objective of the research was to verify and determine SE BLS when placed in different protective enclosures and to propose a measurement methodology providing basic SE and deviation estimates. In the course of the experiment, a board with three striplines connected to a VNA was constructed: S (shielded) - located beneath a shielded enclosure (PCBS), P (parallel) - positioned parallel to S at a distance of 50 mm, O (orthogonal) - positioned perpendicular to

S at a distance of 50 mm. A metal PCB cover was placed on the S stripline, after which the transmission between the outer and inner striplines was measured using a VNA. The SE was then calculated from these measurements. The study's findings indicate that the efficacy of PCBs shielding is contingent on the characteristics of the outer envelope, including its dimensions, geometry, and composition. The measurements obtained in the final enclosure reflect only the specific case under investigation, whereas the Point SE metric in the reverberation chamber allows the average SE and its variability under different conditions to be estimated in advance. This method is therefore considered suitable for general evaluation of shielding properties prior to installation. [23]

4.6 The BLS was measured using a dual VIRC

The present study [24] focuses on the quantitative evaluation of SE BLS materials using the dual VIRC method. The tested materials were of a variety of sizes and materials, including perforated samples for cooling. The materials were then soldered onto specially designed PCBs. The present study examined the attachment of BLS to PCBs and its effect on measurements, as well as on orientation or insufficient adhesion of the shielding screen. Furthermore, reference holes in the PCB (from 25x6 mm to 56x56 mm) were measured separately without a shielding screen to evaluate the energy transfer through the hole and its effect on SE using the dual VIRC method. The measured BLS and PSB are presented in Figure 12. [24]

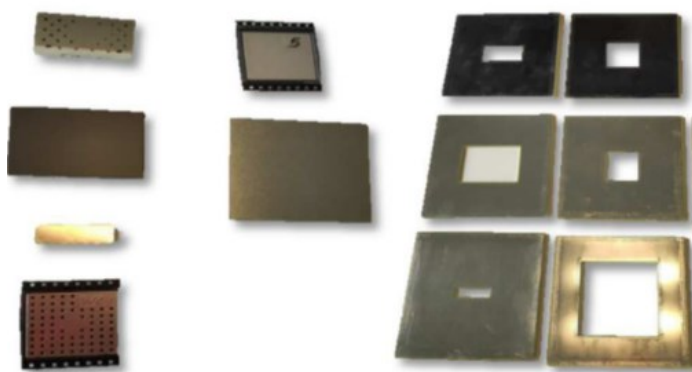


Figure 12 BLS and PCB sample for the VIRC method. [24]

The VIRC method is described in IEEE Standard 2716 and in the previous chapter. [13] Dual VIRC consists of two interconnected chambers with a common opening. Measurements were made in the frequency range from 300 MHz to 18 GHz. Discone antennas were used for measurements up to 1 GHz and broadband parabolic corner antennas

for measurements above 1 GHz. The antennas were connected to a signal generator and a spectrum analyser via feedthroughs in a common wall. First, measurements were made without the DUT to measure the power in the RX-VIRC during transmission from the TX-VIRC through the hole in the PCB. This was followed by measurements with the material under test (MUT) sample attached to the aperture and the MUT power measured. The SE was then calculated from these two procedures. An accurate SE was determined for each PCB. The SE measurement results show that both the physic as well as the quality of assembly and sample orientation. The human factor can cause variability in results even with a laboratory stable dual VIRC. The effect of apertures is also critical, as their size significantly affects the energy transfer between chambers and thus the calculated SE of the material. [24]

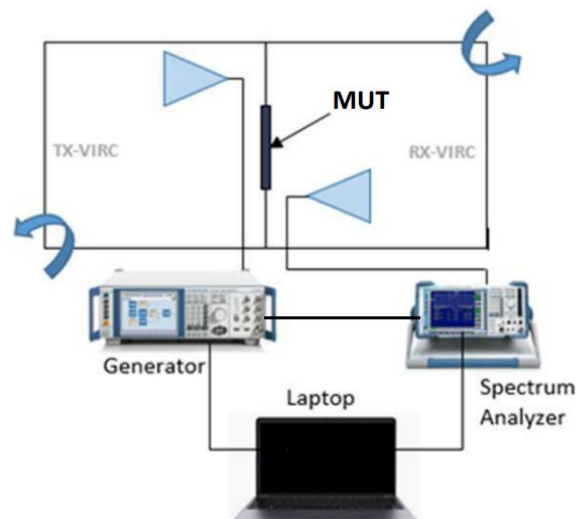


Figure 13 Wiring diagram for dual VIRC MUT. [24]

4.7 Simulation measurements on PCBs

This research [25] deals with the measurement of the near field above a printed circuit board (only the quantities $|E_z|$, $|H_x|$, $|H_y|$). The aim is to get a simple equivalent - several small electric and magnetic dipoles that emit exactly the same but can be simulated more quickly. The authors have proposed a new, very fast method for finding the positions and orientations of these dipoles. First, the measured field is filtered and converted into a binary image. Morphological erosion using the pattern of a single dipole searches for suitable positions and orientations of the sources. This step is repeated, with the most intense areas of the field being partially attenuated in each cycle, so that weaker emissions can also be detected. Once the positions have been determined, the dipole moments are calculated using the Levenberg-

Marquardt method on two measurement height planes and the system is stabilised using Tikhonov regularisation. [25]

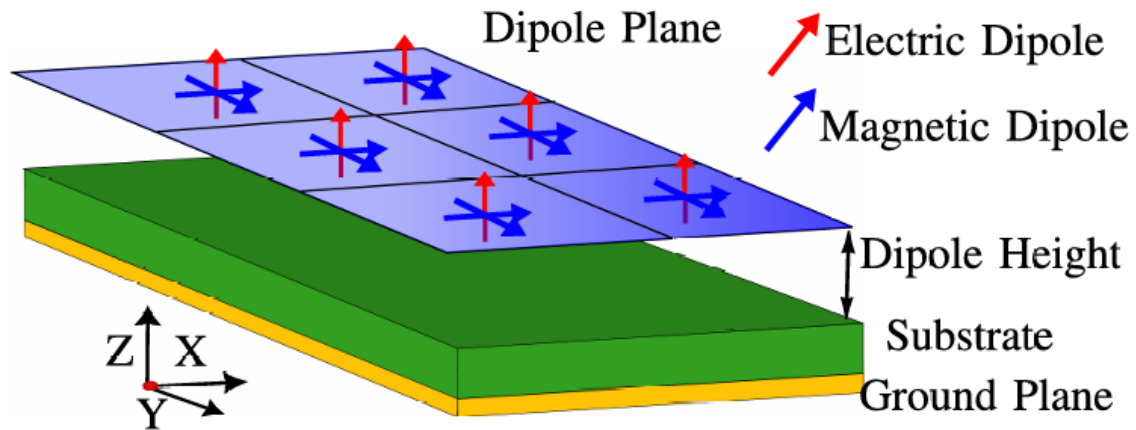


Figure 14 Dipole distribution on the sample.[25]

The method was verified on two simulated microstrip structures (1 GHz) and on a real portable projector motherboard (156, 381 and 514 MHz). The scans were performed at two to three heights above the board, using grids of $21\text{-}27 \times 21\text{-}31$ cells for the simulations and 25×25 cells for the real board. The reconstructed fields showed a correlation of 0.97-0.99 with the original data, requiring only a few dozen dipoles. The total optimisation time remained significantly lower than the conventional approach, which inserts a dipole in each grid cell and often fails to converge at higher resolutions. The method is characterised by high accuracy, a small number of sources and fast convergence. For common EMC tasks, this method is a sufficient solution and can also serve as a starting point for more demanding optimisations on smaller or more specific samples. [25]

4.8 Measurements for comparison of standards

The study [26] investigates how to accurately measure SE EMI gaskets (200 MHz - 1 GHz) according to two standards. The first method follows IEEE 299, a set of tuned half-wave dipoles. [27] The second method is implemented according to the military standard MIL DLT 83528 G, using a log-periodic antenna, which is greatly simplified in practice (one radiator instead of several dipoles). [28] The study verifies whether it provides the same technical information and also examines the angle and distance of measurement, which affect the scattering of the SE values obtained. The aim of the research is to verify whether the log-periodic antenna shields as well as the reference set of tuned dipoles located 30.5 cm from

the opening. Another objective is to use simulations to determine how the SE is affected by changes in the angle of incidence, the distance of the receiver and the position of the transmitting dipole in the chamber. [26]

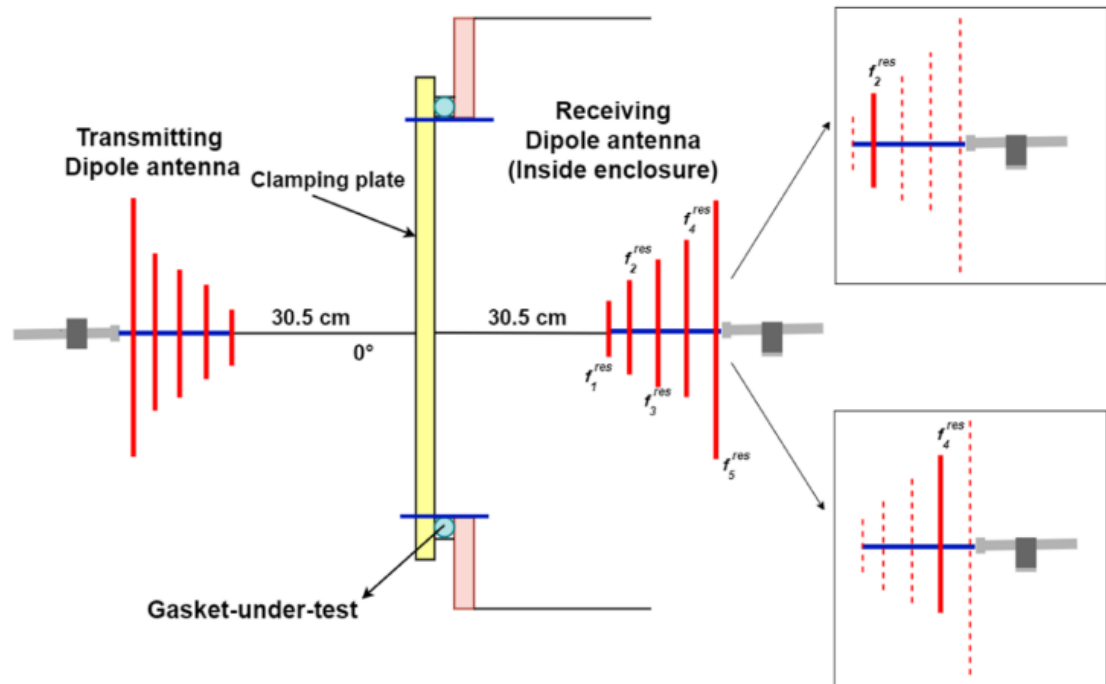


Figure 15 Example of a connection diagram for both methods. [26]

The measurements were taken in a shielded chamber measuring $2 \times 2 \times 2$ m at KU Leuven. The opening, clamping, and all dimensions were copied from the simulation model. The connection consisted of a vector analyzer connected by a $50 \, \Omega$ coaxial cable, and both antennas were always 30.5 cm from the clamping plate and pointed perpendicular to the opening (0°). Furthermore, the distance of the receiving dipole inside the chamber (10-80 cm) and the distance of the external transmitter (30-50 cm) were changed. It was confirmed that the average SE at the antenna position is almost independent. The simulation showed that the SE is the same for both tuned dipoles and log-periodic antennas, with results differing by only a few decibels across the entire band. Measurements confirmed this. Further tests showed that the average SE does not depend on how far the receiving dipole is from the opening; the angle of incidence and the frequency-dependent antenna pattern are the most important factors. The study showed that a log-periodic antenna can fully replace a set of tuned dipoles when measuring SE according to IEEE 299, which simplifies preparation and saves time without losing accuracy. [26]

4.9 Plane wave

This study [29] deals with a plane wave arriving parallel to the ground plane of a microstrip on the wall of a GTEM/TEM chamber, which is essential for immunity testing but has been little studied. The publication emphasises that the original coupling formula has to be adjusted by a factor of $\frac{1}{2}$ because the electric field in the chamber is not doubled as it is with infinite ground. For this study, a $50\ \Omega$ microstrip FR-4 test sample was fabricated and divided into three meander sections. The sample was placed in a GTEM cell and the transmission to the meander was measured. At the same time, full-wave simulations were carried out. The agreement with the measurements confirmed that the correlation factor $\frac{1}{2}$ must be used in the original formula for real GTEM. The output here is the correlation factor; it is sufficient to meander the microstrip to compensate for the loss and the immunity tests can be performed even in a low-cost GTEM without higher power. [29]

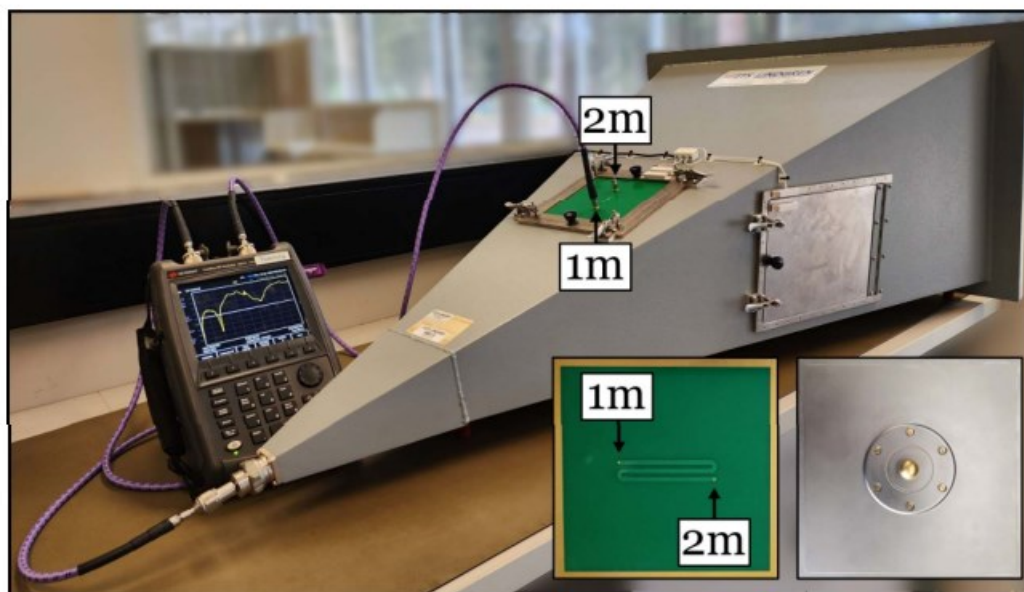


Figure 16 Measurements in GTEM cells. [29]

5 BOX PLOT

Given the nature of the practical part, it is necessary to explain the box plot that will be used to process the data. The box plot is very commonly used in statistics for data processing and analysis. Its advantage over the line graph, which will also be used in this work, is that the box plot is much clearer. However, line graphs are more accurate. Therefore, both graphs are used to visualise the processed results. A box plot consists of the so-called quartiles or interquartile range (IQR), which are divided into - x_{25} lower quartile; - x_{50} median

- x_{75} upper quartile. [30]

It is also used for marking, the terms Q_1 , Q_2 and Q_3 or Q_{25} , Q_{50} and Q_{75} are used. The median is created according to the middle value of the other sorted values in the set. The first and third quartiles are formed by calculating (16) the value of the quartile order, denoted z_p . [30]

$$z_p = \left(\frac{n \cdot p}{100} \right) + 0,5 \quad (16)$$

where n is the number of values and p is the percentage that marks the quartile. Once the quartiles (16) have been calculated, the interquartile range QR must be calculated. (17). [30]

$$QR = x_{75} - x_{25} \quad (17)$$

At the same time, calculation (17) is used to determine the end points A and B , also known as the whisker points. [30]

$$A = x_{25} - 1,5 * QR \quad (18)$$

$$B = x_{75} - 1,5 * QR \quad (19)$$

Once all the steps have been completed, you can construct a box plot. A box plot allows you to identify outliers, determine symmetry, etc. A perfect distribution occurs when the median is exactly in the centre of the box. If the median is close to x_{25} or x_{75} , this may indicate a different distribution of the data. [30]

6 MEASURING TECHNOLOGY

This chapter introduces the measurement equipment used in the practical part. The description starts with the GTEM chamber, which provides a controlled TEM field and is used to measure emissions and immunity. This is followed by a VNA, which is used to analyse the dispersion parameters of the circuit. We will then focus on the EMI receiver, which enables rapid pre-compliance testing of interference signals. Next is a microwave signal generator, which provides spectrally pure excitation over the entire operating band. Finally, the EMxpert desktop near-field scanner provides instant visualisation of hot spots on the PCB surface. Together these instruments form a comprehensive measurement chain. It covers both the generation and controlled exposure of EM fields and their precise detection.

6.1 GTEM cell

The GTEM chamber is a conical coaxial waveguide terminated with a resistive load, in which a stable TEM field with a characteristic impedance of 50 ohms is generated in the working area thanks to a specially shaped septum. Designed in accordance with IEC/EN 61000-4-20 [31], it provides a standardised environment for two sets of tests:

- measurement of emitted emissions, monitoring the intensity of fields emitted by the equipment under test (EUT);
- emission immunity tests, where the EUT is exposed to a defined EM field and its functional stability is evaluated. [32]

The chamber is available in several sizes with a septum distance from the floor ranging from 250 mm (model GTEM 250) to 2000 mm, which determines the maximum dimensions of the EUT; the declared operating range is 0.1 MHz - 18 GHz. The EUT is inserted through a shielded front door and the power or data lines are routed through shielded feedthroughs, so there is no need to pierce the chamber shell. The rear resistive load absorbs incident energy and suppresses reflections, creating reproducible free space conditions in a compact volume. The GTEM cell is therefore used for rapid pre-certification testing, product development and academic experiments focused on EM field distribution or antenna characterisation. [32]

6.2 Vector network analyzer

A VNA is a measuring device that allows you to monitor how high-frequency power is reflected from and passes through the circuit under test across the entire frequency range. This is done by simultaneously measuring the amplitude and phase of the scattering parameters (S-parameters), giving the user a complete picture of the matching and transmission characteristics of the device under test. A practical example is the R&S®ZND two-port analyzer: the basic version performs unidirectional measurements from 100 kHz to 4.5 GHz, while optional extensions enable bidirectional characterization and extension of the operating band up to 8.5 GHz. The device is equipped with a touch screen for intuitive operation and can be supplemented with functions such as time domain or de-embedding, making it a universal tool for routine and advanced analysis of high-frequency networks. [33]

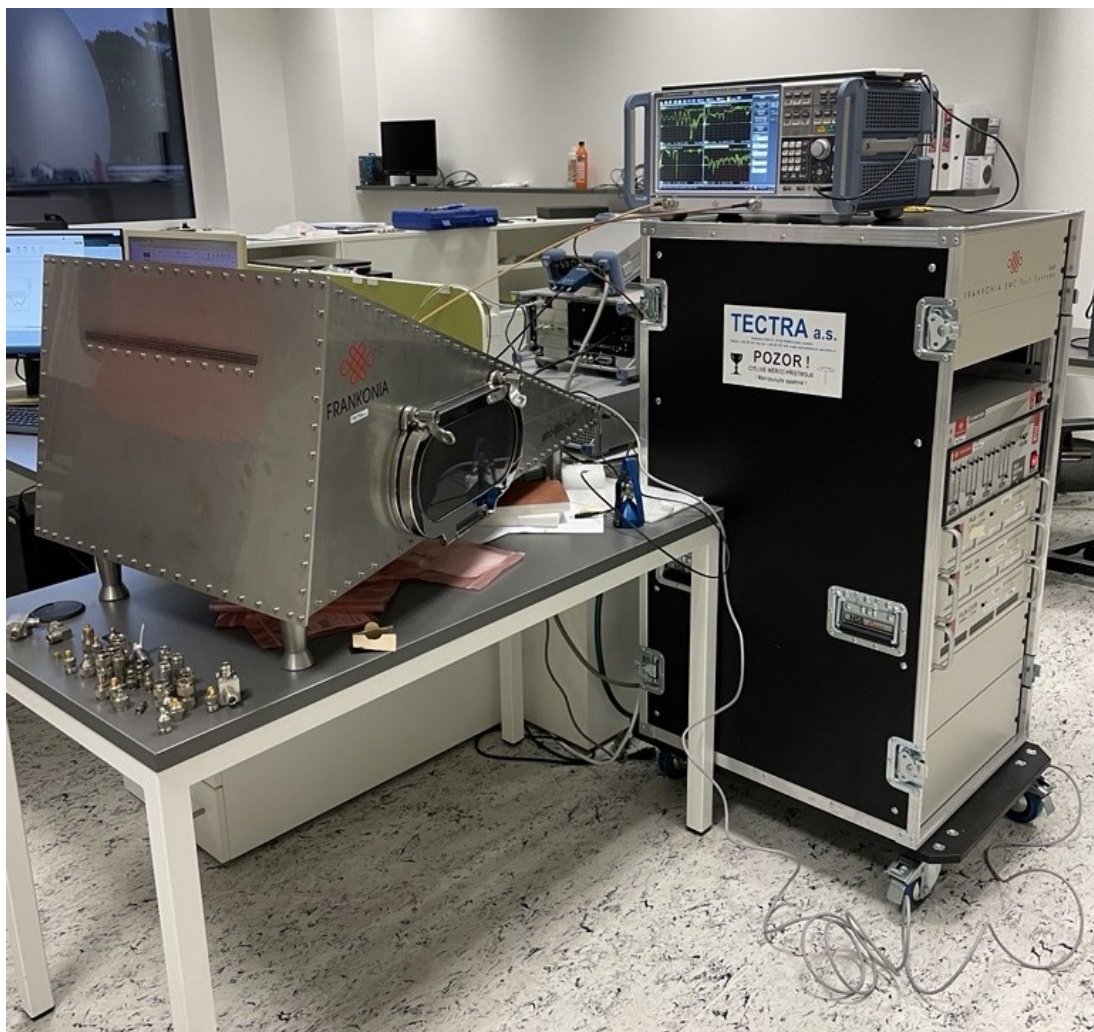


Figure 17 GTEM Cell and VNA.

6.3 EMI test receiver

The R&S®ESRP receiver for EMI testing is used to measure EM interference and for EMC pre-compliance testing. It combines a fully CISPR 16-1-1 [34] compliant measuring receiver with a signal and spectrum analyzer in a single device, covering both detailed diagnostics of interference signals and general laboratory analysis of the broadband spectrum. The receiver measures EMI from 10 Hz to 7 GHz. The user can choose either classic step tuning or a fast time domain scan based on Fast Fourier Transform (FFT), which significantly reduces measurement time. The receiver has a preselection and preamplifier, so it can detect even very weak interference. It supports all detectors and bandwidths required by CISPR and MIL-STD standards. [35]

6.4 Signal generator

The R&S SMF100A is a microwave analogue generator that covers the range from 100 kHz to 43.5 GHz when equipped with the appropriate frequency modules and can generate both pure CW and common analogue modulations. Optional "high output power" equipment increases its level to +25 dBm at 20 GHz, allowing it to compensate directly for cable attenuation or power-hungry measurement chains. With its exceptionally low phase noise and low broadband noise, it is used for analyser calibration, filter, amplifier and converter characterisation, phase noise testing, radar and satellite scenario simulation and generally as a stable microwave signal source for EMC/EMI measurements. [36]

6.5 EMxpert EHX

EMxpert EHX is a very close field desktop scanner designed to quickly locate and analyse sources of EMI on PCBs. It is based on a patented array of 1,218 magnetic probes spaced 7.5 mm apart, with electronic switching to provide an effective resolution of 3.75 mm and map the field distribution across the board in a matter of seconds. The system operates in the 150 kHz-4 GHz range (with optional extension to 8 GHz) and consists of a scanner with compact adapter, a user-supplied spectrum analyser and a PC running EMxpert software; the EHX+ variant has an integrated analyser, making it a plug-and-play solution. This allows designers to immediately see 'hot spots', EM paths or SE on the workbench during design and pre-certification testing, reducing measurement time by up to 100 times and the number of design iterations by around 50%, according to the manufacturer. [37]

II PRACTICAL PART

7 EXPERIMENTAL SAMPLES

For the experimental analysis, a total of six different PCB samples with implemented shielding were designed. Each of these samples differed in the specific method of connecting the BLS to the PCB, allowing a detailed investigation of the effect of different connection techniques on the overall EM characteristics, as can be seen in Figure 19. The primary radiator of the EM signal was the Pulse Electronics W3006 chip antenna. This antenna operates at a frequency of 2.4 GHz, which is a suitable value for experimental verification of SE, as it provides sufficiently intense EM radiation for initial testing and analysis of the influence of shielding on radiation characteristics. A one-piece Laird BMI-S-102 BLS measuring $3 \times 16.5 \times 16$ mm was used for the shielding implementation. This shielding enclosure was applied to all PCB variants. The primary objective was to compare different connection methods and evaluate their impact on EMC. The following sample configurations were tested:

- sample A – correctly implemented shielding;
- sample B – gap on the left under the antenna;
- sample C – gap around the shielding, shielding connected to ground;
- sample D – gap around the shielding, shielding not connected to ground;
- sample E – solder pads under the shielding are not connected to the ground;
- sample F – unsoldered shielding.

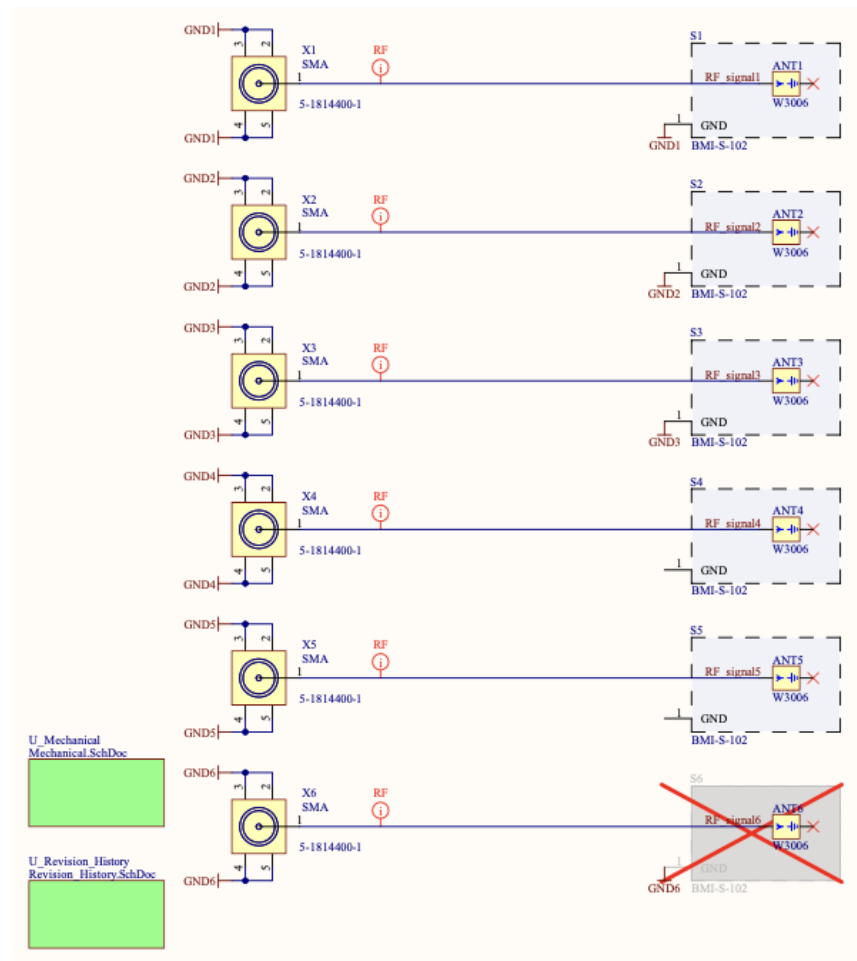


Figure 18 PCB manufacturing requirements. [Own]

The reality turned out to be different from the initial expectations. Model F was originally designed as a reference variant without shielding implemented, but the supplier fitted this sample with a BLS without providing details on how it would be implemented. This unplanned modification disrupted the planned measurement run and required a change in the experimental methodology. Testing was to be conducted without shielding to properly evaluate device performance, but the presence of the shielding complicated the process. At the same time, it meant that the specification was not met, as the model was not supposed to include a shielding enclosure. To obtain reference values and to perform a detailed analysis of the differences between the samples, it was decided to temporarily remove the BLS. This process was done by soldering, which made it easy to remove. Once the initial measurement phase was completed, the BLS was re-implemented. As the PCB boards received did not match the original specification, it was necessary to modify the measurement plan. Thus, testing was eventually conducted in two variants - with and without the enclosure - to

compare their effect on the device characteristics.



Figure 19 The resulting products of the order. [Own]

8 EXPERIMENTS

The measurements in the GTEM were carried out with a gradual rotation of the sample by 45° . The initial position (0°) was set so that BLS, as can be seen in Figure 20, was oriented upwards, and then the sample was rotated to other angular positions. Further experiments were performed in the shielded chamber using the EMxpert tool. Each measurement was performed in two variations, with and without shielding, which allowed a direct comparison of its effect on the EM field. This procedure allowed the optimal BLS design to be determined and revealed weak points that could negatively affect the EM of the device. The formulas (4 - 15) have been used in the calculations of the SE.

Table 1 Used measuring instruments. [Own]

Measuring devices	Type	Working range
Shielded chambers	GTEM CELL 250	DC ... 20 GHz
Vector network analyzer	R&S ZND	100 kHz - 4.5 GHz
EMI test receiver	R&S ESRP	9 kHz – 3.6 GHz
Signal generator	R&S SMF 100A	100 kHz – 43.5 GHz
Spectrum analyzer	R&S FSL	9 kHz – 3 GHz
EMxpert	EHX	150 kHz - 4 GHz

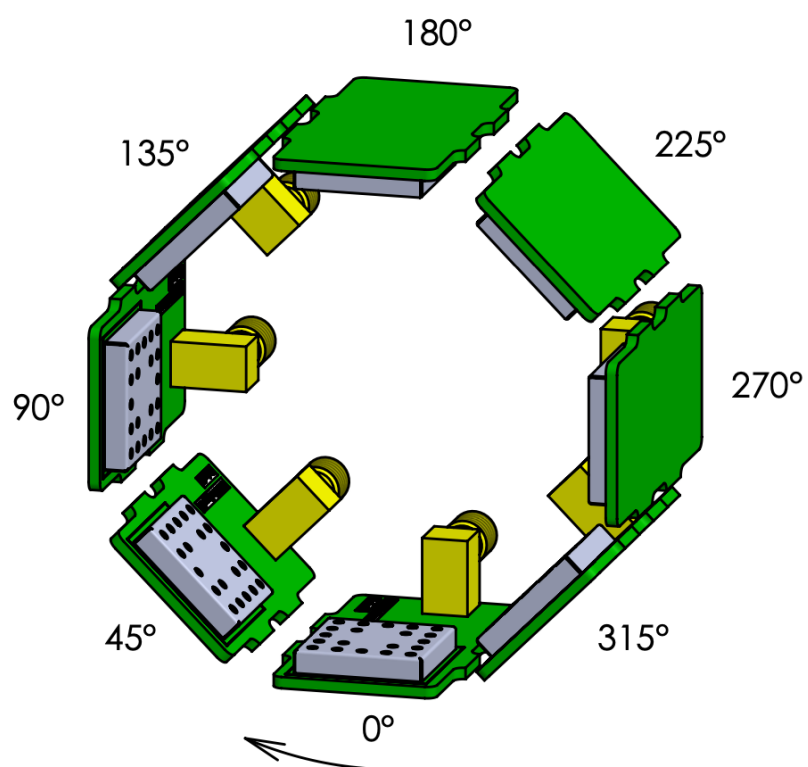


Figure 20 Rotation with sample in GTEM cell. [Own]



Figure 21 Measurement in GTEM cell with BLS. [Own]

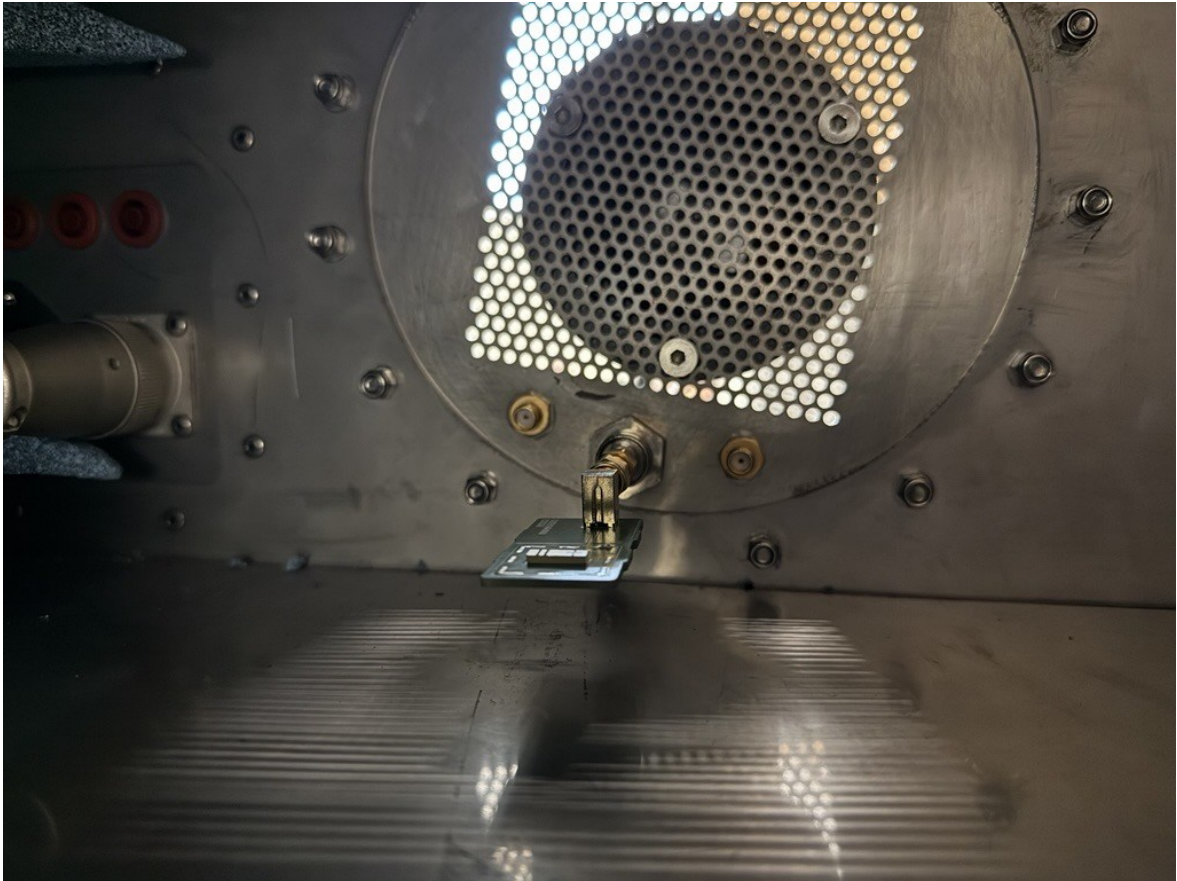


Figure 22 Measurement in GTEM cell without BLS. [Own]

8.1 Measurement method using VNA

The first PCB measurement using a VNA was performed in a GTEM cell. A VNA was used for the measurements, with port 1 connected to the antenna of the measurement sample via the cell grommet. Port 2 was directly connected to the GTEM cell. The PCB was manually rotated in 45° increments, with the initial position set so that the shield was facing upwards Figure 20. The measurements were performed under three different test conditions:

- original BLS including shielding,
- a variant without shielding,
- re-implemented shielding.

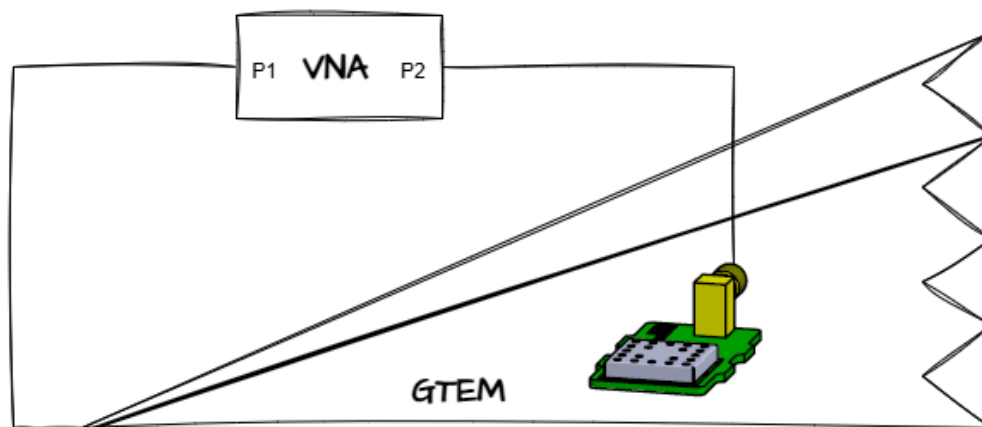


Figure 23 Wiring diagram for the VNA method. [Own]

8.1.1 Results SE with original shield

Measurements using the VNA with the original BLS provided data that allowed evaluation of the original shielding. The analysis compared the results obtained with and without the old shield. The best value was achieved by sample A, with approximately 32 dB, followed by sample F, with 31 dB. The other samples showed lower efficiency, with the worst results for sample D. All measured values are shown in Figure 24 and Figure 25. The frequency distribution of this measurement method appears to be quite satisfactory. Z-scores are used to identify outliers in the data, with values within ± 1 considered normal, values within ± 2 considered elevated but still acceptable, and values exceeding ± 3 indicating significant deviations from expected results. Most of the measured values fall within the range of ± 1 and ± 2 , indicating stable results. Only variants C and D are in the ± 3 interval, but with only a minimal number of values, which does not affect the overall assessment of the measurement.

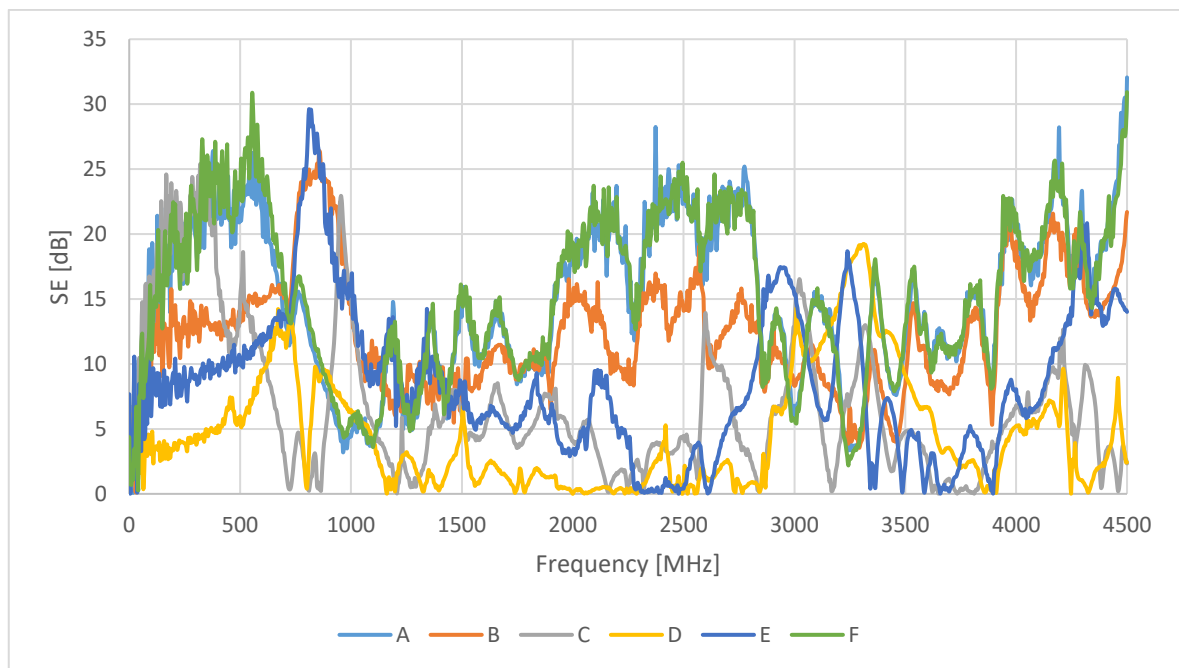


Figure 24 SE as a function of frequency for the original shield – VNA method. [Own]

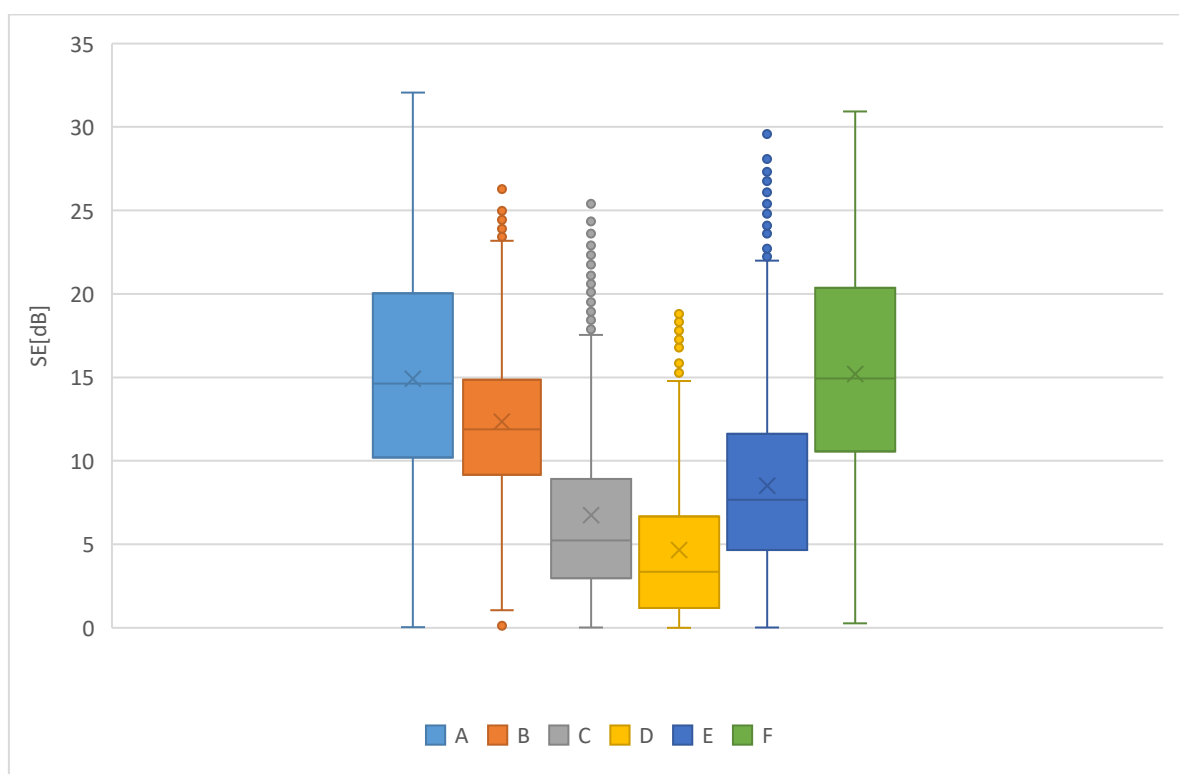


Figure 25 Statistical distribution of SE – original shield. [Own]

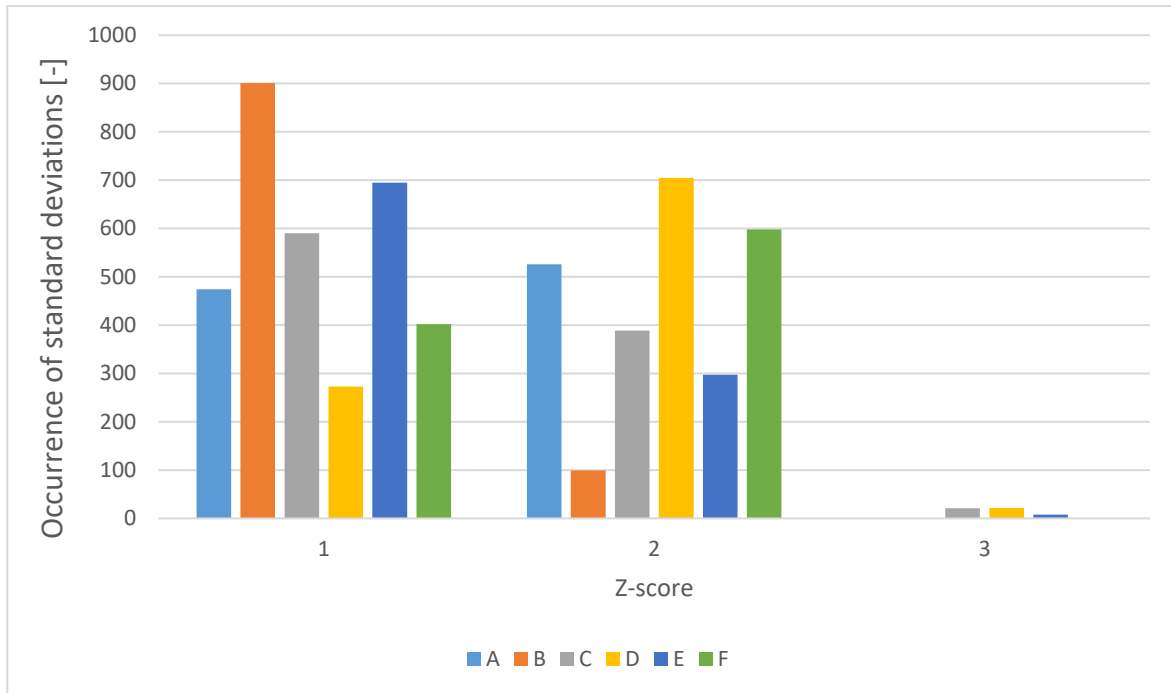


Figure 26 Categorization of SE deviations based on Z-score from the original shield.
[Own]

8.1.2 Results SE with a new shield

The VNA measurement with the new shield differs from the previous results with the old shield because it was performed with the new, back-powered shield. This mechanically modified shield allows comparison of the effect of mechanical intervention on SE. The results show a significant improvement in sample F and a slight deterioration in sample A compared to the measurements of the original shield. Although sample F was ordered to be delivered without the shield, it arrived with it, which affected the results. Notwithstanding this discrepancy, samples A and F come out as the best, even though the brief stated that only sample A should be the best. The results confirm that mechanical intervention, even on a small device, can have a significant impact on SE, and for larger devices, the changes would be even more marked. This demonstrates that even very precise mechanical intervention can significantly affect the performance of a device. The frequency distribution for this measurement method is satisfactory, with most values falling within ± 1 and ± 2 . Only variants C, D, and F are in the interval ± 3 but with only a minimal number of values, which does not affect the overall evaluation of the measurement.

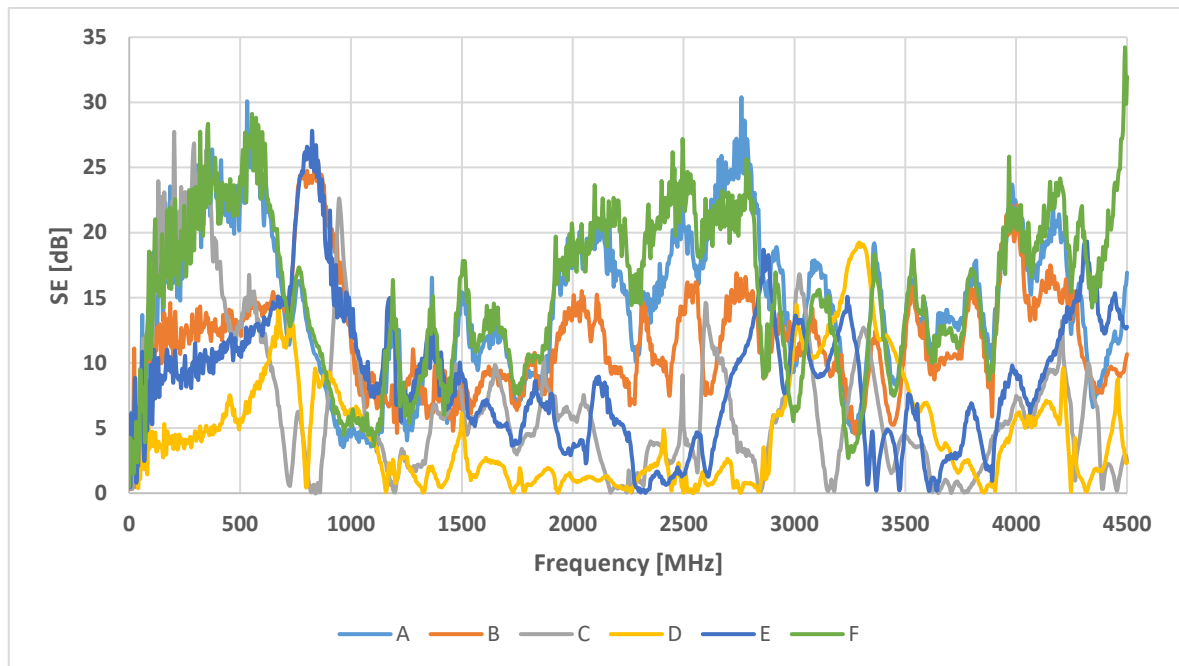


Figure 27 SE as a function of frequency for the new shield – VNA method. [Own]

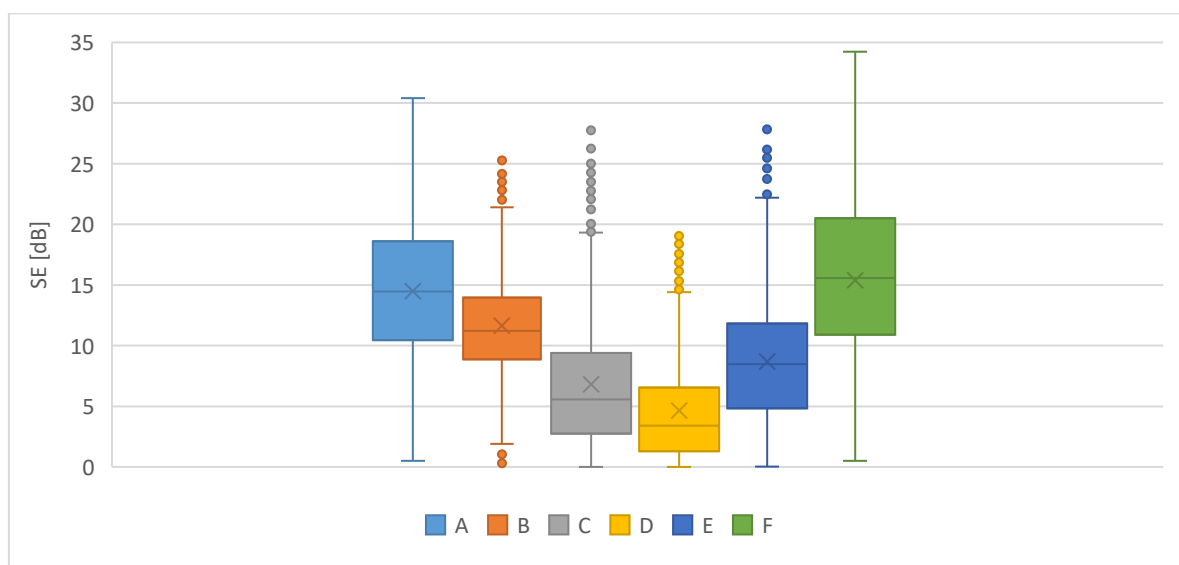


Figure 28 Statistical distribution of SE – new shield. [Own]

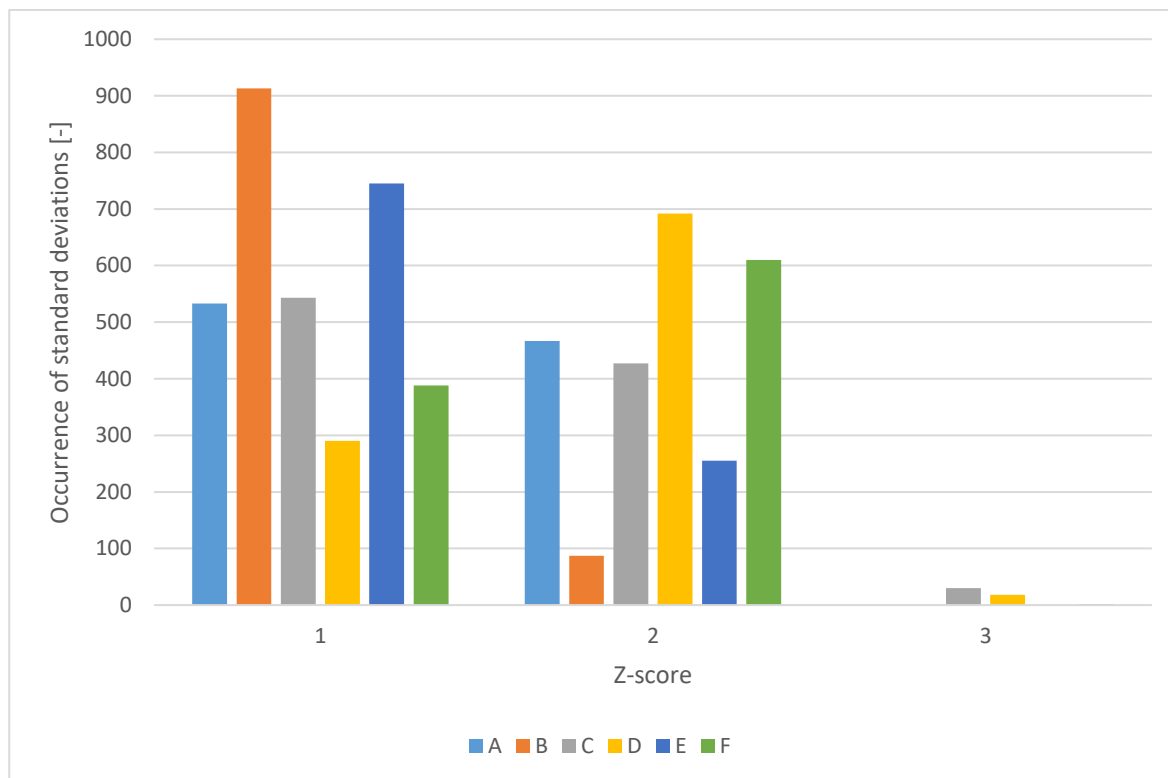


Figure 29 Categorization of SE deviations based on Z-score from the new shield. [Own]

8.2 Measurement method using EMI test receiver

The second measurement was performed using an EMI test receiver and signal generator. In this arrangement, the EMI receiver was connected to the input port of the GTEM cell, while the signal generator was connected via a filter to a PCB located inside the cell. Compared to the first experiment, the methodology was changed, and the testing was limited to two variations - PCB equipped with shielding, PCB without shielding.

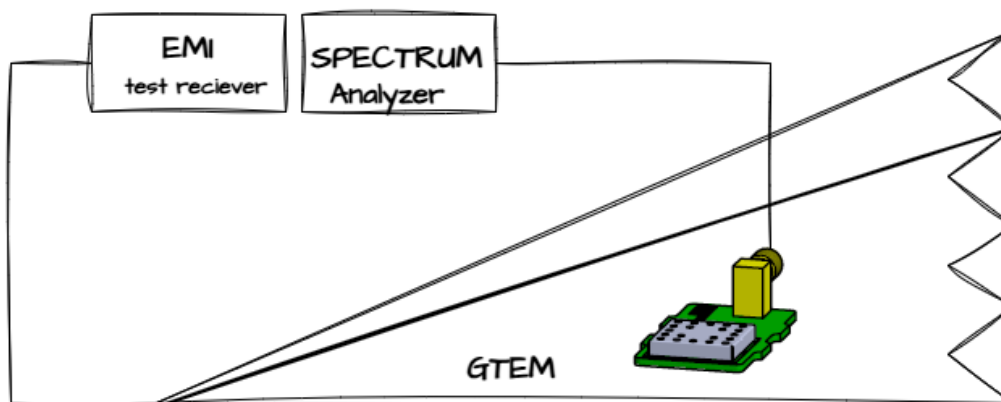


Figure 30 Wiring diagram for the EMI method. [Own]

8.2.1 Result in SE

EMI testing was conducted using the test receiver and signal generator in two configurations: first without the shield, meaning with the antenna only, and then with the newly connected shield. As with the previous methods, the SE was calculated based on the average polarization values of all configurations. The results indicate that the most significant SE values were recorded at 2400 MHz, as illustrated in the graph in Figure 31. This trend is even more pronounced in the box plot in Figure 32. For sample F, the SE reached up to 21 dB at the specified frequency, while sample A trailed only 4 dB behind. The highest shielding level for sample B was noted at 10 dB, whereas the other samples exhibited approximately 3 dB, with sample E showing nearly zero SE. The frequency distribution of the measured values in this experiment differs from the previous methods, which can be attributed to the distinct measurement methodology. The largest proportion of data falls within the ± 1 interval, while slightly fewer values are represented in the ± 2 interval. Conversely, more values were noted in the ± 3 category, including all tested variants. Nevertheless, the overall distribution remains within acceptable limits and does not significantly affect the accuracy of the results.

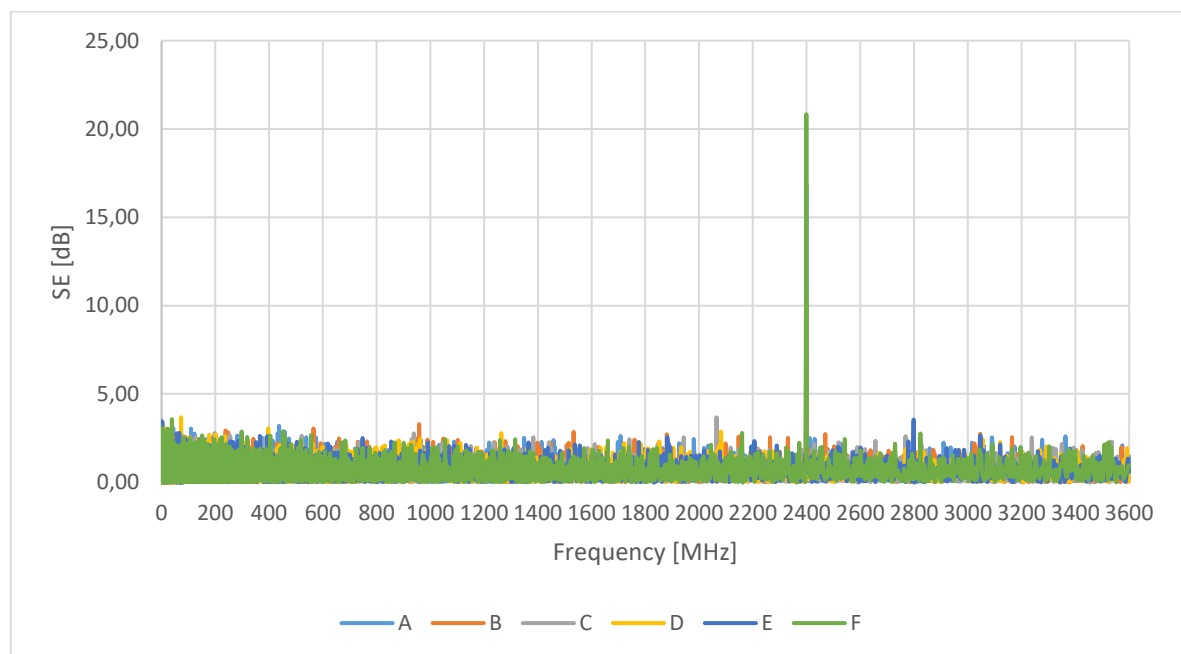


Figure 31 SE as a function of frequency – EMI test receiver method. [Own]

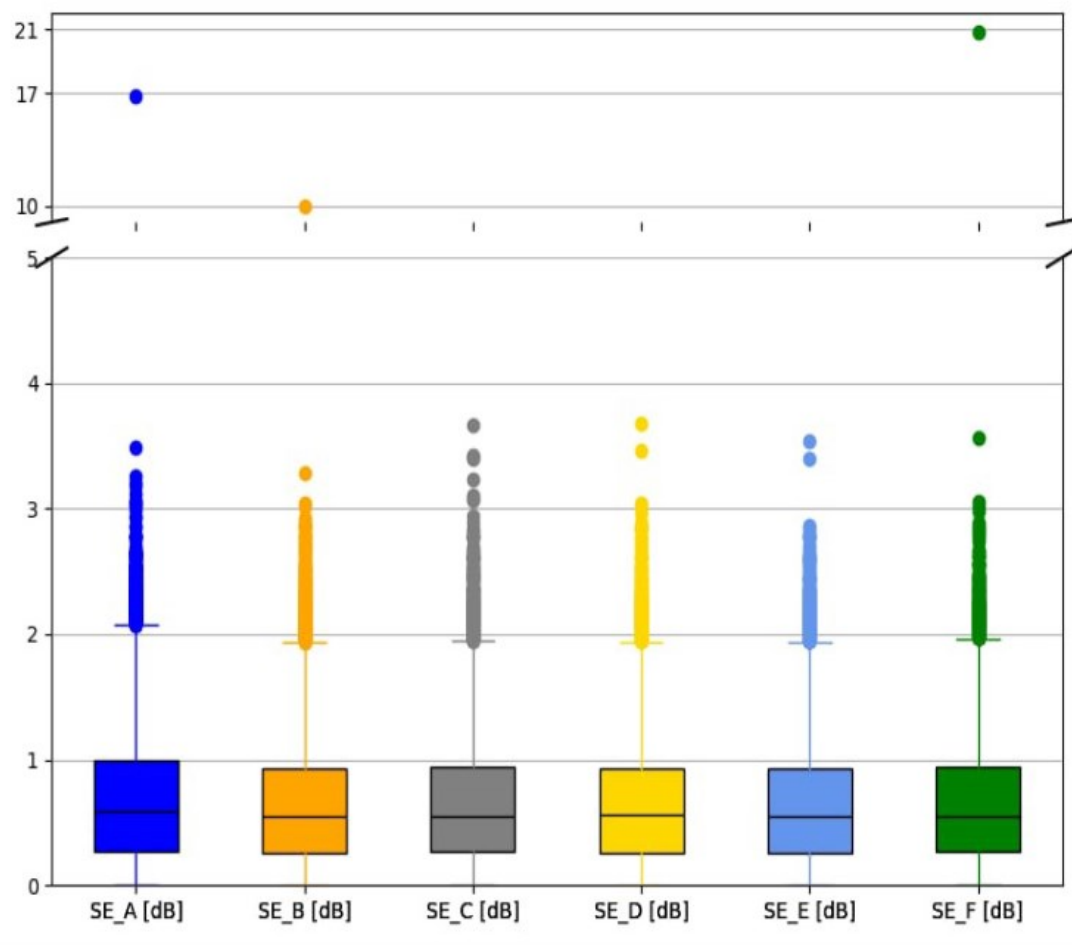


Figure 32 Statistical distribution of SE – EMI test receiver method. [Own]

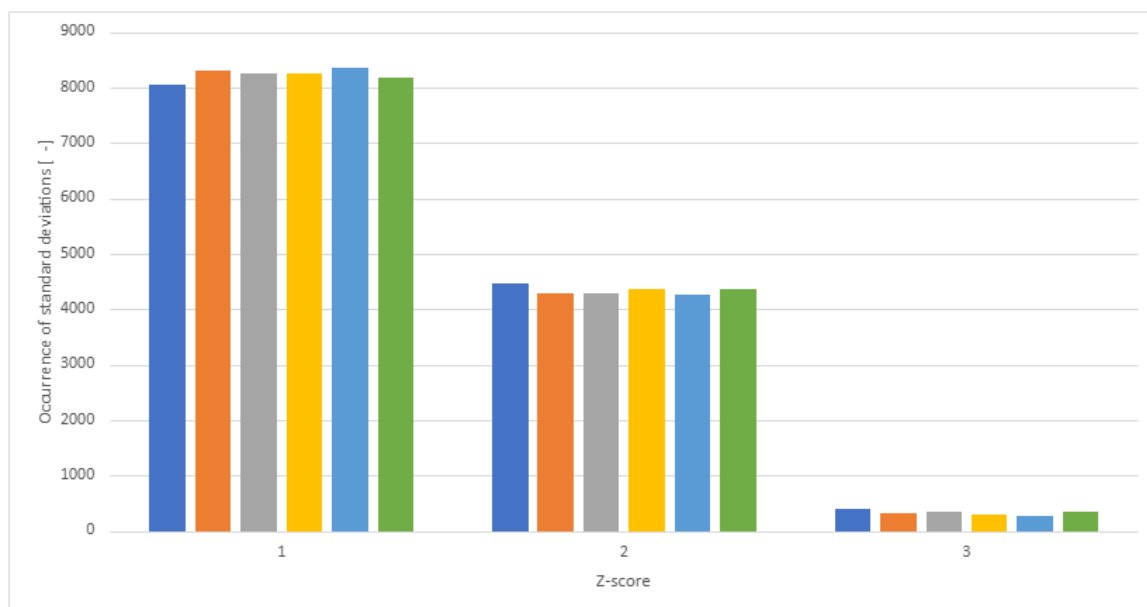


Figure 33 Z-score distribution of SE – EMI test receiver method. [Own]

8.3 Measurement Method Using the EMxpert

The third measurement was performed in a shielded chamber, which is primarily designed to test the SE of flat samples. The interior of the chamber was partially covered with an absorbent material, creating two different environments - one part of the chamber was reflective, while the other was absorptive. This arrangement made it possible to create partially controlled conditions for the measurements. To eliminate the influence of external reflections on the test results, the EMxpert was placed in the absorption part of the chamber. Although not essential to its function, this approach helped to more accurately analyze the properties of the test samples. The EMxpert diagnostic board was connected to the spectrum analyzer via an evaluation unit, while the samples were connected to a signal generator. This configuration allowed a detailed investigation of the EM emission of the samples in a controlled environment while providing the opportunity to analyze the effect of the shielding on their emission properties. The measurements were carried out in two variations - without shielding (BLS), with BLS attached.

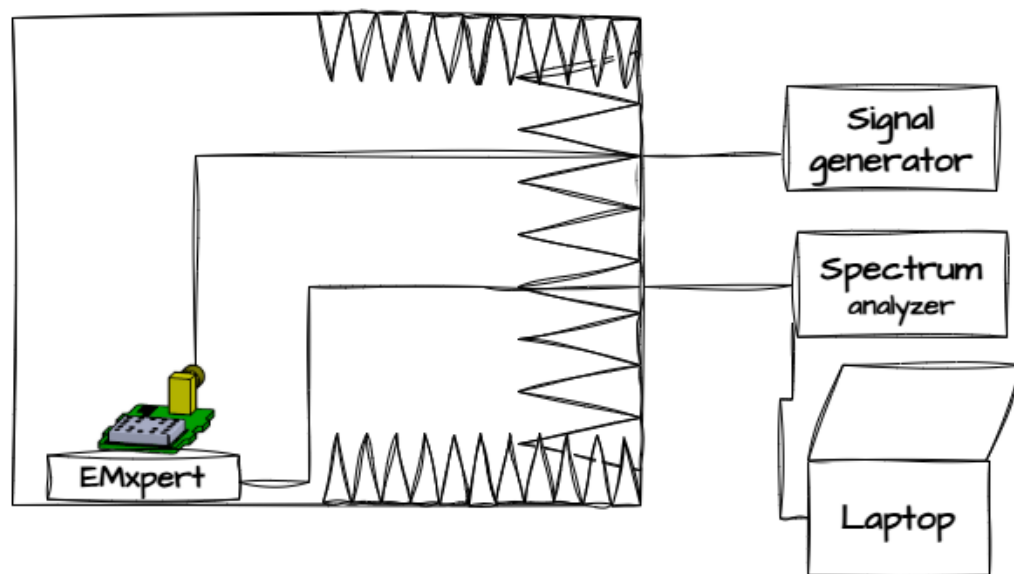


Figure 34 Wiring diagram for the EMxpert method. [Own]

The EMxpert method was used to characterize the near-field SE. This method allows detailed analysis of the EM field leakage and identification of weak points in the BLS implementation. Two measurement methods were used: broad-spectrum and narrow spectrum. Testing was performed on a PCB without a cover and with a newly attached cover to determine how each configuration affects the SE.

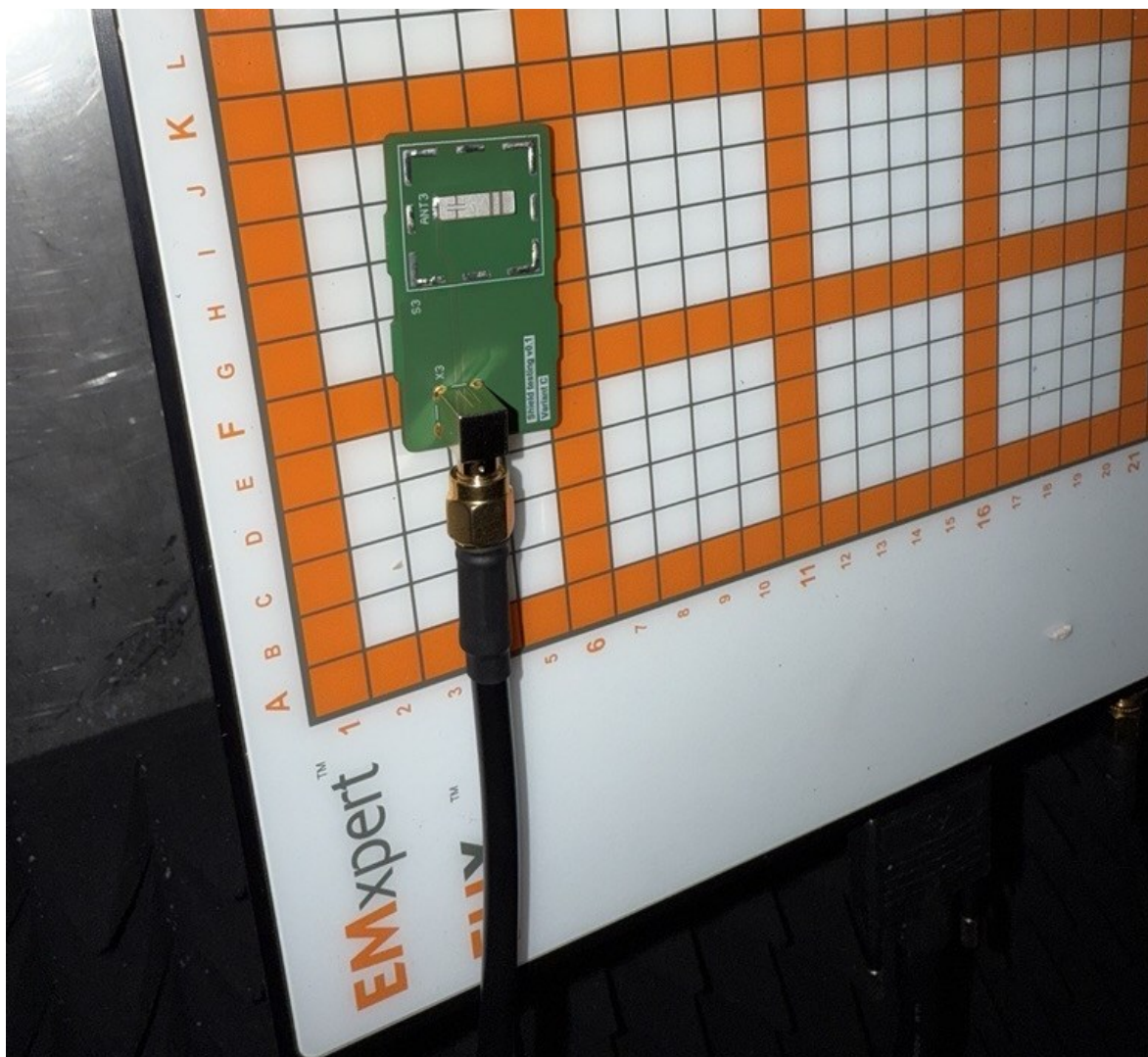


Figure 35 PCB wiring without BLS on EMxpert board. [Own]

8.3.1 Wide frequency measurement

The results showed that the SE of all samples was generally low with little variation. Variant F showed the best values in spectral measurements and achieved the best results compared to the other samples. In contrast, variant C showed significant peaks, especially around 860 MHz, with a value of approximately 11 dB. This phenomenon can be attributed to the functional band of the chip antenna, which, according to the datasheet, is primarily designed for 2400 MHz, but ZigBee technology can also be active at lower frequencies, namely 868/915 MHz. For variant A, which was expected to be the most efficient, the optimal SE values were not achieved, which could have been affected by mechanical interference in the shield. The method also allowed the detection of EM field leakage at frequencies not captured by other measurement techniques. However, the identification of specific weak spots was complicated by the absence of a z-coordinate. Analysis of the frequency

distribution of the measured values showed that the largest number of values fell within the ± 1 interval, with approximately half of the results in the ± 2 range, while the representation in the ± 3 range was the lowest. This trend is consistent with previous measurements and suggests some variability in the results. In addition, parasitic interference was observed to penetrate the shielded room through leaks in the structure. This phenomenon was evident, for example, at 91 MHz, a value close to the radio broadcast band.

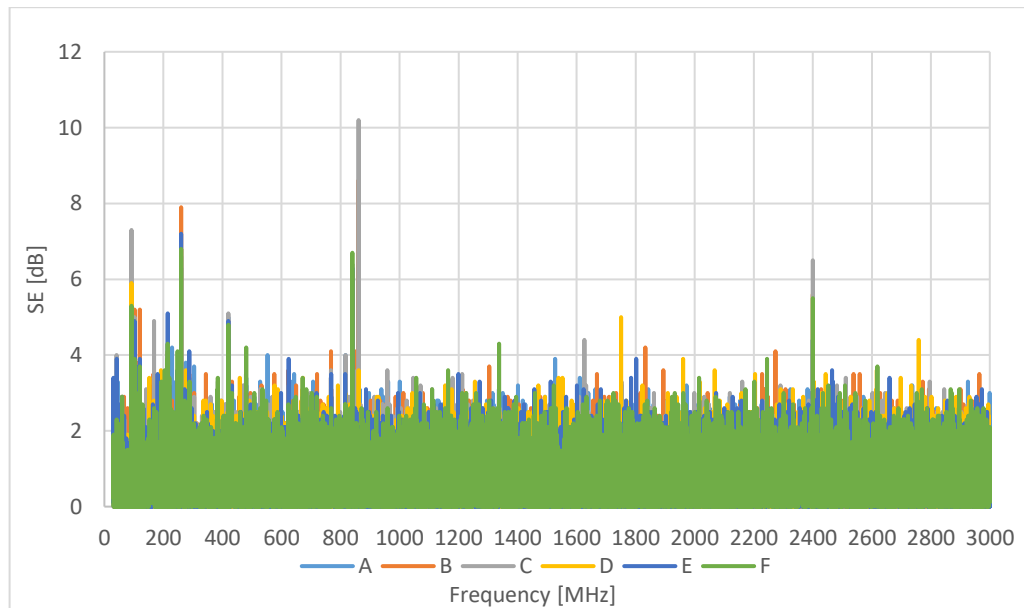


Figure 36 SE as a function of wide frequency measurement– EMxpert method. [Own]

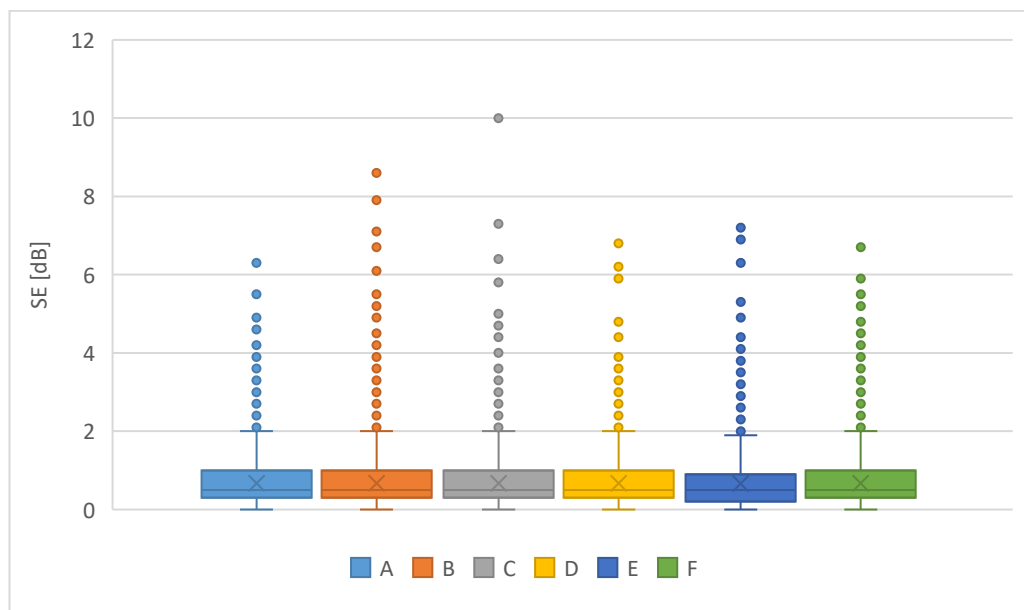


Figure 37 Statistical distribution of SE wide frequency measurement – EMxpert method. [Own]

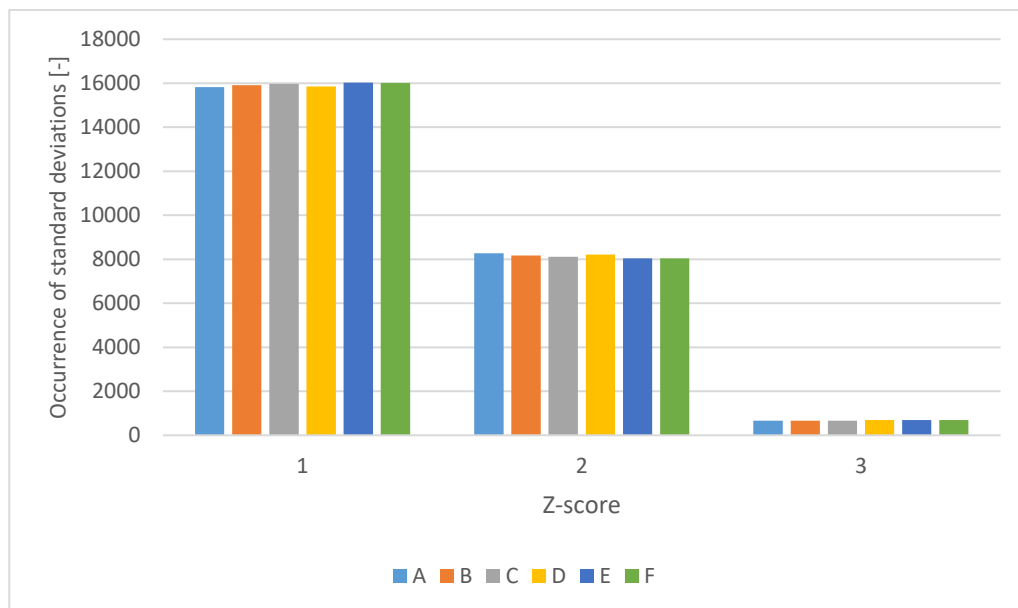


Figure 38 Z-score distribution of SE wide frequency measurement – EMxpert method.
[Own]

8.3.2 Narrow frequency measurement

The resulting SE for the narrowband spectral analysis identifies Option F as the most effective option, achieving the best values in EM radiation suppression. Variant A also shows elevated signal levels at certain frequencies, but they are not as pronounced as those of variant F. Similar to previous measurements, variant C again shows high spectral peaks, with the highest value detected at 2400 MHz. These results confirm that Variant F provides the highest level of EM shielding, while Variant C shows the greatest instability within specific frequency regions. The distribution of the spectral response is consistent with the trends observed in the broadband measurements. The Z-score histogram confirms that most of the measured values lie very close to the mean. For all samples (A – F), the largest number of observed points falls within the ± 1 band. In the ± 2 interval, the number of occurrences decreases, corresponding to about a quarter of the data, and the representation in the ± 3 band drops to units of percent. As with the previous method, the graph confirms that the main variability of the measurement occurs in the narrow vicinity of the mean value, while outlying extremes are rare.

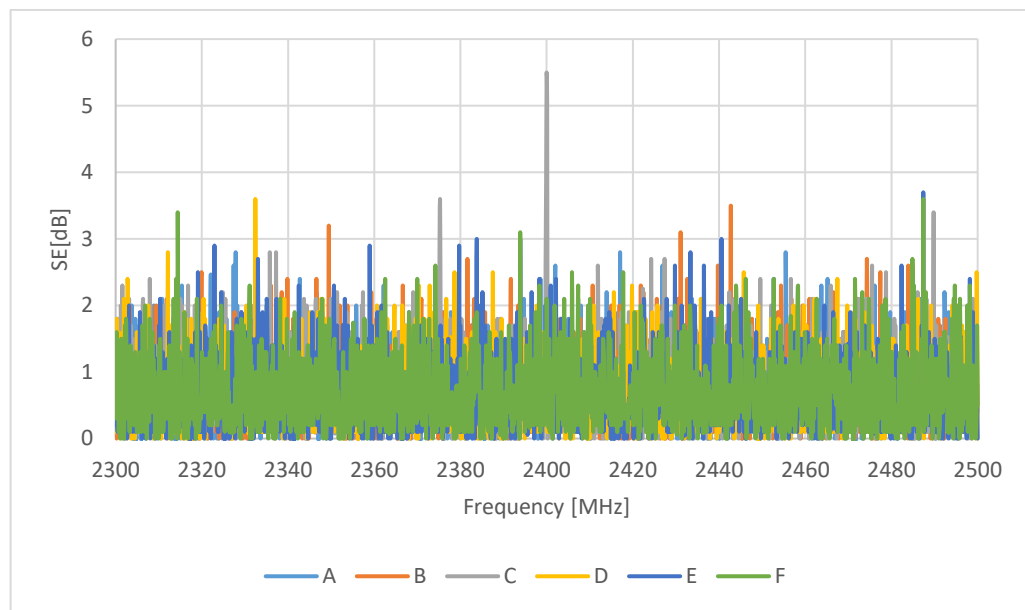


Figure 39 SE as a function of narrow frequency measurement– EMxpert method. [Own]

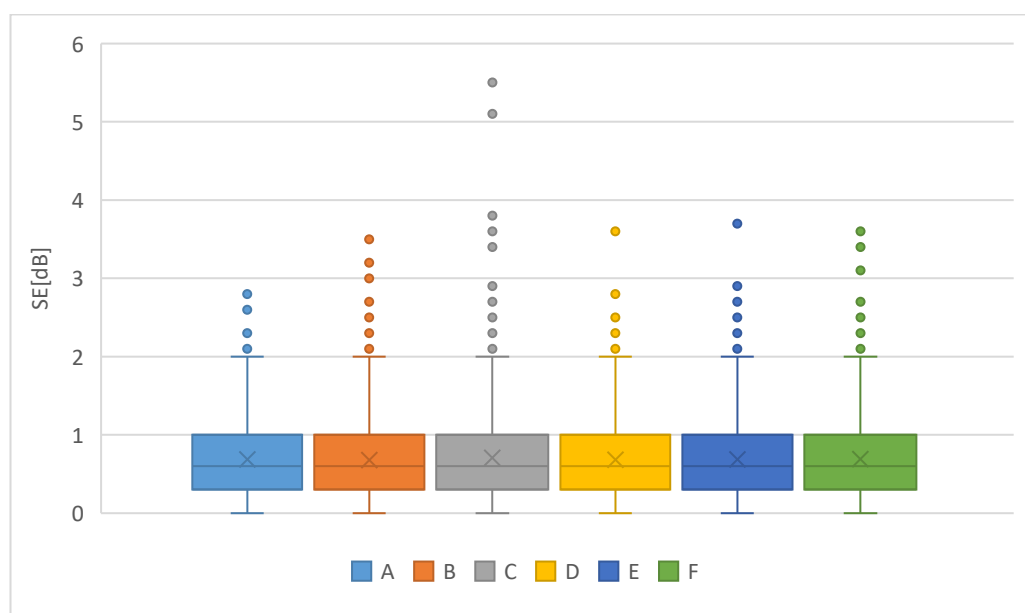


Figure 40 Statistical distribution of SE narrow frequency measurement – EMxpert method. [Own]

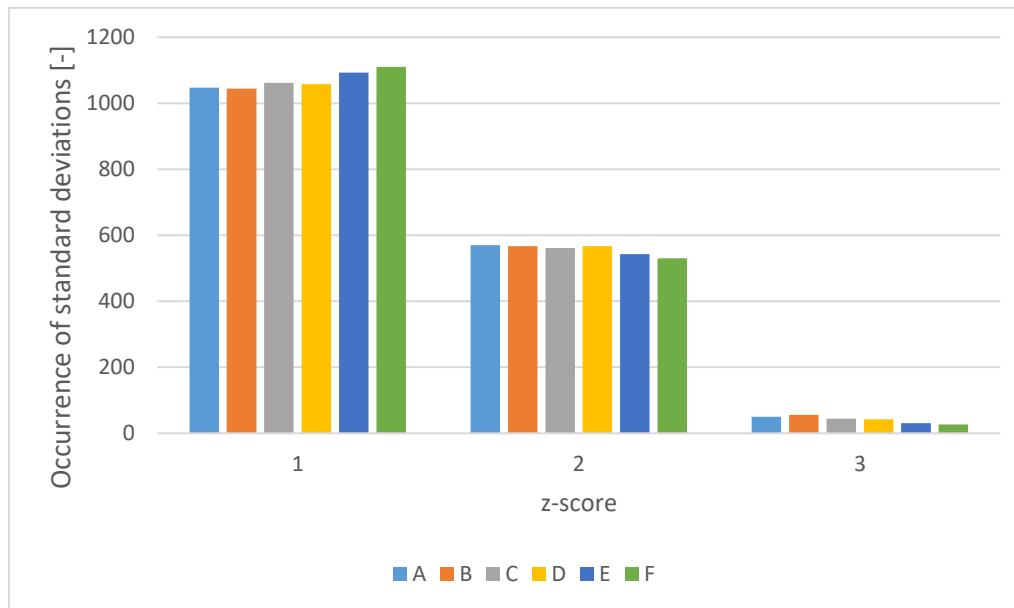


Figure 41 Z-score distribution of SE narrow frequency measurement – EMxpert method.
[Own]

8.4 Overall SE assessment

As expected, sample A was expected to have the best SE values. Surprisingly, however, sample F with BLS implemented showed similar results. The orientation of the PCB inside the GTEM cell also had a significant effect on the measurement accuracy. The data obtained showed that when the PCB was aligned parallel to the radiated field, the results were significantly better than when the antenna was facing downwards. This factor is crucial for proper analysis of the measured data as well as optimization of future experimental procedures. Another crucial aspect was the influence of the soldering quality on the SE. This difference was particularly noticeable during the first measurement with the VNA when it was possible to compare the results with the old cover, without the enclosure, and then with the new enclosure. The results of the analysis showed that the new cover had a significant impact on sample A, which showed a slight reduction in SE. On the other hand, sample F showed an improvement in efficiency, indicating that the mechanical changes had a significant effect on the measured values.

9 SIMULATION

This chapter focuses on a comparative analysis of the results of real measurement experiments and the results in a simulation environment. CST Microwave Studio was chosen as the simulation environment. The simulation configuration was designed to mimic the real measurement conditions as closely as possible. A total of six samples were simulated. Originally, only one of these was supposed to be free of design flaws. However, due to an error in the delivery of the order, the configuration of the samples was changed. For this reason, it was necessary to adopt a slightly different approach to the real measurements. The simulation was performed in two variants, with/without BLS, under the same conditions, which made it possible to observe sample deviations and errors in the experimental procedure. The simulations focused on detecting EM field leakage and BLS implantation errors using S-parameter analysis and measurements with electrical probes placed in the near and far fields. Instead of a classical chip antenna, Touchstone was used with data obtained from measurements in a GTEM cell.

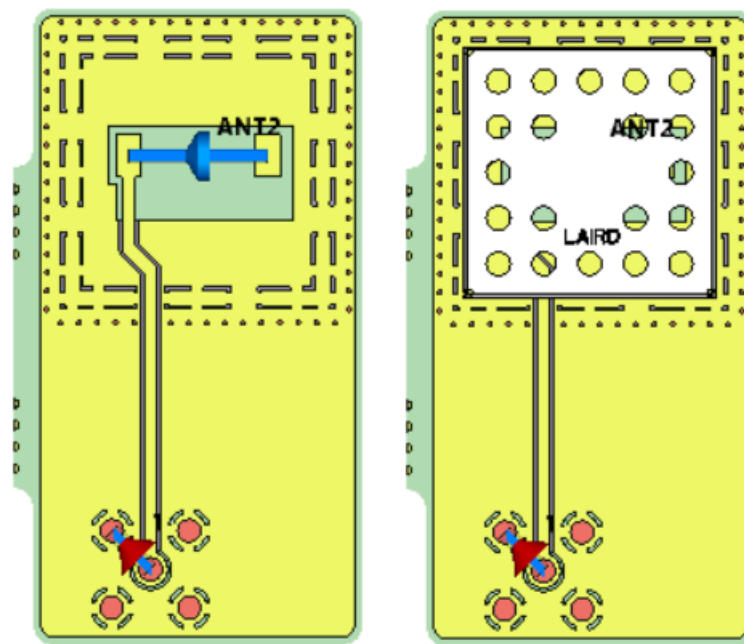


Figure 42 PCB sample with BLS and without BLS. [Own]

9.1 S – parameters Simulation

The first step was to set the frequency range from 0,1 MHz to 4500 MHz. The samples were created in ODB++ format, fully compatible with the CST environment; therefore, no modification was necessary. The samples, illustrated in Figure 45, were separated in the CST environment for separate evaluation. When trimming the samples, the chip antenna was replaced by a touchstone, to which data from real measurements were uploaded for each sample and rotation. As in the real measurements, the sample was rotated by 45°.

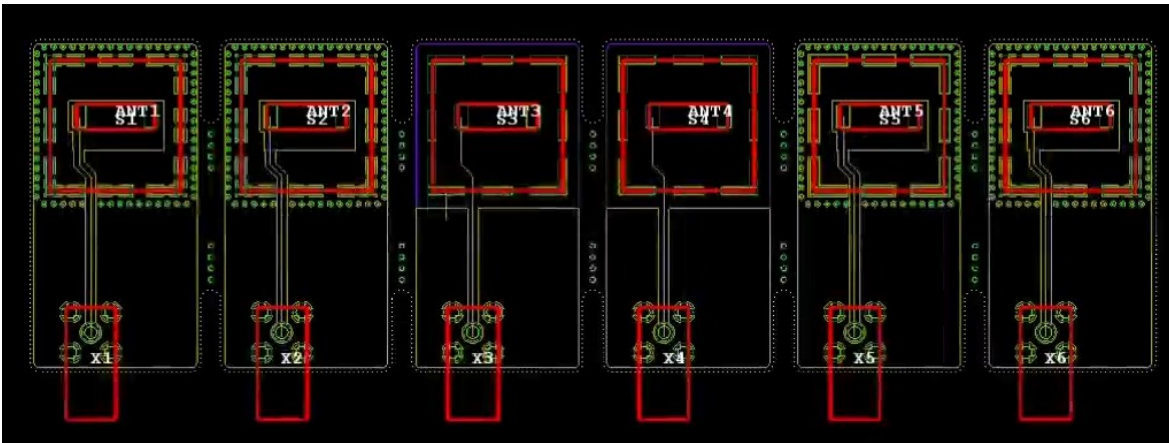


Figure 43 Illustration of all samples under test in the CST environment. [Own]

A Finite Integration Technique (FIT) time-based solver with a hexahedral grid was used in the CST Studio Suite environment to calculate the scattering parameter matrix. This approach allows for efficient simulation of the broadband behaviour of EM structures based on a single time simulation in which a Gaussian pulse was used as the excitation signal. The frequency response was subsequently obtained using the Fourier transform. Two ports were defined in the simulation: a discrete port with impedance matching to 50 Ω , representing the chip antenna connection, and a waveguide port, serving as a simplified model of the GTEM chamber septum. Although the idealized waveguide port did not geometrically correspond to the real septum, it provided a sufficiently accurate approximation to calculate the S-parameters. The computational domain was divided into 285664 hexahedral cells, with adaptive meshing intentionally disabled. The reason was to maintain consistent numerical conditions when comparing variants with or without BLS, as the adaptive mesh could lead to nonlinear differences in the numerical solution. Open boundary conditions were applied at the boundaries of the computational domain with the implementation of Perfectly Matched Layers (PML), which simulate the absorption of EM radiation at the domain boundary and thus ensure free space modelling without back reflection.

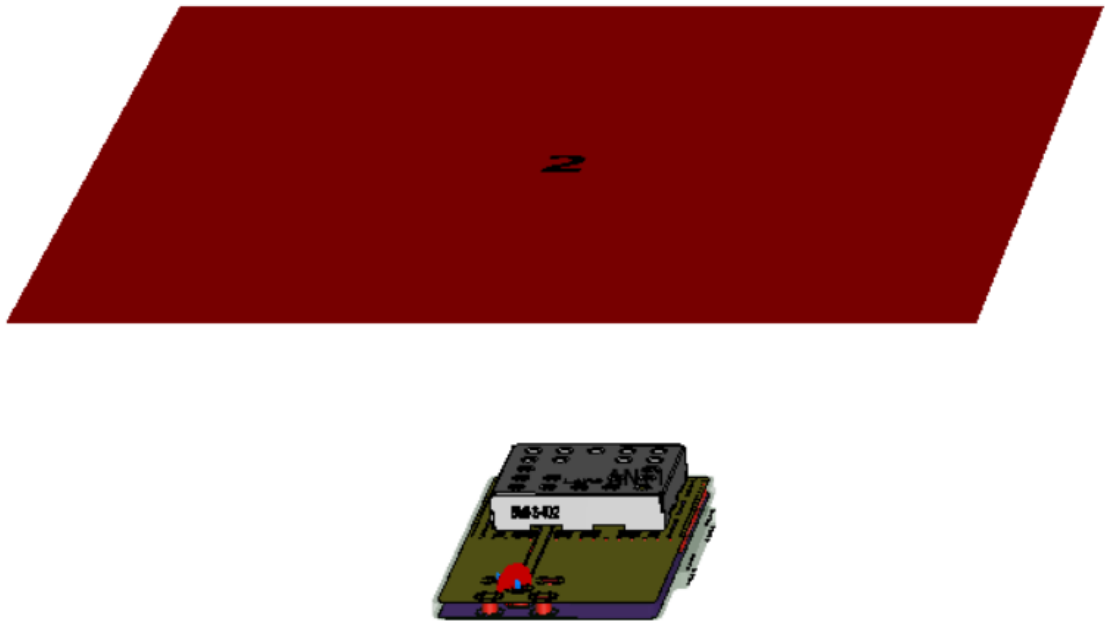


Figure 44 Simulation for S-parameters for 0° . [Own]

9.1.1 Results of S-parameter simulation

On the basis of the line chart it is possible to observe high SE peaks for each sample. Sample A reaches significant peaks at ≈ 280 MHz; simultaneously, it is the only sample that responds to a frequency of 2400 MHz, but it does not have high peaks compared to the others. SE of sample B is higher than that of sample A; the highest peaks are at frequencies of ≈ 0.1 MHz and 2900 MHz. C has the second highest peak at ≈ 2200 MHz. D reaches the highest peak at ≈ 3300 MHz. Sample E reaches low values throughout the frequency range, starting to rise from ≈ 2900 MHz and reaching its highest peak at ≈ 4100 MHz. Sample F reaches its maximum peak at ≈ 3100 MHz.

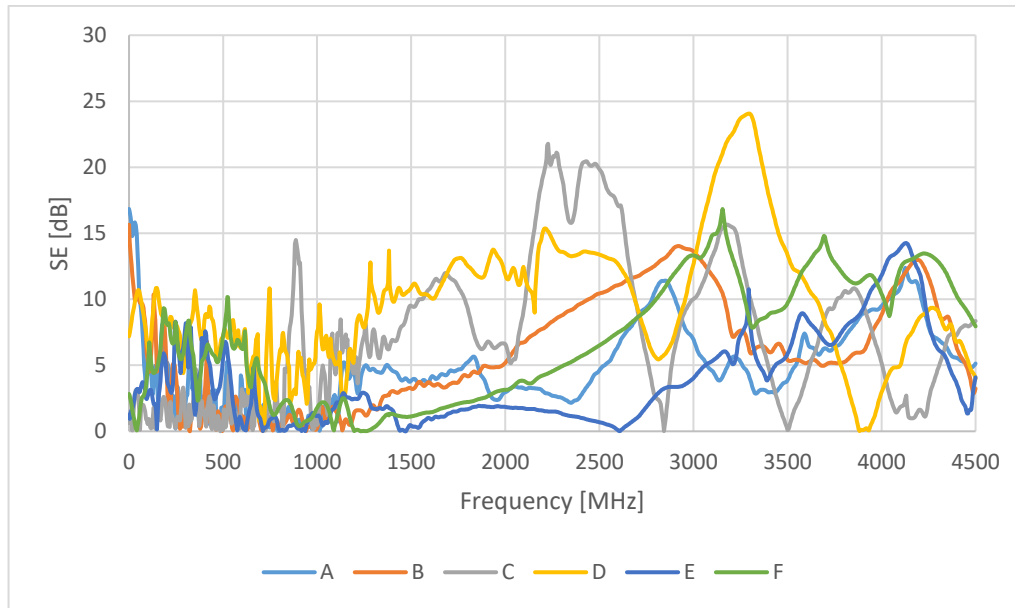


Figure 45 SE as a function of frequency –S – parameters method. [Own]

The box plot provides a compact, visually clear comparison of the SE distribution of each sample. Sample A has a median of approximately 4 dB, the upper whisker reaches 12 dB and outliers range from 12 to 16 dB. These parameters indicate predominantly lower attenuation, albeit with occasional exceptionally good results. Sample B has a higher median of about 5.5 dB, while the upper whisker reaches ≈ 15.5 dB. The distribution is therefore shifted towards more pronounced attenuation values than for sample A, but without extremes. Sample C achieves a median of about 7 dB; the upper whisker reaches up to ≈ 22 dB, indicating the ability to achieve high SE, but also a greater dispersion in the results. Sample D represents the best performing configuration: the median is approximately 9 dB, the upper whisker reaches ≈ 21 dB and outliers range from ≈ 21 to 24 dB. Sample E has the lowest median of about 2 dB. The upper whisker ends at ≈ 13 dB and outliers reach ≈ 13 -14 dB, making it the least effective of the evaluated samples, with higher SE occurring only rarely. Sample F is characterised by a median of around 6 dB; the upper whisker reaches ≈ 16 dB and the dispersion is remarkable, representing a good SE. Overall, sample D can be considered the most suitable in terms of SE, while sample E shows the lowest attenuation.

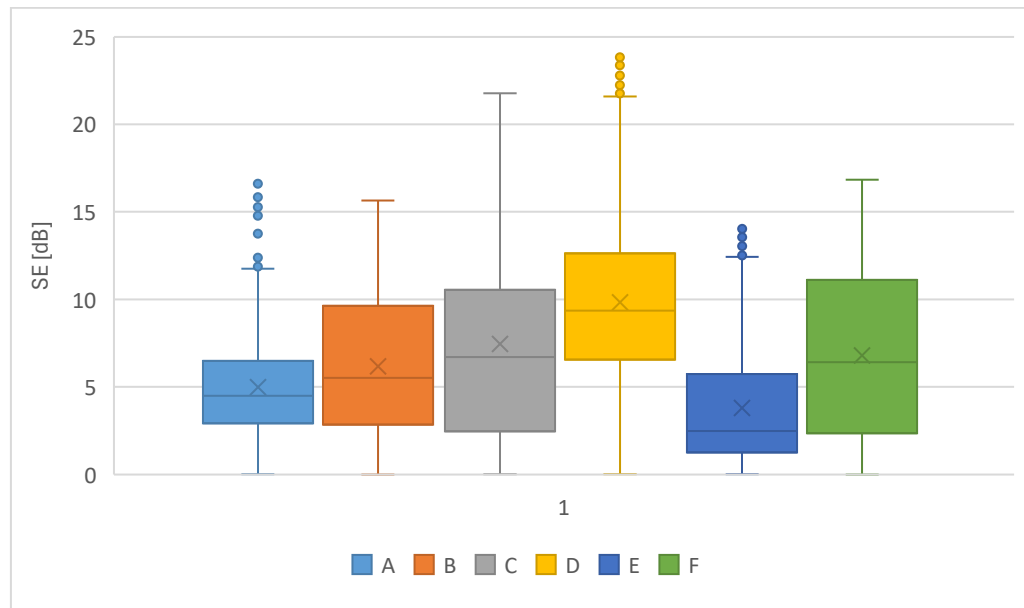


Figure 46 Statistical distribution of SE – S – parameters method. [Own]

9.2 Electric Field Mapping Simulation

First the PSB/BLS model file was loaded into the environment. The Waveguide Port component was then removed. The Field Monitor tool was opened in the top bar of the simulation, where the frequency analysis specifications were defined. The minimum frequency set to 100 MHz and the maximum frequency set to 3600 MHz. To simulate the EM radiation from the PCB with BLS, a frequency solver based on the finite element method (FEM) with a tetrahedral grid with a total number of 76058 elements was used. The decision for the frequency domain was supported by the results of preliminary experimental measurements, during which a significant peak of EM radiation was recorded in the 2.4 GHz region. This fact led to the conclusion that the frequency solver is more suitable for accurately assessing the spatial distribution of the field at a specific resonant frequency. Adaptive meshing was turned off for consistency between the individual variants of the model with the BLS connected and removed, thus eliminating the influence of changes in the computational network on the results. The EM field was monitored using the E-field probes type, which were arranged cylindrically around the PCB model, specifically in one height level with a mutual vertical spacing of 25 mm, an angular rotation of 45°, and a radial distance of 50 mm from the center of the PCB. The excitation was realized by a discrete port with an impedance of 50 Ω , which was implemented in the schematic model as a Gaussian pulse generator and served as a signal source. The initially used waveguide port was removed in this simulation because its presence did not correspond to the real measurement

arrangement. The boundary conditions of the computational domain were set as open with added free space and PML implementation to minimize the influence of the results by reflections from the boundaries. The target parameter of the evaluation was the electric field intensity in units of dB μ V/m. At the same time, the variants with and without a shielding enclosure were compared, similarly to the case of the time-domain simulation.

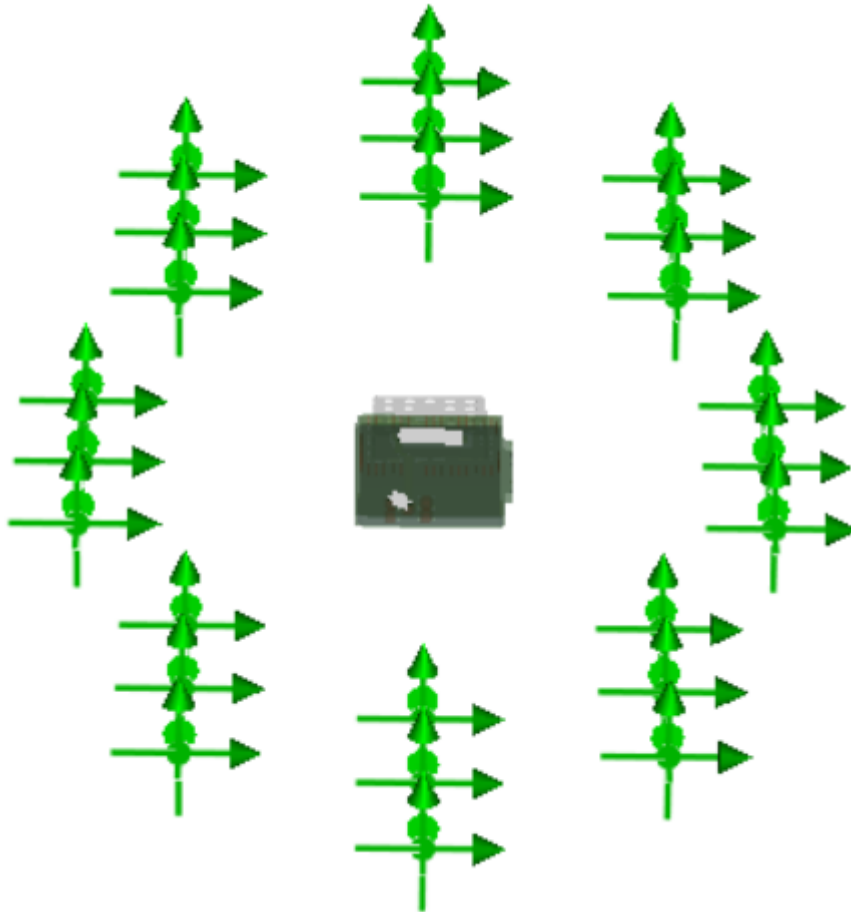


Figure 47 Simulation model for Electric Field Mapping with probes. [Own]

9.2.1 Results SE

Several conclusions can be drawn from the line plot results. Sample A achieves high peaks from ≈ 1500 MHz to around ≈ 2500 MHz, with the last peak occurring at ≈ 2700 MHz and then declining. This sample is the only one that responds at 2400 MHz and therefore has a good SE. B behaves similarly to A, the only difference being that it decays rapidly at 2400 MHz. C has relatively high peaks at about 100 MHz, 800 MHz, 2000 MHz, 2900 MHz and 3400 MHz. D does not reach such high peaks as the previous sample. E confirms the worst SE, as in the previous method, and F reaches relatively high peaks. F therefore gives the best SE and E the worst.

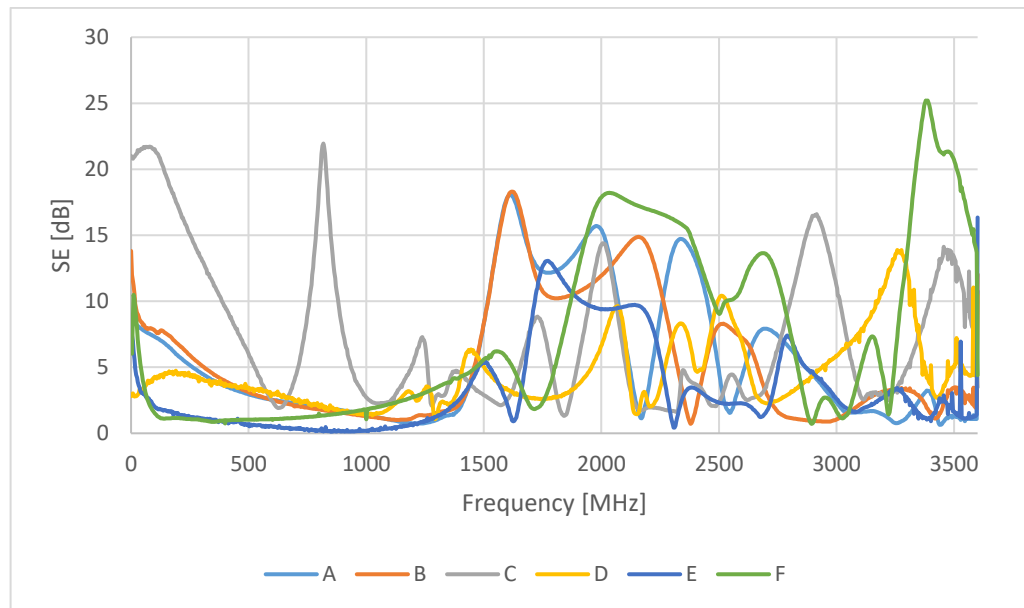


Figure 48 SE as a function of frequency – Electric Field Mapping method. [Own]

Sample A has a median SE of approximately 3 dB. The interquartile range (IQR) is from about 1 dB to 8 dB. The lower whisker falls just below 1 dB, the upper whisker rises to ≈ 17 dB and the only outlier reaches ≈ 18 dB, so the sample occasionally provides significantly better attenuation while normally remaining in the lower efficiency range. For sample B, the median is around 4 dB and the IQR is between 1.5 and 8 dB. The lower whisker drops to ≈ 0.5 dB, the upper whisker also ends at ≈ 18 dB with a single outlier. Compared to A, it shows a slightly higher average attenuation, but still a medium to low efficiency. Sample C shows the highest normal values - the median is around 5 dB and the IQR ranges from ≈ 3 to 11 dB. The upper whisker extends to ≈ 22 dB without significant outliers, indicating that the sample can consistently achieve higher shielding; this is the most effective variant. For sample D, the median is approximately 4 dB and the IQR is ≈ 2 -6 dB. The upper whisker ends at ≈ 10 dB, and above this there is a cluster of outliers of 10-14 dB. The sample therefore normally provides medium attenuation but occasionally reaches higher values. Sample E has the lowest average attenuation: the median is around 2 dB and the IQR is between 1 and 4 dB. The upper whisker reaches ≈ 9 dB and several outliers range from 10 to 16 dB, indicating that most of the data indicate weak shielding with only a few samples performing better. Sample F has a median of about 4 dB, but is characterised by the greatest variability - the IQR ranges from ≈ 1 to 13 dB. The upper whisker extends up to ≈ 25 dB, demonstrating the ability to achieve very high attenuation, but at the cost of considerable variability - from very low to extremely high values.

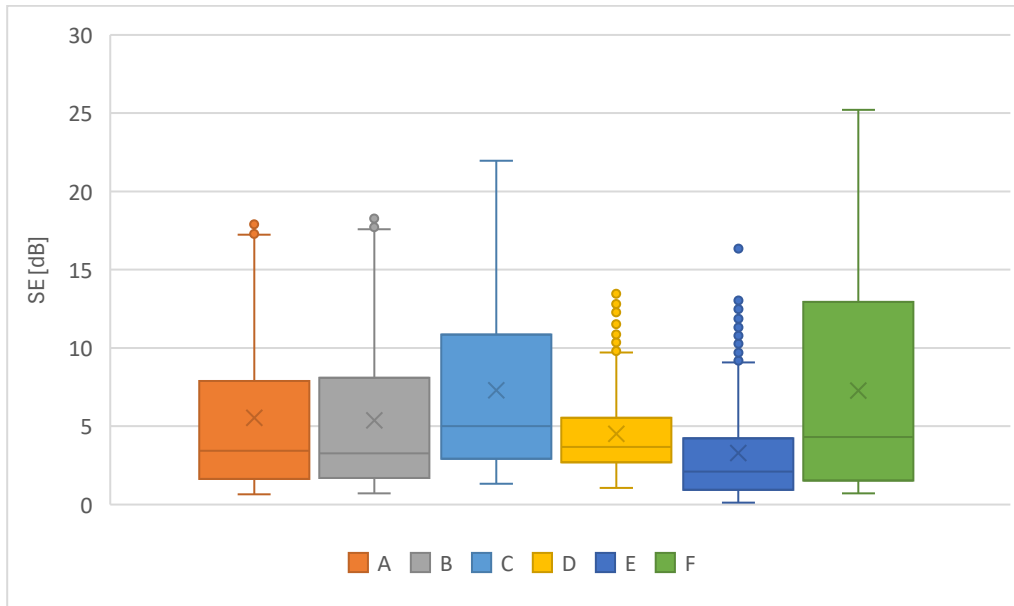


Figure 49 Statistical distribution of SE – Electric Field Mapping method. [Own]

9.3 Near Field Scanning Simulation

The simulation of the EM near field around the PCB was performed in the frequency domain using a FEM-based solver with a tetrahedral mesh containing 45866 elements. Adaptive meshing was turned off to maintain consistent numerical conditions across the variants with and without the BLS connected. Excitation was implemented by a discrete port with an impedance of 50Ω , which was excited by a Gaussian pulse defined in the schematic model. The simulation was performed in the frequency range from 30 MHz to 3 GHz, with the results evaluated at specific points in the monitored space using E-field probes. These probes were arranged in a regular 5×5 matrix configuration with a spacing of 5 mm in the x and y axes, with the height of the probes being 0.5 mm below the bottom edge of the sample. The orientation of the measured electric field vector corresponded to the axial coordinate z , i.e., the direction perpendicular to the PCB plane and pointed towards the structure. The boundary conditions of the computational domain were set as open boundaries with added free space and PML implementation to eliminate unwanted reflections. The target output of the simulation was the electric field intensity, expressed in $\text{dB}\mu\text{V/m}$, which served for spatial comparison of the effect of the presence of BLS on the EM field distribution in the vicinity of the tested structure.

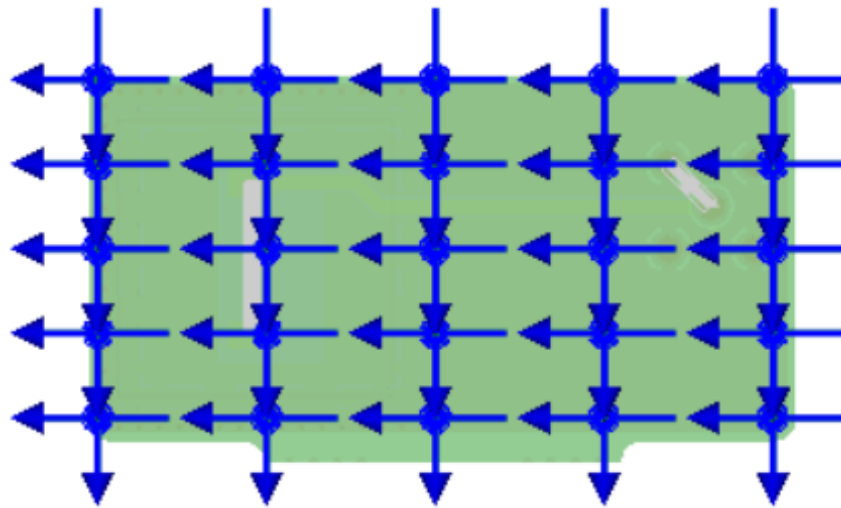


Figure 50 Layout of near-field probes under the test sample in CST Studio. [Own]

9.3.1 Results

Sample A shows a smooth curve without significant peaks; the attenuation remains in the range ≈ 4 -10 dB and no frequency stands out clearly. The curves for samples B and E are also smooth, with only slight local maxima below 10 dB. In contrast, sample C produces a dominant, narrow peak around 800 MHz, where SE exceeds 30 dB, and additional, less steep maxima around 1400 MHz and 2100 MHz. Sample D has only one really significant peak around 2400 MHz with a value of around 21 dB. Sample F performs best, with a curve containing two high peaks: the first at ≈ 1550 MHz and the second around 2200 MHz, giving it the highest and most broadband SE of all the variants tested.

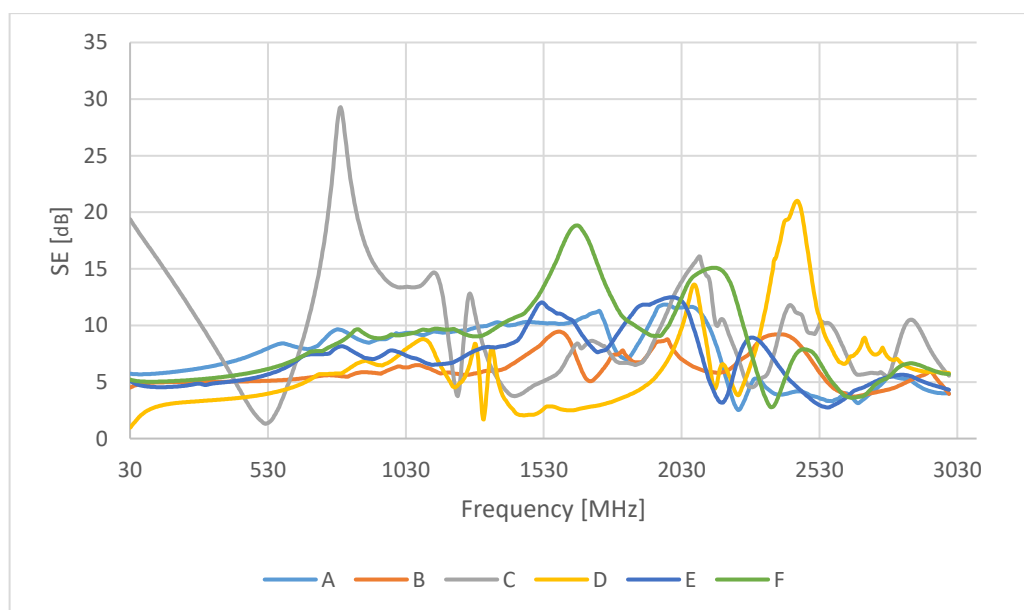


Figure 51 SE as a function of frequency – Near Field Scanning method. [Own]

Sample C stands out with the highest median of ≈ 10 dB and the largest dispersion: its interquartile range extends from approximately 6 to 12 dB, whisker ≈ 24 dB and a number of outliers reaching around 30 dB, thus offering the highest achievable efficiency but with considerable variability. Samples A and F have similar medians of around 8 dB, IQR of around 6-10 dB, and upper whiskers stopping at ≈ 12 and ≈ 17 dB, providing stable mid-high shielding. Samples B and D show medians around 6 dB, with B being the most compact, while D has a wider spread, with whiskers up to ≈ 12 dB and outliers ≈ 13 -21 dB. Sample E is in the middle with a median of ≈ 7 dB, IQR around 6-8 dB, whiskers up to ≈ 13 dB and isolated points above this level. Overall, C has the highest typical effectiveness, B the lowest, while A and F offer solid, relatively consistent shielding, and D and E represent a compromise between medium effectiveness and variability of results.

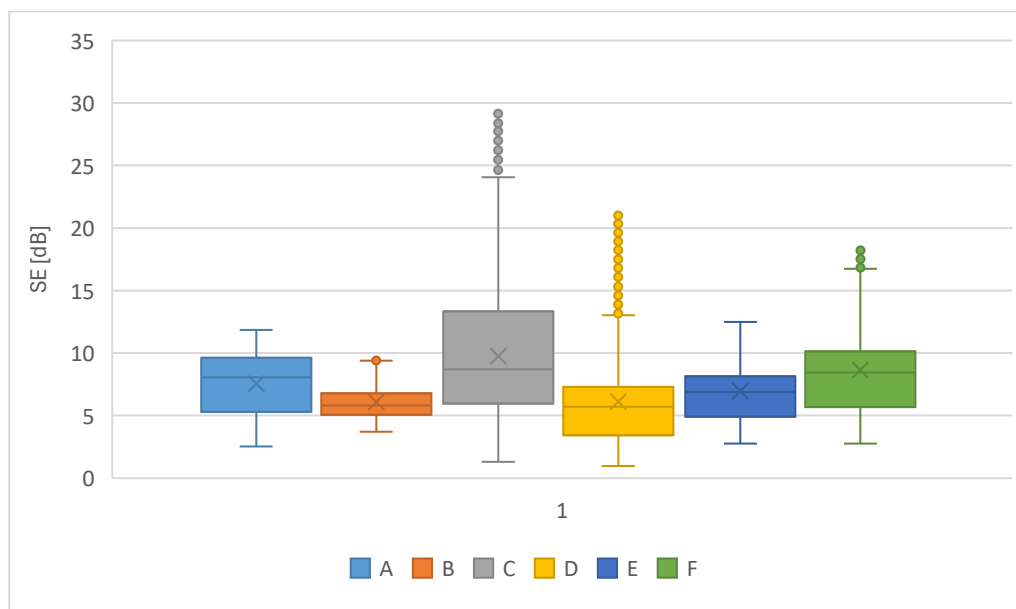


Figure 52 Figure 55 Statistical distribution of SE – Near Field Scanning method. [Own]

10 COMPARISON OF REAL AND SIMULATED MEASUREMENTS

This chapter presents a systematic comparison of real and simulated SE measurements. The comparison is made for three methods: VNA, EMI and EMxpert. Box plots and line graphs are analysed for each method. Medians, interquartile ranges and resonance peaks are observed. Based on the similarities, it will then be possible to determine which measurement and simulation method is most suitable for research.

10.1 Comparison of the VNA method with S-Parameters

A comparison of the box plots shows significant differences between the numerical simulation and the actual measurements of the SE. In the simulation, sample D achieved the highest median (≈ 11 dB), while sample A was evaluated at only about 5 dB. In the laboratory, however, the order was reversed: A showed the most robust shielding (median ≈ 15 dB, Q_1 - $Q_3 \approx 10$ -20 dB) and F had comparable values; conversely, D dropped to only ≈ 5 dB. The other samples (B, C, E) improved by several decibels in the measurements, but their relative positions remained approximately the same. A systematic increase in the real values (typically +3-10 dB) indicates that the numerical model underestimates the losses or does not capture all signal coupling paths. The largest discrepancy in samples A and D points to possible differences in material constants, BLS plating quality or assembly tolerances not accounted for in the simulation. Overall, the simulation reliably identified a highly unsatisfactory design (E remains the weakest in both domains).

Based on the evaluation of the line graph, similarities can be found between the simulation and the measurement. Firstly, it should be noted that the box plot covers the whole frequency band and is clearer, but the line plot is more accurate. Based on this, some selected similarities between the simulation and the measurement are listed here.

- A has the same peak at ≈ 2800 MHz in the simulation; in the measurement the maximum peak is at ≈ 2800 MHz, but the peak in the simulation is lower than in the measurement, which may be influenced by the environment. This sample is the only one that responds to the frequency ≈ 2400 MHz, which is also confirmed by real measurements.
- B has similar peaks in the simulation at ≈ 2900 MHz and in the measurement at ≈ 2800 MHz, as well as in the simulation at ≈ 4100 MHz and in the measurement at $\approx 4000 \approx$ MHz.

- C has a similar peak at ≈ 3170 in simulation and ≈ 3100 in measurement, but at ≈ 900 MHz in simulation and ≈ 900 MHz in measurement.
- D has a similar peak at around 2700 MHz in the simulation and around 3100 MHz in the measurement.
- E drops off at 2400 MHz in both simulation and measurement, but this pattern appears to be the worst within the SE in both cases.
- F has a similar maximum peak of ≈ 3100 MHz in simulation and ≈ 2800 MHz in measurement.

10.2 Comparison of the EMI method with Electric Field Mapping

When comparing the real and simulated box plots of the EMI method, there is a surprising similarity in the overall character of the data. In both cases the distribution is close to zero, confirming that the basic level of shielding is low and that differences between the boards are only apparent at remote points. The simulation and measurements also show a similar hierarchy of extremes: board F reaches the highest maxima (≈ 25 dB in the model and ≈ 21 dB in the measurement), while E remains the weakest, never exceeding single digits. In addition, all boards show a characteristic "jump" between the narrow box and several decibel peaks, which consistently indicates the resonant behaviour of the BLS cover only in limited frequency bands. The frequency of outliers is also similar: both graphs show that significantly higher damping occurs rather sporadically and is spread over the entire monitored band, rather than being concentrated in one place. These parallels confirm that the numerical model captures the basic trend - all samples provide rather weak shielding and only in exceptional cases do they achieve more significant attenuation - while reliably identifying the same best and worst performing designs as the experiment.

The line graph for this SE determination method shows a maximum peak value at 2400 MHz achieved by samples A and F (approximately 21 dB). Lower values are achieved by sample B, followed by D and C, with sample E being the worst sample for SE. If this maximum peak is ignored for the measurement, the values only fluctuate around 3 dB. In the simulations, the SE values fluctuate around 5 dB up to a frequency of 1500 MHz, with the exception of sample C, which reaches higher values. Sample A is the only one with a peak at 2400 MHz, while sample F shows a similar response but with a higher value at around 2100 MHz. This coincidence of resonance peak positions confirms the good

correlation between simulation and experiment. Over the whole band, Samples B and C achieve higher SE values than Sample D, while Sample E, as in the measurement, shows the lowest SE.

10.3 Comparison of the EMxpert method with Near Field Scanning

The simulation shows significant differences between the boards. The SE values range from 5 dB (E) to 12 dB (C). The peaks of some samples (C, F) go up to 30 dB. The order is clear: $C > F \approx A > D > B > E$. Real measurements did not confirm large differences. All medians remain below 1 dB and the whiskers barely exceed 6-10 dB. The curves merge and the method makes virtually no distinction between shielding qualities. The discrepancy may be due to idealised materials and perfect contacts in the model, while real samples suffer from gaps, soldered transitions and different current excitation. The simulation therefore predicts broader dynamics and higher attenuation, but reality shows that all covers perform about equally poorly.

In both plots, most of the spectrum remains at low SE values; real measurements are mostly between 1-3 dB, while simulations show a greater dispersion, with values averaging around 7-10 dB. In this case, the peak for sample F at 2400 MHz is the most similar in both simulation and measurement. However, this method does not find many common peaks.

11 IDENTIFICATION OF SAMPLE ERRORS

The aim of this chapter is to systematically evaluate the implementation defects of the monitored boards with integrated shielding and to determine their influence on the level of EM emissions. To achieve a comprehensive overview, six complementary diagnostic methods were applied. Each method was applied to six samples (A–F) under controlled rotation and position conditions, which made it possible to quantify the dependence of EM field leakage on the angle of rotation, position, and frequency.

11.1 Measurement method using VNA

For all samples analysed it was confirmed that the distribution of the emitted field depends significantly on the position of rotation. In sample A, the highest radiation is obtained at an orientation of 180° ($S_{21} \approx -55$ dB with a maximum around 2400 MHz), while the lowest radiation is recorded at 270° , when the attenuation drops below -100 dB. In sample B, the maximum is at 135° ($S_{21} \approx -45$ dB in the range 1000-3500 MHz) and the minimum again at 270° , where the parameter drops to -110 dB. Sample C shows the highest emission at 225° (peak -40 dB near 1050 MHz and elevated values also in the 2000-3000 MHz band), while the lowest emission occurs at 45° ($S_{21} \approx -110$ dB). For sample D, the highest emission is associated with an orientation of 135° (-40 dB in the 2500-3600 MHz band) and the lowest with an orientation of 225° , where the curve drops below -100 dB. Sample E reaches its maximum at 135° (dominant peak -40 dB at 3200 MHz), while the minimum is at 270° ($S_{21} \approx -110$ to -120 dB). Finally, sample F has the highest emission at 135° (peak -55 dB at 3300 MHz) and the lowest at 225° , where the attenuation reaches values around -120 dB. In the series of measurements carried out, the highest emissions are concentrated in three orientations: 135° (mainly in samples B, D, E and F), 180° (in sample A) and 225° (especially in sample C). This shows that the 135° angle is the position of maximum EM radiation, with possible local extremes at 180° and, exceptionally, at 225° . The lowest level was recorded at the angles of 270° and 225° : the angle of 270° shows minimal emissions in samples A, B and E, while the angle of 225° shows minimal emissions in samples D and F; sample C is an exception, with the global minimum occurring at 45° . The rotation angles of 135° and 225° represent ideal conditions for detecting defects in the implementation of this configuration.

The measurements carried out showed that this method can detect faults in the implementation of the BLS, particularly in cases where there is a break in the continuity of

the shielding or inadequate earthing. These faults can be identified from characteristic changes in the level of the emitted field as a function of the angle of rotation. However, the accuracy of the method in its current form is limited - it can reliably discriminate between well and poorly shielded samples, but additional measurements on a larger number of samples are required to determine the type and location of the defect in detail. The measurement results were probably also influenced by other factors, in particular the polarisation of the EM field, since a chip antenna was used inside the BLS, and the proximity to the GTEM cell walls, since the sample was mounted on a bushing. These phenomena could have affected the field distribution and contributed to local emission maxima or minima.

11.2 Measurement method using EMI test receiver

EMI measurements were also carried out using a GTEM cell, similar to the previous methodology, to identify implementation failures at board level. This analysis showed that all the samples tested, regardless of orientation, exhibited significant EM field leakage at a frequency of 2400 MHz, making this frequency a universal diagnostic point for detecting implementation deficiencies. The lowest emission levels, and therefore the most effective shielding, were recorded for Sample A at 1100 MHz and 2100 MHz (270°) and 1700 MHz (180°); for Sample B at 800 MHz (270°), 1200 MHz (180°) and 1500 MHz (225°); for sample C at 2300 MHz (45°), 1000 MHz and 1100 MHz (270°) and 700 MHz (180°); for sample D at 1000 MHz (180°) and 1100 MHz (45°); for sample E at 700 MHz (315°), 1100 MHz (270°) and 2300 MHz (45°); and for sample F at 1400 MHz (180°) and 2200 MHz (270°). These results also confirm that the 270° and 180° orientations generally provide the highest attenuation of the emitted field, which is consistent with the results obtained using the previous method in the same measurement environment. The EMI method proved to be suitable for identifying unambiguous emission leaks in accordance with the requirements of the ČSN EN standards, but based on the samples analysed, it appears to be insufficiently effective for reliably identifying specific faults in the implementation of BLS.

11.3 Measurement Method Using the EMxpert

This method differs from previous approaches mainly in the type of instrumentation used and the method of implementation. The measurements were carried out using the EMxpert system, which allows detailed spatial localisation of emissions in the near field. In sample A, the highest emission was recorded at a frequency of 2400 MHz, with significantly lower

levels in other parts of the spectrum. The same emission characteristics were also observed in the other samples tested. Sample B showed a dominant emission around 2200 MHz, while samples C and D also had maximum emissions concentrated around a frequency of 2400 MHz. Sample E showed increased emissions in the 1700-1800 MHz band and sample F again at 2200 MHz. The measured data shows that the EMxpert system is most sensitive to detecting defects in the 2000-2400 MHz range, providing consistent and repeatable results in all cases. This phenomenon can be attributed to the functional band of the chip antenna used, which according to the technical documentation is primarily intended for the 2.4 GHz band, but some technologies (e.g. ZigBee) may also be active at lower frequencies (868/915 MHz). The advantage of the method was its ability to detect EM field leakage even at frequencies not detected by other measurement methods. However, the identification of specific weak spots was hampered by the lack of information on the height coordinate (z-axis), which limited the possibility of precise spatial localisation. In addition, the results could have been affected by parasitic interference entering the shielded room through gaps in the structure; this phenomenon was observed, for example, at a frequency of 91 MHz, which is in the radio broadcasting band. Finally, it should be noted that in the low frequency band, the level of interference is so high that the method does not give reliable results in this range. Overall, the method is ineffective; although it can detect the antenna, the lack of co-ordinates makes it impossible to locate any defects accurately. This shortcoming is also mentioned in the SE description of this method.

11.4 S- Parameters Simulation

In sample A, the maximum radiation leakage occurred at an orientation of 315° at a frequency of around 1500 MHz, while the lowest radiation level, and therefore the most effective shielding, was recorded at 90° in the 300-500 MHz band. For sample B, the maximum leakage was at 270° around 1500 MHz, with the minimum again at 90° . Sample C showed the highest leakage at 270° , with the lowest emission at 315° . Sample D showed the highest leakage at 0° and 270° , with the lowest leakage at 45° . Sample E reached its maximum at 180° at 1500 MHz and at 225° ; the lowest emissions were observed at 225° at 3300 MHz and at 315° at 4000 MHz. For sample F, the highest leakage occurred at 180° at 1500 MHz and at 315° at 3200 MHz, while the lowest emission level was recorded at 225° at 3500 MHz and at 270° at 3100 MHz. The results show that the most reliable detection of implementation errors is achieved with orientations of 225° and 270° .

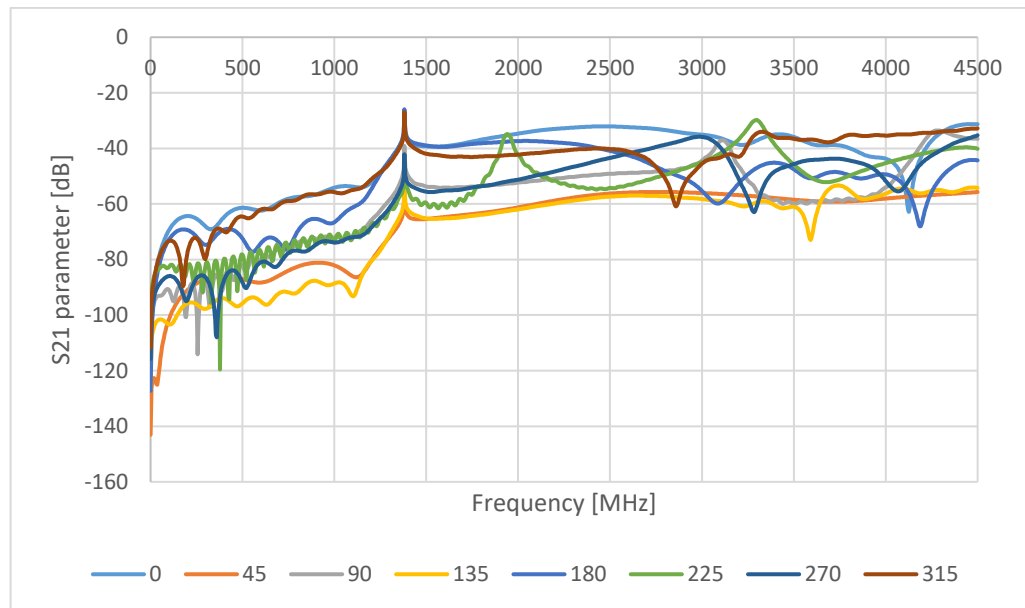


Figure 53 Radiation leakage for S- Parameters. [Own]

11.5 Electric Field Mapping Simulation

In sample A, the minimum emission level of $-47,744 \text{ dB}\mu\text{V/m}$ (3600 MHz) was achieved at an orientation of 135° , while the maximum leakage of $99.173 \text{ dB}\mu\text{V/m}$ (2401.2 MHz) occurred at 0° . In sample B, the lowest attenuation of $-46.807 \text{ dB}\mu\text{V/m}$ (3600 MHz) again occurred at 135° , and the highest of $101.771 \text{ dB}\mu\text{V/m}$ (2401.2 MHz) at 0° . Sample C showed a minimum of $-34.554 \text{ dB}\mu\text{V/m}$ (90.097 MHz) at 180° and a maximum of $107.575 \text{ dB}\mu\text{V/m}$ (2401.2 MHz) at 90° . For sample D, the weakest emission was $-37.397 \text{ dB}\mu\text{V/m}$ (3600 MHz) recorded at 270° , while the highest leakage of $113.159 \text{ dB}\mu\text{V/m}$ (2401.2 MHz) was detected at 180° . Sample E reached a minimum of $-71,558 \text{ dB}\mu\text{V/m}$ (0.1 MHz) at 225° and a maximum of $97,3 \text{ dB}\mu\text{V/m}$ (2401,2 MHz) at 90° . For sample F, the lowest value of $-75.723 \text{ dB}\mu\text{V/m}$ (0.1 MHz) was measured at 225° , while the highest emission of $84.190 \text{ dB}\mu\text{V/m}$ (2401.2 MHz) occurred at 90° . Based on the evaluation, implementation defects can be identified at coordinates 0° , 90° , and 180° .

11.6 Near Fiels Scanning Simulation

The latter method shows that the highest emission levels ($165\text{-}190 \text{ dB}\mu\text{V/m}$) occur mainly in orientations with a negative y-component - positions probes are defined by the vector coordinates (x, y, z) in particular in vectors $(-10, -20, 0.5)$ in samples A and C or $(10, -20, 0.5)$ in sample D - and either in the low frequency range around 30 MHz (sample B) or in the 1.3-2.45 GHz band (samples A, C, D, E, F); these orientations therefore represent critical

points for the detection of implementation errors. On the other hand, the lowest emission levels (81-109 dB μ V/m) are consistently associated with orientations whose vectors have a small or zero x-component and a positive or slightly negative y-component - e.g. (0, 20, 0.5) for A, (-10, 0, 0.5) for B, (0, -10, 0.5) for E or (-5, -10, 0.5) for D and F - and occur predominantly at frequencies of 0.8-1.1 GHz or around 2.76 GHz (sample D). This distribution confirms that orientations with a strongly negative y-component significantly increase the EM leakage, while vectors with a balanced or slightly negative y-component and a small x-component provide the best SE; in practical terms, this means that during testing it is desirable to focus primarily on rotations characterised by vectors (-10, -20, 0.5) to (10, -20, 0.5), while for operating configurations with minimal radiation, orientations in the vicinity of (0, $\pm$ 10-20, 0.5) are suitable, allowing emissions to be reduced by up to 80 dB μ V/m. Based on the evaluation, defects can be identified at coordinates (-10 -20 0.5).

CONCLUSION

The main objective of this thesis was to evaluate commonly available measurement techniques such as semi-anechoic chambers, GTEM cells and EM scans to identify potential design flaws in integrated shielding enclosure. To achieve this goal, a combination of real measurements and simulation tools were used to predict the behaviour of EM fields and their interactions with the designed covers. The results include an evaluation of the ability to detect subtle implementation errors using existing methods and an assessment of the need to introduce innovative methods for their more effective identification. Measurements and simulations were carried out on six samples in two configurations, with and without a enclosure.

The VNA method provided results comparing the original and new shielding enclosure. The highest SE of the original cover was achieved by variant A with a value of approximately 32 dB, followed by variant F with a value of 31 dB. The introduction of mechanical modifications to the new cover led to a significant improvement in the results of variant F and a slight deterioration in variant A, which points to the significant influence of mechanical interventions on the shielding capabilities of the device. The frequency distribution of the obtained values showed stable results with a predominance of values in the range ± 1 to ± 2 . The EMI method showed the highest SE values at a frequency of 2400 MHz, with variant F achieving the best results, up to 21 dB. Variant A achieved values lower by 4 dB. Other samples showed significantly lower efficiency, reflecting the specifics of this measurement technique. The frequency distribution of the EMI method results was wider than that of the VNA but still remained within acceptable accuracy limits. The results of broadband measurements using the EMxpert method showed generally lower SE with small deviations. The best results were achieved by variant F, while variant C showed significant spectral peaks in the band around 860 MHz, probably influenced by the chip antenna function. Narrowband analysis confirmed the dominance of variant F in suppressing EM radiation, while variant C again showed instability in certain frequency ranges. The frequency distribution of the narrowband analysis results was consistent with the broadband trends and confirmed the stable nature of the results with minimal presence of extreme values.

SE simulations were performed using three methods- S-parameters, Electric Field Mapping, and Near Field Scanning. The S-parameter method showed that variant D has the best overall SE with a median of around 9 dB and maximum values of up to 24 dB. Variant E, on the other hand, showed the lowest effectiveness with a median of approximately 2 dB.

The Electric Field Mapping method identified variant C as the most effective with a median of approximately 5 dB and the highest consistent effectiveness, while variant E again recorded the lowest values. The Near Field Scanning method showed the highest typical effectiveness for variant C, with significant peaks of up to 30 dB, and the lowest consistent effectiveness for variant B. Variants A and F provided stable, moderately high effectiveness, while variants D and E represented a compromise between moderate effectiveness and variability of results.

A comparison of real and simulated measurements showed interesting similarities. The VNA method and S-parameters showed similar resonance peaks for most variants, especially for variants A, B, and F. The EMI method and Electric Field Mapping had the same character of low base values and occasional high resonance peaks, with variants A and F showing similarities especially at a frequency of 2400 MHz. The EMxpert method and Near Field Scanning had the least significant agreement, with the simulation overestimating the shielding dynamics, while the real measurements showed more balanced results.

Analysis of implementation errors in samples revealed a significant dependence of field emissions on orientation and measurement frequency. All methods identified critical angles and frequencies at which the highest emissions occur. In general, angles of 135°, 180°, and 225° proved to be the most problematic, while angles of 270° and 225° exhibited the lowest emissions. The findings suggest that defects can be localized, but further measurements on additional samples and more detailed diagnostic procedures are necessary to determine their type and location more precisely.

Of the measurement methods, the VNA method was the most effective, as it provided clear and stable results and allowed a good distinction of SE between the different variants of BLS. It was also able to identify significant changes after mechanical modifications to the shield, demonstrating its sensitivity to subtle implementation changes. Of the simulation methods, the Electric Field Mapping method was determined to be the most reliable and showed high agreement with real EMI measurements. Both methods showed similar behaviour with clearly defined resonance peaks and a similar hierarchy of sample efficiencies.

The contribution presented at the September international EMC Europe 2025 conference in Paris will include part of the measured results. Selected simulation outcomes were showcased as a poster at the SIMULIA Regional User Meeting — EuroCentral 2025,

held in Bamberg, Germany. The presented contribution received the Best Poster of the Event award, granted by a professional jury composed of academic and industrial experts.

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LIST OF FIGURES

Figure 1 The principle of EM shielding. [10]	19
Figure 2 Wiring diagram for the Stripline method. [14]	22
Figure 3 Stripline connection example. [14]	23
Figure 4 Stirred Reverberation Chamber – Wiring Diagram. [14]	24
Figure 5 Stirred Reverberation chambre. [14]	25
Figure 6 Wiring diagram for nested reverberation chambers.[14]	26
Figure 7 Dual reverberation chamber wiring diagram. [14]	26
Figure 8 Two VIRC chambers made of flexible material, with a red mark indicating the sample location.[14]	27
Figure 9 Description of GTEM cell.[14]	28
Figure 10 Wiring diagram for measurement using DTEM. [18]	29
Figure 11 Sample of tested samples.[21]	31
Figure 12 BLS and PCB sample for the VIRC method. [24]	32
Figure 13 Wiring diagram for dual VIRC MUT. [24]	33
Figure 14 Dipole distribution on the sample.[25]	34
Figure 15 Example of a connection diagram for both methods. [26]	35
Figure 16 Measurements in GTEM cells. [29]	36
Figure 17 GTEM Cell and VNA.....	39
Figure 18 PCB manufacturing requirements. [Own]	43
Figure 19 The resulting products of the order. [Own]	44
Figure 20 Rotation with sample in GTEM cell. [Own]	46
Figure 21 Measurement in GTEM cell with BLS. [Own]	46
Figure 22 Measurement in GTEM cell without BLS. [Own]	47
Figure 23 Wiring diagram for the VNA method. [Own]	48
Figure 24 SE as a function of frequency for the original shield – VNA method. [Own]	49
Figure 25 Statistical distribution of SE – original shield. [Own].....	49
Figure 26 Categorization of SE deviations based on Z-score from the original shield. [Own]	50
Figure 27 SE as a function of frequency for the new shield – VNA method. [Own]	51
Figure 28 Statistical distribution of SE – new shield. [Own]	51
Figure 29 Categorization of SE deviations based on Z-score from the new shield. [Own].	52
Figure 30 Wiring diagram for the EMI method. [Own]	52
Figure 31 SE as a function of frequency – EMI test receiver method. [Own].....	53
Figure 32 Statistical distribution of SE – EMI test receiver method. [Own].....	54

Figure 33 Z-score distribution of SE – EMI test receiver method. [Own]	54
Figure 34 Wiring diagram for the EMxpert method. [Own]	55
Figure 35 PCB wiring without BLS on EMxpert board. [Own]	56
Figure 36 SE as a function of wide frequency measurement– EMxpert method. [Own]....	57
Figure 37 Statistical distribution of SE wide frequency measurement – EMxpert method. [Own]	57
Figure 38 Z-score distribution of SE wide frequency measurement – EMxpert method. [Own]	58
Figure 39 SE as a function of narrow frequency measurement– EMxpert method. [Own]	59
Figure 40 Statistical distribution of SE narrow frequency measurement – EMxpert method. [Own]	59
Figure 41 Z-score distribution of SE narrow frequency measurement – EMxpert method. [Own]	60
Figure 42 PCB sample with BLS and without BLS. [Own]	61
Figure 43 Illustration of all samples under test in the CST environment. [Own]	62
Figure 44 Simulation for S-parameters for 0°. [Own]	63
Figure 45 SE as a function of frequency –S – parameters method. [Own]	64
Figure 46 Statistical distribution of SE – S – parameters method. [Own]	65
Figure 47 Simulation model for Electric Field Mapping with probes. [Own]	66
Figure 48 SE as a function of frequency – Electric Field Mapping method. [Own]	67
Figure 49 Statistical distribution of SE – Electric Field Mapping method. [Own]	68
Figure 50 Layout of near-field probes under the test sample in CST Studio. [Own]	69
Figure 51 SE as a function of frequency – Near Field Scanning method. [Own]	69
Figure 52 Figure 55 Statistical distribution of SE – Near Field Scanning method. [Own].	70
Figure 53 Radiation leakage for S- Parameters. [Own]	77

LIST OF TABLES

Table 1 Used measuring instruments. [Own].....	45
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LIST OF ABBREVIATIONS

EMC	Electromagnetic compatibility
EMS	Electromagnetic susceptibility
EMI	Electromagnetic interference
PCBs	Printed circuit boards
σ	Conductivity
μ_r	Relative permeability
ϵ_r	Permittivity
SE	Shielding effectiveness
K_s	Shielding coefficient
E_t	Electric field intensity at a specific point in the shielded space
E_i	Electric field intensity strikes the shielding material
H_t	Magnetic field intensity at a specific point in the shielded space
H_i	Magnetic field intensity strikes the shielding material
dB	Decibel
Etc.	Et cetera
A	Absorbance
R	Reflected Wave
M	Multiple reflection attenuation
T	Transmittance
MHZ	Megahertz
BLS	Board level shielding
GHz	Gigahertz
VNA	Vector network analyser
CW	Continuous wave
VIRC	Vibrating intrinsic reverberation chamber

GTEM Gigahertz transverse electromagnetic

DTEM Dual transverse electromagnetic

MIT Magnetic induction tomography

S Shielded

P Parallel

MUT Material under test

x₂₅ Lower quartile

x₅₀ Median

x₇₅ Upper quartile

Q₁ Lower quartile

Q₂ Median

Q₃ Upper quartile

EUT Equipment under test

R&S Rohde Schwarz

dB μ V/m Decibel microvolt to meter

ODB++ Open Database

FIT Finite Integration Technique

FEM Finite Element Method

APPENDICES

Appendix P I:	Measurements with GTEM and VNA
Appendix P II:	Measurements with GTEM and EMI
Appendix P III:	Measurements with EMxpert
Appendix P IV:	S-parameter simulation
Appendix P VI:	Electric Field Mapping Simulation
Appendix P VII:	Near Field Scanning Simulation

