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Technical report

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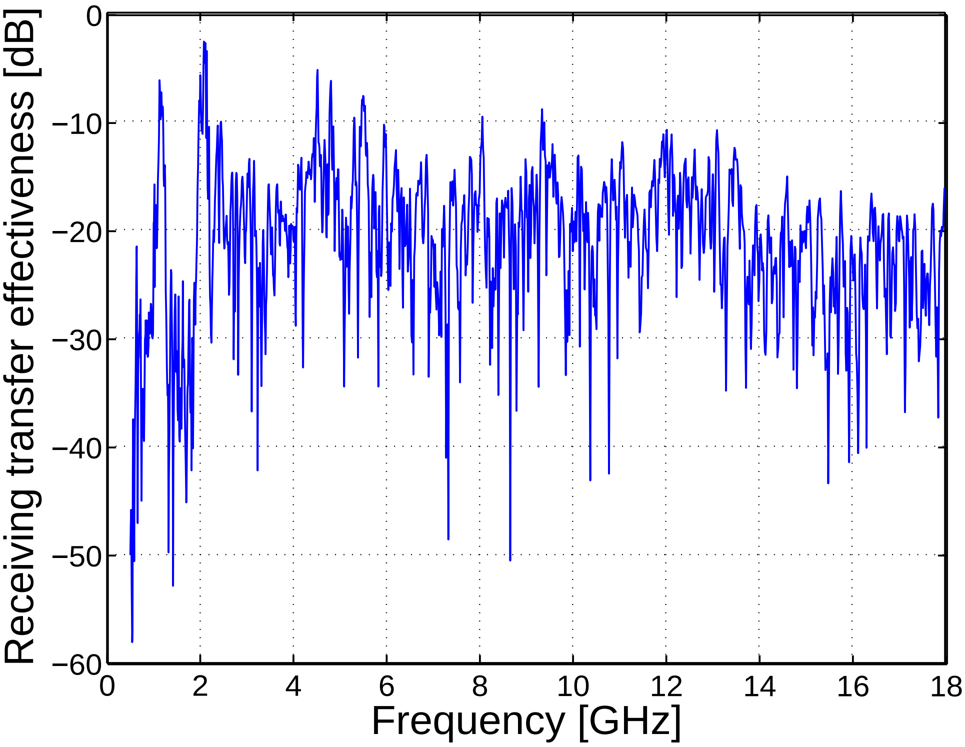
Electromagnetic Transfer Effectiveness of Complex Electronic Equipment



$$T_r(\hat{\Omega}, \hat{e}_i, \nu) = 2q(\nu)\eta(\nu)p(\hat{\Omega}, \hat{e}_i, \nu)D(\hat{\Omega}, \nu)$$

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Electromagnetic Transfer Effectiveness of Complex Electronic Equipment

Abstract (not more than 200 words)

High Power Microwaves (HPM) can disturb and/or destroy electronic equipment. This report provides a systematic approach describing the disturbance and destruction processes.

We show outgoing from measurement results on real rather well protected electronic equipment, how the electromagnetic coupling to the electronic equipment can be described by the here proposed quantity: receiving transfer effectiveness. The smaller the receiving transfer effectiveness is, the better protected the most critical electronic component is. The receiving transfer effectiveness consists of the product of four factors. The two first factors, the impedance mismatch factor and the radiation efficiency are the fundamental parts in the protection. It is striking to see how the radiation efficiency can be close to 0 dB four a few discrete frequencies compared to its typical value of minus a few tens of dB. The product of the last two factors, the partial directivity, depends on from which direction the test object is irradiated, together with the orientation and type of polarisation in use.

By help of the knowledge gained, we show in a practical example, how the uncertainty in a Radiated Susceptibility test can be lowered by interchanging testing in the directional domain by testing in frequency domain.

Keywords

High Power Microwaves, Receiving Transfer Effectiveness, Transmission Transfer Effectiveness, Directivity, Radiation Efficiency

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Elektromagnetisk kopplingseffektivitet hos komplex elektronikutrustning

Sammanfattning (högst 200 ord)

HPM kan störa och/eller förstöra elektronik utrustning. I denna rapport beskrivs störelse- och förstörelse-processerna på ett systematiskt sätt.

Vi visar, utgående från mätresultat på verklig tämligen välskyddad elektronikutrustning, hur kopplingen till elektronik utrustning kan beskrivas med hjälp av den av oss föreslagna storheten: mottagningskopplingsverkan. Ju mindre mottagningskopplingsverkan är, desto bättre skyddad är den mest kritiska elektronikkomponenten. Mottagningskopplingsverkan består av produkten av fyra faktorer. De två första faktorerna, impedansmissanpassningsfaktorn och strålningsverkningsgraden är de två fundamentala bidragen i skyddsverkan. Det är slående att se att för ett fåtal diskreta frekvenser så kan strålningsverkningsgraden vara nära 0 dB, jämfört med dess typiska värde på minus något tiotal dB. Produkten av de två sista faktorerna i mottagningskopplingsverkan, den partiella direktiviteten, beror av från vilket håll testobjektet bestrålas samt orienteringen och typen av polarisation som används.

Med hjälp av uppnådd kunskap visar vi i ett praktiskt exempel hur osäkerheten i RS-testning kan minskas genom att byta ut RS-testning i riktningsdomän mot testing i frekvensdomän.

Nyckelord
HPM, Transmissionskopplingsverkan, Mottagningskopplingsverkan, Direktivitet, Strålningsverkningsgrad

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Contents

Chapter 1

Introduction

Electromagnetic fields couple to electronic equipment and that form one of the bases for the interest into the branch of High Power Microwaves (HPM). In principal it is easy to protect your electronic equipment. E.g. a metal shield, even a thin one ($\sim mm$), brings in most cases more than sufficient protection. However, in practice there is almost always need for small apertures, and electromagnetic energy will penetrate through these apertures. It is also often a need for the electronic equipment to communicate with the outer world. The communication may be wireless, and done through antennas or optical counterparts. The electronic equipment may also be connected to many kind of different sensors, e.g. infrared seekers. All these sensors implies apertures in the electromagnetic shield where electromagnetic power may penetrate. In the case of antennas the case may be even worse, because they may be constructed to be efficient receivers of microwaves, and therefore constitute a sensitive port. Even the case of wire communication is not safe, because wires act as unintentional antennas and receive electromagnetic energy.

Even what may look like small and unimportant penetration paths through the shield, may constitute substantial coupling paths to the interior of the electronic equipment. Some main reasons to that are resonances in the apertures and inside the structure. Already here we can se that the coupling to the interior of the electronic equipment has two major contributions, first how "efficient" the coupling through apertures in the shield is, and secondly the interior of the electronic equipment will affect how much energy that is absorbed in the very most critical component.

In this report we show outgoing from measurement results on real rather well shielded electronic equipment, how the shielding effectiveness consist of many subcontributions. In this work we will also find that transfer effectiveness is a more convenient quantity to use than shielding effectiveness. The presentation may look rather theoretical, but that is only an optical illusion. It does only include a few new ways to tackle an important problem complex. The report is concluded with a practical example. We are actually so far only in the beginning of using this model; we have here substantial work to do in understanding the complex nature of electromagnetic coupling to real electronic equipment.

We study the electromagnetic coupling to the interior of electronic equipment. The presentation in [1] support that the results of Coupling Measurements is also applicable to high level Radiated Susceptibility testing. Although the work in [1] still holds, it does not include all the effects caused be non-linearities in electronics, and here we have a new open and relevant research field.

Chapter 2

Shielding

2.1 Shielding effectiveness

Shielding effectiveness is a quantity which intuitively is easy to understand. Some electronic equipment is surrounded by some sort of screen which protect the electronic equipment from incident electromagnetic power, and the shielding effectiveness describes how efficient that screening is. Despite that the concept is so easy to understand, it is in many, to the Electromagnetic Compatibility (EMC) community practical situations, not easy to define the quantity shielding effectiveness, and the concept has caused a lot of problem including improper design and protection properties being much lower than expected. The problems has been so large that some, in one or an other way, have suggested to just skip the concept. However, the concept is still widely used, and it is fascinating to see how new engineers and scientist entering the field, including the author of this report, intuitively begin to use the concept almost at once. Consequently, the concept of shielding effectiveness will probably continue to be used for a long time, and we will here try to bring some light on the concept.

The shielding effectiveness (Λ)[1] is generally defined as the quotient between the absolute value (E_i) of the electric field of an incident electromagnetic plane wave,

$$\overline{E}_i = E_i \hat{e}_i \ , \tag{2.1}$$

and the absolute value (E_t) of the transmitted electric field behind the screen,

$$\overline{E}_t = E_t \hat{e}_t \ , \tag{2.2}$$

$$\Lambda = \frac{E_i}{E_t}. \tag{2.3}$$

[1] The shielding effectiveness is often denoted SE, but a one letter notation is preferable in mathematical formulas, so we introduce the letter Λ do denote the shielding effectiveness.

The definition of the shielding effectiveness according to (2.3) is a quotient between two field values. That probably reflects that the EMC-community is used to express their measurements in electric (and magnetic) fields. It is however somewhat surprising that the shielding effectiveness is not defined as quotient between two power values. As will be shown below power values will turn out to be the most obvious choice. Some people get around this issue by only defining the shielding effectiveness in dB,

$$\Lambda_{dB} = 20\log_{10}\frac{E_i}{E_t} \equiv 10\log_{10}\frac{E_i^2}{E_t^2}. \tag{2.4}$$

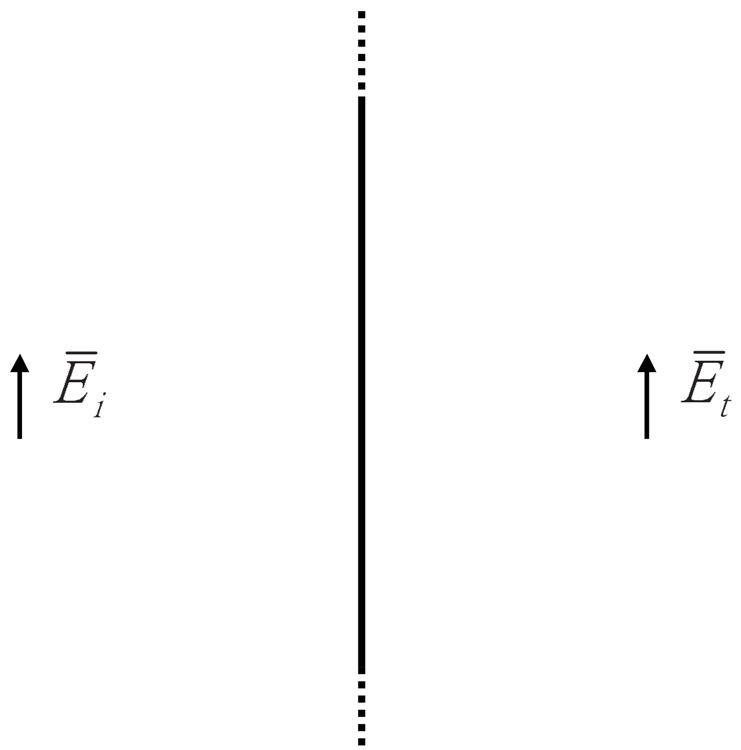

Figure 2.1: *Intuitively, the shielding effectiveness is the quotient between the field in front of and behind a screen, respectively.*

However, disregarded from that important but somewhat philosophical issue, the above definition of the shielding effectiveness has severe obscurities. The definition is clear and unequivocal if we like in Fig. 2.1 has an incident plane wave on a two dimensional infinite flat screen, and the wave is transmitted as a plane wave. The measurement procedure performed in Fig. 2.1 is actually a measure of the shielding properties of the material in the shield. That is a relevant measurement procedure if the shielding properties of a new material is to be tested. However, for typical shielding materials used in the EMC-branch, e.g. metal 1 mm thick, the shielding properties for microwaves is far more than sufficient. It is also very well known that leakages through shielding screens is through practical imperfections in the screen such as riveted seams, gaskets, ventilation apertures etcetera and not through the screen itself.

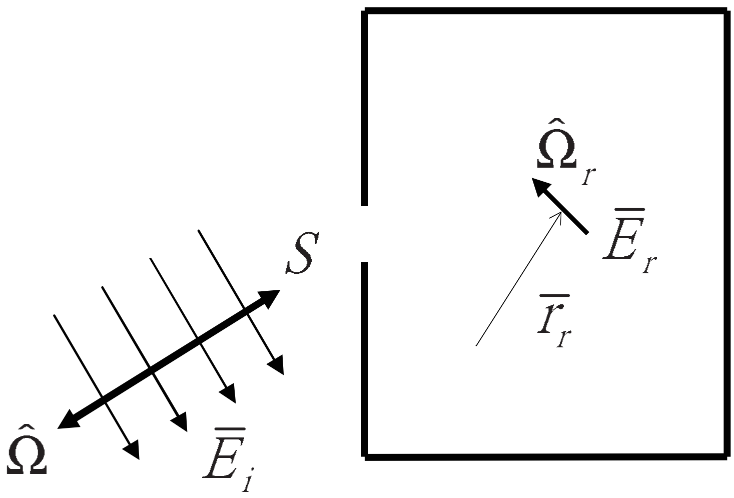

Figure 2.2: *In practice the situation is most often not as easy as indicated in Fig. 2.1. The protection obtained by the screen depends on the irradiation direction* ($\hat{\Omega}$) *and polarisation* ($\overline{E}_i / |\overline{E}_i|$) *of the incident field as well as the position* ($\overline{r}_r$) *and orientation* ($\hat{\Omega}_r$) *of the measurement probe behind the screen.*

Fig. 2.2 shows a typical situation where the protection is performed in form a box, and electromagnetic energy leaks through one or more apertures in the screen. If we put a probe inside the box, and measure the field, we will find that the result will depend on from which direction,

$$\hat{\Omega} \triangleq \frac{1}{\sqrt{2}}(\hat{e}_\theta, \hat{e}_\phi), \tag{2.5}$$

we irradiate our box, and in difference to the situation in Fig. 2.1, we cannot say that the maximum field measured by the probe is reached for normal incidence. The field measured by our probe (E_r) will also depend on the polarisation of the incident field,

$$\hat{e}_i \triangleq \frac{\overline{E}_i}{|\overline{E}_i|} \equiv \frac{\overline{E}_i}{E_i}. \tag{2.6}$$

To that it has also to be added that the result depends on the position ($\overline{r}_r$) as well as the orientation,

$$\hat{\Omega}_r \equiv \frac{1}{\sqrt{2}}(\hat{e}_{\theta r}, \hat{e}_{\phi r}), \tag{2.7}$$

of the probe inside the box. Hence it is not possible to define an unequivocal shielding effectiveness in accordance to (2.3).

To complicate the situation even further, it should be mentioned that the result of a shielding effectiveness measurement in accordance with Fig. 2.2 and (2.3) is not only a function of the leakage through apertures, but also a function of the size and electromagnetic loading of the box, see [2]. Observe that also the measurement probe in itself will load the box and change the result.

2.2 Transmission cross section

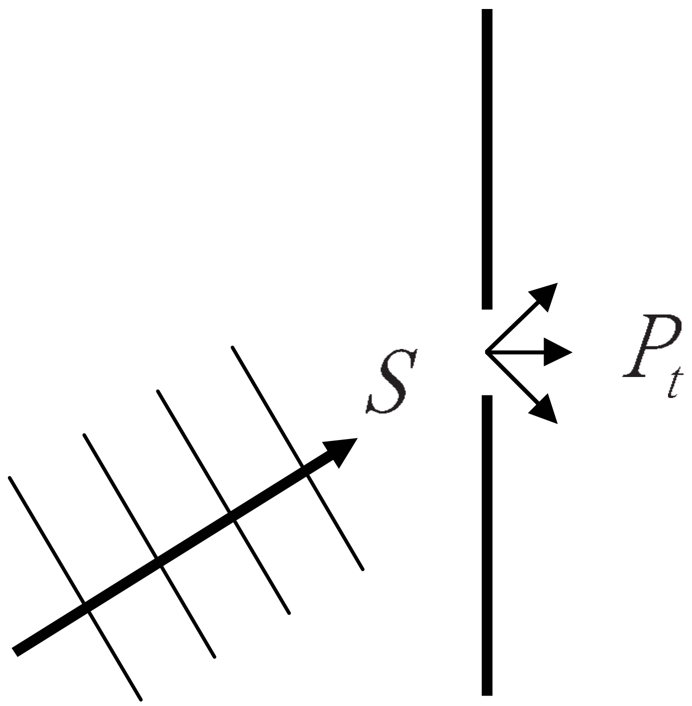

Figure 2.3: *The interesting parameter characterizing an aperture is the transmitted power (P_t) through the aperture relative to the threat seen from outside. The threat can e.g. be measured in form of the power density (S) of the incident wave. An alternative measure of the outside threat is proposed in section 2.3.*

However, if one withdraw from insisting on measuring the field, it is possible to solely characterize the electromagnetic leakage through an aperture. The most intuitive quantity to characterize the leakage through an aperture is the (real, not reactive) power (P_t) being transmitted though the aperture[2], see Fig. 2.3. It is often convenient to define the transmission cross section,

[2]Please observe that it is not easy to define something like the "transmitted field through the aperture".

$$\sigma_t \triangleq \frac{P_t}{S}, \tag{2.8}$$

by normalising the transmitted power by the power density (S) incident on the aperture. In the optical limit when the dimensions of the aperture is much larger than the wavelength of the field, and at normal incidence, the transmission cross section equals the physical area of the aperture, but for dimensions smaller and similar to the wavelength of the field, the transmission cross section does generally differ substantially from the physical area of the aperture.

In a case like e.g. Fig. 2.2, the transmission may be through many apertures, but then P_t is simply the total power transmitted through all apertures, and the definition in (2.8) is still completely valid. However, it should be noticed that the transmitted power through the apertures does depend on the irradiation direction as well as the polarisation of the incident electromagnetic field,

$$\sigma_t(\hat{\Omega}, \overline{p}) = \frac{P_t(\hat{\Omega}, \hat{e}_i)}{S}, \tag{2.9}$$

and for a complex aperture, the maximum transmission cross section is not necessarily reached at perpendicular incidence. The maximum transmission cross section,

$$\sigma_{t,max} = \frac{max_{\hat{\Omega},\hat{e}_i}\{P_t(\hat{\Omega}, \hat{e}_i)\}}{S}, \tag{2.10}$$

is perhaps the most interesting quantity, but to perform enough measurements to, with a reasonable accuracy, find the irradiation direction and polarisation corresponding to the maximum transmitted power through the aperture, is often in practice considered as too time-consuming. An other interesting quantity is the average transmission cross section,

$$< \sigma_t >= \frac{< P_t(\hat{\Omega}, \hat{e}_i) >_{\hat{\Omega},\hat{e}_i}}{S}, \tag{2.11}$$

and this quantity can actually easily be measured by irradiating the aperture from a reverberation chamber[3].

2.3 Transmission Transfer/Shielding Effectiveness

Still many people want to use the concept of shielding effectiveness. We therefore here propose a new way to define the shielding effectiveness of the transmission through a screen with apertures. In doing so we will however first define the inverse of the shielding effectiveness, the transfer effectiveness. The reason for starting by defining

[3]It has not been possible to include how that is done in this report. Some descriptions of how that can be done is found in [3, 4, 5]; though we admit that the these references do not in detail describe how the measurement is performed.

the transfer effectiveness is that it has some nice mathematical features which the shielding effectiveness does not have. Actually, as will hopefully be seen in this and in the next section, the transfer effectiveness is a more convenient quantity than the shielding effectiveness.

In defining the transfer effectiveness of the transmission through a screen with apertures, we normalise the power transmitted through the apertures with the power received by an antenna being irradiated with the same electromagnetic plane wave as the screen. The power received by an antenna irradiated by a plane wave of power density S is [6, p. 86], [7, pp. 64],

$$P_r = q\eta p((\hat{\Omega}, \hat{e}_i))D(\hat{\Omega})\frac{\lambda^2}{4\pi}S. \tag{2.12}$$

As seen in 2.12, the received power by an antenna depends on the impedance mismatch factor (q), the radiation efficiency (η), the polarisation efficiency (p) and the directivity (D)of the antenna as well as the wavelength of the electromagnetic field. Hence the power received by an antenna is not unequivocal. To get an unequivocal value, we will use the received power by an idealised antenna, being completely impedance matched implying that $q = 1$ and having 100% radiation efficiency implying that $\eta = 1$. Our idealised antenna will also have a directivity equal to the average value for the directivity,

$$< D >= 1, \tag{2.13}$$

as well as a polarisation efficiency equal to the average value for the polarisation efficiency,

$$< p >= \frac{1}{2}. \tag{2.14}$$

Under these assumptions the received power by the antenna has an unequivocal value,

$$P_{ri} = \frac{\lambda^2}{8\pi}S, \tag{2.15}$$

and we define the transmission transfer effectiveness through apertures in a screen as[4],

$$T_t \triangleq \frac{P_t}{P_{ri}} = \frac{8\pi}{\lambda^2}\frac{P_t}{S}. \tag{2.16}$$

The transmission shielding effectiveness through apertures in a screen, is defined as the inverse,

[4]Please observe that the assumption of an idealised antenna ($q = \eta = D = 1, p = \frac{1}{2}$) was only necessary to get an unequivocal definition of the transmission transfer effectiveness. To perform an actual measurement it is only necessary to measure the power density of the incident field with any convenient antenna.

$$\Lambda_t \stackrel{\triangle}{=} \frac{1}{T_t} = \frac{P_{ri}}{P_t} = \frac{\lambda^2}{8\pi}\frac{S}{P_t}. \tag{2.17}$$

In accordance with (2.10) and (2.11), we also introduce the maximum transmission transfer effectiveness,

$$T_{t,max} = \frac{max_{\hat{\Omega},\hat{e}_i}\{P_t(\hat{\Omega},\hat{e}_i)\}}{P_{ri}} = \frac{8\pi}{\lambda^2}\frac{max_{\hat{\Omega},\hat{e}_i}\{P_t(\hat{\Omega},\hat{e}_i)\}}{S}, \tag{2.18}$$

the minimum transmission shielding effectiveness,

$$\Lambda_{t,min} \equiv \frac{1}{T_{t,max}} = \frac{P_{ri}}{max_{\hat{\Omega},\hat{e}_i}\{P_t(\hat{\Omega},\hat{e}_i)\}} = \frac{\lambda^2}{8\pi}\frac{S}{max_{\hat{\Omega},\hat{e}_i}\{P_t(\hat{\Omega},\hat{e}_i)\}}, \tag{2.19}$$

the average transmission transfer effectiveness,

$$< T_t >= \frac{< P_t(\hat{\Omega},\hat{e}_i) >_{\hat{\Omega},\hat{e}_i}}{P_{ri}} = \frac{8\pi}{\lambda^2}\frac{< P_t(\hat{\Omega},\hat{e}_i) >_{\hat{\Omega},\hat{e}_i}}{S}. \tag{2.20}$$

and the average transmission shielding effectiveness,

$$< \Lambda_t >= P_{ri} < \frac{1}{P_t(\hat{\Omega},\hat{e}_i)} >_{\hat{\Omega},\hat{e}_i} = \frac{\lambda^2}{8\pi} S < \frac{1}{P_t(\hat{\Omega},\hat{e}_i)} >_{\hat{\Omega},\hat{e}_i}. \tag{2.21}$$

It should be observed that generally,

$$< \Lambda_t > \neq \frac{1}{< T_t >}. \tag{2.22}$$

We will now stop the description of the transmission transfer/shielding effectiveness, and in the next section turn into an other description of transfer/shielding effectiveness.

2.4 Receiving Transfer/Shielding Effectiveness

In testing of real objects we are often not only interested in the penetration of electromagnetic power through apertures, but also of how much power is coupled to critical electronic components inside the object. A simple schematic picture can be found in Fig. 2.4. The Equipment Under Test (EUT) is irradiated with a plane electromagnetic wave of power density S, and somewhere in a critical component inside the EUT, the power P_r is received. The smaller the received power in the critical component is, the better the protection is. To get an as simple description as possible of this electromagnetic coupling to our component, we may look upon

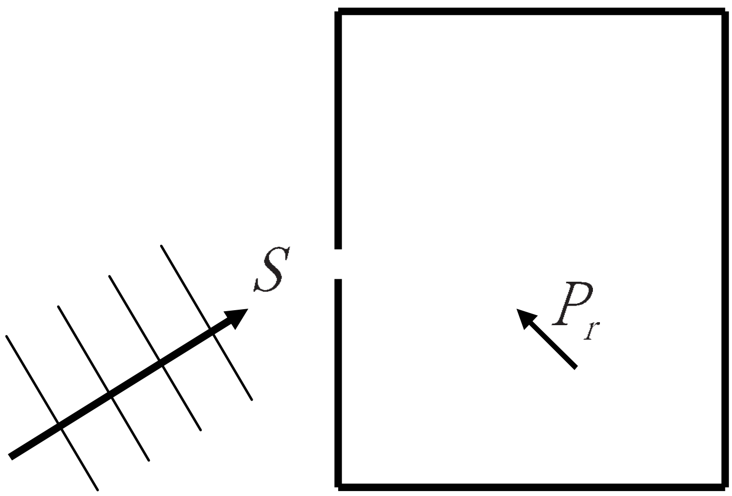

Figure 2.4: *Electromagnetic power penetrates through the screen and somewhere in a critical component inside the EUT, the power P_r is absorbed.*

the whole EUT (including the critical component) as being an antenna[5]. The EUT is of cause not an intentional and optimized antenna, rather the opposite, but it receives energy from the incident electromagnetic field and hence it is antenna. As a consequence thereof, the received power in the critical component can be described with (2.12).

By simply dividing the power received in the critical component as given by (2.12), by the power received by the idealised antenna described in (2.15), we propose to define the receiving transfer effectiveness as,

$$T_r \triangleq \frac{P_r}{P_{ri}} = 2q\eta pD, \tag{2.23}$$

and the receiving shielding effectiveness as,

$$\Lambda_r \triangleq \frac{1}{T_r} = \frac{P_{ri}}{P_r} = \frac{1}{2\eta pD}. \tag{2.24}$$

The directivity (D) of the EUT may in some directions be much larger than one, and consequently, the receiving shielding effectiveness may be smaller than one (or negative in a dB-scale). It is however nothing strange in that this definition for some irradiation directions and polarisations of the incident field may give a negative receiving shielding effectiveness. It only reflects that unluckily, for some irradiation directions, the directivity of the EUT is so high that we got gain instead of shielding of the incident electromagnetic field.

[5]Caution has to be taken here. Power will be absorbed in many different components of the EUT, and the whole EUT actually consists of many antennas. However, we do here solely pay attention to the power absorbed in the very most critical component, and for that power, the whole EUT together with the critical component act as one antenna.

In accordance with (2.18)-(2.21), we introduce the maximum receiving transfer effectiveness,

$$T_{r,max} = max_{\hat{\Omega},\hat{e}_i}\{2q\eta p(\hat{\Omega},\hat{e}_i)D(\hat{\Omega})\} = 2q\eta D_{max}, \tag{2.25}$$

the minimum receiving shielding effectiveness,

$$\Lambda_{r,min} \equiv \frac{1}{T_{r,max}} = \frac{1}{max_{\hat{\Omega},\hat{e}_i}\{2q\eta p(\hat{\Omega},\hat{e}_i)D(\hat{\Omega})\}} = \frac{1}{2q\eta D_{max}}, \tag{2.26}$$

the average receiving transfer effectiveness,

$$< T_r >=< 2q\eta p(\hat{\Omega},\hat{e}_i)D(\hat{\Omega}) >_{\hat{\Omega},\hat{e}_i} = q\eta, \tag{2.27}$$

and the average receiving shielding effectiveness,

$$< \Lambda_r >=< \frac{1}{2q\eta p(\hat{\Omega},\hat{e}_i)D(\hat{\Omega})} >_{\hat{\Omega},\hat{e}_i} = \frac{1}{2q\eta} < \frac{1}{p(\hat{\Omega},\hat{e}_i)} >_{\hat{\Omega},\hat{e}_i} < \frac{1}{D(\hat{\Omega})} >_{\hat{\Omega}} . \tag{2.28}$$

If it has not been obvious earlier, comparing (2.27) and (2.28), should make it obvious that the transfer effectiveness is a more convenient quantity than the shielding effectiveness. It is actually natural, because we are normally interested in what stress does the incident electromagnetic power cause onto our electronic equipment. The receiving transfer effectiveness is a measure of that. The receiving shielding effectiveness is a measure of what incident power caused a certain stress onto our electronic equipment.

Often there is demand for a one value description of a phenomenon. The real world is often more complex, and a more complex description than one value is necessary, but if someone stresses the need for one value describing the protection, we suggest the average transmission receiving effectiveness of (2.27).

2.5 Receiving cross section

Just as we defined the transmission cross section in section 2.2, we may also define the receiving cross section,

$$\sigma_r \triangleq \frac{P_r}{S} = \frac{\lambda^2}{8\pi}T_r, \tag{2.29}$$

where the last equality is found using (2.15) and (2.23). Obviously, the receiving cross section and the receiving transfer effectiveness are similar quantities. Which one to use is actually a very subtle question. Both the receiving transfer effectiveness and the receiving cross section describe how well we have managed to protect the critical electronic component from the incident electromagnetic field. The receiving transfer effectiveness gives a clear dimensionless value of the electromagnetic protection, but the receiving cross section tells us directly how much power will be absorbed in the critical component due to an incident electromagnetic plane wave.

The receiving cross section has, in difference to the receiving shielding effectiveness, the same nice properties as the receiving transfer effectiveness. In accordance to (2.25) and (2.27), the maximum receiving cross section is,

$$\sigma_{r,max} = \frac{P_r}{S} = \frac{\lambda^2}{4\pi} q\eta D_{max}, \tag{2.30}$$

and the average receiving cross section is,

$$< \sigma_r >= \frac{\lambda^2}{8\pi} q\eta. \tag{2.31}$$

Chapter 3

The Contributions to the Transfer Effectiveness

3.1 Coupling Measurements

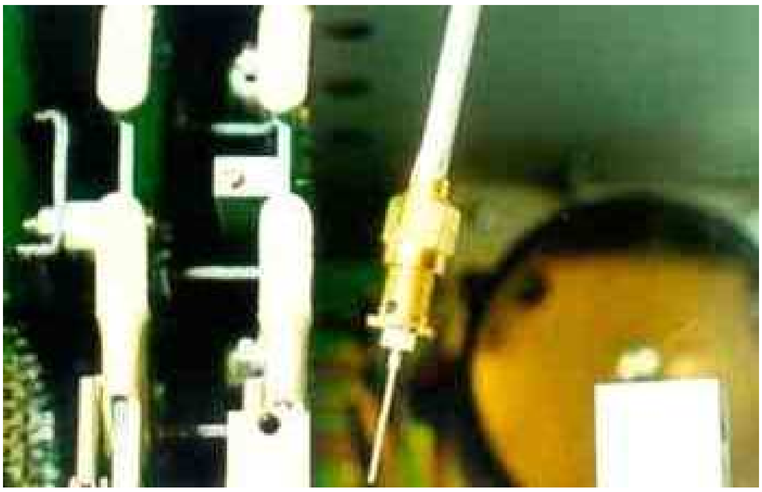

Figure 3.1: *A close-up of the measurement probe inside one of test objects.*

In a real Coupling Measurement (CM) on complex electronic equipment, it is hardly possible to know which is the most critical component, and hardly possible to measure the power absorbed in it. As a consequence thereof we us a different approach. We introduce a probe inside the Equipment Under Test (EUT), and measure the power received in that probe. The probe is representative for typical wires receiving electromagnetic power inside the electronics. The probe is also positioned

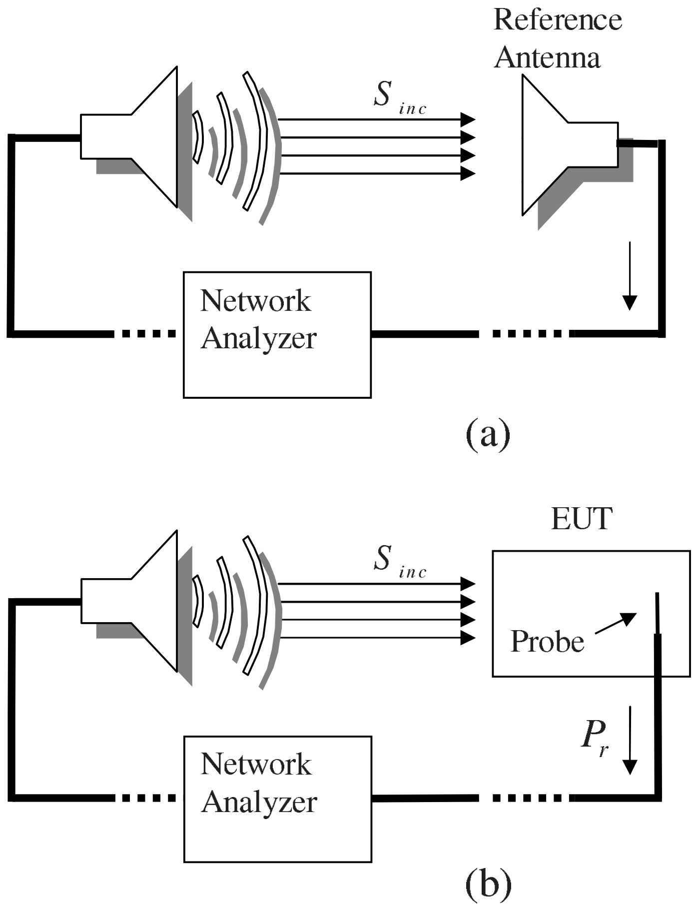

Figure 3.2: *Principal figures of the measurement set-ups. In Fig. a, the power received by the in section 2.3 proposed ideal antenna (P_{ri}) is measured with help of a reference antenna. In Fig. b, the power received in our measurement probe (P_r) is measured.*

at a representative place inside the EUT, see Fig. 3.1. Thereby we do not measure the exact power received in the very most critical component inside the EUT, but instead a representative power, which could have been the power received in the very most critical component. In doing these Coupling Measurements we actually perform a measure of the in (2.23) defined receiving transfer effectiveness,

$$T_r(\hat{\Omega}, \hat{e}_i, \nu) = 2q(\nu)\eta(\nu)p(\hat{\Omega}, \hat{e}_i, \nu)D(\hat{\Omega}, \nu). \tag{3.1}$$

In (3.1), we have included that the receiving transfer effectiveness does not only depend on the direction ($\hat{\Omega}$) from which the EUT is irradiated and the polarisation of the incident field ($\hat{e}_i$) but also on the frequency (ν) in use.

It is actually very possible that even if we receive a lower power in our probe than is received in the very most critical component, we will receive the higher power value in our pin probe for a slightly different irradiation direction, polarisation and/or frequency, and hence the result of our measurement of the receiving transfer effectiveness

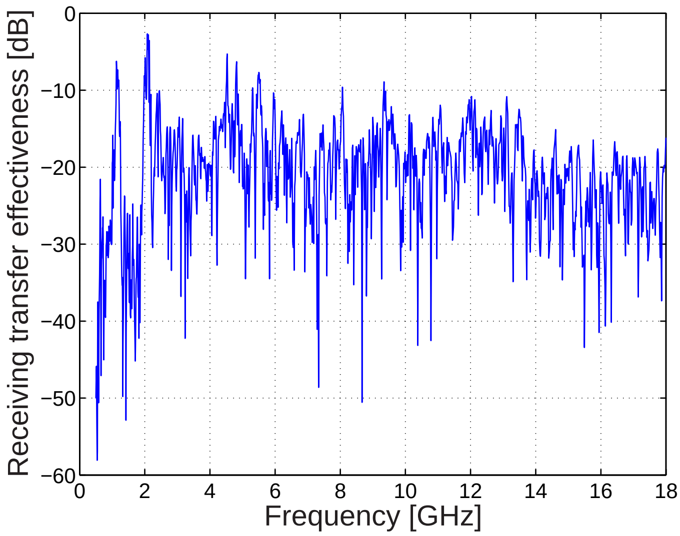

Figure 3.3: *The receiving transfer effectiveness as function of frequency for one irradiation direction for a typical test object.*

is representative for the real situation.

Fig. 3.2 shows in principal how a measurement of the receiving transfer effectiveness is performed. First, the power received by the in section 2.3 proposed ideal antenna (P_{ri}) is measured with help of a reference antenna. Secondly, the power received in our measurement probe is measured, and finally, in direct accordance with the definition in 2.23, the receiving transfer effectiveness is simply calculated as the quotient between the two power values. The description in Fig. 3.2 is however only measurement theory describing the principles, in practice the measurement procedure is slightly more complex, but this description does include all the here important aspects. The real measurement procedure is similar to the one described in [8]. The real measurement procedure does also describe why we use a Network Analyzer and not the more obvious choice of a power meter.

Fig. 3.3 and 3.4 show some typical measurement results of the receiving transfer effectiveness. In Fig. 3.3, the receiving transfer effectiveness is shown as function of frequency for one test object. In Fig. 3.4 the receiving transfer effectiveness is shown for the same test object as in Fig. 3.3, but here as function of irradiation direction within one plane for the specific frequency 12.0 GHz. In both Fig. 3.3 and 3.4 the EUT has been irradiated with the same linearly polarised field.

As can be seen in (3.1) there are four factors which contribute to the receiving transfer effectiveness. They do all four depend on the frequency in use, two depends on from which direction the EUT is irradiated but only one depends on the polarisation of the incident field. We will now take a closer look on these four factors.

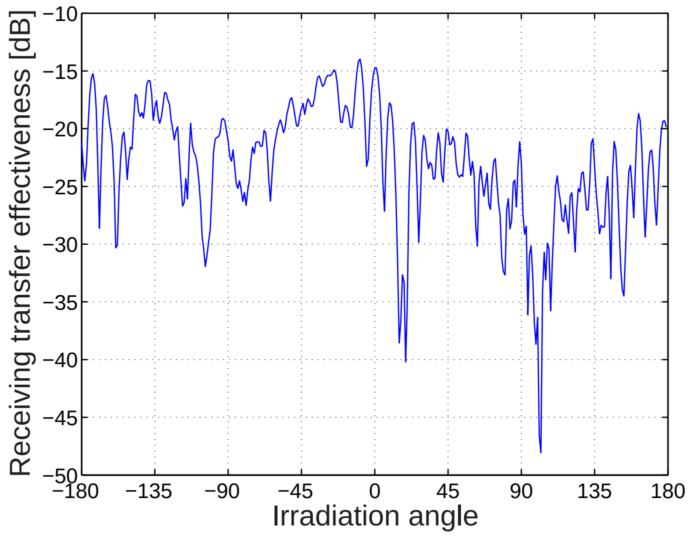

Figure 3.4: *The receiving transfer effectiveness for the same test object as in in Fig. 3.3, but here for the specific frequency 12.0 GHz and as function of the irradiation direction in one plane.*

3.2 Impedance mismatch factor

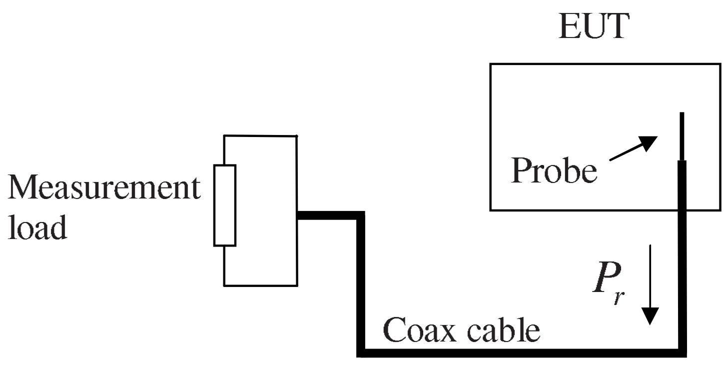

Figure 3.5: *The power received in our probe is measured in a load.*

As can be seen in Fig. 3.1 our measurement probe is connected to a coax cable. At the other end of the coax cable the power is received and measured in a load, see Fig. 3.5. The first factor in (3.1), the impedance mismatch factor, is the received power in our measurement load compared to the maximum possibly receivable power reached

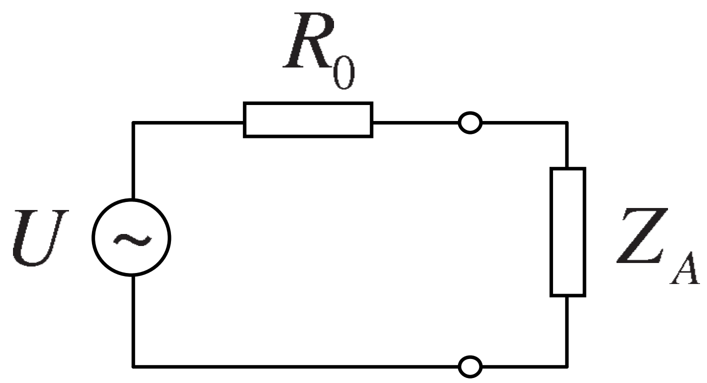

Figure 3.6: *A circuit diagram of the measurement of the impedance mismatch factor.*

by using an impedance matched load. Due to this impedance mismatch, power will be reflected and reradiated by our EUT. Apart from this reflected and reradiated power, the incident electromagnetic field on the EUT will also cause currents on the EUT, which will radiate power and which any choice of load to our probe cannot prevent. This so called structural scattering is not, and shall not be, included in (3.1). For a further description of this phenomenon, see e.g. [6, p. 93].

In our measurement system, the measurement load is the input impedance of our network analyser and it is impedance matched to the characteristic impedance of the coax cable. Both the characteristic impedance of the coax cable and the impedance of the load is resistive, $R_0 = 50\Omega$. A circuit diagram can be seen in Fig. 3.6, where Z_A is the impedance of our "antenna", i.e. our EUT including the measurement probe. We can easily measure the reflection coefficient seen from the network analyser,

$$\Gamma = \frac{U^-}{U^+} = \frac{Z_A - R_0}{Z_A + R_0}. \tag{3.2}$$

In (3.2) we have also included a theoretical expression for the reflection coefficient [9, p. 400]. The theoretical expression makes it clear that the absolute value of the reflection coefficient is identical independent if seen from the network analyser or the "antenna". Hence, the impedance mismatch factor can be calculated as,

$$q = 1 - |\Gamma|^2 = 1 - \left|\frac{R_0 - Z_A}{R_0 + Z_A}\right|^2. \tag{3.3}$$

Fig. 3.7 shows one example, for a typical test object, of how the impedance mismatch factor varies with the frequency. As discussed already in section 2.1, the impedance mismatch factor of the pin probe does not only vary with the frequency but also with the orientation of and the position of the pin probe inside the test object. That can also be seen in Fig. 3.7, where the result of two different positions and orientations of the pin probe is shown.

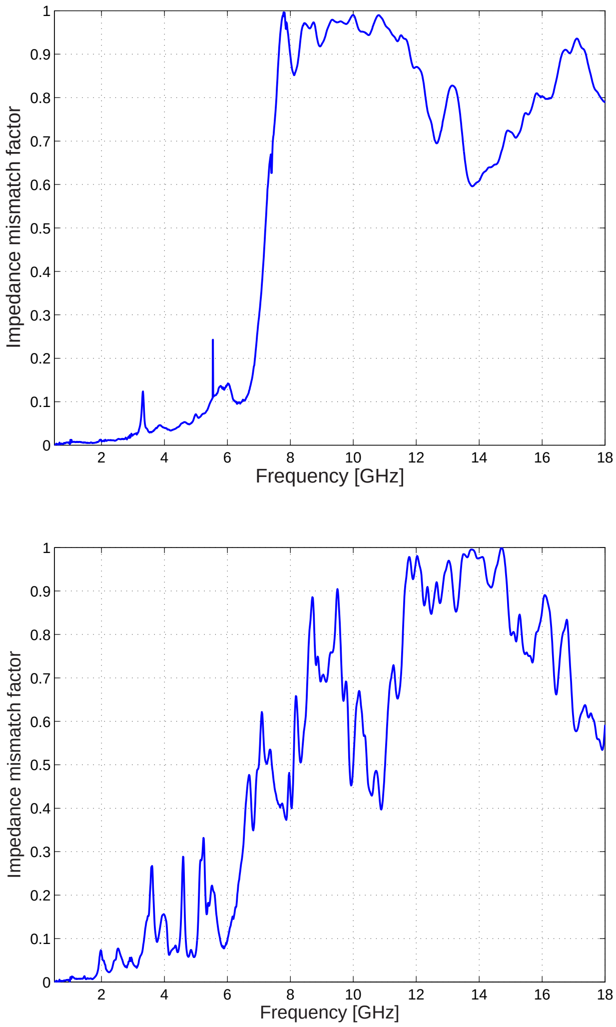

Figure 3.7: *The impedance mismatch factor for two identical measurement probes but at two different positions and orientations in the same test object.*

The impedance mismatch factor is an important part of the electromagnetic protection built into the EUT, but by combing the two graphs in Fig. 3.7, it is easily concluded that there is a large risk that the very most critical component is situated in such a way that the impedance mismatch factor is close to one. The, by us chosen position and orientation of our pin probe does however often not for the whole frequency interval give a value of the impedance mismatch factor which is close to one. To compensate for that we thereby may underestimate the receiving transfer effectiveness, we often calculate the impedance matched receiving transfer effectiveness,

$$T_{rq}(\hat{\Omega}, \hat{e}_i, \nu) \triangleq \frac{T_r(\hat{\Omega}, \hat{e}_i, \nu)}{q(\nu)} = 2\eta(\nu)p(\hat{\Omega}, \hat{e}_i, \nu)D(\hat{\Omega}, \nu). \tag{3.4}$$

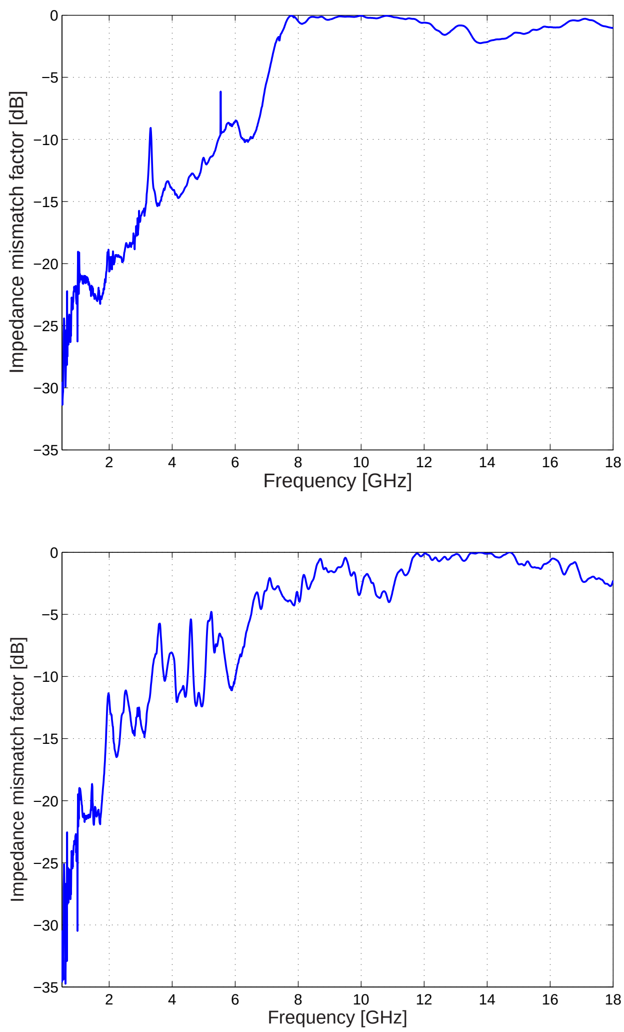

Figure 3.8: *The same graphs as in Fig. 3.7, but here in dB-scale.*

The impedance matched receiving transfer effectiveness is often a more relevant quantity than the (non impedance matched) receiving transfer effectiveness. However, it is overpessimistic for the lower frequencies, where the impedance mismatch for typical electronic objects always will be an important part of the protection of the electronic components.

3.3 Polarisation efficiency

Now we will look upon the third term in (3.1), the polarisation efficiency, but we will not omit the second term, we will come back to it later in this chapter. The polarisation efficiency is defined [10, p. 22] as the power received by our measurement probe in the EUT from a given plane wave with arbitrary polarisation to the power

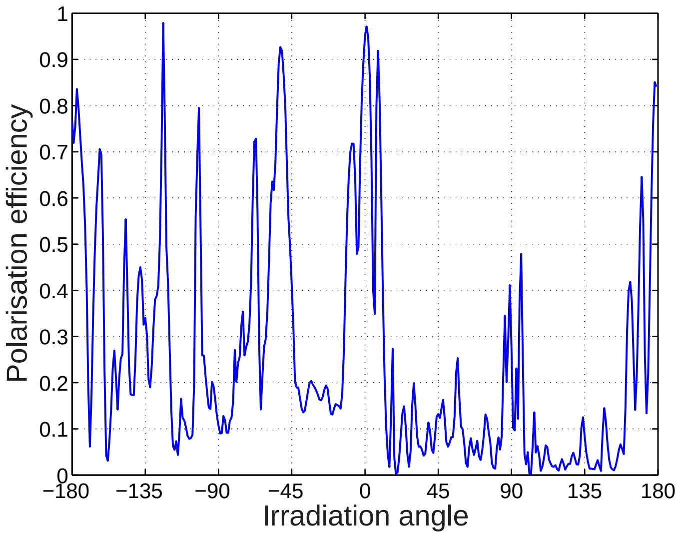

Figure 3.9: *A typical example of how the polarisation efficiency varies with the irradiation direction within one plane of the EUT. Precisely this graph shows the result at 12.0 GHz for the same test object as in Fig. 3.10.*

that would be received by the same probe from a plane wave of the same power flux density and direction of propagation, whose state of polarisation has been adjusted for a maximum received power. As a direct consequence of the definition, the polarisation efficiency varies between,

$$0 \leq p(\hat{\Omega}, \hat{e}_i, \nu) \leq 1. \tag{3.5}$$

The polarisation efficiency is also called the polarisation mismatch factor, but that is actually a misleading name, because the factor is a measure of the polarisation match and not a measure of the polarisation mismatch.[1]

By use of standard antenna theory [11, p. 106] it can be shown that the polarisation efficiency can be calculated outgoing from measurements of the receiving transfer effectiveness, and in performing this measurements it is only necessary to irradiate the EUT two times[2]. The two measurements of the receiving transfer effectiveness are performed identically, but with the exception that the polarisation of the incident field differs between the two measurements. It is most convenient to let the two polarisations be orthogonal and we will assume so here, because it simplifies the theoretical description, increases the accuracy in the final result and does almost always

[1] Actually the same thing is true for the impedance mismatch factor, it is a measure of the impedance match, not a measure of the impedance mismatch. However, no other commonly accepted term than impedance mismatch factor is known to us, and hence we decided to use the term impedance mismatch factor.

[2] A bit of caution here; Two measurements are sufficient to take the influence of the polarisation of the incident field into account. As pointed out in e.g. 3.1 the polarisation efficiency does also depend on from which direction the EUT is irradiated as well as the frequency in use.

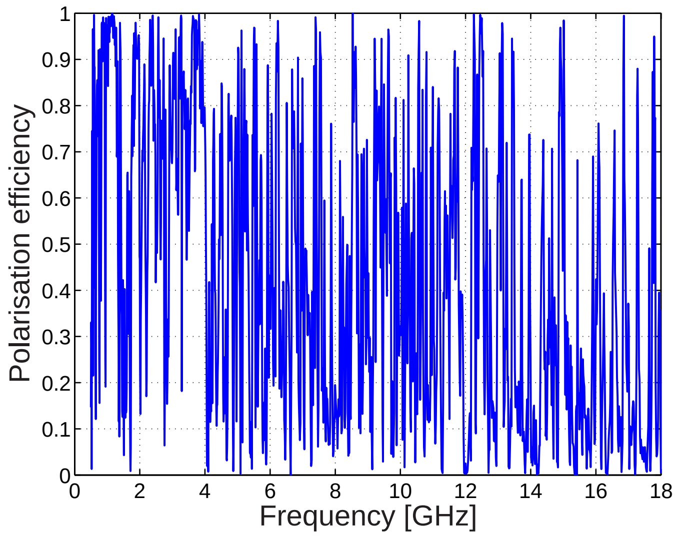

Figure 3.10: *As function of frequency, the polarisation efficiency varies rapidly between zero and one.*

in practice not imply any restriction, but formally any two non-identical polarisations would do.

We denote the two orthogonal polarisations $\hat{e}_{iH}$ and $\hat{e}_{iV}$. One might think of the H- and V-polarisations as being horizontal and vertical polarisations, respectively, but the statements below hold for any two orthogonal polarisations. To the two polarisations correspond two polarisation efficiencies,

$$\begin{array}{c} p_H(\hat{\Omega},\nu) \stackrel{\triangle}{=} p(\hat{\Omega},\hat{e}_i=\hat{e}_{iH},\nu) \\ p_V(\hat{\Omega},\nu) \stackrel{\triangle}{=} p(\hat{\Omega},\hat{e}_i=\hat{e}_{iV},\nu) \end{array} \quad , \tag{3.6}$$

and two receiving transfer effectiveness,

$$\begin{array}{c} T_{rH}(\hat{\Omega},\nu) \stackrel{\triangle}{=} T_r(\hat{\Omega},\hat{e}_i=\hat{e}_{iH},\nu) = 2q(\nu)\eta(\nu)p_H(\hat{\Omega},\nu)D(\hat{\Omega},\nu) \\ T_{rV}(\hat{\Omega},\nu) \stackrel{\triangle}{=} T_r(\hat{\Omega},\hat{e}_i=\hat{e}_V,\nu) = 2q(\nu)\eta(\nu)p_V(\hat{\Omega},\nu)D(\hat{\Omega},\nu) \end{array} \quad . \tag{3.7}$$

Any polarisation can be described as a superposition of the two orthogonal polarisation modes introduced above. Hence the two polarisation modes are a complete set, orthogonal and actually, as a consequence of the exact definition of the polarisation efficiency, also orthonormal. That implies that the maximum possible electromagnetic energy transport to the EUT is equal to the sum of the electromagnetic energy transport in the two orthonormal modes, and consequently, the sum of the two modes polarisation efficiencies is,

$$p_H(\hat{\Omega},\nu) + p_V(\hat{\Omega},\nu) = 1. \tag{3.8}$$

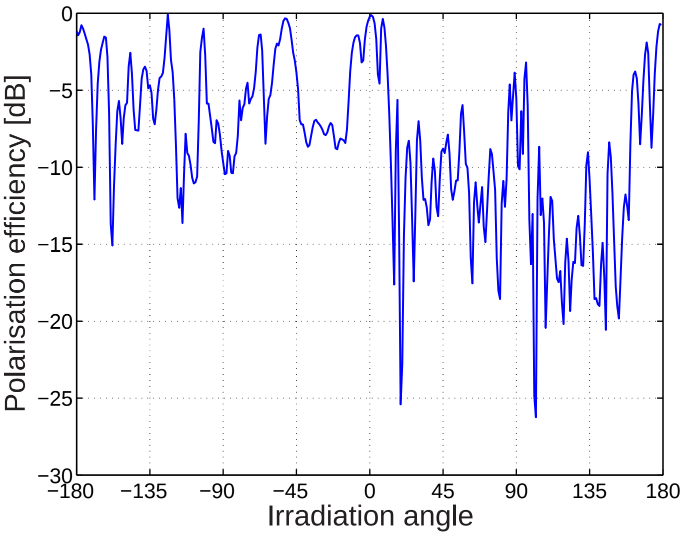

Figure 3.11: *The same graph as as in Fig. 3.9, but here in dB-scale.*

By simply combining 3.7 and 3.8 we finally get the following expressions for the polarisation efficiencies,

$$\begin{aligned} p_H(\hat{\Omega},\nu) &= \frac{1}{1+\frac{T_{rV}(\hat{\Omega},\nu)}{T_{rH}(\hat{\Omega},\nu)}} \\ p_V(\hat{\Omega},\nu) &= \frac{1}{1+\frac{T_{rH}(\hat{\Omega},\nu)}{T_{rV}(\hat{\Omega},\nu)}} \end{aligned} . \tag{3.9}$$

Fig. 3.9 shows for one of our test objects how the polarisation efficiency varies with irradiation direction within one plane and for one fixed linear polarisation. The polarisation efficiency varies rather systematic, but hardly predictable in advance. The one not convinced of the unpredictability of the polarisation efficiency, may look upon Fig. 3.10, where we have fixed the irradiation direction but varied the frequency.

The polarisation of the incident field can often easily be changed so that the polarisation efficiency is close to one. Hence it is relevant to in accordance with (3.4) define the polarisation matched receiving transfer effectiveness,

$$T_{rp}(\hat{\Omega},\nu) \triangleq \frac{T_r(\hat{\Omega},\hat{e}_i,\nu)}{p(\hat{\Omega},\hat{e}_i,\nu)} = 2q(\nu)\eta(\nu)D(\hat{\Omega},\nu), \tag{3.10}$$

and, of course, also the impedance and polarisation matched receiving transfer effectiveness,

$$T_{rqp}(\hat{\Omega},\nu) \triangleq \frac{T_r(\hat{\Omega},\hat{e}_i,\nu)}{q(\nu)p(\hat{\Omega},\hat{e}_i,\nu)} = 2\eta(\nu)D(\hat{\Omega},\nu). \tag{3.11}$$

However, the quantities in 3.10 and 3.11 are in practice preferably calculated as,

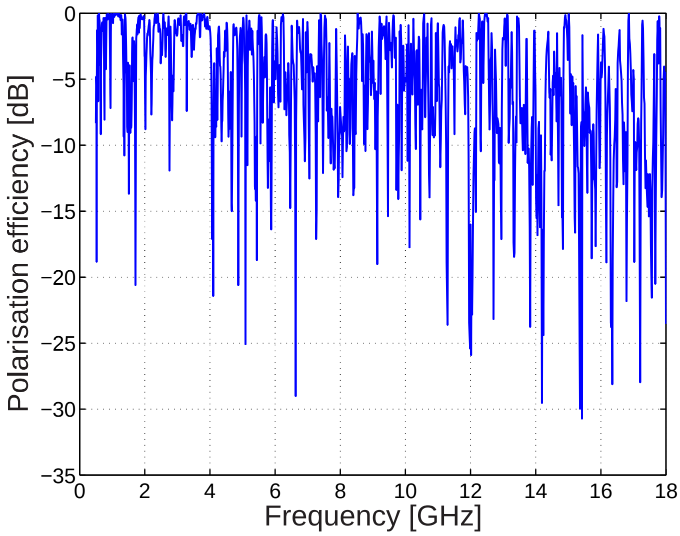

Figure 3.12: *The same graph as as in Fig. 3.10, but here in dB-scale.*

$$T_{rp}(\hat{\Omega},\nu) = T_{rH}(\hat{\Omega},\nu) + T_{rV}(\hat{\Omega},\nu), \tag{3.12}$$

and

$$T_{rqp}(\hat{\Omega},\nu) = \frac{1}{q}[T_{rH}(\hat{\Omega},\nu) + T_{rV}(\hat{\Omega},\nu)]. \tag{3.13}$$

The equations (3.12) and (3.13) are easily shown by by plugging (3.7) and (3.8) into (3.10) and (3.11), respectively. Some thinking does also make them obvious.

3.4 Directivity

The forth term in (3.1) is the directivity. The directivity is the ratio of the power received in our measurement probe when the probe is irradiated from a specific direction ($\hat{\Omega}$) to the received power averaged over all irradiation directions. For all irradiation directions the polarisation efficiency is assumed to be one, or at least identical for all irradiation directions. The directivity can consequently be calculated as,

$$D(\hat{\Omega},\nu) = \frac{T_{rqp}(\hat{\Omega},\nu)}{< T_{rqp}(\hat{\Omega},\nu) >_{\hat{\Omega}}}. \tag{3.14}$$

It is formally easy to calculate the directivity in accordance with (3.14), but to be able to calculate a good value for the average impedance and polarisation matched receiving transfer effectiveness, we have to irradiate our EUT from many different

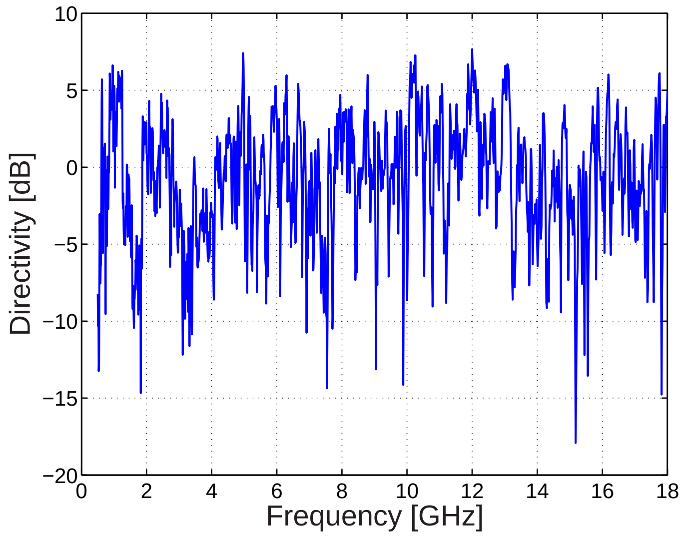

Figure 3.13: *The directivity of a test object as function of frequency.*

directions. We have in our experiments made the averaging over 1074 different irradiation directions. In Fig. 3.13 we show an example of the directivity as function of frequency for one test object, and in Fig. 3.14 we show the directivity as function of the irradiation angle in one plane at 12.0 GHz.

The directivity has one property which make it different to all the other quantities in 3.1, it has in principal no upper limit for its value; all the other quantities in 3.1 are upwards limited to the value 1. However our knowledge from testing of many objects tells us that for normal test objects, the maximum directivity is very seldom larger than $15dB$.

3.5 Partial Directivity

The fact that the power received, varies strongly with from which direction the EUT is irradiated has reached more and more attention in reascent years. Often the expression "directivity-problem" and similar expressions are used. However, what people often do is that they rotate the EUT in one plane and irradiate the EUT from different directions. It is certainly true that the directivity of the EUT varies between the different irradiation directions but also the polarisation efficiency will change between the different irradiation direction. Please observe that this is true even if the polarisation of the incident field on the EUT is not changed, see Fig. 3.9. Hence, the term "directivity-problem" is slightly misleading, because it is not only a directivity issue but also an issue of polarisation match between the incident field and the EUT. It is actually the product of the directivity and the polarisation efficiency which is the interesting quantity, and that product has actually been given its own name in the IEEE-standard [10, p. 20]: partial directivity,

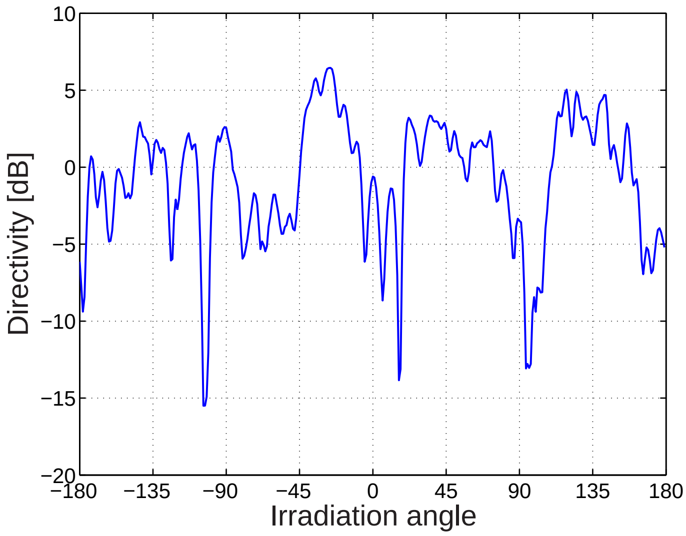

Figure 3.14: *The directivity of the same test object as in Fig. 3.13, but here as function of irradiation direction within one plane of the test object at the frequency 12.0 GHz.*

$$D_p(\hat{\Omega}, \hat{e}_i, \nu) \triangleq D(\hat{\Omega}, \nu)p(\hat{\Omega}, \hat{e}_i, \nu). \tag{3.15}$$

We urge on the community to use the expression partial directivity to recognize that in many cases there is not only a directivity issue but also a polarisation efficiency issue.

3.6 Radiation efficiency

The second term in (3.1) is by the antenna community called the radiation efficiency. The name is perhaps not so descriptive in our case, but we will keep it. The antenna terms which we have introduced are, with the exception of the polarisation efficiency, not defined in the receiving mode of the antenna but in the transmitting mode of the antenna [10]. However, as the description of the terms above shows it is possible to define the impedance mismatch factor and the directivity also in the receiving mode of the antenna, but when it comes to the radiation efficiency the situation is different. We have not managed to find a reasonable definition of the radiation efficiency in the receiving mode, and we therefore define it in the transmitting mode[3].

[3]One could assume that it should be possible to define the radiation efficiency in the receiving mode as something like the fraction of the total power absorbed in the EUT that is received by our measurement probe. That definition is simple but not appropriate, the reason being the in section 3.2 briefly described structural component. Part of the absorption is, in the general case, in the structural part, and that part of the absorption is included in the definition just proposed in this footnote, but it should not be in an appropriate definition. It is e.g. possible to through

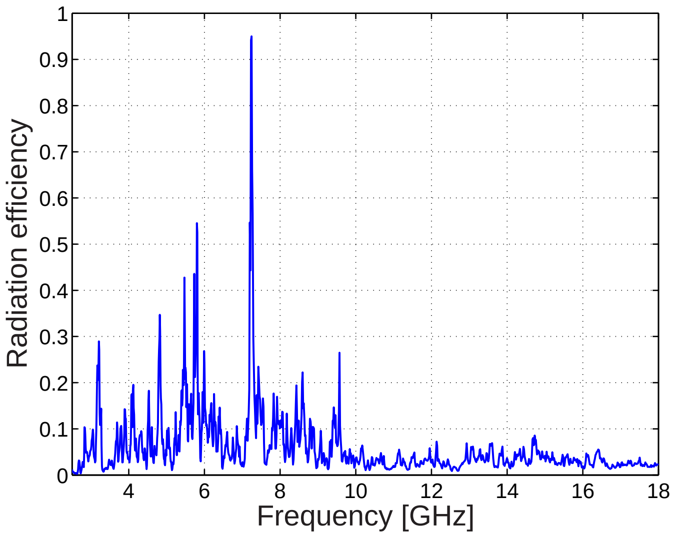

Figure 3.15: *The radiation efficiency as function of frequency. Generally the value of the radiation efficiency is small, being equivalent to that the EUT has a good protection performance, but for a few discrete frequencies the radiation efficiency is close to one.*

Suppose that we feed the probe in Fig. 3.1 with a current, the radiation efficiency is then the ratio of the total power radiated by our EUT (including the probe) to the net power accepted by the EUT (including the probe) from the feeding current [10].

The reason why we saved the radiation efficiency to the last, is that it is very hard to measure. However, we have above managed to directly measure, or outgoing from measurement data, calculate all the other quantities in (3.1), and hence we can in principle simply solve (3.1) for the radiation efficiency. To increase the accuracy of the result it is however beneficial to use average values, and we get from (2.27),

$$\eta(\nu) = \frac{< T_r(\hat{\Omega}, \hat{e}_i, \nu) >_{\hat{\Omega}, \hat{e}_i}}{q(\nu)}. \tag{3.16}$$

When we perform the averaging in (3.16), we take as many irradiation directions ($\hat{\Omega}$) as possible into account, to get an as good accuracy as possible. In performing the averaging over polarisations ($\hat{e}_i$) it is only necessary to use two polarisations. That is easily shown. By help of (2.14) and (3.1) it follows that,

$$< T_r(\hat{\Omega}, \hat{e}_i, \nu) >_{\hat{e}_i} = q(\nu)\eta(\nu)D(\hat{\Omega}, \nu), \tag{3.17}$$

but at the same time (3.7) and (3.8) show that,

$$\frac{T_{rH}(\hat{\Omega}, \nu) + T_{rV}(\hat{\Omega}, \nu)}{2} = q(\nu)\eta(\nu)D(\hat{\Omega}, \nu), \tag{3.18}$$

the structural component have a substantial absorption in the EUT, but at the same time have a radiation efficiency close to 1.

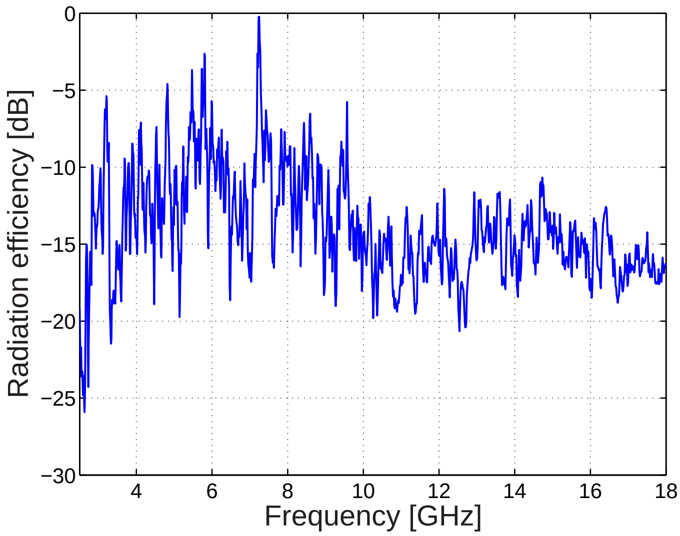

Figure 3.16: *The same graph as in Fig. 3.15, but here in dB-scale.*

and it follows that the average taken over two orthogonal polarisations is sufficient,

$$< T_r(\hat{\Omega}, \hat{e}_i, \nu) >_{\hat{e}_i} = \frac{T_{rH}(\hat{\Omega}, \nu) + T_{rV}(\hat{\Omega}, \nu)}{2}. \tag{3.19}$$

Fig. 3.15 shows the radiation efficiency as function of frequency for a typical test object. Generally the value of the radiation efficiency is small. That is not surprising, our Equipment Under Test is not constructed to be an intentional and optimized antenna as seen from our measurement probe, rather the opposite. We may actually hope that the EUT is constructed to be an as bad antenna as possible. A small value of the radiation efficiency is actually a sign of that the electronics inside the EUT are well protected. It should therefore be noticed that for a few discrete frequencies, the radiation efficiency is close to one, corresponding to a bad protection of the electronics inside the EUT. Fig. 3.16 show the same graph as in Fig. 3.15 but in dB-scale.

3.7 Inherent and semi-inherent properties of the Equipment Under Test

As stated in section 3.4, the directivity has a property making it different to all the other quantities in (3.1), but the polarisation efficiency has a property making it even more different to all the other quantities in (3.1), including the directivity. All the other properties are inherent[4] properties of the EUT only, but the polarisation efficiency is not. It is obvious that the impedance mismatch factor and the radiation

[4]By inherent property of the EUT, we mean a property that we can define solely outgoing from knowledge of the EUT.

efficiency are inherent properties of the EUT and not properties of the irradiated field on to the EUT. The directivity differ with from which direction we irradiate our EUT, but that is equivalent to not moving the radiating source but only rotating the EUT, see Fig. 3.17. Hence, the directivity is also an inherent property of the EUT.

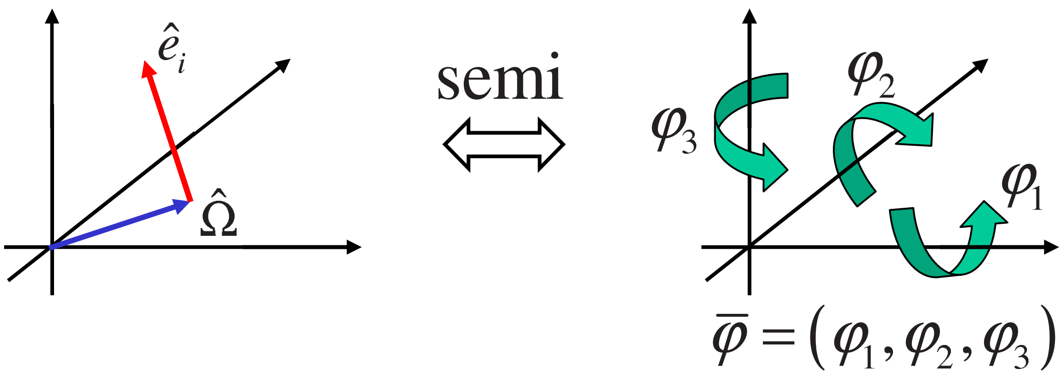

Figure 3.17: *Changing the irradiation direction ($(\hat{\Omega})$ of the EUT, is equivalent to rotating the EUT in a specific way. Chancing the orientation of the polarisation ($\hat{e}_i$) of the plane wave incident on the EUT is equivalent to rotating the EUT around the irradiation direction ($\hat{\Omega}$). However, it is also possible to change the type of polarisation, e.g. the extreme case of changing linear polarisation to circular polarisation. Such a change in polarisation has no equivalence in rotating the EUT. Hence changing both the orientation and the type of the polarisation of the incident plane wave is semi-equivalent to rotating the EUT.*

In this report we have assumed that the irradiated field is a plane wave, but we do not a priori assume anything about the polarisation of the field. In most cases the field is linearly polarised. For a linearly polarised field we can change the orientation of the polarised field, but that is equivalent to rotate the EUT around the irradiation direction ($\hat{\Omega}$). So if we assume a linearly polarised field[5], the polarisation efficiency is an inherent property of the EUT.

However, we may actually also change the type of polarisation. Fig. 3.18 shows the general case of elliptic polarisation. The xy-plane is here chosen to be perpendicular to the direction of propagation of the irradiated field. The general (complex) elliptic polarisation vector can be written as,

$$\hat{e}_i = \sqrt{1-a^2}(\cos\alpha\ \hat{e}_x + \sin\alpha\ \hat{e}_y) \pm \jmath a(-\sin\alpha\ \hat{e}_x + \cos\alpha\ \hat{e}_y), \tag{3.20}$$

where a is a real constant,

$$0 \le a \le \frac{1}{\sqrt{2}}, \tag{3.21}$$

α is a real constant,

[5]The statement actually holds for any specific type of polarisation.

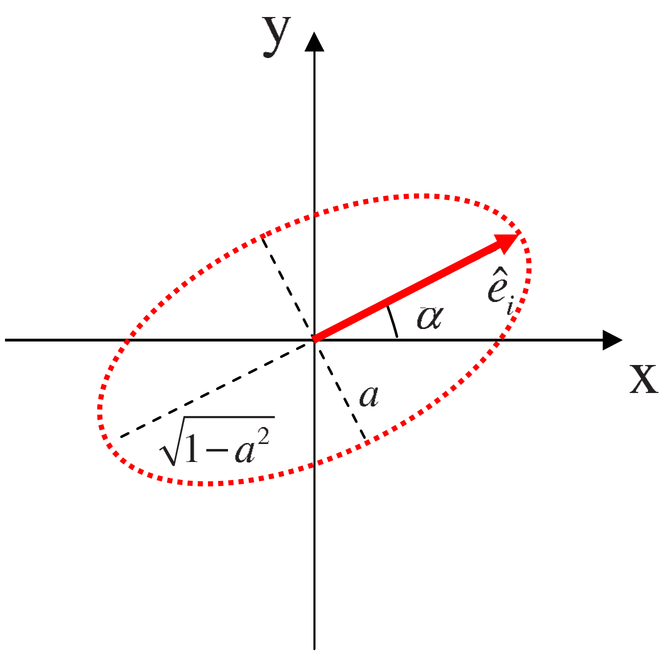

Figure 3.18: *The general elliptic polarisation. The field vector rotates around the dashed ellipse.*

$$0 \leq \alpha < \pi, \tag{3.22}$$

$\hat{e}_x$ and $\hat{e}_y$ are two unit vectors in the x- and y-directions, respectively, and $\jmath$ is the imaginary unit. The choice of plus or minus-sign depend on if the field is right or left polarised[6]. By changing the parameter α we rotate the polarisation ellipse in the xy-plane, and thereby we also affect the polarisation efficiency. We will however reach exactly the same affect by simply rotating our EUT in the reverse direction around the irradiation direction ($\hat{\Omega}$). By changing the parameter a we change the ellipticity of the polarisation ellipse, or differently stated, we change the type of polarisation. In the extreme cases of, $a = 0$ and $a = 1/\sqrt{2}$, the field is linearly and circularly polarised, respectively. The choice of polarisation will affect the coupling between the irradiated field and the EUT, and hence also the polarisation efficiency. There is no way to get the same effect by rotating the EUT. Consequently, the polarisation efficiency is not generally a property of only the EUT, but also affected by the type of polarisation of the irradiated field[7]. We say that the polarisation efficiency is a

[6]Which is which of right and left polarised field there are many opinions about, see e.g. [12, p. 300], despite there actually should be place for only two different points of view. We here withdraw from defining which is which of left and right polarised field.

[7]Actually, if we look upon Fig. 3.17, we can see in the left figure that the irradiation direction ($\hat{\Omega}$) plus the polarisation of the incident field ($\hat{e}_i$) gives us in total four degrees of freedom, but the rotation in the left figure gives us only three degrees of freedom, and hence rotating the EUT cannot be sufficient to include all coupling cases between the incident field and the EUT.

semi-inherent property of the Equipment Under Test.

From the above discussion and (3.1) it follows that the receiving transfer effectiveness also is a semi-inherent property of the EUT, but the in (3.10) defined polarisation matched receiving transfer effectiveness is a truly inherent property of the EUT. It is therefore often beneficial if the polarisation efficiency can be treated separately. In [13] a statistical description of the polarisation efficiency can be found.

Chapter 4

An application: Interchanging directional and frequency dependencies

4.1 Introduction

So far our presentation has been rather theoretical in chapter 2 and descriptive in 3, but we will know turn to an application of the model proposed in chapter 2 and 3. This is done in a rather simple way, and despite that the full potential of the model is not used, this example still shows an interesting application. We start by describing a problem with the radiated susceptibility testing of today.

4.2 A shortcoming in radiated susceptibility testing

As can be seen in Fig. 3.4, the receiving transfer effectiveness varies substantially with from which direction the Equipment Under Test (EUT) is irradiated. The case shown in Fig. 3.4 is not extreme, our measurements performed on real electronic equipment have shown differences as large as $40-50dB$ [14]. True high level Radiated Susceptibility testing performed later [1, 15] showed smaller differences for high level Radiated Susceptibility Testing than for the low level Coupling Measurements, but a substantial difference is still left, and applying the results of [1, 15] on [14] could leave a difference of the order of $20 - 30dB$.

In general it is not possible to guess in advance the angle of incidence corresponding to the largest susceptibility of electromagnetic irradiation. In [16] it is convincingly shown that even an experienced EMC-engineer cannot in advance point out the most susceptible orientation of the EUT. It has been shown, theoretically [17, 18] as well as experimentally [17, 18, 19], that thousands of different angles of incidence may be needed in Radiated Susceptibility testing to, with a reasonable uncertainty, find the most susceptible orientation of the EUT. Such an extensive susceptibility testing is in almost all cases treated as far too expensive to perform. In practical commercial testing only a few, or even only one, irradiation direction(s) are used. Hence, the risk for a substantial undertesting is not only huge, but almost "guaranteed".

4.3 A proposal of an alternative test method

As can be seen in Fig. 3.3 and 3.4 the receiving transfer effectiveness varies not only with from which direction the EUT is irradiated, but also with the frequency in use. We therefore simply simply propose to interchange the very most proper test, using thousands of different irradiation directions, with a test using only a few irradiation directions but also including many frequencies in a frequency interval around the frequency of interest. A criterion for how well the proposed method works is to what extent it reduces the risk of undertesting, but it should also not substantially increase the risk for overtesting. Overtesting gives us the impression that the EUT sustains less than it actually does. It is, of course, not as critical as undertesting, but may lead to redesign or unnecessary restrictions. Overtesting may also cause the testing procedure to be more extensive and expensive than what is necessary.

4.4 Evaluation of the alternative test method

To be able to evaluate the proposed method we have tested it on different test objects using the low level coupling measurements described in chapter 3. We decided to evaluate the proposed method for the in our measurement probe received power (P_r), and not for the receiving transfer effectiveness. That because we think that the received power is the interesting quantity which causes disturbances in and/or destructions of electronic equipment. It is however also interesting to test the proposed method for the receiving transfer effectiveness (T_r), and we will do so in the future. We should also not forget that, as (2.15) and (2.23) show, the two quantities are close connected,

$$P_r(\hat{\Omega}, \hat{e}_i, \nu) = T_r(\hat{\Omega}, \hat{e}_i, \nu) P_{ri} = T_r(\hat{\Omega}, \hat{e}_i, \nu) \frac{\lambda^2}{8\pi} S = \frac{c^2}{8\pi\nu^2} T_r(\hat{\Omega}, \hat{e}_i, \nu) S, \tag{4.1}$$

where c is the speed of light. In similarity to the treatment in section 3.2, it can be shown that the impedance matched received power,

$$P_{rq}(\hat{\Omega}, \hat{e}_i, \nu) = \frac{c^2}{8\pi\nu^2} T_{rq}(\hat{\Omega}, \hat{e}_i, \nu) S, \tag{4.2}$$

is often a more relevant quantity, and we will therefore use it in this chapter.

To be able to test our method we want to now the true maximum value of the impedance matched received power,

$$P_{rqmax}(\nu) \stackrel{\triangle}{=} max_{\hat{\Omega}, \hat{e}_i} P_{rq}(\hat{\Omega}, \hat{e}_i, \nu), \tag{4.3}$$

which we approximate with the maximum value taken over our 1074 different irradiation directions, and for every irradiation direction two orthogonal polarisations. This value we compare with the maximum value taken over a frequency interval ($\Delta\nu$) around the frequency of interest (ν), but with only a few irradiation directions ($\hat{\Omega}'$),

$$P_{rq\nu}(\nu, \Delta\nu) \triangleq max_{\hat{\Omega}\in\hat{\Omega}', \hat{e}_i, \nu\in\Delta\nu} P_{rq}(\hat{\Omega}, \hat{e}_i, \nu), \tag{4.4}$$

which we call the frequency maximum impedance matched received power. We have performed the comparison in the frequency interval $0.5 - 18\ GHz$.

As a measure of the error we introduce by using the frequency maximum impedance matched received power ($P_{rq\nu}$) instead of the true maximum impedance matched received power (P_{rqmax}), we define the error bias as[1],

$$\mathcal{E}(\nu, \Delta\nu) \triangleq \frac{P_{rq\nu}(\nu, \Delta\nu)}{P_{rqmax}(\nu)}, \tag{4.5}$$

and the logarithmic error bias as,

$$\mathcal{E}_{dB}(\nu, \Delta\nu) = 10 \log_{10}[\mathcal{E}(\nu, \Delta\nu)]. \tag{4.6}$$

To be able to get a correct comparison between ($P_{rq\nu}$) and (P_{rqmax}) we keep the incident power density constant in all measurements[2]. As a consequence thereof, (4.2) tells us that if we use a small a frequency interval ($\Delta\nu$) around the center frequency (ν), an error bias based upon the receiving transfer effectiveness (T_r) would not differ much to the in (4.5) defined error bias which is based upon the received power (P_r).

It is to be noticed that the value of frequency maximum impedance matched received power ($P_{rq\nu}$), and hence also the error bias, depends on the size of the frequency interval in use, as well as the explicit irradiation directions ($\hat{\Omega}'$) in use. A priori the logarithmic error bias can be both smaller and larger than zero, because the frequency maximum impedance matched received power can be both larger and smaller than the true maximum impedance matched received power, but the logarithmic error bias will increase (or at least not decrease) with the size of the frequency interval in use. To test the influence of the size of the frequency interval, we have tested ten different sizes of frequency intervals, but to increase the readability, we here limit the presentation to five sizes of frequency intervals. For a more complete description, see [20]. The actual sizes of the frequency intervals are chosen in a somewhat complicated fashion and vary with the frequency, see [20], but interval 2 (3, 4 and 5) is always two (three, four, five) times as large as interval 1. One example of the sizes of the frequency intervals can be seen in Table 4.1.

We are not interested to investigate how the error bias depends on the explicit choice of irradiation direction, because that would only implicitly bring us back to

[1]The error bias is often denoted EB, but a one letter notation is preferable in mathematical formulas, so we introduce the calligraphic letter $\mathcal{E}$ to denote the error bias.

[2]In those cases it is not kept constant, we compensate for the discrepancy.

Interval number	Frequency Interval [GHz]	
	min	*max*
1	2.9	3.1
2	2.8	3.2
3	2.7	3.3
4	2.6	3.4
5	2.5	3.5

TABLE 4.1: *Frequency intervals at* 3 *GHz*

the original question of directional and polarisation dependence. Instead we do a statistical investigation of the error bias. That is done outgoing from a set of 100 randomly chosen subsets of irradiation directions ($\hat{\Omega}'$). The number of irradiation directions within every subset ($\hat{\Omega}'$) is somewhat arbitrarily chosen to be three, and for every irradiation direction we have chosen two orthogonal (linear) polarisations. In order to get a random model, the method of selecting 100 samples, containing 3 angles of incidence each, must satisfy the rules of random selection [21]. We use the so-called urn model [21], and thereby three random directions are generated 100 times.

4.5 Results

In Fig. 4.1 the distribution of the logarithmic error bias is plotted in form of a histogram over all 100 samples of the error bias[3]. It is known to the EMC-community that logarithmic values tend to be normal (=gauss) distributed. That can also be explained by the Central Limit Theorem [22], and that logarithmic data are additive. Hence it is reasonable to assume that also the logarithmic error bias should tend to be normal distributed. In Fig. 4.1 we have superimposed the normal distribution, where the sample mean value,

$$\mu = \sum_{k=1}^{N} \frac{\mathcal{E}_{dBk}}{N}, \tag{4.7}$$

and the sample standard deviation,

[3]The results are shown for frequency interval 1.

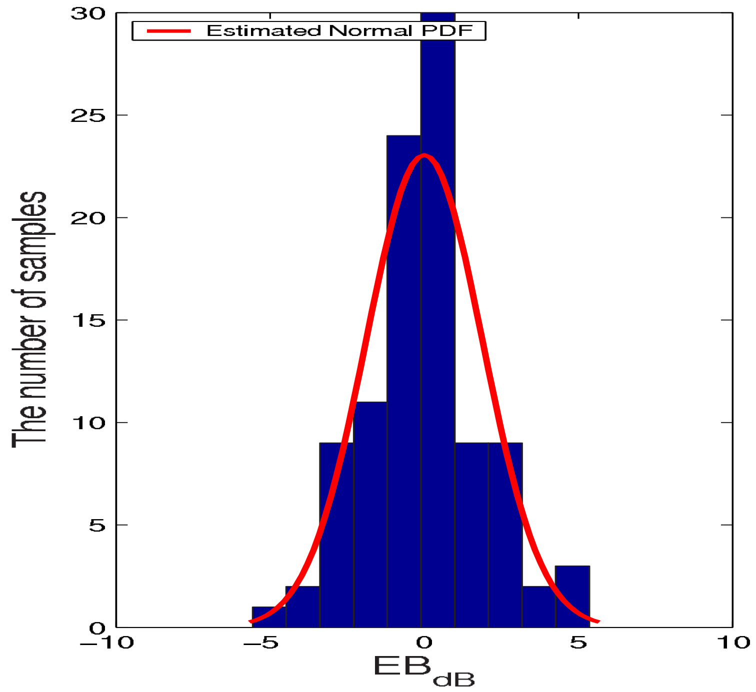

Figure 4.1: *Histogram of the error bias at 3 GHz for one of the test objects. The normal (= gauss) distribution, with the sample mean value and sample standard deviation as parameters, is superimposed (red curve). (The figure shows the results for frequency interval 1.)*

$$\sigma = \sqrt{\sum_{k=1}^{N} \frac{(\mathcal{E}_{dBk} - \mu)^2}{N - 1}}, \tag{4.8}$$

have been used as parameters to the normal distribution[4]. Outgoing from Fig. 4.1 we can say that the normal distribution is not a too bad estimate, but a more rigorous investigation will follow.

We will however first notice that Fig. 4.1 does only show the result for one frequency. To be able to show the result for the whole frequency interval $0.5 - 18$ GHz, we show in Fig. 4.2, a colour plot with the frequency shown on the abscissa and the distribution of the logarithmic error bias shown on the ordinate and in the colours. The redder, or lighter, colours correspond to a larger value in the histogram. As a general statement, the logarithmic error bias seems to be distributed around a value close to $0dB$, but in the centre of the frequency interval, the spread of the logarithmic error bias is larger. The reason for the larger spread in the centre of the frequency interval is to be further investigated, but our experience make us guess that it is due to aperture resonances in the test objects.

[4]The parameter N is the number of observed data. In our case, the number of chosen subsets of irradiation directions, which were 100.

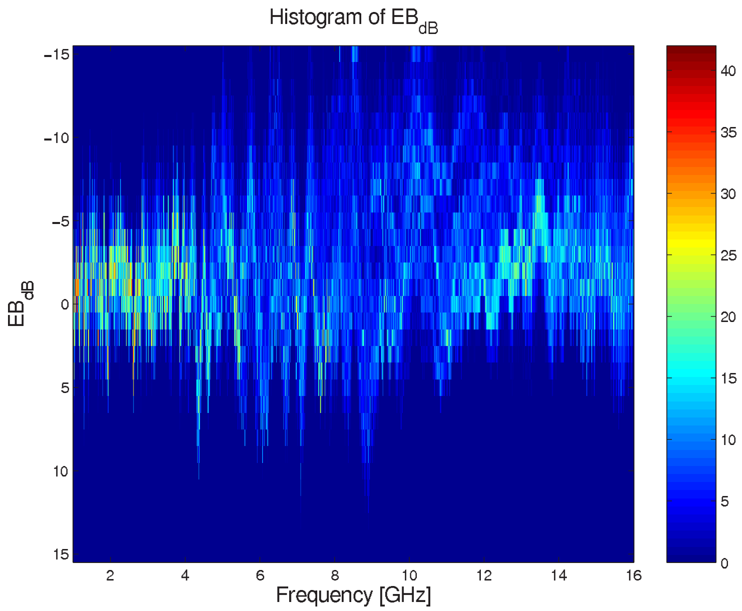

Figure 4.2: *Histogram of the error bias as function of the frequency for one of the test objects. (The figure shows the results for frequency interval 1.)*

Until now we have shown the results for frequency interval 1, but an interesting question to investigate is the influence of the size of the chosen frequency interval. Fig. 4.3 and 4.4 respectively, show the sample mean and sample standard deviation of the logarithmic Error Bias as function of the frequency for the five different frequency intervals mentioned above. The different curves are not easily distinguished in the black and white version of this report, but actually not too easily in the coloured version either. That actually brings us to the conclusion that the advantage of increasing the frequency interval is limited. The risk of undertesting is slightly reduced, but to the price of increased risk of overtesting. Here the results are only shown for one test object, and for one position of the measurement probe in the EUT, but the results are generally applicable to our test objects. In [20] it can also be seen that increasing the frequency interval even further does not change the conclusions drawn above. The larger spread in the histograms in the frequency region $4 - 11$ GHz in Fig. 4.2 is, of course, reflected in an increase of the standard deviation in Fig. 4.4 but it is also striking how independent the standard deviation seems to be of the size of the frequency interval in use. A key point to observe in Fig. 4.3 is the dip at 7 GHz. The minimum values in the dip are almost identical, independent of the size of the frequency interval in use. Our method simply fails here. The reason is that there is a strong peak in the true receiving cross section at 7 GHz. Hence, for all the frequencies around the centre frequency (7 GHz), the receiving cross section is always smaller than the receiving cross section at the centre frequency, and consequently our model fails at the frequencies where the EUT has a major resonance peak in the receiving cross section. Just as stated above we assume that the physical explanation to the

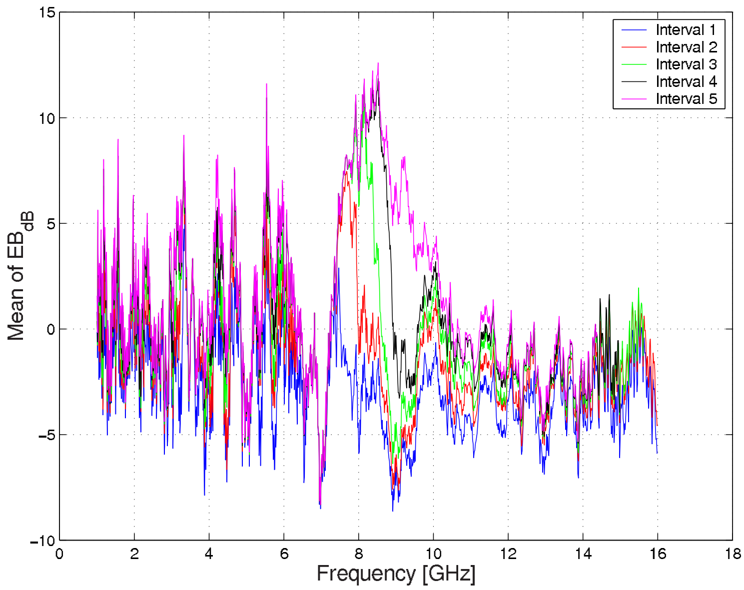

Figure 4.3: *The mean of the error bias as function of frequency. Interval 1-5 correspond to frequency intervals described adjacent to table 1 above.*

peak resonance in the receiving cross section is a major aperture resonance in the EUT. Some mathematical thinking does also tell us that the major peak resonance in the true receiving cross section explains the striking behaviour of the curves in Fig. 4.3 and Fig. 4.4 from 6 to 12 GHz.

In Fig. 4.1 we superimposed the normal distribution and we concluded somewhat vaguely that the normal distribution is not a too bad estimate. It is obvious that the histogram in Fig. 4.1 is not exactly normally distributed, but we cannot conclude that the logarithmic error bias is not normal distributed outgoing from only the diagram in Fig. 4.1 because the discrepancy might be due to quantisation errors or simply random errors. To be able to draw a stricter conclusion on whether the distribution is normally distributed or not, we have performed a chi-square goodness-of-fit test. The chi-square goodness-of-fit test is one of the oldest and best known tests in statistics, and it is described in many text books e.g. [23, pp. 261-278]. To be able to understand the results we will briefly review it here. The chi-square goodness-of-fit test is performed outgoing from a histogram, e.g. the one seen in Fig. 4.1. A test variable is defined,

$$Q \triangleq \sum_{k=1}^{N} \frac{(O_k - E_k)^2}{E_k}, \tag{4.9}$$

where n is the number of data intervals (10 in Fig. 4.1), O_k is the number of observations in interval k and E_k is the expected number of measurements in interval k, given the measurements really are governed by the assumed distribution (in our case the normal distribution). It is obvious that the larger the test variable is, the unlikelier it is that the assumed distribution is correct, and if Q is very large we can with a very

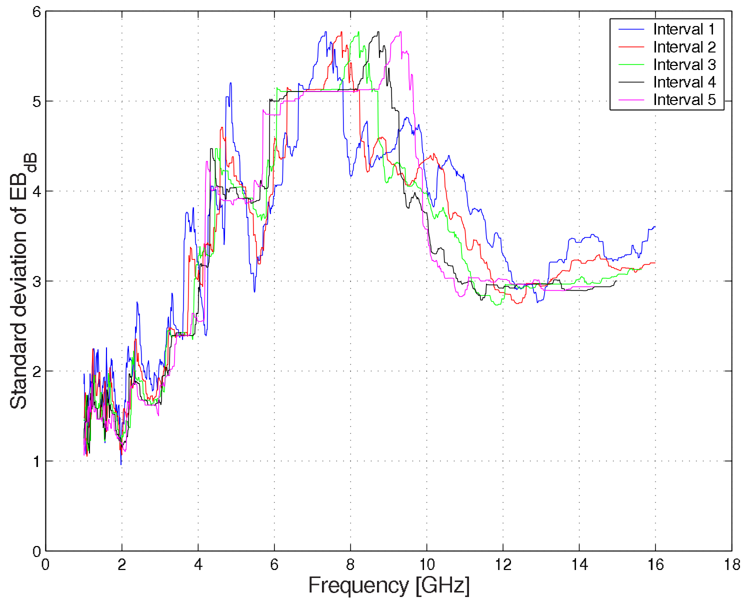

Figure 4.4: *The standard deviation of the error bias as function of frequency. The same frequency intervals as in Fig. 4.3 are used.*

large probability reject the assumed distribution. The Q-values for the histograms in Fig. 4.1 can be seen in Fig. 4.5.

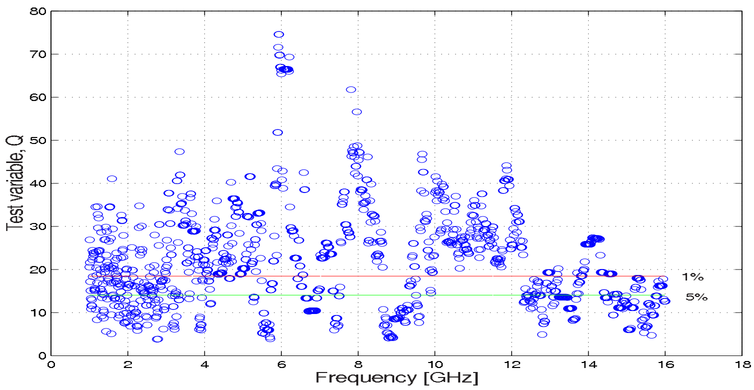

Figure 4.5: *The test variable Q for every measured discrete frequency. The risk of erroneously reject the normal distribution is less than 1% (5%) above the red (green) curve.*

We can however be more specific than that. We can quantify the probability of rejecting a correct distribution, because it can be shown that the test variable is chi-square distributed with $n-r$ degrees of freedom, where r is the number of parameters that have to be calculated from the data to compute the expected numbers E_k. That is the case independent of the assumed underlying distribution [23]. In our case, the normal distribution, we need to calculate three parameters, the number of observed data, the sample mean value and the sample standard deviation.

Hence, we know that for our case, our test variable Q is chi-square distributed with 7 degrees of freedom, and by looking in a mathematical table or using a mathematical software it is easy to see that if Q is larger than e.g. 14 (18), the probability of making a mistake by rejecting the assumed distribution is less than 5% (1%). These levels have been superimposed in Fig. 4.5. It is not proper to draw a conclusion for a specific frequency in Fig. 4.5 because the result for a specific frequency is also random. However, we may e.g. draw the conclusion, that the normal distribution cannot be rejected for the higher frequency interval, but by looking on the whole frequency interval we can probably reject the normal distribution because there are so many points above the horizontal curves.

The later statement can be proven in a more strict way, by use of Fisher's method [24]. In Fisher's method we test the hypothesis that the assumed distribution (the normal distribution in our case) is true for every tested frequency. We will again only briefly review the method here. In Fig. 4.5 we have drawn the lines for 1% and 5% significance rejection level, but it is also possible to calculate the specific significance rejection level for every measurement point in Fig. 4.5. Those specific significance rejection levels are denoted p_i. In Fisher's method, all specific significance rejection levels are added logarithmically,

$$P \triangleq -P \sum_{i=1}^{M} \ln p_i, \tag{4.10}$$

where M is the number of tested frequencies. If we assume that our assumed distribution (the normal distribution in our case) is correct at every tested frequency, some thinking tells us that every p_i is uniformly distributed on the interval 0 to 1. As a consequence thereof, it can be shown that P in (4.10) is chi-square distributed with $2M$ degrees of freedom. Hence, we can calculate a significance rejection level (p_p) for the whole frequency interval, just as we calculated the specific significance rejection levels for every specific frequency (p_i). The result in our case is that p_p is extremely small[5] and hence we can, with an extremely large confidence, reject the hypothesis that the error bias is normally distributed for all measured frequencies.

4.6 Measurement Uncertainty

Generally the measurement accuracy of our measurement system is low in the lower frequency intervals around and below 1 GHz, but is much better in the higher frequency intervals [25]. In [18], with help of [25], the measurement uncertainty in the received power in our measurement probes is calculated to be approximately ± 3 dB at 0.5 GHz, and ± 0.5 dB at 18 GHz. E.g. the in (4.5) defined error bias is a quotient between two power values, and both power values have attached measurement

[5]The value is so small that the software MatLab represents it as 0.

uncertainties (e_P). We calculate the total measurement uncertainty (e_{tot}) as the root sum of squares,

$$e_{tot} = \sqrt{e_P^2 + e_P^2} = \sqrt{2}e_P, \tag{4.11}$$

giving us a total measurement uncertainty of 4 dB at 0.5 GHz, and 0.7 dB at 18 GHz. The measurement uncertainties should only be taken as estimations, because, the formulas used for adding measurement uncertainties in [18, 25] and in (4.11), are based on the assumption of small measurement uncertainties, which is not really the case here.

4.7 Discussion

Above we concluded that the error bias is not normally distributed. The conclusion is scientifically correct, but does unfortunately not give much practical guidance. One major reason why we could reject the normal distribution was the extensive amount of measurement data; 1074 different irradiation direction, 2 different polarisations and 1403 different frequencies, giving us in total 3013644 different measurement points. With such an extensive amount of data almost any distribution can be rejected. On the other hand, from a practical point of view, the normal distribution may be completely sufficient as an approximation of the histogram in Fig. 4.1. Here there is a lack of new test models. What is wanted is a test giving the result that it can not be rejected that the measured distribution almost follows an assumed distribution. Such a test must still give quantified results, making it better than only judging by subjectively looking on the measurement data in form of e.g. a histogram. The test should also preferably, not automatically increase the rejection confidence when the amount of measurement data is increased. This topic is to be further investigated.

If we turn into a more practical point of view, one may ask why we bother about the statistics of the Error Bias. The reason is that we want to be able to estimate the error we introduce by using our frequency substitution method instead of an accurate angular and polarisation resolved susceptibility test. That can be done quit easily if the distribution of the error bias is known [23]. However, the methods proposed in [23], and other text books as well, assumes that approximate values for the distribution parameters, e.g. mean value and standard deviation, can be calculated. That is however not so easily done in our case, because in using our method in practice, we will not do an angular and polarisation resolved measurement and hence the distribution parameters for the error bias cannot be calculated. One way to get around that obstacle is to use typical values outgoing from measurements on many objects, in a similar manner as it was proposed that the typical directivity of electronic equipment is $10-15dB$ in [14]. Here there is work to be done by systematically going through all our measured objects. We invite people with further measurement data from other test objects to contribute. However, we can already now by studying Fig. 4.2 to Fig. 4.4 conclude that the error margin we have to add may tentatively be 5 dB and most important, is smaller than the directivity margin of $10 - 15\ dB$ which the result in [14] implies. Hence, it may be vindicable to do that work.

4.8 Conclusions

Generally, the model of substituting angular resolved susceptibility testing with frequency resolved susceptibility testing seems to work. However, the model, though it does not completely fail, is not at its very best within some limited frequency intervals; the reason being strong peak resonances in the true receiving cross section. Our experience let us guess that the peak resonances are due to aperture resonances in the test objects. The error bias introduced by using the proposed method is roughly normal (=gauss) distributed. The lack of knowledge of good test criterions precludes a more precise judgement.

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