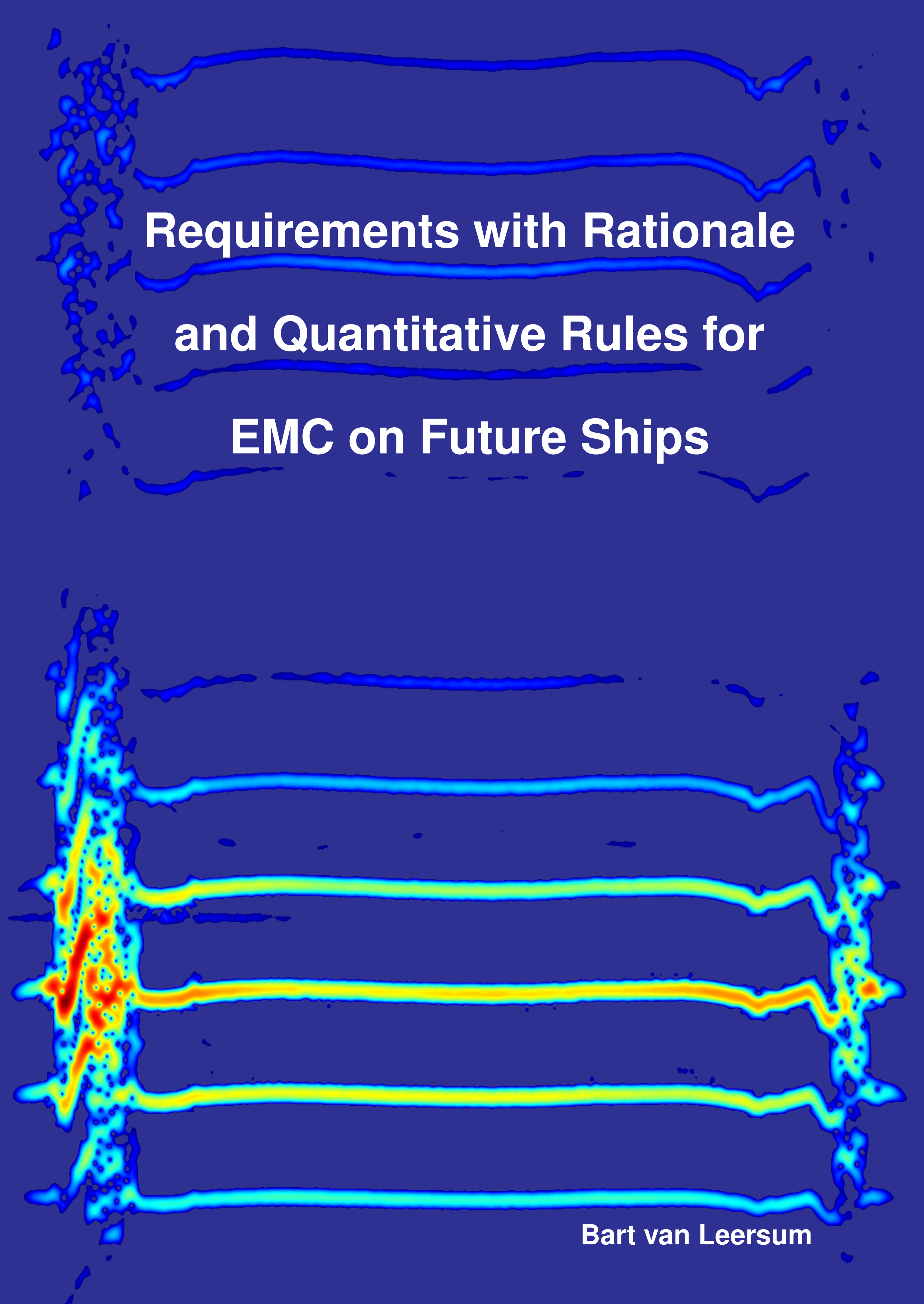

Requirements with Rationale and Quantitative Rules for EMC on Future Ships

Bart van Leersum

REQUIREMENTS WITH RATIONALE AND QUANTITATIVE RULES FOR EMC ON FUTURE SHIPS

Bart van Leersum

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Abstract

To ensure the performance on equipment and subsystem level in a naval environment, the conventional approach has been to strictly require national and international military standards on equipment and installations. This approach made Electromagnetic Compatibility (EMC) a cost driver in naval shipbuilding. Many standards lack a clear rationale and scientific reference, appear to be written for old technology and contain more qualitative than quantitative rules.

An alternative is a risk based approach, that replaces the strict and extensive acceptance procedures that come with the military standards. Technological developments and diminishing funding dictate the use of Commercial off the Shelf (COTS) equipment below deck. Civil development produces reliable new technology in large series at a high pace, that is uncommon in the defence industry. The short economic life cycle of COTS equipment forbids electromagnetic hardening of individual equipment that is not designed for a military environment. Building adequate electromagnetic environments for this equipment is the only affordable alternative.

A protected environment below deck is created by zoning and taking the appropriate protective measures. These measures are based on best practices, which are established techniques. The research in this thesis has aimed at requirements with clear rationale, put in todays perspective, and installation guidelines with quantitative rules.

Crosstalk between cables is one of the oldest types of interference. Cable separation rules have been in use for over five decades and were derived in an era where equipment did not meet legal or contractual requirements, where signals in the cables where analogue and knowledge on EMC was still in development. Different equipment that is designed for the intended use in the same environment, e.g. residential or office use, will be compatible and therefore the risk of crosstalk between cables from these equipment is low. Calculations and measurements have shown that commonly used high quality cables can be put close together for most of the systems on a ship, provided that these cables are properly installed.

EMC is achieved by the decoupling of Common Mode (CM) current loops at the inside and outside of current boundaries. This can even be realised by cable terminations instead of shielding walls, to create a barrier for these currents. A numerical analysis including measurements of the magnetic decoupling between these loops has shown the importance of a low bonding resistance.

Systems and cables on naval ships act as antennas and are susceptible to the external electromagnetic environment, which may cause Electromagnetic Interference (EMI). Signals, radiated from above deck cables, may also be of a concern for a possible increase of the noise floor of on-board receivers, as well as leaking information or detection by third parties. A quantitative investigation of the susceptibility of exposed cables has shown that risks can be kept low by a small exposure length or by placing cables close to a ground plane.

All equipment on the market today is strictly limited in unintentional radiated emission to prevent the interference to radio reception in general. Specific maritime requirements prohibit the use of COTS equipment to insure the availability of the maritime VHF radio to make a distress call. An analysis of the limit setting rationale has led to a practical approach to avoid interference.

Samenvatting

Van oudsher worden strenge regels uit nationale en internationale militaire standaarden toegepast voor apparatuur en systemen op marineschepen. Door deze aanpak is Electromagnetic Compatibility (EMC) een belangrijke kostenfactor geworden in scheepsbouw voor de Marine. In veel standaarden ontbreekt het aan een duidelijke onderbouwing en wetenschappelijke referenties. Ze lijken geschreven voor verouderde technoligieën en bevatten eerder kwalitatieve dan kwantitatieve regels.

Een aanpak die is gebaseerd op risicoanalyses is een alternatief voor het strikt eisen van militaire standaarden met bijbehorende omvangrijke afnameprocedures. Technologische ontwikkelingen en krimpende fondsen dwingen het gebruik van commercieel verkrijgbare apparatuur benedendeks af. Door civiele ontwikkelingen is betrouwbare nieuwe technologie voorhanden die wordt geproduceerd in grote oplagen. Deze civiele ontwikkelingen gaan veel sneller dan gebruikelijk is in de defensie industrie. Door de korte economische levenscyclus van commercieel verkrijgbare apparatuur is het het aanpassen van individuele apparatuur aan een militaire omgeving een ongewenste oplossing. Het creëren van een adequate electromagnetische omgeving voor deze apparatuur is het enige betaalbare alternatief.

Benedendeks wordt een beschermde omgeving gecreëerd door het toepassen van zonering met de bijbehorende beschermende maatregelen, die zijn gebaseerd op best practices, bewezen technieken. Het onderzoek in dit proefschrift heeft zich gericht op eisen met een duidelijke onderbouwing, geplaatst in hedendaags perspectief en op kwantitatieve installatiemaatregelen.

Overspraak tussen kabels is een van de oudste types van interferentie. Kabelseparatie regels zijn al een halve eeuw in gebruik en stammen uit een tijdperk waarin apparatuur niet voldeed aan wettelijke of contractuele eisen, toen signalen nog analoog waren en EMC nog in de kinderschoenen stond. Verschillende apparatuur die is ontworpen met de intentie om te gebruiken in dezelfe omgeving, zoals huishoudelijk of in een kantooromgeving, zal elkaar goed verdragen. Het risico op overspraak tussen kabels van deze apparatuur zal dan laag zijn. Berekeningen en metingen hebben aangetoond dat algemeen gebruikte en hoogwaardige kabel in de meeste gevallen dicht bij elkaar geïnstalleerd kan worden, mits deze kabels op de juiste manier zijn afgemonteerd.

EMC wordt bereikt door de ontkoppeling van Common Mode (CM) stroomlussen aan de binnen- en buitenkant van stroomgrenzen. Dit kan zelfs worden gerealiseerd met alleen kabel afsluitingen om een stroomgrens te creëren in plaats van compleet afschermende panelen. Een numerieke analyse inclusief metingen van de magnetische ontkoppeling tussen deze lussen toont aan hoe belangrijk een elektrische verbinding met een lage weerstand is.

Systemen en kabels op een marine schip fungeren als antennes en zijn gevoelig voor Electromagnetic Interference (EMI) door externe elektromagnetische beïnvloeding.

Daarnaast kunnen elektromagnetische golven die afkomstig zijn van bovendekse kabels, de schijnbare ruisvloer van ontvangers aan boord doen toenemen, informatie lekken en detectie door derden bevorderen. Een kwantitatief onderzoek naar de ontvankelijkheid van blootgestelde kabels heeft aangetoond dat het risico laag gehouden kan worden door de blootgestelde delen kort te houden dan wel door de kabels dicht tegen een grondvlak te plaatsen.

Alle commercieel verkrijgbare apparatuur voldoet tegenwoordig aan strikte eisen voor de onbedoelde uitstraling van radiogolven ter voorkoming van interferentie op radio ontvangst in het algemeen. Specifieke maritieme eisen verhinderen echter het gebruik van commercieel verkrijgbare apparatuur ter bescherming van de mogelijkheid om een noodoproep te plaatsen met een marifoon. Een analyse van de beweegredenen achter de bewuste limieten heeft geleid tot een praktische aanpak om storing te voorkomen.

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Chapter 1

Introduction

To ensure the performance on equipment and subsystem level in a naval environment, the conventional approach has been to strictly require national and international military standards on equipment and installations. This approach made Electromagnetic Compatibility (EMC) a cost driver. Technological developments and diminishing funding dictate the use of Commercial off the Shelf (COTS) equipment below deck. The short economic life cycle of COTS equipment forbids electromagnetic hardening of individual equipment. Building adequate electromagnetic environments for this equipment is the only affordable alternative.

Today we are building naval ships integrating preferably only COTS products into a naval environment. In an effort to reduce the costs, dedicated designed equipment, such as military or hardened COTS, has to be minimised. Nowadays, civil development has produced reliable new technology in large series at a high pace, that is uncommon in the defence industry, providing more value for money and faster technical upgrades at lower costs.

Another cost driver is the extensive testing that is common to the use of traditional military standards, including hardened COTS equipment. The challenge is to integrate any equipment without degradation of performance, robustness, safety and continuity. However, the introduction of COTS has also complicated the specification and acceptance procedures of naval projects.

There is a need to develop a new EMC management framework with quantifiable and reproducible performance criteria that are independent of specific equipment. This framework must fit in the early stage of the design and integration process and moves the acceptance procedures from the equipment to the platform level as much as possible. It is necessary to develop a new method to perform a reproducible performance and risk assessment that can replace the strict and extensive acceptance procedures that come with the military standards. The basis for this framework must be formed by functional requirements, for example to guarantee the availability of essential functionality for safety reasons or limited generated disturbance from equipment and a level of immunity. These functional requirements leave room for alternative implementations as long as these are substantiated by proper research. The same basis holds for the jungle of existing standards, but the pitfall is to take these standards as the basis itself.

The aim of this research is to establish a cost effective integration of commercially available equipment and infrastructure into a military maritime environment ensuring performance, robustness, safety and continuity.

To achieve EMC in complex systems in an environment that is more hostile than an ordinary residential scenery, a protected environment has to be created that matches the intended environment of the integrated equipment. Therefore, additional EMC measures, or best practices, such as shielding, zoning, earthing, bonding, use of screened cables, implementation of installation guidelines, etc. are necessary to achieve EMC on system and platform level.

1.1 EMC management

EMC is "the ability of an equipment or system to function satisfactorily in its Electromagnetic Environment (EME) without introducing intolerable electromagnetic disturbances to anything in that environment [1]". Electromagnetic Interference (EMI) is "the degradation of the performance of an equipment, transmission channel or system caused by an electromagnetic disturbance [1]". Note: In English, the terms "electromagnetic disturbance" and "electromagnetic interference" designate respectively the cause and the effect, but they are often used indiscriminately [1]. The term "EMC management" is not well defined but within the context of this document is understood as:

EMC management

The strategy to select a set of activities to ensure that the equipment operates satisfactorily, i.e. there is no degradation of performance - or in some cases a graceful degradation - on equipment, system, installation or platform level.

1.1.1 Essential requirements for EMC

There are EMC related quantifiable variables like field strength, susceptibility level, immunity limit, attenuation, shielding effectiveness, etc. but EMC itself is not a quantifiable variable. An equipment or system is able to function, or is it not. The basis for EMC is formed by essential requirements, for example to guarantee the availability of essential functionality. The European Union (EU) has legal requirements in the EMC Directive [2] and requires limited generated disturbance from equipment and a level of immunity. The Radio Equipment Directive [3] supports the efficient use of radio spectrum in order to avoid harmful interference and to ensure access to emergency services. The third Directive of interest is written for Marine Equipment [4]. These EU documents may point to essential requirements by other bodies like the International Convention for the Safety of Life at Sea (SOLAS) or the International Maritime Organization (IMO). Most of the essential requirements are written as functional requirements, whereas detailed, quantitative specifications are written in harmonised standards, developed by organisations like the European

Committee for Standardization (CEN), the European Committee for Electrotechnical Standardization (CENELEC) or the European Telecommunications Standards Institute (ETSI). Compliance with harmonised standards provides a presumption of conformity with the corresponding legal requirements. The use of these standards remains voluntary. Everyone is free to choose another technical solution to demonstrate compliance with the mandatory legal requirements.

The essential requirements in the EMC Directive [2] are in Table 1.1.

Table 1.1: EMC Directive 2014/30/EU [2, Annex I].

Essential Requirements

1. **General requirements**

   Equipment shall be so designed and manufactured, having regard to the state of the art, as to ensure that:

   (a) the electromagnetic disturbance generated does not exceed the level above which radio and telecommunications equipment or other equipment cannot operate as intended;

   (b) it has a level of immunity to the electromagnetic disturbance to be expected in its intended use which allows it to operate without unacceptable degradation of its intended use.

2. **Specific requirements for fixed installations**

   Installation and intended use of components

   A fixed installation shall be installed applying good engineering practices and respecting the information on the intended use of its components, with a view to meeting the essential requirements set out in point 1.

1.1.2 Motivations for EMC management

There are various reasons why one would deploy EMC management, dependent on their role and the situation. Some examples:

– **Risk management**
  Activities are carried out to meet the essential requirements: Satisfactorily functioning in a specific EME without intolerable disturbances, i.e. a low risk of getting EMI. Tests remain necessary to work on the confidence level of the project team.

- **The law**
  As an example, the Radio Frequency (RF) spectrum is protected by law for the protection of radio reception, which is the reason for many strict emission rules in EMC standards, most of them maintained by the International Special Committee on Radio Interference (CISPR).
- **Imago management or market confidence**
  Industrial companies do not want to get complaints about EMC problems that may harm their good name.
- **Liability**
  Equipment manufacturers want to comply with the appropriate standards for safety or liability reasons.

Most of these motivations for EMC management are rule based: follow the law, comply with customers requirements, apply standards, etc. This rule based approach brings two important pitfalls of ignorance:

- **Conservatism** Established standards are implemented without realising what is the rationale behind them and without putting them in today's perspective.

  "In the 1970's we've studied this already thoroughly!"

  "This is the best way to do it.
  We've done it in this way for over 30 years."

- **Safeguarding**
  Some project managers who do not want to be responsible for safety or liability issues try to get some kind of certificate that safeguards them from the consequences of a bad design. They claim they have done all they could to get a compliant product and assume that quality is guaranteed as long as all parts comply with standards.

1.1.3 The risk based approach

The strategy as proposed in this thesis to achieve EMC is the risk based approach, that starts with functional performance requirements and no specific requirements on equipment level. All equipment, preferably COTS, is selected for its function and performance. This equipment might be developed for the intended use in a different environment. This mismatch between the actual and intended environment poses a risk for EMI, for which measures have to be taken. A risk is often defined as the product of probability and impact, but these variables are too difficult to define and quantify unambiguously for EMC. The risk based approach involves the assessment of the expected actual environment, immunity and emission characteristics of equipment and necessary measures. These measures involve the creation of an environment similar to the intended environment for which the involved systems were designed. These measures do not include the hardening and testing of the equipment to specific standards, as this is referred to as the rule based approach.

Traditionally, EMC is achieved by the rule based approach, where high requirements are set on all equipment that will be installed on board, e.g. Allied Environmental

Conditions and Tests Publication (AECTP) 501 [5] or Mil-Std 461 [6], almost regardless of the intended use and the actual environment it will be placed in. The equipment is to be extensively tested to a wide variety of possible electromagnetic disturbances. In this way, the risk of EMI is minimised by the rules, i.e. standards. These traditional rules to achieve EMC on naval ships are a cost driver and demand dedicated military or maritime grade equipment instead of enabling the possibility to apply widely available COTS equipment from the rapidly expanding civil market.

1.2 Motivations for the research

Three reasons are addressed for the importance of this research.

1.2.1 EMC as a cost driver

The rule based approach that is established in the military world is based on hardening all systems on equipment level against all possible electromagnetic (EM) threats. This disqualifies COTS equipment for integration on a naval vessel and inhibits the quick and effective implementation of emerging technologies. Cost drivers for system integration in a military environment are:

- the hardening on equipment level
- and the extensive testing of each piece of equipment.

1.2.2 Emerging technologies

An emerging technology, as distinguished from a conventional technology, is a field of technology that brings up new territory in some significant way, with new technological developments. Examples of new technology are wireless systems below deck, fast switching power electronics, non linear loads on the power supply network and in the future probably DC-grids, whereas analogue communication is nowadays more and more replaced by digital solutions on standardised buses.

Whilst in the past, electronics for residential or industrial use was seen as a welcome spin-off from the huge and high technology defence and space industry as illustrated in Figure 1.1, nowadays civil development is leading (Figure 1.2), producing reliable new technology in large series at a high pace, that is uncommon in the defence industry. So besides the cost driver of hardening and extensive testing, it is important to be able to integrate the newest components from the civil market into highly specialised, dedicated military applications. This is only possible by replacing the traditional rule based approach at equipment level by a risk based approach at ship level.

The last few decades, COTS equipment has improved a lot in quality and robustness, due to the increased use of electronics in everyday's life, implementation of the EMC Directive [2], awareness by manufacturers and installers, etc.

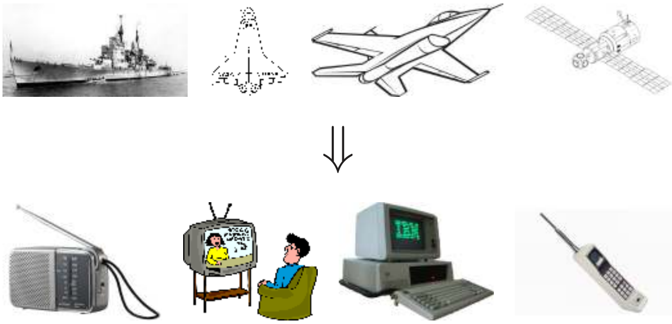

Figure 1.1: Past: Military and space technology provided consumer spin-off.

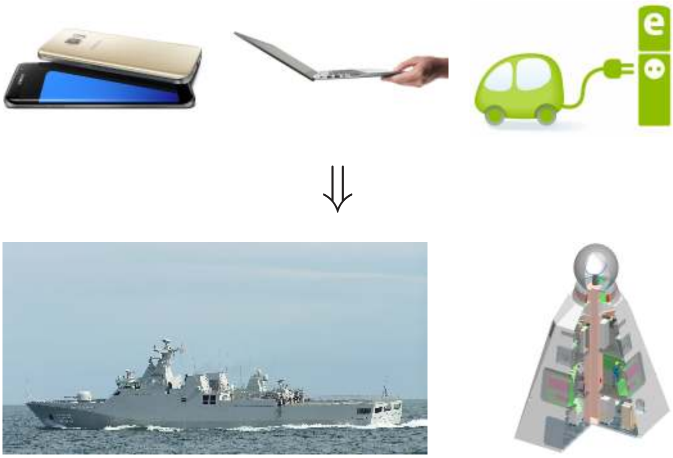

Figure 1.2: Present: Civil market is leading, COTS components are integrated in military applications.

1.2.3 Technology shortfalls and lack of rationale

EMC is a discipline that has produced an overwhelming number of standards and installation guidelines over the past 60 years. The development of standards seems a continuous and slow process resulting in a lot of useful information but with a huge amount of variations in conditional parameters and test techniques that are sometimes contradictory. Besides the basic and generic standards, there are product family documents, emerged from industrial lobbies, mixing EMC with functional specifications, and in fact overruling the essential requirements in the EMC Directive [7]. Many standards lack a clear rationale and scientific reference, because these standards are taken as reference itself or because it is simply forgotten over time. These rules also appear not to be written for state of the art complex installations on nowadays naval vessels, but are based on old technology, like analogue signals in unscreened cables, whereas nowadays most data goes on standardised high speed data links with a lot of error recovery techniques, using high quality screened cables.

A system designer can choose from a wide range of techniques, called best practices, that should minimise the coupling of disturbing signals into his system. But many of these rules include qualitative texts like “as short as possible” and “should be avoided”, which makes those rules less usable. These cases demand for research to recover the rationale behind the best practices, which will result in a balanced and most likely cost effective implementation of these best practices.

There is a need for
- requirements with clear rationale, put in today’s perspective,
- and installation guidelines with quantitative rules.

1.3 Benefit of this research

Stakeholders should benefit from this work by a cost effective integration of COTS equipment, taking advantage of flexibility, allowing rapid change in technology, avoiding obsolescence, and managing life cycle costs. Commercial technology brings great benefits in functionality, performance and price, whereas the legacy rules, based on history, are not adequate for modern technology. With a risk based approach, the implementation of EMC in system integration can be tailored to the specific ship’s environment that can vary greatly with its purpose. The stakeholders of this research are
- ship’s users, such as an operational naval command, a defence materiel organisation, or a shipping company,
- the shipyard as the main contractor to deliver the vessel to a navy or other customer,
- the E-supplier, providing the design for the energy supply with its installation, networks, cabling, etc.,
- the combat system integrator, providing the architectural design for all navy specific systems,
- various equipment suppliers for either off the shelf or dedicated systems.

A shipbuilder wants to integrate all necessary functionality at the lowest possible costs, and achieving the performance that the customer demands. A shipping company or navy want their ships to sail safely and timely at all times. A naval commander wants to rely on all sensor, weapon and communication systems when he needs them. An electrotechnical installer often acts as the responsible for the integration of all equipment and installations, compatible with the internal as well as external environment, whereas equipment may be used in an other than their intended environment. To meet these EMC challenges, a clear and uniform approach with verification and control is proposed during the several shipbuilding phases:
- Contract Phase: EMC management,
  the definition of the ship’s mission and intended environment with functional specifications. An EMC management plan will define these items along with the organisation and responsibilities. This is a contractual document.
- Engineering Phase: EMC Control and risk analysis,

the high level measures needed to mitigate the electromagnetic threats are stated in the EMC control plan, which is a continuously updated document, that contains the Integrated Topside Design (ITD), a below deck zone plan, and general approaches to achieve EMC. Specific equipment requirements can be derived from this document, written for Subject Matter Experts (SMEs);

- Production Phase: EMC Implementation,
  detailed installation measures to be taken to implement the approaches to control EMC. The implementation plan, or specific parts of it are written as instructions for installers. This document has the widest audience;
- Test and Acceptance Phase: EMC Verification
  to demonstrate the functional specifications in the contract.

Test and verification is not limited to the last phase and not limited to the functional specifications in the contract, but is a process of gradual acceptance that includes the review of the risk analysis, various engineering analysis reports, the control plan, implementation plan, etc. Also during the production phase, implementation has to be continuously monitored for quality assurance. Verification and control might be done by a marine classification society like Lloyd's Register, who intend to include this approach [8], [9] in their rules [10].

1.4 Outline of this thesis

This thesis consists of two parts. The first part focuses on the what and how. It will give a structured overview of known items, but in a way that fits a risk based approach aimed at functional requirements. The basis will be civil standards, most from the International Electrotechnical Committee (IEC), applied in a naval environment, tailored to customer's need, with the lessons learnt from military standards, aimed at make things work, rather than follow rules The second part is an attempt to provide the insight in the how much and why. It will give a detailed investigation of the application of some best practices to be able to get quantified rules that have the desired effect of meeting the functional requirements.

Part I: Concepts and rationale

Equipment is designed to operate in a certain intended environment, which is the basis of all EMC standards, as well as the risk based approach of this thesis. This environment is defined by all kinds of electromagnetic disturbances and interference mechanisms, of which a survey will be given in Chapter 2: "Electromagnetic phenomena".

Based on these phenomena, a classification of electromagnetic environments with disturbance levels, compatibility levels and possible performance criteria is made in Chapter 3: "Electromagnetic environment".

EMC standards are developed for equipment to work satisfactorily in its intended environment. To integrate COTS equipment in another environment, the strict use of these standards should not be followed, as motivated in Chapter 4: “Equipment standards”.

Instead of hardening equipment, different environments are created in which the certain types of COTS equipment can work as intended in the design. At the interfaces between zones, installation measures must be taken to maintain the integrity of the zones. Besides shielding, measures will be introduced as current boundaries. This approach is in Chapter 5 “Integration aspects”.

Besides the creation of zones, special actions must be taken, especially at zone boundaries, but also at installations in general. These best practices are known by experienced and skilled engineers, yet there is often a lack of rationale and quantification behind these rules in Chapter 6: “Best practices for protection against EMI”.

Part II: Quantification

Crosstalk between cables is one of the oldest types of interference. Cable separation rules have been in use for over five decades and were derived in an era where equipment did not meet legal or contractual requirements, where signals in the cables where analogue and knowledge on EMC was still in development. Calculations and measurements will give more insight in cable crosstalk in Chapter 7: “Crosstalk between cables”.

Transient disturbances originating from switch operations appear as Common Mode (CM) currents on all cables entering equipment, and are very effective in causing interference and loss of data throughput. EMC is achieved by the decoupling of the CM current loops at the inside and outside of an equipment cabinet. This can even be realised by cable terminations instead of shielding walls, to create a barrier for CM currents. A numerical analysis including measurements of the magnetic decoupling between these loops is written in Chapter 8: “Cable terminations”.

Systems and cables on naval ships act as antennas and are susceptible to the external EME, which may cause EMI. Signals, radiated from above deck cables, may also be of a concern for a possible increase of the noise floor of on-board receivers, as well as leaking information or detection by third parties. A quantitative investigation of the susceptibility is in Chapter 9: “Protection of Exposed Cables”.

All equipment on the market today is strictly limited in unintentional radiated emission to prevent the interference to radio reception in general. Specific maritime requirements prohibit the use of COTS equipment to insure the availability of Global Maritime Distress and Safety System (GMDSS). A review of the limit setting rationale and a practical approach to avoid interference is written in Chapter 10: “RF Protection of maritime VHF radio”.

Part I

Concepts and rationale

Chapter 2

Electromagnetic phenomena

Electromagnetic Compatibility (EMC) is the ability of an equipment or system to function satisfactorily in its Electromagnetic Environment (EME) without introducing intolerable electromagnetic disturbances to anything in that environment [1]. Equipment is designed to operate in a certain intended environment, which is the basis of all EMC standards, as well as the risk based approach of this thesis. This environment is defined by all kinds of electromagnetic sources.

All problems of Electromagnetic Interference (EMI) are determined by the triptych of a source, coupling path and victim. In this chapter, a classification of electromagnetic (EM) disturbances and interference mechanisms is made. Each class is based on a typical triptych and is derived from civil and military standards.

Figure 2.1 illustrates the EM environment. Table 2.1 is a taxonomy of possible sources for electromagnetic disturbances and interference mechanisms, that will be discussed in the next sections. These phenomena are based on what has been found in the basic EMC standards from the the International Electrotechnical Committee (IEC), supplemented with those that are merely in military standards (preferably AECTP) and reflects all Electromagnetic Environmental Effects (E^3) that are relevant for adequate system integration. Figure 2.2 shows the coupling paths.

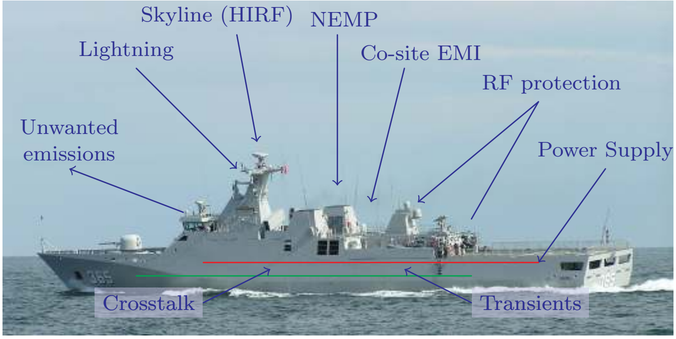

Figure 2.1: Naval Electromagnetic Environment.

Table 2.1: Classification of possible sources and interference mechanisms

Section 2.1: Interference to radio reception and radar detection (RF protection)

1. **Unintended Radiated Emission (RE)**
   from equipment, increasing the noise level and interfering with the intended reception of radio and telecommunication equipment.

Section 2.2: Interference from radio and radar transmitters

2. **Intentional radiated fields**
   from radio and radar transmitters interfering with electronics.
3. **Non-ionising Radiation Hazards (RadHaz)**,
   to personnel, fuel, and ordnance.
4. **EMI**
   between transmit and receive antennas, mainly above deck: Co-site analysis and Integrated Topside Design (ITD).

Section 2.3: Environmental aspects in power distribution systems

5. **Power Quality (PQ) related sources**
   of disturbance, such as power supply harmonics, interharmonics, voltage dips, interruptions, voltage and frequency variations, DC-ripple, voltage unbalance.

Section 2.4: Conducted interference

6. **Crosstalk**,
   and Common Mode (CM) disturbances can cause interference between equipment and between cables.

Section 2.5: Surges and fast transients

7. **Lightning**:
   A direct lightning hit causes high currents. The EM field from a nearby lighting stroke induces surges in power and communication circuits, called Lightning Electromagnetic Pulse (LEMP).
8. **Surges and Electric Fast Transients (EFT)**,
   generated by switching devices, propagating over cables can corrupt data and disrupt communication links.
9. **Electrostatic Discharge (ESD)**
   is the "transfer of electric charge between bodies of different electrostatic potential in proximity or through direct contact" [1].
10. **NEMP**
    results from a High Altitude Electromagnetic Pulse (HEMP).

Section 2.6: Other source categories

11. **Unwanted Emissions**:
    Emission Control (EMCON), preventing detection, classification and identification. TEMPEST, preventing information leakage.
12. **Intentional EMI**,
    deploying one of the above disturbing mechanisms intentionally.

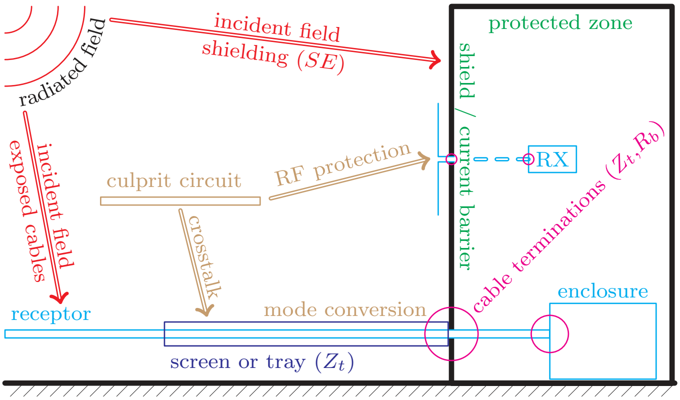

Figure 2.2: Simplified view of the relevant coupling paths.

2.1 Interference to radio reception and radar detection (RF protection)

Unintended emissions can cause radio interference. A classic EMI example is the sputtering noise on a radio receiver from a nearby motorcycle or the car's ignition on its own radio [11]. This phenomenon resulted in the first military specification in 1934 [12]. Radiated emissions are nowadays restricted in both civil and military standards.

Due to governmental regulations, equipment on the market today is developed in such a way that it will not interfere with analogue radio and television receivers from a distance of about 10 meters (Figure 2.3). The frequency range is from 150 kHz up to 1 or 2 GHz for civil equipment. Radar systems and a lot of new communication devices are not yet covered by the standards although the highest frequency requirements are slowly shifting up to 6 GHz to cover the frequency bands that have come in to use the past years. In the military world, requirements already range from 10 kHz to 40 GHz. The limits should be related to natural and man-made background noise [13] and not to receiver front-end sensitivity. Receiver front-end technology has not changed for decades and the sensitivity, in the order of 1 µV for most communication systems, is much lower than the background noise. One example is the limit for the maritime Very High Frequency (VHF) radio, i.e. 156-165 MHz [14], that follows receiver sensitivity. The rationale behind this standard and its implications will be addressed in Chapter 10.

The generic IEC standards are based on the assumption that RF emissions below 30 MHz should be measured as conducted emissions and above 30 MHz as radiated emissions. Peak and quasi peak detection methods have been investigated thoroughly and included in the test methods [15] to relate interference to perception on analogue communication lines. However, this perception does not apply to digital transmissions.

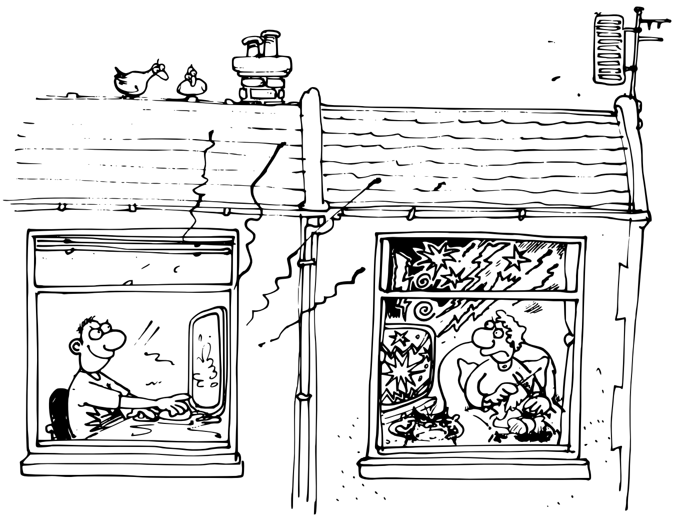

Figure 2.3: Protection of broadcast reception [drawing by Rupert Besley].

The lack of adequate requirements in the frequency range from 9 kHz to 15 kHz, for radiated and conducted emissions by Commercial off the Shelf (COTS) equipment for civil use, makes it difficult to assess the risk of integration of such equipment on naval ships [16]. Sonar and Extremely Low Frequency (ELF)/Very Low Frequency (VLF) communications that are dedicated to naval use ask for special attention.

2.2 Interference from radio and radar transmitters

The electromagnetic spectrum is used for communication by radio and sensing by radar. Therefore all equipment must operate in always present electromagnetic field from these transmitters. This field from intended transmitters can be managed by the distance to the antenna and the shielding effectiveness of the protected environment. There is a mismatch between the definitions of immunity and susceptibility in various standards. These terms are defined for this thesis as:

Immunity limit
A certain limit of a given electromagnetic disturbance incident on a particular device, equipment or system for which it is tested to remain capable of operating at a required degree of performance

Susceptibility level
The maximum level of a given electromagnetic disturbance incident on a particular device, equipment or system for which it remains capable of operating at a required degree of performance

For example, an equipment can pass an immunity acceptance test with an immunity limit of 3 V/m over the required frequency range, whereas it is susceptible to a much higher, but frequency dependent, field strength. In this thesis, the term immunity test is used as in the IEC standards, whereas military standards use susceptibility.

The basic standards IEC 61000-4-6 [17] and IEC 61000-4-3 [18] specify test procedures and basic test levels (Table 2.2) to get protection against RF EM fields from any source. The generic and product standards choose between these basic levels as function of frequency, where the conducted tests are required below and the radiated tests above a certain frequency.

Table 2.2: Basic RF imunity test levels.

Level	61000-4-6 (conducted) Voltage level V_0 (e.m.f.)		61000-4-3 (radiated) Test field strength
	dBμV	V	V/m
1	120	1	1
2	130	3	3
3	140	10	10
4			30
x	Special		Special

In general, equipment on the market today is developed to withstand the electromagnetic fields from radio and television transmitters in a residential or commercial environment. In the USA only the emission is regulated, as mentioned in Section 2.1, and not the immunity of commercial equipment for civil use, because immunity is seen as a measure of quality, not needing a legal intervention. In Europe, immunity is part of the EMC Directive [2].

It is observed that when CPU clock frequencies increased to the GHz range and above, manufacturers of COTS PC's had to implement a set of mitigation measures to fulfil the civil radiated emission limits. A result is that COTS PC's became also more robust since then [19] with susceptibility levels that are much higher than the immunity limits.

One difference between military and civil immunity requirements is the frequency range for which equipment has to be tested. In the IEC standards, immunity of equipment is assessed by radiated tests [18] from 80 MHz and by conducted tests [17] below 80 MHz, whereas military standards have an overlap between frequencies in conducted and radiated tests. Due to different test methods, test results can not be compared in a generic way.

In the military standards, the immunity limits of 10 V/m for equipment below deck are 26 dB lower than the 200 V/m above deck. This implies that these military equipment standards assume a protection by the ships hull that provides a shielding effectiveness of 26 dB. This 200 V/m limit [5] does not represent the worst-case environment to which equipment may be exposed. The actual HIRF environment should be calculated for each ship and is dependent on the location on the ship.

Examples can be found in AECTP 250 [20] Leaflet 258, and in Mil-Std 464 [21]. The term HIRF originates from the aerospace domain to denote tracking radar beams. Sometimes it is called the skyline (see Section 3.4.1), which includes all kinds of transmitted fields from radar and communication systems.

The ITD process of the ship includes a co-site analysis of all transmitters and receivers in a Source Victim (SV) matrix, as well as a calculation of the expected field strengths for RadHaz. During the ITD process, locations of high power transmitters should be carefully chosen as part of the risk management. Areas on a ship that are less protected for the higher frequencies are the bridge, hangar and other open spaces. The use of COTS equipment in these areas cannot be trusted without a detailed risk assessment and appropriate EMC protection measures.

2.3 Environmental aspects in power distribution systems

Electrical power systems consist of power generation units, a power distribution network and a collection of power users. The generated power that is delivered by the distribution network at the power leads of all equipment has to meet certain power quality requirements, quantified in voltage, frequency, and linear and non-linear distortion criteria. It also has to be safe and have a high availability. Performance degradation in power distribution systems in civil EMC standards is in most cases a dedicated topic, called power quality. This is also a matter of EMC, because the quality of power is affected by the interaction between all connected equipment, the distribution network, and the power generation. Power quality on naval ships is regulated by NATO Standardization Agreement (STANAG) 1008 [22], which is different from EN 50160 [23] for voltage characteristics of electricity supplied by public distribution networks. A harmonisation between these standards would be beneficial for COTS integration [24], [25].

2.3.1 Choice of earthing system

Naval electrical power systems have an isolated network architecture, called an Isolated Terra (IT) network, Figure 2.4. The reason for this is to ensure continuity of supply in case of a single earth fault. This earth fault is to be detected with a Power Insulation Monitor (PIM) and be repaired before the next earth fault will occur.

Besides continuity of supply, a historical reason for an IT network was thought to be safety. If the power supply were completely isolated, no current would flow through a person's body in case of an accidental touch of a live conductor. But the actual capacity to earth of supply systems on board is too high to guarantee safety. So the main reason for an IT network on ships is continuity of supply [26]. Another reason is to prevent hull currents that can lead to corrosion, especially on aluminium ships.

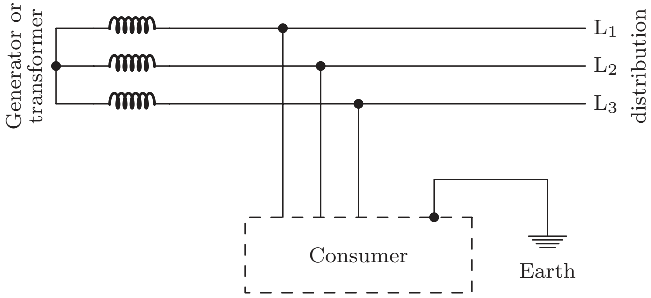

Figure 2.4: IT (Isolated Terra) earthing network [27].

The characteristics of a shipboard system are different from a land system. Therefore equipment requirements are also different and there may arise problems when installing COTS equipment on a naval IT network [24]. E.g. in case of an earth fault the voltage between line and earth may increase to the line-line voltage, stressing Y-capacitors. Besides that Y-capacitors will carry earth currents of an entire grid instead of only the earth current of the equipment they belong to. They were not designed and so not rated to carry such large currents.

In general COTS equipment will be developed for power supply grids with an earthed neutral conductor, like the TN-S system in Figure 2.5. Alternatively, the PE has no lead to the source, but a local earth connection (TT system), or the PE and N leads are combined to one PEN lead (TN-C system).

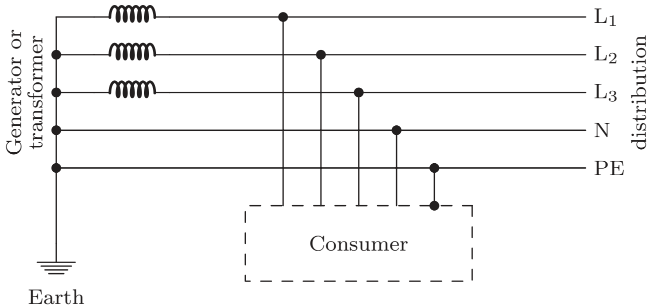

Figure 2.5: TN-S (Terra/Neutral-Separate) earthing network [27].

COTS equipment can cause problems when it is installed in an IT grid, as is the standard on naval ships, because common mode filters with capacitors to earth can be present in COTS equipment. An excess capacitance to earth impacts the working of PIMs. The maximum allowable capacitance to earth is limited by the characteristics of a PIM. Dependent on the nominal voltage, STANAG 1008 [22] suggest a maximum aggregate value of the capacitance of 100 nF for 60 Hz, in order to limit the earth leakage to 30 mA. This 30 mA is not for safety reasons, but is serves as the minimum leakage that a PIM must tolerate. The use of certain PIMs justify a much higher earth leakage. Research in [28] shows that a PIM with the right measurement method can handle a ground capacitance of 500 µF, which is allowed by STANAG 1008 through approval by the power supply design authority.

2.3.2 Risk of electric shock

Especially for distribution grids that include socket outlets and lights, the safest solution is to apply grids with a solidly earthed star point and have limited short circuit power with 30 mA Residual Current protection Devices (RCDs). In IT grids RCDs are less reliable and for that reason each individual socket outlet should be fitted with a 10 mA earth leakage circuit breaker [26].

2.3.3 Risk of an arc flash

Arc flashes may occur when there is a short circuit. The less impedance there is in the short circuit, the higher the energy levels of the arc. The impedance in an earthed grid with a short circuit to the hull can even be lower than the impedance of a short circuit between the phases. For that reason it is best to use an insulated star point or a star point that is earthed by an impedance to limit the fault current [26] with added protection by $\partial I/\partial t$ monitoring or the use of arc flash protectors.

2.3.4 Risk of fire

Under adverse conditions a fire can be ignited by a current of 300 mA if it lasts long enough. This means that only grids that clear the earth fault in case of a leakage current in excess of 300 mA prevent the risk of fire caused by an earth fault. Only in earthed grids this is easy to achieve, because the only point where the current will re-enter the power grid is through the star point of the grid and an earth fault will result in a short circuit, generating a current that will trip the safety device. This ensures that the earth leakage detector, i.e. RCD, will detect this current. In insulated grids it is not known where the current will re-enter the grid and so it is not certain that the fault circuit includes the RCD and that the fault will be cleared. In an IT-grid just a warning will be raised in case of an earth fault by the PIM.

2.3.5 Ability to sustain service under fault conditions

In a truly insulated grid, the installation will be available during a single earth fault situation. However, if filters are connected, dangerously high currents (fire risk) can flow through the fault location, the hull and earth connections to the various filters. These grids are sometimes referred to as randomly earthed grids. Besides that the rise of the voltage in the other two phases with respect to earth in an insulated grid in case of an earth fault may induce new faults. These faults can cause a short circuit between two phases through earth shutting down the power supply. The reliability of the power supply depends on many more factors than just the star point configuration of the grid and other options are available. For small grids with limited capacitance to earth and only connected equipment that is developed for insulated grids this can be a good solution to increase the reliability of the supply grid. For more complex grids, other solutions may give better results [26].

2.3.6 PE connection to shore in case of shore supply

When the shore connections is used to deliver electrical power to the ship, the star point configuration of the shore supply as well as the installation on board has to be considered carefully. Earth currents may occur when earthed grids are applied on shore as well as on the ship. Galvanically separated grids will reduce the AC current flowing between ship and shore, and with it the corrosion of ship and quay, but only if the star point of the secondary side of the transformer is not earthed.

In order to prevent dangerous step and touch voltages an earth connection between ship and shore is made in case there is a connection between shore power supply grid and ship. This earth connection can increase galvanic corrosion because a current loop is made which includes different metals in an electrolyte. The DC current can be significantly reduced by applying galvanic isolators under the conditions that there are no other conductive paths between the hull of the ship and shore.

2.3.7 Conclusions

The primary choice of earthing system on naval ships is the IT system because of continuity of supply. This choice is also agreed within NATO by STANAG 1008 [22]. With the selection of the right type of PIM, the tolerable capacitance to earth can be three to four orders of magnitude higher than the assumed 100 nF limit.

For personal safety, i.e. against the risk of electric shock, it is recommended to have a local earthed system with RCDs in areas with sockets where passengers can bring their own equipment. These aspects and the other mentioned risks should be managed by the the power supply design authority.

2.4 Conducted interference

In Section 2.1 it was covered that equipment, not being transmitters, have a very low unintended radiated emission to protect radio reception and radar detection. The same equipment is immune to a many orders higher power from intentional transmitters, as covered in Section 2.2. So there is no RF coupling between equipment for the frequencies covered by these interference classes. Coupling between equipment is solely determined by conducted interference.

Conducted interference is one of the oldest types of interference, but the interest in this topic is rapidly increasing due to the introduction of new technologies [29]. Already in 1892 a Law on Telegraphy Installations [30] was published in Germany, to prevent interference between power lines and telegraph lines. The military standards published in the 1950's covered also conducted interference but the objective (then) was still to protect the radio spectrum. The Mil-Std 461 (1967) also added conducted emission and susceptibility effects on power supply network and interfaces, starting at 30 Hz up to the MHz region [31]. IEC TC77 was established in 1973 and tasked for "EMC between electrical equipment including networks". The introduction of computers in common living environments sparked the interest for surges and transients [29]. Fast transients were first included in the standards in 1988, as will be discussed in Section 2.5.3. Another form of EMI is due to crosstalk: radiating cables induce unwanted signals on other cables. To minimise this type of interference, a set of measures can be taken, such as the use of screened cables, a proper cable layout with sufficient separation, proper installation of cable trays, etc. This will be covered in Chapter 7. The coupling on cables from any radiated field should be taken into account as well, as will be covered in Chapter 9.

Military standards include tests to ensure that the common mode conducted emissions on all control, signal, secondary power lines and safety earth from the Equipment Under Test (EUT) are controlled to defined limits. This is not only to protect the radio reception, but also to minimise disturbance to any sensitive electronic equipment based on signals in the µV to mV range. This is a heritage from the analog era. In modern industrial installations, weak signals can be limited to the dedicated sensitive sensors that convert measurement values directly into digital data that is transported over professional data buses, such as Ethernet or RS-485, that are standardised by industry, effectively eliminating the reason why the above requirement existed in the first place. This is an example where the state of the art technology has overtaken a settled standard.

Conducted EMI over more than a century [29]:
"In the past conducted interference was mains hum, then power supply distortion due to harmonics and flicker, then single (transient) effects causing computer interference. Now it is rather continuous, non-stationary, switching of all kind of non-linear electronic devices."

2.5 Surges and fast transients

A surge is a transient wave of electrical current, voltage, or power propagating along a line or a circuit and characterized by a rapid increase followed by a slower decrease [1]. The duration of a surge is not tightly specified, but it is usually less than a few milliseconds [32]. Surges originate from lightning, switching events in power stations, and system interaction or crosstalk of surge events, and might have a damaging or an upsetting effect. On the next pages, several forms of surges are defined.

2.5.1 Lightning Electromagnetic Pulse

Lightning is a sudden electrostatic discharge during an electrical storm. A lightning strike is an electric discharge between the atmosphere and an earth-bound object. A lightning flash or stroke is a single event that can contain many Giga Joules of energy. A direct hit has a highly destroying effect but can be diverted to earth (or the sea) by the steel hull of a ship. A complete Lightning Protection System (LPS) consists of four parts: [33], [34], [35], [36]:

1. **Interception**: strike points can be calculated by the rolling sphere method
2. **Diversion** of the charge in currents up to 200 kA
3. **Equipotentialisation** to minimise the currents in installations
4. **Surge protection** to absorb the remaining energy

A lightning surge or LEMP is characterised by many different standards [33], [20], [21] from a lot of statistical data gathered in the past. Figure 2.6 shows some of these waveforms. Lightning protection in particular is not part of this thesis. Research on lightning protection at the University of Twente is published in [37].

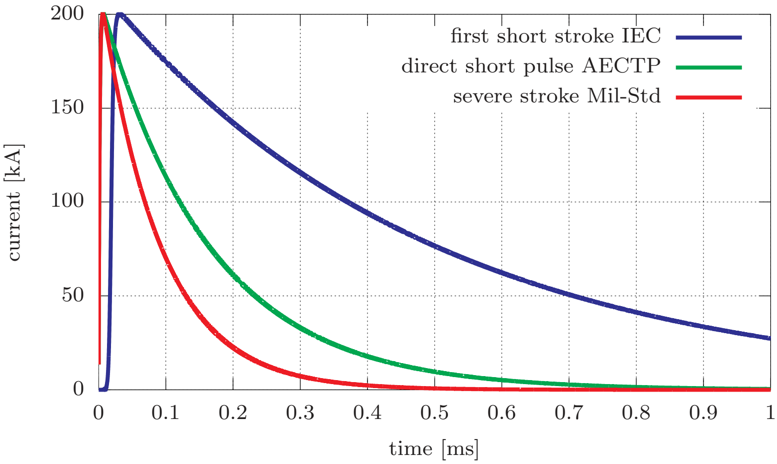

Figure 2.6: Lightning Electromagnetic Pulse.

2.5.2 Surges

Surge voltages and currents are caused by lightning and switching. Surges propagate on the power system and can interact between different systems, i.e. crosstalk from e.g. power lines to communication lines. The characteristic waveforms of surges are caused by the switching of inductive devices and long lines. To investigate surges, many site surveys have been performed since the 1960's [38]. Three waveforms that are used for testing are shown in Figure 2.7. A fourth waveform (10/700 µs) is omitted here. The waveform definitions are similar in [39] and [40]. The test levels depend on the installation conditions, installation classes (will be explained in Section 3.2.2), and the coupling mode and vary from 0.5 to 4 kV.

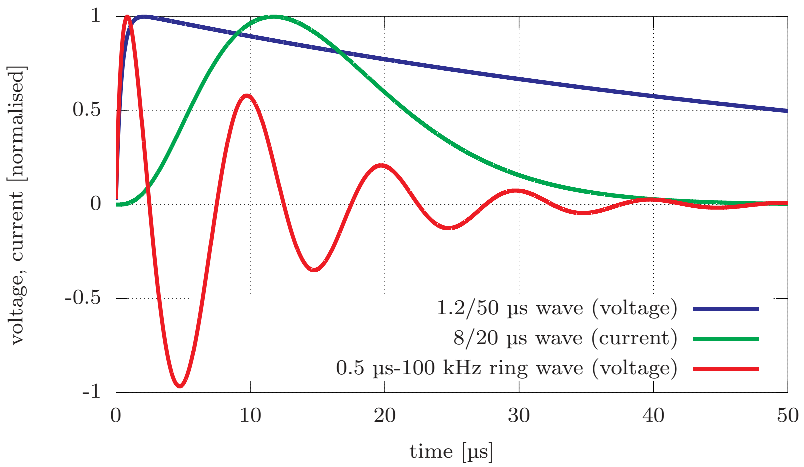

Figure 2.7: IEEE Std C62.45-2002 [39]: Surges.

2.5.3 Electric Fast Transients

An Electric Fast Transients (EFT) is within the definition of a surge, but as a common practice it is distinguished from a surge because of its characteristics: the duration is usually less than a few microseconds. Like surges, EFTs are also caused by switching, more specifically by reignitions and usually come in bursts. “This is the phenomenon that plagued new electronic controls in the 1970s and 1980s, and one of the motivations for the development of new standards” [38]: the IEC 801-4 in 1988 (the predecessor of IEC 61000-4-4 [41]) and IEEE 37.90.1 [42] in 1989. The EFT test is very popular in the civil world as a quick first test for immunity. In military standards, like the AECTP 501 [5], it is non existent. The EFT waveform is defined by a rise-time of 5 ns and a pulse-width of 50 ns, represented in Figure 2.8 as a double exponential function that meets this definition. The amplitude is dependent on the required limits in Table 2.3, defined in the generic and product standards. Test are required on signal ports and power ports [43], [44] with performance criterion B (see Section 3.1). The selection of the levels will be explained in Section 3.2.1.

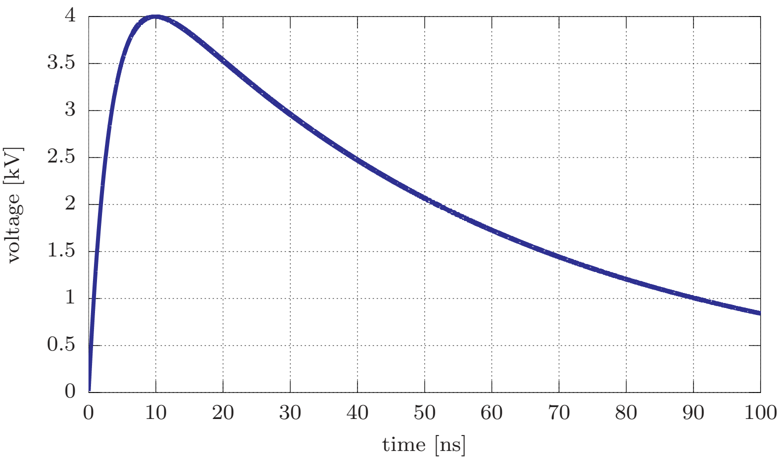

Figure 2.8: IEC 61000-4-4 [41]: EFT.

Table 2.3: Open circuit levels for basic EFT immunity tests

Level	On power port, PE	On I/O signal, data and control ports
	Voltage peak [kV]	Voltage peak [kV]
1	0.5	0.25
2	1	0.5
3	2	1
4	4	2
x	Special	

2.5.4 Electrostatic discharge

Electrostatic Discharge (ESD) is the "transfer of electric charge between bodies of different electrostatic potential in proximity or through direct contact" [1]. During maintenance, contact of personnel with the structure can create an electrostatic charge build-up on both personnel and structures, particularly on non-conductive surfaces. This build-up and subsequent discharge can constitute a safety hazard to personnel or may damage electronics. ESD can be a serious hazard to munitions, fuel and helicopter operations. This is not covered in this thesis. ESD tests are defined for immunity on the enclosure port only [43], [44] with performance criterion B (see Section 3.1). Immunity levels are defined as 2, 4, 6 or 8 kV [45]. Figure 2.9 shows the resulting ideal contact discharge current waveform at an output voltage of 4 kV from an ESD generator [45]. The amplitude is dependent on the required limits (see Table 2.4), defined in the generic and product standards.

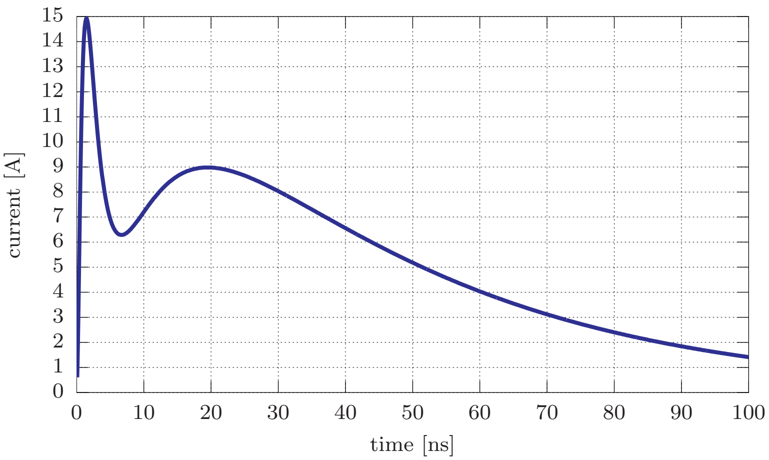

Figure 2.9: IEC 61000-4-2 [45]: Ideal ESD current caused by 4 kV contact discharge.

Table 2.4: Test levels for basic ESD immunity tests

Level	Contact discharge Test voltage [kV]	Air discharge Test voltage [kV]
1	2	2
2	4	4
3	6	8
4	8	15
x	Special	

2.5.5 Nuclear Electromagnetic Pulse

Nuclear Electromagnetic Pulse (NEMP) results from a High Altitude Electromagnetic Pulse (HEMP). The waveform defined by Equation (2.1) in Figure 2.10 is the result from a secret study performed by USA and UK, based on measurements during a few events, combined with a theoretical analysis.

$$E(t) = \begin{cases} 0 & t \le 0 \\ E_0\, k_1 \left(\mathrm{e}^{-\alpha t} - \mathrm{e}^{-\beta t}\right) & t > 0 \end{cases} \tag{2.1}$$

$$\text{where: } \begin{aligned} E_0 &= 50\,000\ [\mathrm{V/m}] \\ k_1 &= 1.3 \\ \alpha &= 4 \cdot 10^7 \left[\mathrm{s}^{-1}\right] \\ \beta &= 6 \cdot 10^8 \left[\mathrm{s}^{-1}\right] \end{aligned}$$

The energy density of this pulse is 0.11 $\mathrm{J/m^2}$, the rise-time is 2.5 ns, the fall-time or decay-time is 55 ns, the pulse-width or full-width-half-maximum is 23 ns.

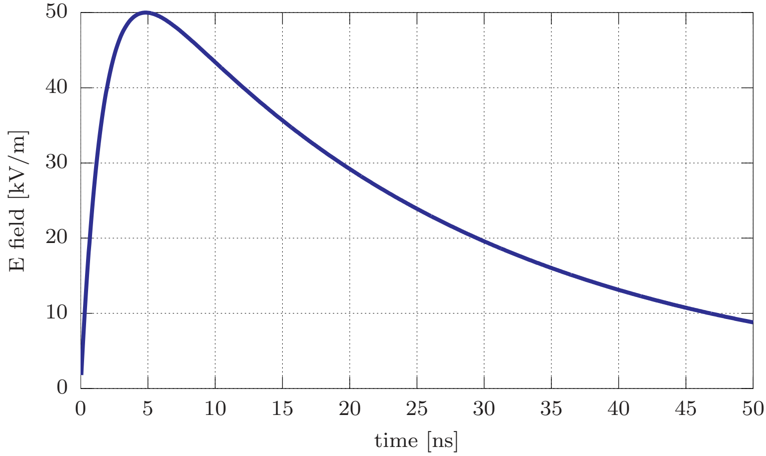

Figure 2.10: IEC 61000-2-9: Nuclear Electromagnetic Pulse.

2.5.6 Overview of surges and fast transients

Figure 2.11 shows the normalised frequency content of most of the waveforms in this section. These waveforms are also present with similar definitions in military standards, like AECTP 501 [5], except for the EFT waveform.

One way of mitigating surges and fast transients is the use of a Surge Protection Device (SPD), which divert damaging surges, not upsetting surges (see Section 6.4). Another way is to create a proper propagation path for these phenomena as will be discussed in Section 5.2.

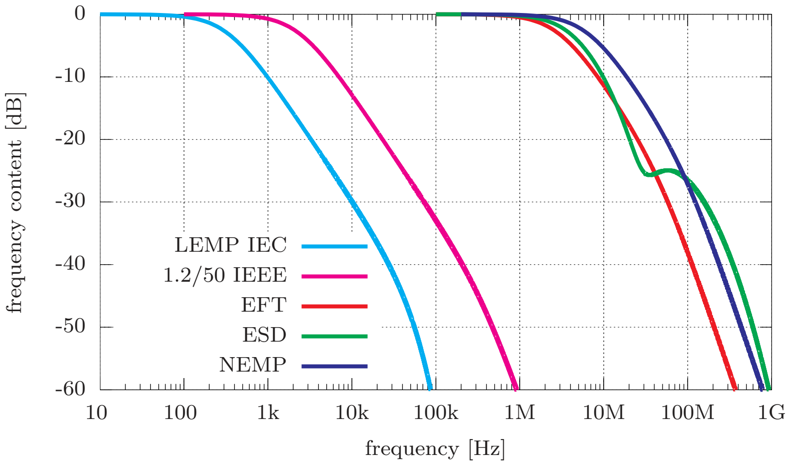

Figure 2.11: Normalised frequency content of several surges and fast transients.

2.6 Other source categories

The following source categories are included for completeness, but not further covered in this thesis.

2.6.1 Unwanted Emissions

Unwanted emissions are covered by two terms. EMCON avoids to reveal presence, whereas TEMPEST is about compromising information contents. Mitigation measures generally will serve both. TEMPEST is a codename for methods to spy upon others through leaking emanations as well as how to shield equipment against such spying, also referred to as Emission Security (EMSEC). It is not guaranteed that requirements for TEMPEST and EMCON are met if the EMC requirements are met.

EMCON generally provides for protection against detection by hostile forces who may monitor the electromagnetic spectrum for any emissions that indicate the presence and operation of military electronics. These unintentional emissions may originate from spurious signals, such as local oscillators, being present at antennas or from electromagnetic interference emissions from platform cabling caused by items such as microprocessors.

Operations on naval ships are frequently conducted in electromagnetic silence which is the most stringent state of EMCON. Other systems located on board the ship (such as aircraft, tow tractors, fire control radars, and ship communication systems) are not permitted to transmit on any radios, radars, and navigation equipment over the frequency range of 500 kHz to 40 GHz. This operation has resulted in requiring systems deployed on ships are capable of controlling emissions from their on-board active transmitters by quickly changing operating mode to receive, standby, or off and to control all other unintentional emissions such that they are undetectable [21].

EMCON and TEMPEST are solely a matter of military concern, so they will not be found in civil standards. Generally speaking, EMCON requirements are in the same order of magnitude as the various radiated emission requirements from military and civil standards, although these measurements are hard to compare, since there is a huge difference in test set-up, frequency range and specific test methods, such as peak detection, quasi-peak detection, etc.

2.6.2 Intentional EMI

Intentional Electromagnetic Interference (IEMI) is defined as the intentional malicious generation of EM energy introducing unwanted signals into systems disrupting, confusing or damaging these systems for terrorist or criminal purposes. It is often referred to as High Power Microwaves (HPM) and HPM source capabilities have been kept secret by allies and enemies.

Since IEMI is deployed by HPM weapons, the expected High Power Electromagnetics (HPEM) environment for which equipment has to be protected is hard to predict. In fact, IEMI should be treated like Electronic Warfare (EW). Therefore IEMI standards are not and cannot be written in the same way as the standards discussed in the previous sections.

Assuming that naval vessels are generally protected against a range of electromagnetic threats and because the distances between a vessel and a malicious HPM source is usually rather large, IEMI might be seen as a negligible threat.

2.7 Conclusion

This chapter defined the possible sources and interference mechanisms, determined by a triptych of a source, coupling path and victim with the specifications of the various phenomena. In the next chapter, electromagnetic environments will be defined, based on these electromagnetic sources and interference mechanisms.

Chapter 3

Electromagnetic environment

To get insight in the risk that comes with the integration of equipment in another than its intended environment, the actual environment must be compared with the intended environment. In this chapter, an attempt is made to classify intended electromagnetic environments with disturbance levels, compatibility levels and possible performance criteria. All environments are based on the electromagnetic (EM) phenomena that are addressed in Chapter 2

There are many classifications of intended environments and even more standards to describe them. For example, part 2 of the IEC 61000 series of publications is dedicated to the environment for Electromagnetic Compatibility (EMC). Specifically IEC 61000-2-5 [46] provides extensive but not complete [47] knowledge of the existing electromagnetic environment, intended for guidance for considering and developing immunity requirements. Emission limits from the International Special Committee on Radio Interference (CISPR) define the environment for Radio Frequency (RF) protection.

The first sections of this chapter will summarise different electromagnetic environments, based on the characteristics that are found in several EMC standards. It is observed that the information about environment classifications is not consistent over the different IEC standards. The taxonomy in these standards could be much more uniform. This chapter starts with generic Commercial off the Shelf (COTS) equipment in Section 3.1. Section 3.2 is dedicated to conducted interference. Section 3.3 refers to civil maritime standards that will be further discussed in Chapter 10. Section 3.4 defines the naval environment, which is a maritime environment for specific miltary use.

3.1 Generic environment categories

The IEC generic EMC standards define the performance criteria, (A, B and C), and the generic environment categories (Residential, commercial and light industrial, versus Industrial). They specify a limited number of essential emission and immunity tests, as well as minimum test levels that are applicable when there are no product standards available. The aim is to ensure adequate compatibility at the same time as achieving a good balance between technical and economic considerations.

Performance criteria

Emission and immunity is to be demonstrated under one of the next performance criteria from IEC, as specified for each test in a generic or product standard.

- Performance criterion A: The apparatus shall continue to operate as intended during and after the test.
- Performance criterion B: The apparatus shall continue to operate as intended after the test.
- Performance criterion C: Temporary loss of function is allowed, provided the function is self-recoverable or can be restored by the operation of the controls.

This can be interpreted as A: no effect, B: temporary effect, C: no permanent damage. The AECTP 501 [5] uses four different performance criteria, which gives guidance in how to formulate the performance criteria and whether they are measurable or visually inspectable.

Generic environments, based on RF protection

Two generic environment categories are well defined in some product standards (e.g. [48]), but not up-to-date in IEC/TR 61000-2-5 [46], where you would expect it. These categories are based on the classes A and B from CISPR (CISPR 11 [49] and CISPR 22 [50]). So these environments are based on RF emission limits and therefore basically deal with RF protection (Section 2.1).

- **Residential, commercial and light industrial environments (class B)**
  Environment encompassed by the generic emission standard IEC 61000-6-3 [51]. This category varies from low-end consumer electronics to professional Information and Telecommunication Equipment (ITE). Until the early 2000's, there was a distinction between residential, commercial and light industrial environments, but now they are combined into one category for houses, apartments, shops, supermarkets, offices, banks, cinemas, public bars, dance halls, petrol stations, car parks, amusement and sport centres, workshops, laboratories, service centres, etc. [48]. The protection distance for the protection of radio reception against radiated emissions in this category is 10 m, reflecting apartment size, according to an older version of the standard [52]. The immunity of equipment in this environment is arranged in the generic standard IEC 61000-6-1 [43].

- **Industrial environment (class A)**
  Environment encompassed by the generic emission standard IEC 61000-6-4 [53]. Industrial locations are in addition characterised by the existence of one or more of Industrial Scientific and Medical (ISM) apparatus; frequently switched heavy inductive or capacitive loads; high currents and associated magnetic fields [48]. The immunity of equipment in this environment is arranged in the generic standard IEC 61000-6-2 [44].

3.2 Environments for conducted disturbance

Environments for conducted disturbance are addressed in several IEC standards. The aim of these standards in this section is to provide protection equipment against conducted phenomena, not being RF protection.

3.2.1 Transient environments and their protection levels

Environments for transient interference are defined in the IEC 61000-4-4 [41]. The IEC 61000-4-16 [54] and not yet active IEC 61000-4-19 [55] for conducted immunity use the same definitions.

- **Level 1: Well-protected environment**
  The computer room may be representative of this environment.
- **Level 2: Protected environment**
  The control room or terminal room of industrial and electrical plants may be representative of this environment.
- **Level 3: Typical industrial environment**
  The area of industrial process equipment may be representative of this environment.
- **Level 4: Severe industrial environment**
  The outdoor area of industrial process equipment where no specific installation practice has been adopted, power plants, the relay rooms of open-air H.V. substations and gas insulated substations of up to 500 kV operating voltage (with typical installation practice) may be representative of this environment.
- **Level 5: Special situations to be analysed**
  The minor or major electromagnetic separation of disturbance sources from equipment circuits, cables, lines etc., and the quality of the installations may require the use of a higher or lower environmental level than those described above. It should be noted that equipment lines of a higher environmental level can penetrate a lower severity environment.

3.2.2 Surge environments and their protection levels

The surge immunity test standard IEC 610200-4-5 [40] has a similar classification as for the transient environment above:

- Class 0: Well-protected electrical environment, often within a special room. Surge voltage may not exceed 25 V.
- Class 1: Partly protected electrical environment. Surge voltage may not exceed 500 V.
- Class 2: Electrical environment where the cables are well-separated, even at short runs. Surge voltage may not exceed 1 kV.
- Class 3: Electrical environment where cables run in parallel. Surge voltage may not exceed 2 kV.

– Class 4: Electrical environment where the interconnections run as outdoor cables along with power cables, and cables are used for both electronic and electric circuits. Surge voltage may not exceed 4 kV.
– Class 5: Electrical environment for electronic equipment connected to communication cables and overhead power lines in a non-densely populated area. Surge voltage may not exceed 4 kV.
– Class x: Special conditions specified in the product specification.

3.2.3 Environments for PDS, UPS, and AIC

An adjustable speed electrical Power Drive System (PDS) or an Uninteruptible Power Supply (UPS) can be found in many systems nowadays. Since Photo Voltaic (PV) installations are emerging, also the Active In-feed Converter (AIC) is added in this list. These systems come in various sizes and are intended for various environments with different emission and immunity levels.

– EMC standard IEC 61800-3 [56] for PDS
– EMC standard IEC 62040-2 [57] for UPS
– Technical specification IEC 62578 [58] for AIC

The standards for PDS and UPS define the next two environments and four categories of equipment, all with their own emission and immunity limits. The technical specification for AIC refers to these two standards for EMC considerations. The EMC standard IEC 61204-3 [48] is dedicated to Switched Mode Power Supplies (SMPSs), but the emission and immunity limits are copied from the generic standards.

Figure 3.1 shows a typical current waveform with its spectrogram that can be found in an industrial environment with several Surge Protection Devices (SPDs). These measurements were performed with a conventional current clamp with a cut-off frequency of about 150 kHz and showed the same characteristics in the entire environment, Not only on cables, but also on water pipes, the construction, etc.

Environments

– **First environment**
Environment that includes domestic premises and establishments directly connected without intermediate transformers to a low-voltage power supply network which supplies buildings used for domestic purposes.
– **Second environment**
Environment that includes all establishments other than those directly connected to a lowvoltage power supply network which supplies buildings used for domestic purposes.

Equipment categories

- **Equipment category C1**
  - PDS of rated voltage less than 1 000 V, intended for use in the first environment.
  - UPS intended for use without any restriction in the first environment.
- **Equipment category C2**
  - PDS of rated voltage less than 1 000 V, which is neither a plug in device nor a movable device and, when used in the first environment, is intended to be installed and commissioned only by a professional.
  - UPS with an output current not exceeding 16 A and intended for use without any restriction in the second environment and with restrictions in the first environment.
- **Equipment category C3**
  - PDS of rated voltage less than 1 000 V, intended for use in the second environment and not intended for use in the first environment.
  - UPS with an output current exceeding 16 A and intended for use in the second environment. Such UPS are suitable for use in commercial or industrial installations having a minimum boundary of 30 m from other buildings classified as first environment.
- **Equipment category C4**
  - PDS of rated voltage equal to or above 1 000 V, or rated current equal to or above 400 A, or intended for use in complex systems in the second environment. A PDS on an Isolated Terra (IT) grid inherently has to be categorised as class C4, which means that unlimited Radiated Emission (RE) are allowed.
  - UPS intended for use in complex environments and subject to an agreement between supplier and customer regarding applicable emission and immunity levels.

3.2.4 Low frequency aspects

The development of fast switching high power transistors made it possible to implement sophisticated power electronics in a variety of widely used applications, such as SMPS, PDS, AIC for PV installations and energy efficient compact lamps. Also modern washing machines, ventilation systems, air-conditioning units, water pumps and other mechanical applications use a kind of PDS. These equipment cause a lot of noise on the power leads, mainly in the frequency range from a few kHz to 150 kHz, but often even much higher. For PDS there is a product standard [56] that warns for possible radio interference in which case supplementary mitigation measures may be required. At the same time, there is an increased use of signalling on the Low Voltage (LV) grid, e.g. for Power Line Communication (PLC) for smart metering. It should not be a surprise that interference problems are observed.

Until recent, emission limits in civil EMC standards ([51] and [53]) have been focused

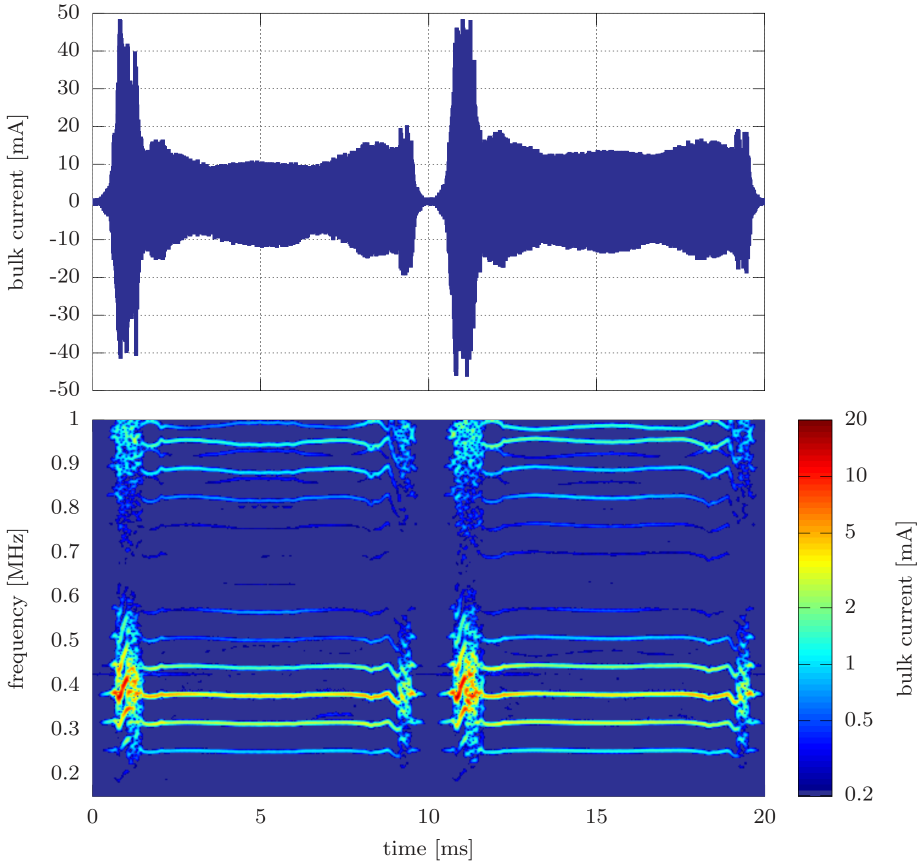

Figure 3.1: Typical bulk current in an industrial environment with its spectrogram.

on the protection of radio broadcast and mobile communication services. Discussions on radiated and conducted emission requirements started with the beginning of long wave radio broadcasts in the 1920's [11]. Therefore it is no coincidence that these standards start at 150 kHz. For the purpose of Power Quality (PQ) there are requirements on harmonics and inter-harmonics up to 2 or 2.4 kHz. Military standards, like the AECTP-501 [5] do require conducted emission tests on the power leads from 30 Hz to 10 MHz in order to reduce EMI towards the power distribution system, to prevent hull currents on naval ships, and to protect military radio services that operate well below the civil 150 kHz boundary. There are no civil standards dealing with coupling in the same way as military standards do. This is one of the differences between civil and military standards that puts a challenge on the integration of COTS equipment in modern naval shipbuilding [59]. So there is an uncovered frequency range of 2 to 150 kHz in civil EMC standards (with the exception of CISPR 15 [60]) that only recently gets attention for EMC as mentioned before in [61]. There are two new standards that provide procedures for the testing of conducted immunity in the frequency range below 150 kHz. The standard for Common Mode (CM) immunity [54] (levels in Figure 3.2) has been accepted as a basic standard. The other one is for Differential Mode (DM) immunity [55] (levels in Figure 3.3) and is still in development. The red limit lines for comparison in Figure 3.2 are from the military standards.

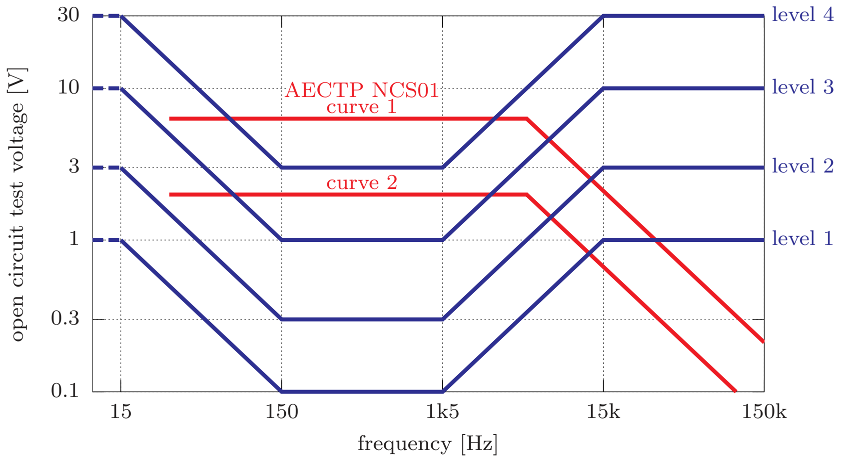

Figure 3.2: IEC 61000-4-16 [54]: Immunity to conducted CM 0 Hz to 150 kHz, compared to AECTP 501 [5].

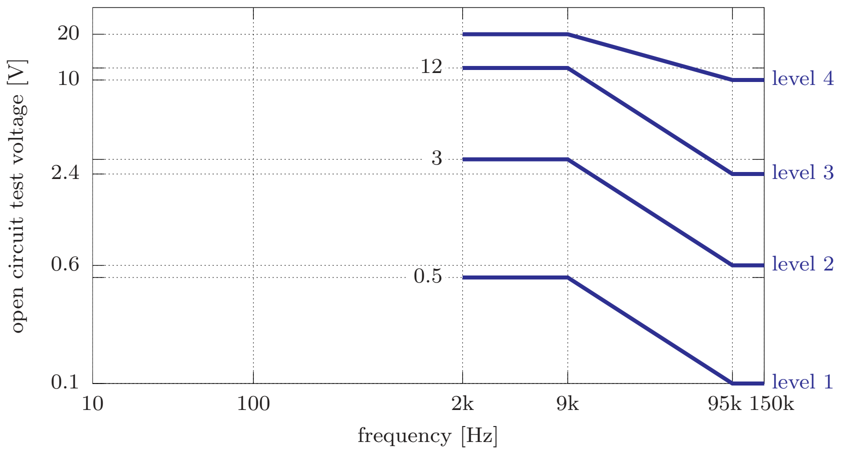

Figure 3.3: IEC 61000-4-19 [55]: Immunity to conducted DM 2 kHz to 150 kHz.

The time dependent behaviour of the conducted spurious phenomena in the power supply network of complex installations calls for dedicated measurement techniques in time domain. Frequency domain measurement equipment is not suitable for these time variant disturbances. On this topic, a paper is published [62], in which quantities to measure are defined for DM as well as CM as in Figure 3.4. Various measurement sensors are designed, implemented, characterised and tested. The proposed measurement methods provide a basis for the analysis of conducted behaviour of equipment as well as fixed installations. This research is continued by others at the University of Twente.

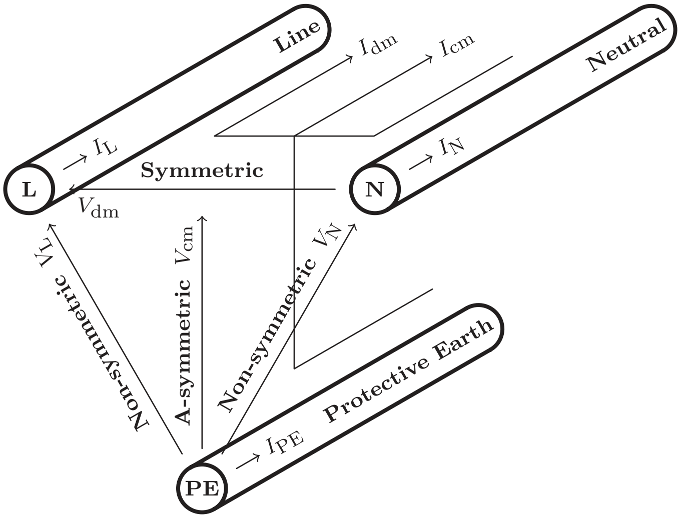

Figure 3.4: Definitions of non-symmetric, symmetric (DM) and a-symmetric (CM) mode.

3.3 Maritime environment

The IEC 60533 [63] is an EMC standard for electrical and electronic installations in ships. Its scope is to assist in meeting the requirements of International Maritime Organization (IMO) resolution A.813 [64], which "**invites** Governments to ensure that all ship's electrical and electronic equipment is tested to the relevant electromagnetic compatibility standards.".

Another maritime standard is the IEC 60945 [14].

The limits and test methods in these standards are different from the generic standards in a number of ways. It is not always clear why certain choices have been made. These differences make it impossible to use generic COTS equipment without extensive testing and maybe hardening. Therefore the IEC 60533 is not cost effective and difficult to implement for the matter of equipment emission and immunity limits.

These maritime standards will be extensively reviewed in Chapter 10, including their rationale and possible alternatives.

3.4 Naval environment

Specific equipment for military applications may be commercially available and is in most cases specified by a NATO Standardization Agreement (STANAG) and may have export restrictions. This kind of equipment is sometimes referred to as Military off the Shelf (MOTS) and will have been certified according to the AECTP 501 [5], a national standard like the Mil-Std 461 [6] or Def-Stan 59-411-3 [65]. Not all electromagnetic disturbances will be present on all kinds of vessels. A tug for example will not be exposed to the highest field strengths and will not have sensitive surveillance radars as a frigate will. In the risk-based approach, measures to be taken to achieve EMC must be tailored to the customer's need, i.e. the contractual environment, that is based on the anticipated external exposure and the capabilities of the ship. The most important inputs for this contractual environment are (see also Figure 2.1): The maximum power of all types of transmitters, overview of sensor and communication capabilities, choice of power distribution network (insulated, earthed, Direct Current (DC), etc.), presence of electric propulsion, required protection levels for lightning, Nuclear Electromagnetic Pulse (NEMP), and requirements for unwanted emissions.

3.4.1 Exposed environment above deck

The exposed or unprotected environment above deck is characterised by external exposure as well as sensors and actuators that operate using intentional electromagnetic fields. All phenomena from Chapter 2 play a role to an extent that is dependent on the definition of the contractual environment. On many naval ships, most equipment need to be hardened according to military standards, like AECTP 501 [5], tailored to the contractual environment, the type of equipment and the position of the ship.

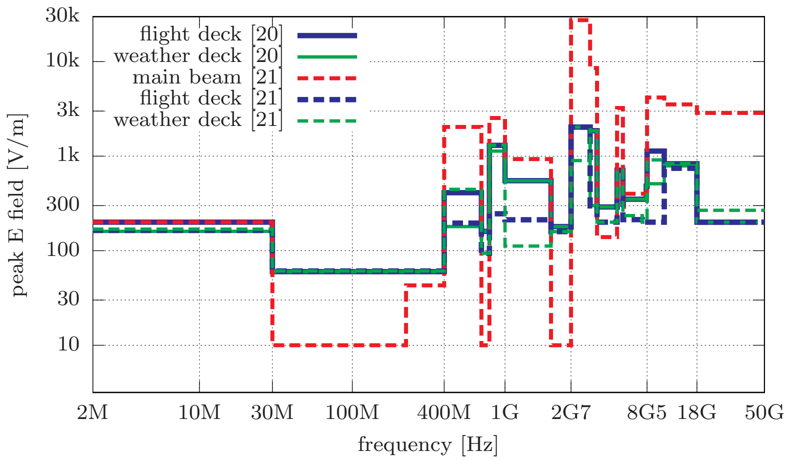

Figure 3.5: Maximum expected exposed environment on a naval ship according to AECTP 250 [20] and Mil-Std 464 [21].

The 200 V/m limit from AECTP 501 does not represent the worst-case High Intensity Radiated Fields (HIRF) environment to which equipment may be exposed. Electromagnetic environments can be highly variable. As a result the field strength can even be much higher. During the Integrated Topside Design (ITD) study the maximum electric field strength values will be estimated by calculations at locations of the exposed equipment. This maximum electric field strength as function of frequency is called the *skyline*. Examples can be found in AECTP 250 [20] Leaflet 258, and in Mil-Std 464 [21], see Figure 3.5, where field levels are based on the Effective Isotropic Radiated Power (EIRP) from existing emitters in defined frequency bands. Semi-open spaces, such as the bridge and hangar need special attention. Relatively high field strengths from the top-side can be expected. A lot of bridge equipment is commercially available, but might not be suitable for this environment unless special care is taken. For the prevention of intra-ship Electromagnetic Interference (EMI), antennas are placed during the ITD process such that the field strength at the bridge is less than 10 V/m.

3.4.2 Protected environment below deck

The immunity levels for equipment below deck are 10 V/m in contrast to the 200 V/m above deck. This implies that these military equipment standards assume a protection by the ships hull that provides a total shielding effectiveness of at least 26 dB, regardless of the status of doors and hatches, etc.

3.4.3 Specific military applications that need attention

Extremely Low Frequency (ELF) and Very Low Frequency (VLF) radio are purely a matter of military concern. Sonar is used for military and civil ships. A possible EMI threat is application of COTS equipment with non-linear behaviour, such as harmonic distortion, causing problems in the frequency range for conducted immunity below 150 kHz and for radiated immunity below 80 MHz. If ELF and VLF radio equipment is installed on board with polluting COTS equipment as described above it is possible that problems will arise when no special measures are taken. whereas the AECTP 501 [5] provides a requirement (NRE01) to protect this kind of equipment, civil standards contain only little data on these low frequencies below 150 kHz.

3.5 Conclusion

This chapter summarised different electromagnetic environments, based on the electromagnetic phenomena in Chapter 2, inspired by several EMC standards. Not all electromagnetic disturbances will be present on all kinds of vessels. In the risk-based approach, measures to be taken to achieve EMC must be tailored to the customer's need, i.e. the contractual environment, that is based on the anticipated external exposure and the capabilities of the ship.

Chapter 4

Equipment standards

Efforts in the past to harmonise military and civil standards have been unsuccessful. The approach is not the hardening of Commercial off the Shelf (COTS) equipment to comply with the rather conservative standards, but to develop a risk based philosophy where Electromagnetic Compatibility (EMC) management is embedded in the design process. The role of EMC standards in the design and procurement process has to be put into perspective. It is important to learn from the rationale behind some aspects of the military equipment standards with the aim to obtain a solution of equipment integration in another environment than its intended. Part of this chapter is also presented in [59].

4.1 Confidence level of EMC testing

Research on functional safety is considered out of the scope of this thesis about EMC, but it is important for systems on board that are mission critical or essential for safety. Lloyd's Rules [10] require in their Section 4.13.1 under EMC that: "Propulsion, steering, navigation and other essential systems, including weapons systems are to be designed and installed such that their performance does not degrade from the manufacturer's specifications as a result of susceptibility to electromagnetic interference generated during both normal operation and during military activities."

Many papers have been published on the relation between EMC and functional safety [66], [67], [68], [69]. In these papers, it is pointed out that applying the rules from many of the existing EMC standards does not always produce a satisfactorily safety level that is necessary or desirable in some cases. EMC testing is insufficient for Functional Safety [68]. Increasing the immunity test levels is not sufficient for high-reliability and critical equipment [66]. Other techniques must be used to demonstrate the achievement of the desired reliability [67].

Measurement methods are standardised to obtain the same results from different test houses. The confidence level is a measure for the reproducibility of such measurement method. Any EMC assessment has a limited confidence level. For the research on functional safety, a confidence level of 90 % is assumed in [69] whereas the International Special Committee on Radio Interference (CISPR) gives an interpretation of the radio disturbance limit by the so called 80/80 rule:

> **80/80 rule [70]**
> "The significance of the requirements for compliance of the apparatus with the standard shall be that, on a statistical basis, at least 80 % of the series produced apparatus complies with the requirements with at least 80 % confidence."

The confidence level should not be confused with a quantified risk for Electromagnetic Interference (EMI). There is no such thing as a quantified EMC level. Equipment and systems are either compatible in a defined and quantified environment with a certain performance criterion, or they are incompatible. The only quantifiable EMC rate of equipment would be a susceptibility level (defined in Section 2.2), which is normally not included in acceptance tests.

4.2 Differences between military and civil standards

In the past an attempt was made to identify the technical differences and to calculate what is needed to harmonise military standards and civil standards with respect to measurement methods, frequency range and limits [71], [72], [73], [74], [75], [76]. The most important conclusions from these so-called gap analyses are: the different intended environment (frequency ranges, limits, etc.), the different test methods that can not always give a useful comparison, and the fact that according to military standards equipment is tested more extensively against a much wider range of threats. Therefore, when using equipment complying to civil standards in the military environment without changing the integration philosophy poses a high uncertainty, and probably a high risk of not getting the desired performance, robustness, safety and continuity.

Another known practice is the hardening of civil COTS equipment followed by extensive testing for compliance to military standards. This approach is not preferable in the below deck environment in modern naval shipbuilding for several reasons: It requires special design for the hardening of the equipment. COTS components get obsolete, so also replacement parts must undergo special design and compliance testing. This makes it inflexible to change the design and replace obsolete parts efficiently during the platform's life cycle. Therefore, this is not a cost effective approach.

Because of the just mentioned two reasons, it is not a good idea to perform a technical gap analysis between military and civil standards. It is clear that there are differences.

The philosophy is not to bring them together but to create an environment in which other equipment than the so-called Mil-Std equipment will function as intended. In this way, COTS equipment is integrated as sheltered equipment in a created industrial or light-industrial environment. This is the risk based EMC approach embedded into the design process as proposed in Section 1.1.3.

4.3 Rule based vs. risk based

The traditional rule based approach is based on requiring compliance to Allied Environmental Conditions and Tests Publication (AECTP) 501 [5] or Mil-Std 461 [6] for all equipment and components. These are installed on the platform, applying proper installation measures, such as shielding, earthing, bonding, cable separation, etc. The idea behind these equipment standards is to provide the necessary performance, robustness, safety and continuity on platform level, with an acceptable risk, estimated with a high certainty, obtained by clear acceptance procedures. This is a proven practice, based on experience gained from many decades.

This practice does not guarantee success and it will lead to overkill measures in particular situations. The limits for the tests should be representative of those typically found in most installations in the past and have mostly been derived by empirical measurements. Therefore, these EMC standards should be tailored by skilled people to meet the intent of the requirements, as also noted in the documents themselves (e.g. [6]). The procuring authority should give consideration to tailoring the limits where applicable.

The use of strict equipment standards puts restrictions on the choice of equipment. Besides military equipment it is desirable to integrate also equipment that is put on the market, intended for instance for residential, office, industrial, maritime and medical use. A pitfall in the procurement process is that standards are used as is without tailoring, assuming that it is the best way to do risk management and assuming that in this way no EMI will occur. So, compliance with equipment standards is only a presumption of achieving low risk EMC management.

Also, most knowledgeable people in this field, who know about these findings in the past, already retired, will retire soon, or moved out of their technical field. Moreover, tailoring needs insight in the rationale behind the standards, which is often hidden in scientific publications and in background material of standards, such as the appendices of the Mil-Stds. Knowledge can not be managed solely by archiving the outcome of research activities. It requires also skills and experience within the team.

4.4 Conclusion

The strict use of military equipment standards is a pitfall in procurement that makes naval shipbuilding unnecessarily expensive and might give a false presumption for EMC. Nowadays, state of the art technology is integrated on naval platforms conform standards with legacy rationale. Therefore there is a need for a clear rationale that fits more to the state of the art technology. Some addressed aspects of the effects of a military naval environment on civil COTS equipment show that a careful design with properly engineered EMC protection measures can be an alternative for the hardening and compliance requiring for all integrated equipment.

Chapter 5

Integration aspects

Some decades ago, electronics became smaller, digital logic faster, voltages lower, to a degree where equipment no longer worked. Designers were facing the same problems: cross-talk and transmission line effects on Printed Circuit Boards (PCBs) made the, originally independent, hardware modules interfere with each other. It was difficult to build the increasingly complex hardware. This hardware crisis was similar to the software crisis, even some decades earlier [77]. It had become increasingly difficult to produce software as the programs became larger. One programmer could no longer solve the problem on his own and many programmers had to work together on the task. The answer to this challenge was "modularisation": Individual programmers write modules that would then be combined as building blocks for the larger program. In fact, this principle was copied from the hardware into the software discipline: Cars had been built from engines, gearboxes, wheels and chassis for decades already.

The true reasons for this modularity are *hierarchy* and *abstraction* [78]. Considering the first, a complete system is built as an hierarchy of independent building blocks of ever increasing complexity. At the hardware bottom, components and modules can be bought on the market. These are used to build larger assemblies with a more complex behaviour. This process repeats until the desired hardware platform functionality has been achieved. At every level, engineers combine assemblies from the preceding layer to create more complex building blocks. The second essential element is abstraction, which means that the engineer using a building block has no need to know what is inside, but can trust blindly on the specifications of the block. Software engineers focus on the creation of loosely coupled, coherent modules as building blocks in an effort to make their behaviour as independent as possible of the behaviour of other modules. This can be copied into the world of hardware, and more specific for

Hierarchy

Building the system as a layered structure with increasingly complex behaviour where modules from a lower level serve as building blocks for higher level modules.

Abstraction

Hiding the inner workings of modules from the engineers that use them as building blocks. This in order to reduce complexity.

Electromagnetic Compatibility (EMC), modules would be electromagnetically independent i.e. electromagnetically compatible. In the end, hundreds of engineers, each with their own specialisms, are working together in hierarchical layers to eventually design, build, test and deliver a complete platform. "Hierarchy" and "abstraction" are metaphor's. Translated into the realm of EMC for naval shipbuilding, equipment or groups of equipment that intensively interface with each other are separated electromagnetically from other groups using available, or specially built, rooms which usually have metal walls, floors and ceilings into regions or zones that are inherently shielded from each other. Doing so places each group in its own electromagnetic environment that can be tuned to match the environment for which the equipment was originally built. To maintain this shielding when interconnecting cables are laid between the groups, requires provisions that keep this separation intact. Installing these measures is commonly referred to as zoning.

Zoning on a naval ship will increase robustness and decrease complexity and it helps to separate responsibilities. Zoning is inevitable in cost effective naval shipbuilding. Section 5.1 will provide a manual to define the different EM zones on board with the relations and interfacing requirements between them. In Section 5.2, three types of current boundaries will be introduced to decouple the relevant environments on either side of a zone boundary. This Section is a part of publication [79].

5.1 EMC zones

The purpose of zoning is to create separate environments in which equipment that was designed for different electromagnetic environments and mostly also performing different tasks can work. In this way, electromagnetic disturbances are contained in their zone where they are produced. This separation will avoid harmful interference between different kinds of equipment. Zoning allows for tailored EMC measures in each zone and on zone boundaries. A malfunction of one kind of equipment will not cause a widely distributed disturbance. Therefore zoning will increase robustness and decrease complexity. Equipment placed together must be carefully selected for mutual compatibility. In general, all equipment of the same kind, i.e. that is intended to be used in a particular environment, will be mutual compatible. It is necessary to have a proper zone plan to create an environment for each class of equipment, so it can operate in its intended environment. Appropriate engineering practices have to be applied at all zone transitions for the attenuation of radiated and conducted electromagnetic phenomena. The zoning concept in IEC 60533 [63] is a good start, but is limited to measures taken at the power distribution. It is assumed that the metallic hull on commercial ships does not provide sufficient shielding to create a Radio Frequency (RF) protected environment [80], whereas naval ships do. A zoning concept should go much further. To create the proper protected environments below deck, measures must be taken that are common on naval ships, though should be tailored to the customers need, i.e. the anticipated and contracted electromagnetic environment, defined by the external environment but also possible disturbances within the platform itself.

5.1.1 Definition of EMC zone types

The concept of zoning is illustrated in Figure 5.1. The possible zone definition in Table 5.1 has four different electromagnetic zones with several types of sub zones.

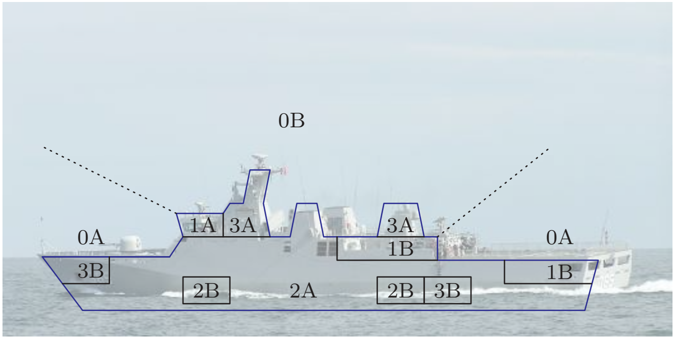

Figure 5.1: Example of general zoning set-up.

Table 5.1: Zone type definitions

	type	area	description
Exposed Environment	**0**	**Outer Deck Area**	
	0A	General outer deck	Platform equipment such as lights, winches, pumps, cranes, etc. Also Replenishment at sea
	0B	Antenna Zone	Mast for sensor weapon and communication (SEWACO)
	1	**EM Outer Deck Area**	
	1A	Bridge area	Bridge, Flying Control Centre (FLYCO)
	1B	Other electromagnetic outer deck	Roll on Roll off deck, Hangar, Gun/Missile rooms, Flight deck officer room
Protected Environment	**2**	**General Inner Ship Area**	
	2A	Living quarters	Offices, Crew quarters, Recreation areas, Sanitary spaces, Storage rooms
	2B	General power distribution	Machine room, Galley, Work shop
	3	**Special electromagnetic Areas**	
	3A	Electronic spaces	Compass room, OPS room, Command information centre, Radio Room, Radar and radio equipment rooms, Computer rooms, etc. TEMPEST requirements might be applicable.
	3B	Special power distribution	Frequency drives for propulsion, large pumps, winches. Motors connected to large frequency drives.

Zone 0 and 1 are exposed to electromagnetic events outside the ship, whereas zone 2 is protected against these events. Zone 3 is also protected and contains equipment that has special requirements regarding its electromagnetic environment. Zone type 3A also includes TEMPEST areas. A number of examples are given to clarify which spaces could belong to a certain zone. Some sub-zones have an explicit physical barrier, whereas other sub-zones are only separated by distance and design rules. It is even possible that some zones or sub-zones may not interface with other zones directly. The zone plan must be designed in such a way that it follows the principles of hierarchy and abstraction employing loosely coupled zones, i.e. not requiring a high number of interfacing cables between them.

5.1.2 Source victim analysis

Next, the electromagnetic interactions between the equipment in different zones must be checked against the phenomena in Table 2.1. The possible sources, victims, and phenomena are summarised in table 5.2. The following two examples show how to follow this process.

Example: Bow thruster room

The bow thruster room will get type 3B, "special power distribution zone." The neighbouring zone is of type 2A, "living quarters." The bow thruster room will house an electro motor and a Power Drive System (PDS). This kind of equipment usually generates a significant amount of radiated and conducted emissions, that might interfere with radio reception and radar detection. These RF signals must be kept in this zone and care must be taken to the installation of radio equipment within this zone. Low Frequency (LF) phenomena such as surges and High Frequency (HF) phenomena like EFT propagate as CM currents and might couple to other cables and equipment via crosstalk. Additional cable separation might be required and the integration of Commercial off the Shelf (COTS) equipment in this zone is only possible after a more detailed analysis after which additional measures might be prescribed. The cable feeding the PDS is likely to contain more CM disturbances than expected in an environment for which the equipment in the neighbouring zone is intended for. The bow thruster and auxiliary equipment can be classified as industrial equipment with immunity limits above the expected environmental levels in a below deck protected environment. Other items on the check list in Table 2.1 are not applicable here. Concluding, the following precautions are applicable:

- The bow thruster room is to be separated from the living quarters by a zone boundary.
- Cables and pipes through this boundary must be limited to the ones that are strictly necessary, whereas others are routed around the zone.
- Cables and pipes through this boundary must be circumferentially bonded to the boundary.
- A cable feeding a PDS that runs through the living quarters, because it cannot be routed around it, shall be installed in a properly mounted cable tray,

Table 5.2: Summary of sources, victims, and phenomena

Sources / **Victims**	Above deck transmitters	Above deck receivers	Equipment enclosure port	Equipment power port	Equipment signal port	Networks & cables	Personnel, fuel & ordnance	TEMPEST & EMCON
HIRF	4	4	2	2	2		3	11,12
Lightning direct hit	7	7				7		
Lightning Electromagnetic Pulse (LEMP)				7	7	7		
Radio Frequency (RF) environment		1						
Power Supply (PS)				5	6,8	8		
Electrostatic Discharge (ESD)			9					
Nuclear Electromagnetic Pulse (NEMP)	4	10			10	10		
Unwanted emissions								11,12
Intentional Electromagnetic Interference (IEMI)		12	12	12	12	12		

1. **Unintended Radiated Emission (RE)** from equipment
2. **Intentional radiated fields** from radio and radar transmitters
3. **Non-ionising Radiation Hazards (RadHaz)**, to personnel, fuel, and ordnance.
4. **Electromagnetic Interference (EMI)** between transmit and receive antennas
5. **Power Quality (PQ) related sources** of disturbance on the Power Supply (PS).
6. **Crosstalk**, and Common Mode (CM) disturbances
7. **Lightning**: A direct lightning hit and Lightning Electromagnetic Pulse (LEMP).
8. **Surges and Electric Fast Transients (EFT)**, generated by switching devices
9. **Electrostatic Discharge (ESD)**
10. **Nuclear Electromagnetic Pulse (NEMP)**
11. **Unwanted Emissions**: Emission Control (EMCON) and TEMPEST
12. **Intentional EMI**, deploying one of the above disturbing mechanisms intentionally.

separated from other cables and equipment.

- Integration of COTS equipment in the bow thruster room must be limited to necessary equipment and needs an extra engineering analysis for compatibility.

Example: Command Information Centre (CIC)

The CIC also will get type 3A, "electronic space." It will contain consoles with switches, keyboards, computer screens, communication terminals, computing power, network equipment, etc. Everything can be built from COTS equipment, typically Information and Telecommunication Equipment (ITE) that is designed for the office and light industrial environment. Disturbances from other parts of the ship must be kept out of this zone. Equipment in the CIC will not produce high field strengths and will not contain sensitive radio receivers, except for Wi-Fi like equipment, which has proven to work well in office environments. Cables to and from this zone will be of type power and Ethernet (glass or copper), with hardly any exception, assuming for example that communication is implemented as Voice over IP (VoIP). A neighbouring zone of interest in this example is a radio room, which is another "electronic space." with different characteristics for which RF protection is an issue. Concluding, the next precautions are applicable:

- The CIC is to be separated from the living quarters by a zone boundary.
- Cables and pipes through this boundary must be limited to the ones necessary, whereas other are routed around the zone.
- Cables and pipes through this boundary must be circumferentially bonded.

5.1.3 Lightning protection zones

Similar to the zoning concept above, Lightning Protection Zones (LPZs) are defined in [81] to describe the level of interaction between the lightning strike and the consequences inflicted on the environment. The general principle is that the equipment should be located in a zone whose electromagnetic characteristics are compatible with the equipment immunity capability. If the boundary between zones is penetrated by some interface, then this interface must be protected either by means of shielding or filtering, including over-voltage protection where necessary, in order to maintain the zoning protection.

The LPZs represent the space surrounding a Lightning Protection System (LPS). There can be at least two, if not more, of such zones. Zone LPZ 0A is the most violent, with complete exposure to a direct strike. Everything located in this area has a maximum potential to be impacted by the lightning current and the full electromagnetic field. In the special case when such objects located in LPZ 0A present any form of protective shell, the volume under this shell becomes LPZ 0B. The particularity here consists in the fact that such a shell protects this volume against a direct lightning strike. However, everything remains exposed to the full electromagnetic field.

Other zones are LPZ 1, where everything in these zones is only protected against direct lightning strike, and is partially affected by the lightning currents and the full electromagnetic field. A reduction of the lightning current is achieved with the help of Surge Protection Devices (SPDs), mentioned in Section 6.4. Each additional level of attenuation together with the reduction of the generated electromagnetic field, through the use of SPDs and shielding materials, will generate new zones, in the lines of LPZ 2, LPZ 3 and so on, up to the point when the remaining currents and electromagnetic field no longer represent a threat.

This section on LPZs is also published in [37].

5.2 Current boundaries

In Section 5.1, zoning was introduced to facilitate modularity in the system design and integration process for reasons of hierarchy and abstraction. The next step is to apply the appropriate provisions at the interfaces between zones to shield radiated electromagnetic (EM) fields and to contain conducted disturbances in their own zone. These zone interfaces must act as current boundaries for all cables, pipes and other infrastructure that may carry CM current over these current boundaries.

5.2.1 Definition of the current boundary

The term "electromagnetic barrier" was mentioned in [82] for the same purpose. The term "current" has been added here to indicate the barrier functions by short circuiting common-mode currents. The barrier for CM currents is located at the current boundary. The current boundary is a concept or metaphor in the realm of EMC "bonding" [82], [83], [84]. The current boundary will be introduced by showing how it separates electromagnetic environments, firstly considering a system as a combination of cable-interconnected cabinets.

Type I: The Cabinet Level Current boundary

Figure 5.2 shows a simple mains-power CM current loop. The loop being formed by the cabinet's mains cables, their interconnecting data and signalling cable and the mains cabling, closing the loop. Any CM noise currents generated by other equipment on the mains or induced by fields in the environment may flow in this loop even when the equipment is off and, in general, the cabinet designer has no control over them. In addition, CM currents can be generated by either or both of the two cabinets when switched on.

As shown by the equivalent electrical model in Figure 5.3, the resulting CM current I_{cm} will flow through the cabinets. If nothing is done, the noise currents on the cables may pollute the cabinet internal environments. A current barrier can now be built for each cabinet as shown in Figure 5.4. The original CM current path still flows through the left cabinet, but in the right cabinet, the routing of the CM path is changed and the newly created inside loop is short circuited at the current boundary. This is called current boundary type I. It prevents the CM current from flowing through the cabinet. A current barrier is a short circuit for CM currents.

This short circuit is crucial as it separates a large CM current loop, into two loops. To avoid mutual induction crosstalk, loop areas on both sides of the current boundary should subsequently be reduced. Whether complete shielding is necessary, depends on the (noise) frequencies at play. If the major threat is a relatively low frequency lightning induced CM current, the current barrier alone may be sufficient. Another important aspect is that a current barrier works in both directions: it keeps external CM currents out but also keeps cabinet internal CM currents in.

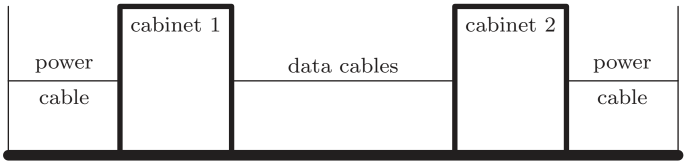

Figure 5.2: Mains Power CM-Current Loop.

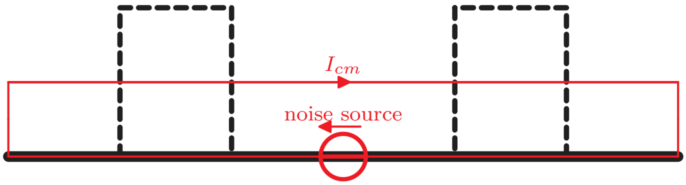

Figure 5.3: Equivalent electrical model.

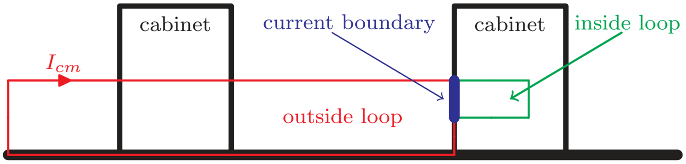

Figure 5.4: Provision of a current boundary Type I on the right cabinet.

Figure 5.5: Connector plate as part of a shielding cabinet
as an example of a current boundary type I.

In practical applications, the current boundary is usually shaped as a connector or EMC gland plate as shown in Figure 5.5. Preferably, the current barrier should be mounted at one location only on a cabinet. More than one connector plate implies there is a CM current path between them which then needs to be carefully defined on the cabinet. An inherent assumption is that CM and Differential Mode (DM) currents in cables are separated by cable screens that carry the CM currents which are then transferred to the current boundary via the low impedance cable terminations.

If there is no cable screen, e.g. on an unscreened power cable, a filter can be installed at the current boundary to separate the CM currents from the DM currents. This filter technique assumes that the DM currents are low frequency, traditionally the Alternating Current (AC) mains, whereas the CM currents are high frequencies. As before, the CM-currents are passed to the current boundary in this case through the filter CM path to flow back to their source via other connected cables. Current boundary type I prevent CM currents to pass the current boundary and provides a means to minimises the magnetic coupling between CM loops. A more quantitative approach to the magnetic decoupling by current boundaries can be found in Chapter 8 and [85].

Type II: Cable Protection using Current boundaries

At the inter cabinet level, current boundary type II is used to protect and/or separate cables. In modern installations equipment and cabling is tested for emissions and immunity implying the cabling in itself is adequate for the signals transported over them and the level of disturbance in the environment. But for extreme threats like exposure to direct lightning, extra protection is called for against the vast $I \times R$ voltages that may occur. In such cases, extra protection can be obtained from a metal strip following the cable from cabinet current boundary to cabinet current boundary with a low impedance connection to both: a metal cable tray [84, pp. 33-35] as in Figure 5.6. Often, structural metal, available in the installation, can be used. The important requirement is this continuous conductive path from cabinet current boundary to cabinet current boundary whereas the cable under protection should be kept as close to the metal as possible to reduce the CM loop area [84, page 38]. The metal strip forms a low impedance short circuit across the cable as a preferred path for a threatening CM current. Keeping the cable close to the strip reduces the loop between them. In some standards, e.g. [86] or [63], cable categories are distinguished from sensitive to disturbing in combination with a required separation distance between those categories.

It is important to note that such distances imply the presence of a common metal strip or ground plane current boundary. Without it, separation distances have no meaning. It short circuits the length of the cable and serves as a return path for cable generated CM currents. These return currents will select a path that minimises induction which is called the proximity effect as it is the path closest to the cable and actually separates cables on the strip by reducing the mutual induction between them as shown in Figure 5.7. The current distribution $J(x)$ in the ground plane normalised to its amplitude J_0 is a function of the ratio between the lateral distance x along and the height h above the ground plane [87, Eq. (10-14)]

$$\frac{J(x)}{J_0} = \frac{1}{1 + \left(x/h\right)^2} \tag{5.1}$$

Current boundary type II minimises both the capacitive and magnetic coupling between CM circuits. The inherent assumption is that the sensitive or victim cable is

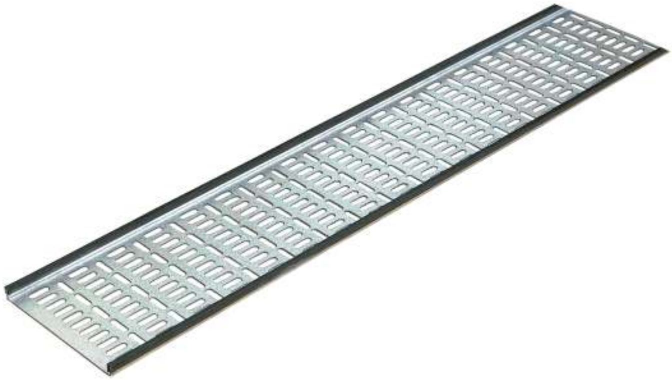

Figure 5.6: Metal cable tray to protect and separate cables as an example of current boundary type II.

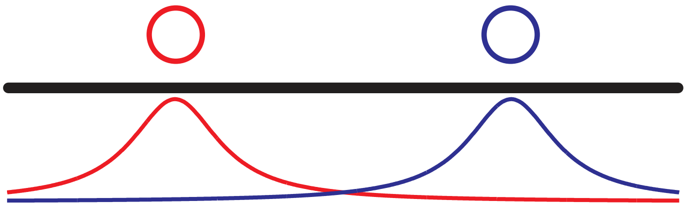

Figure 5.7: Distribution of the common mode current from two cables above a ground plane.

also kept close to the current boundary type II to minimize the loop area that could pick up fields. A quantitative analysis of this type of current boundary is given in Chapter 7 and published in [88].

Type III: Cabinet Shielding

A complete metal shielding of all circuits within a cabinet is current boundary type III. This short circuits the CM currents induced by the external or internal fields. The shield doubles as connector plate, current boundary type I. A type III current boundary acts as a Faraday cage and minimises magnetic coupling, capacitive coupling, as well as radiated coupling. Note that a loop that is small compared to the wavelength does hardly radiate, as will be quantified in Section 8.1.1.

5.3 Conclusion

System reliability depends heavily on the correct behaviour of all building blocks at all times. Electromagnetic Interference (EMI) is a major threat that often manifests only in the final integration and tests phases of the platform. It is shown that creating electromagnetically independent modules is easy if a few simple steps are consistently followed. The method pivots on two essential systems engineering aspects:

1. **Hierarchy**: Building the system as a layered structure with increasingly complex behaviour where modules from a lower level serve as building blocks for higher level modules.
2. **Abstraction**: Hiding the inner workings of modules from the engineers that use them as building blocks. This in order to reduce complexity.

Different electromagnetic (EM) zones on board a naval ship are defined. The relations and interfacing requirements between the zones are given. Zoning will increase robustness and decrease complexity and it helps to separate responsibilities. Zoning is inevitable in cost effective naval shipbuilding. The purpose of zoning is to separate equipment that was designed for different EM environments and usually performs different tasks. Zoning is not limited to shield radiated EM fields. Also conducted disturbances should be contained in their own zone.

The goal is to protect equipment against environmental effects that it is not intentionally designed for and to protect radio services and sensor performances against possible interferences from equipment that is allowed to emit in its intended environment.

It is necessary to have a proper zone plan to create an environment for each class of equipment, so it can operate in its intended environment. It is important to have a tailored zone plan as early as possible in the project. The appropriate installation measures have to be applied at all zone transitions for the attenuation of radiated and conducted electromagnetic phenomena.

Three different types of current boundaries have been introduced. Whereas current boundary type I is merely focused on magnetic decoupling between Common Mode (CM) current loops, type II aims at avoiding crosstalk due to magnetic and capacitive coupling between loops that are positioned alongside each other. Type III creates a Faraday cage that also prevents coupling through radiation. Zoning itself also prevents radiated coupling at very high frequencies, i.e. where the wavelength is short with respect to the distances.

Chapter 6

Best practices for protection against EMI

As all problems of Electromagnetic Interference (EMI) are determined by a triptych of a source, coupling path and victim (Chapter 2), measures must be taken to make the actual and intended environments (Chapter 3) compatible. These measures, or mitigation techniques are generally known and are often called best practices.

A best practice is a method or technique that has consistently shown results superior to those achieved with other means, and that is used as a benchmark. In addition, a best practice can evolve to become better as improvements are discovered. Best practice is sometimes used to describe the process of developing and following a standard way of doing things that multiple organisations can use. Best practices are used to maintain quality and can be based on self-assessment or benchmarking. Best practices can be considered as installation guidelines for topics such as Electromagnetic Compatibility (EMC) zones, earthing, bonding, cables and equipment. Installation guidelines provide clear information how items shall be installed by an installation engineer on board a naval vessel. Best practices are used to cover the electromagnetic effects on equipment as well as ships level.

Best practices are generally not quantitative in nature and inevitably include guidelines like “as short as possible” and “should be avoided”. In Part II an effort is made to make rules quantitative.

Not all electromagnetic disturbances will be present on all kinds of vessels. In the risk-based approach, measures to be taken to reach EMC must be tailored to the customer’s need, i.e. the contractual environment, that is based on the anticipated external exposure and the capabilities of the ship. The best practices for EMC must be tailored accordingly. The best practices in this chapter are to separate all equipment from possible disturbances, defined by the contractual environment.

The application of zones and current boundaries are two important best practices that are already discussed in Chapter 5. The next sections will cover Integrated Topside Design (ITD) in Section 6.1, Shielding by ships enclosure in Section 6.2, Hardened equipment in Section 6.3, Over-voltage protection in Section 6.4, Cabling in Section 6.5, and Earthing and bonding in Section 6.6.

6.1 Integrated Topside Design (ITD)

Integrated Topside Design (ITD) is the process of positioning the suite of sensor weapon and communication (SEWACO) equipment on the above deck portion of the ship to get an acceptable performance grade of this complete SEWACO-suite for each required mission. ITD involves many disciplines, such as safety, survivability, mechanical vulnerability, sensor performance, signatures, interference analysis, etc. The tasks that involve EMC are:

- Perform EMI analysis
  to control interference between transmitters and receivers. Usually, the results are shown in a Source Victim (SV)-victim matrix.
- Radiation Hazards (RadHaz) analysis
  to prevent unwanted exposure of human beings, ordnance or fuel to high electromagnetic field strengths.
- Field estimate from transmit antennas
  to accommodate the previous two tasks and to limit the field strength in sensitive areas such as the bridge and other semi-open spaces. These field estimates are also necessary for setting the damage levels of sensors on the own ship as well as on other ships in the convoy.
- Rolling sphere analysis
  to determine the possible locations where a direct lightning strike might hit the ship.

In case of unacceptable results from above analyses, some options for mitigation techniques can be:

1. frequential
   frequency management, apply filters;
2. spatial
   rearranging of topside elements, modify the superstructure, sector blanking;
3. temporal
   time blanking, scheduling;
4. coding domain
   apply error correction, robust coding;
5. if these four diversity measures are not sufficient, it is possible to mount Radar Absorbing Material (RAM), or apply shielding.

ITD can be used to restrict the existence of High Intensity Radiated Fields (HIRF) to certain areas of the ship. In this way, the field strength on for example the bridge can be limited to a value below 10 V/m to prevent intra-ship EMI. The below deck surroundings are a protected environment, sheltered from the outside world. Also disturbances from below deck cannot adversely affect radio communication and radar detection. There is not just one protected environment, but each class of equipment is integrated in a separate zone, as defined in Section 5.1. Many of the next best practices take place at the boundary between zones, including the boundary between the topside and the protected environment below deck.

6.2 Shielding by ships enclosure

The metal ships enclosure acts as a Faraday cage and creates a protected environment below decks by shielding the radiated electromagnetic fields. The quality of shielding can be expressed quantitatively by the Shielding Effectiveness (SE), which is the ratio between the field strength inside the enclosure and the illuminating field strength if no shielding were present. The SE can be measured according to IEEE Std 299 [89] and IEEE Std 299.1 [90].

The AECTP 501 [5] and the Mil-Std 461 [6] have built in the assumption that naval ships have a minimum SE of 26 dB by requiring a Radio Frequency (RF) field immunity of 200 V/m above deck and 10 V/m below deck. The latter immunity level also applies to generic industrial equipment according to IEC 61000-6-2 [44]. The radiated emission limits for RF protection in [5] and [6] are 20 dB higher for below deck compared to above deck. For commercial ships, the hull has not always a sheltered effect. An observed low SE by the superstructure [80] was the rationale to skip the differentiation between above and below decks from the first to the second edition of IEC 60945 [14].

It is a best practice to put a current boundary (Section 5.2) at the shielding enclosure, see Section 6.2.2. As an alternative to the Faraday cage which shields electromagnetic fields, it may be sufficient in some cases to create a magnetic decoupling of current loops. This will be discussed in Chapter 8.

6.2.1 Screening on windows

Bridge areas, including the Flying Control Centre (FLYCO), have windows, whereas some SE might be necessary. Windows with special metal coatings are available on the market. A drawback of this measure is reduced visibility, which in general is not acceptable for the user. Equipment to be installed in the bridge must be positioned out of view of the window to avoid line of sight illumination, such that the irradiation through the window is minimised. The field strength from on-board transmitters in the bridge area should be less than 10 V/m by design (Section 6.1). In this way intra-ship EMI is prevented. Risks that will remain are Nuclear Electromagnetic Pulse (NEMP) and radiated field from transmitters on nearby ships.

6.2.2 Circumferentially bonded feed-throughs

To maintain the SE it is important that any cable, pipe, hose, etc. shall be circumferentially bonded where it penetrates the hull. This means a continuous metal-to-metal bond around the outer perimeter of a metallic item or cable screen terminating at or penetrating through a metal surface, acting as a current boundary. A circumferential bond keeps the current uniformly distributed around the circumference of the cable screen, which is required for the magnetic shielding of the cable [87, Section 2.15]. If the bond is not uniformly distributed, a pigtail exists, which has an adverse effect on crosstalk [91]. A circumferential bond is a current boundary type I as described in Section 5.2.1. Its effect is:

1. to retain the SE between two zones, or the SE of an enclosure, such as a cabinet, junction box, etc.,
2. to obtain a low transfer impedance in Ohm (Z_t) of the connection,
3. to limit the size of Common Mode (CM) loops, i.e. their area and circumference,
4. to contain conducted CM disturbances in one location.

When even one of these bonds is not properly installed, this can have an adverse effect on other cables in its vicinity and on the zoning integrity [92], [93]. A quantitative approach of cable terminations is given in [85] and Chapter 8.

Circumferential bonds can be achieved by cable glands, Multi Cable Transits (MCTs), and connectors, which are usually applied to meet requirements for air or water tightness. These items can have additional specifications for EMC, i.e. including the circumferential bond. Figure 6.1 shows an example of MCTs. When such an MCT is placed on the outer deck, corrosion may deteriorate its EMC performance, especially when it is applied in the horizontal plane. Figure 6.2 shows an alternative screen termination that is more cost effective. This alternative circumferential bonding is not symmetric, compromising the SE of the screened cable for higher frequencies. This is acceptable if the wavelengths of the offending CM-currents are long, i.e. the conducted EMI effects far dominate the radiated.

Figure 6.1: Roxtec Multi Cable Transit (MCT).

Figure 6.2: Screen termination at earth strip.

6.2.3 Waveguide below cut-off principle

Small openings in the hull, e.g. for ventilation, will not affect the *SE* significantly, as long as no insulated conductors penetrate through these apertures and the diameter of the hole is small compared to the wavelength. Fiber-optic cables and non-conductive plastic hoses should go in conductive pipes that are circumferentially bonded. This provision operates on the waveguide below cut-off principle, explained e.g. in Mil-Hdbk-1195 [94] or Mil-Hdbk-1857 [95].

6.3 Hardened equipment

A known practice is the hardening of civil Commercial off the Shelf (COTS) equipment followed by extensive testing for compliance to military standards, e.g. AECTP 501 [5]. This approach made EMC a cost driver and might give a false presumption of EMC. In Chapter 4 and [59] it was shown that this approach is not preferable in the below deck environment in modern naval shipbuilding. Technological developments and diminishing funding dictate the use of COTS equipment below deck. The short economic life cycle of COTS equipment forbids electromagnetic hardening of individual equipment. For above deck equipment, the requirement of hardening might be inevitable, depending on the expected environment at its location.

All equipment has a certain immunity level. The generic standards IEC 61000-6-1 [43] and IEC 61000-6-2 [44] show an expected immunity for RF electromagnetic field, Electrostatic Discharge (ESD), Electric Fast Transients (EFT), surges, voltage dips and voltage interruptions to a limit that is sufficient for the intended environment. If the immunity limits are low, compared to the voltage and signal levels at which the equipment itself operates, then hardening efforts can be small and good design practice with a sense for EMC will be a good start. In that case, immunity compliance testing can be replaced by an analysis or demonstration. If the immunity limits go up to above the equipment's own signal and power levels, hardening demonstration gets less evident and especially for military limits, an acceptance test becomes inevitable.

6.4 Over-voltage protection

A surge, including a fast transient, is a transient wave of electrical current, voltage, or power propagating along a line or a circuit and characterized by a rapid increase followed by a slower decrease [1]. Several forms of surges and fast transients have been addressed in Section 2.5. They can appear on power lines, signal lines and RF frond-ends.

In general, there are two ways to mitigate surges and fast transients: One way is to create a short circuit or low impedance path for these phenomena and direct them to where they can not damage sensitive equipment nor cause EMI in another way. This is called a current boundary as described in Section 5.2.1 and can be achieved by using screened cables, cable separation (Chapter 7), proper cable terminations (Chapter 8), etc. Additionally, high impedance blocking, e.g. by a Common Mode Choke (CMC), prevents currents through the sensitive equipment.

Another way is to absorb the over-voltage with a Surge Protection Device (SPD). An SPD or surge protector is an appliance designed to protect electrical devices from voltage surges. A surge protector attempts to limit the voltage supplied to an electric device by shorting to earth any unwanted voltages above a safe threshold. Over-voltage protection is applied at the entrance or zone transition. Sometimes it is called a Transient Protection Device (TPD). It can be applied on the power leads as well as on data lines. SPDs can be put in cascade. When applied in an RF front-end, it is usually called a limiter. An SPD is a non-linear device, meaning that it has no or a negligible effect for signals below the clamping voltage and it acts above this clamping voltage. Therefore, SPDs divert damaging surges, not upsetting surges. Requirements and tests can be found in IEC 61643-1 [96]. Important specifications for over-voltage protection devices are:

- Clamping voltage
  Also known as the let-through voltage. This specifies the resulting voltage caused by the protective components inside a surge protector to divert unwanted energy from the protected line.
- Joules rating
  This number defines how much energy a surge protector can theoretically absorb in a single event, without failure.
- Response time
  Surge protectors do not operate instantaneously; a slight delay exists. The longer the response time, the longer the connected equipment will be exposed to the surge.

Literally millions of SPDs, varistors in particular, have been installed in low-voltage Alternating Current (AC) power circuits since their introduction in 1972 [38]. All distributed SPDs on a distribution network together provide adequate protection for all equipment in a certain area, also for unprotected equipment. Surges will still exist, but should be monitored as currents instead of voltages [97]. This distributed protection mechanism is not guaranteed for EFT, where the geometry of an installation becomes larger than the wavelength of EFT phenomena. Research, published in [92] (Section 7.8), has shown that frequently occurring or repetitive transients, such as EFT/bursts below the clamping voltage, can easily disrupt an Ethernet communication link. So, for fast transients, and surges below the clamping voltage of the SPD, a proper propagation path for the surges and fast transients is the only solution. When the repetition frequency of transient disturbances is high, then SPDs have to clamp often, which has an adverse impact on the throughput of data and may disrupt data links.

6.5 Cabling

The performance of equipment is well defined by many standards that exist on EMC. The essential requirements from the European Union (EU) in Table 1.1 state functional, though specific requirements for equipment ("Equipment shall be so designed and manufactured, $\cdots$"). But for fixed installations, i.e. the infrastructure of cables, connectors, cable conduits etc., the EMC Directive speaks about "good engineering practices $\cdots$". Especially in large and complex installations, this is where best practices play a role.

6.5.1 Cables above a ground plane

It is a good practice to place cables close to a ground plane. In this way there is less crosstalk between cables, the cable is less susceptible for external fields, and will produce less RF emissions. A ground plane forms a current boundary type II as introduced in Section 5.2.1. It serves as a return path for cable generated CM currents, that will select a path that minimises induction. This is called the proximity effect as it is the path closest to the cable as is illustrated in Figure 5.7 in Section 5.2.1. In Chapters 7 and 9 the effect of a ground plane will be analysed quantitatively. The use of cable trays, screened cables, or rigid pipes can be seen as a ground plane that is folded around the cable.

6.5.2 Cable trays

The use of cable trays provides a reduction of the transfer impedance, as do screens of cables. It is an economical choice which to choose, or both in some circumstances. An alternative is to mount cables close to a conductive ground plane, or use the structure of the ship, e.g. steel beams, as cable guides. A grid of continuously connected cable trays provide a dense earth-mesh that attenuates the propagation of conducted interference. Cable trays are commercially available and widely used in buildings.

It is important to stress that cable trays only function if they are also conducting the CM currents and should follow the protected cable over its full length: from current boundary to current boundary. Interrupted cable trays shall be electrically interconnected to realise a continuous ground plane for all cables.

Figure 6.3 shows five different configurations from a ground plane to a closed construction. Various shapes are investigated in [98] together with their Z_t, which is

Figure 6.3: Cables above a ground plane. Improvement from left to right.

a good protection measure. Whereas a completely closed structure performs best, a cable conduit with noncontacting cover is still excellent [99] and an open metal conduit performs better [100] than just a ground plane.

6.5.3 Apply screened cables

By applying cable screening the following electromagnetic phenomena will be reduced: cable cross-talk, interaction between different electromagnetic zones, radiated emission and immunity. Figure 6.4 shows an example of a screened cable. The screen will shield electromagnetic fields and act as a current path for conducted disturbances. The quality of a screened cable can be expressed quantitatively either by the SE or the Z_t. The latter is defined by the ratio of the Differential Mode (DM) voltage and the CM current, assuming one of them induces the other. Sometimes, the quality of a screened cable is specified by a certain minimum optical coverage of the screen (e.g. 84 or 95 %), if it is constructed of braided copper. The preferred quantitative measure is Z_t. This also applies to the terminating connectors, glands, etc.

In order to reduce costs it is a common practice to apply unscreened cables that comply with all of the following requirements:

- are used as power supply lines (24V / 115V / 230V / 400V / 440V);
- that power equipment that causes little disturbance (e.g. suitable for the residential, commercial and light industrial environment);
- that do not cross any EMC zone transitions;
- that are applied in the inner deck zone (zone types 2A and 2B in Figure 5.1).

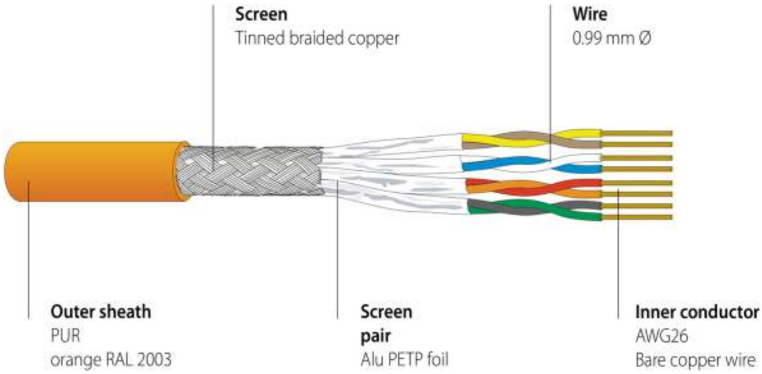

Figure 6.4: Example of a screened cable (Datwyler CU 7702, Cat. 7 Ethernet).

6.5.4 Cables in a metal enclosure

In some cases it is not practicable to use a properly bonded screened cable, or the SE is not sufficient, e.g. above deck, or the system developer prohibits any external connection of the outer screen of a cable. In these cases, other common practices are available. Cables can be run in a metal enclosure, such as a solid pipe, flexible metal conduit (Figure 6.5), or a closed cable conduit, provided that these items are bonded on both sides, at all zone transitions, and preferably at more points. When using properly mounted high quality screened cables below deck, generally a metal cable tray is sufficient.

Figure 6.5: Example of a flexible metal conduit (Anaconda-Sealtite®).

6.5.5 Cable separation

Cable separation rules to prevent crosstalk between different cable categories are in use for over five decades. These cable separation practises have been derived in an era where equipment did not meet legal or contractual requirements, where signals in the cables where analogue and knowledge on EMC was still in development. The rationale behind these rules is lacking and these rules appear not to be written for state of the art complex installations on nowadays naval vessels. Therefore it is impractical for system integrators to implement these rules and there is a need for an update. In a recent study [88], calculations and measurements are performed that give more insight in cable crosstalk in complex installations. Results from these measurements show that cable type selection is the most important factor for cable coupling. Using a properly mounted high quality screened cable together with a ground plane or cable conduit has more effect on crosstalk mitigation than cable separation. The measurements show that increasing a cable separation above approximately 5 cm has very little effect [88]. Cable separation without some kind of ground plane has little to no effect. Calculation of crosstalk between cables will be covered in Chapter 7.

6.6 Earthing and bonding

"Earthing or grounding?" is a frequently asked question. The answer is simple: It is the same, just a matter of taste. Grounding is used at the west side of the Atlantic and appears in military standards, whereas earthing tends to be used more in Europe and is the preference for the IEC [1]. In this thesis, earthing will be used, alongside screened cables and shielded rooms, whereas in the west, shielded cables and screened rooms are the preference.

A lot of words have been spent on earthing in literature. Good references are the IEC 61000-5-2 [84] and the book from Elya B. Joffe and Kai-Sang Lock [101]. But still there is a lot of discussion among system integrators and EMC engineers about earthing philosophy. Earthing for EMC usually has nothing to do with earth, but should rather be seen as bonding at current boundaries, a term that was introduced in Section 5.2.

EMC measures focus on reducing CM loops and one way to do that is use wide metal parts as return paths for CM currents. These metallic parts, such as cable trays, are usually connected to a conductor called Protective Earth (PE) for electrical safety reasons. This associates the CM return paths with "earthing".

6.6.1 Bonding

Mil-Std 464C [21] defines six bonding classes, a heritage from MIL-B-5087B (1964). Among them is a class H bond for shock hazard, with a Direct Current (DC) resistance requirement of 0.1 Ohm and a class R bond for RF potentials, requiring 2.5 milli-Ohm DC bonding resistance R_b from electronic units to structure.

Class A for antenna installation - no bonding resistance specified.
Class C for current return path - fault current versus resistance table provided.
Class H for shock hazard - 0.1 Ohm.
Class L for lightning protection - control internal vehicle voltages to less than 500 V.
Class R for RF potentials - 2.5 milli-Ohm from electronic units to structure.
Class S for static charge - 1.0 Ohm.

Mil-Std 464C [21] also gives bonding requirements for control of Electromagnetic Environmental Effects (E^3) such that the system operational performance requirements are met: "DC bonding levels shall apply throughout the life of the system:

- 10 milli-Ohm or less from the equipment enclosure to system structure, including the cumulative effect of all faying surface interfaces.
- 15 milli-Ohm or less from cable screens to the equipment enclosure, including the cumulative effect of all connector and accessory interfaces.
- 2.5 milli-Ohm or less across individual faying interfaces within the equipment, such as between subassemblies or sections."

An electric bond is an important ingredient to provide a current boundary type I of Section 5.2.1. The effect of not meeting the class R bonding requirement on the magnetic coupling between the loops on either side of the boundary is analysed in [85] and Chapter 8.

6.6.2 Multi-point bonding of screened cables

The standard bonding method for screened cables is circumferentially bonding at both sides [84] and at all EMC zone transitions, although some equipment suppliers demand one side bonding only. One side only bonding means that their screened cables shall not be bonded at EMC zone transitions which results in an electromagnetic leakage between EMC zones and EMI due to undefined CM loops. It can be valid not to connect a screen in cases where the screen is the return path for a low level, Low Frequency (LF) signal, resulting in EMI from the common impedance between the inside and outside of the cable. A best practice is to apply an additional screen around such cables which can be bonded at both sides and EMC zone transitions. This is sometimes called the triax solution.

For example, the Open DeviceNet Vendor Association Inc. (ODVA) requires that the shield should be isolated at one end of the cable, to minimise the effects of ground offsets:

Grounding of Shielded Cables [102]:

> "Shields play an important role in providing noise immunity for systems. However, an improperly installed shielded cable can cause problems due to voltage offsets in a grounding system. To minimize the effects of ground offsets, the shield should be isolated at one end of the cable. In this case, the shield should be isolated at the device. The ground can be applied at the switch or other infrastructure component. It should be noted that some European wiring practices recommend grounding the cable shields at both ends, requiring that particular care be taken to avoid ground loops. The quality of a plant's grounding system must be thoroughly evaluated prior to using this approach."

The effect of single or multi-point bonding is analysed in [92] and Section 7.8.

6.6.3 Functional earthing

Functional earthing is also referred to as EMC earthing, High Frequency (HF) earthing or RF earthing, the earth that conducts RF energy in the ships ground plane and establishes a common RF potential with ships ground plane between the connections. Whereas for protective earthing, the quality of the earth connection is quantified by its DC resistance of maximum 0.1 Ohm, at higher frequencies, the inductance, skin effect and geometry of the current loop determine the partial impedance of an earth connection.

Def-Stan 59-411 Part 5 [103] suggest the use of a bonding strap of minimum dimensions 16 mm wide and 1 mm thick. This will reduce the impedance at 10 MHz to 8 Ohm approximately for a 400 mm length. It requires a bond strap with a maximum length of one fifth of the wavelength of the highest frequency sources which can only be assessed on a product-by-product basis. It also suggests that bond straps are only useful when their inductance is lower than 25 nH. Mil-Std 1310H (2009) [104] suggest a so-called type I bond strap that will provide less than 25 Ohm impedance at 30 MHz. There is no need to perform routine RF impedance measurements on every bond for acceptance. Note that both 8 Ohm at 10 MHz and 25 Ohm at 30 MHz represent an inductance of 130 nH, neglecting the skin-effect.

Lightning also requires functional earthing [81]. This will not be further addressed in this thesis.

6.7 Conclusion

This chapter has given an overview of best practices that are used to achieve EMC. A best practice is a method or technique that has consistently shown results superior to those achieved with other means, and that is used as a benchmark. Best practices serve as measures, or mitigation techniques for the compatibility of actual and intended environments in which equipment and installations must operate. They provide protection for these equipment and installation against electromagnetic disturbances. These best practices form the basis for EMC, but are generally not quantitative in nature and often lack a rationale. In Part II an effort is made to make rules quantitative.

Part II

Quantification

Chapter 7

Crosstalk between cables

A key contributor to Electromagnetic Interference (EMI) in complex installations is the crosstalk between cables. Already in 1892 a law [30] was published on the prevention of EMI after a conducted EMI case between power cables and telegraph lines. Many requirements, rules, standards and guidelines have been published since then. Cable separation rules are in use for complex installations such as large buildings, chemical plants, oil drilling platforms and naval vessels.

Although most of the rules are derived from other rules, guidelines and standards we observe variations between them. These cable separation practises have been derived in an era where equipment did not meet legal or contractual requirements, where signals in the cables where analogue and knowledge on Electromagnetic Compatibility (EMC) was still in development. Most of all it is observed that the rationale for these rules appears to be lost.

In this chapter, the crosstalk between unscreened and screened cables is analysed by calculations and measurements to identify and quantify various coupling mechanisms. Part of this chapter is published in [88].

To define the necessary parameters for quantification, this chapter starts with Multiconductor Transmission Line (MTL) theory, that is thoroughly assessed by Clayton Paul in e.g. [105]. The model of a two conductor Transmission Line (TL) in Section 7.1 has already been derived in 1967 [106], whereas the MTL model in Section 7.2 has been published in 1985 [107] and 1988 [108]. The screened cable model in Section 7.5 has been published in 1981 [109], 1990 [110] and 1991 [111]. Despite this long known theory and established models, this topic still gets attention in new scientific publications.

The purpose of this chapter is to provide generic relations for crosstalk between various classes of cables, based on MTL theory, models and measurements. Section 7.4 shows a generic relation between cable separation and the maximum expected crosstalk, relative to cable radii and height above a ground plane.

7.1 Two conductor transmission line

Cables and wire pairs that carry a signal will be modelled by a two conductor TL as in Figure 7.1. The TL will carry a voltage $V(z,t)$ and current $I(z,t)$ as function of time t and distance z from 0 to its length $\mathcal{L}$. A fair approximation of crosstalk can be made considering only lossless TLs.

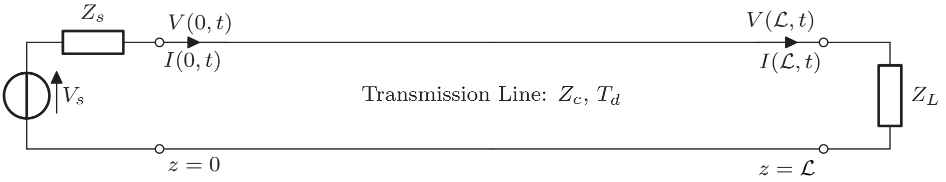

Figure 7.1: A two conductor transmission line.

The closed form analytical solution for a lossless TL is derived from many small sections of length Δz, characterised by the per unit length parameters for series inductance l and parallel capacitance c. One such section is sketched in Figure 7.2.

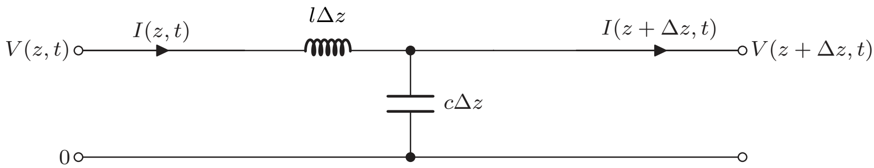

Figure 7.2: Two conductor transmission line of length Δz.

Kirchhoff's laws on this section state that

$$V(z+\Delta z,t) = V(z,t) - l\Delta z \partial_t I(z,t) \tag{7.1}$$
$$I(z+\Delta z,t) = I(z,t) - c\Delta z \partial_t V(z+\Delta z,t) \tag{7.2}$$

where ∂_t is a notation for the partial derivative $\partial/\partial t$ to t. Taking the $\lim_{\Delta z \to 0}$ gives the set of differential equations

$$\partial_z V(z,t) = -l\partial_t I(z,t) \tag{7.3}$$
$$\partial_z I(z,t) = -c\partial_t V(z,t) \tag{7.4}$$

whith ∂_z the partial derivative to z. Rearranging this gives

$$\partial_z^2 V(z,t) = lc\partial_t^2 V(z,t) \tag{7.5}$$
$$\partial_z^2 I(z,t) = lc\partial_t^2 I(z,t) \tag{7.6}$$

which has general solutions that consists of two waves V^+ and V^-, propagating in opposite directions:

$$V(z,t) = V^+(t - z/v) + V^-(t + z/v) \tag{7.7}$$
$$Z_c I(z,t) = V^+(t - z/v) - V^-(t + z/v) \tag{7.8}$$

where $v = 1/\sqrt{lc}$ is the propagation velocity over the TL and $Z_c = \sqrt{l/c}$ the characteristic impedance of the TL. These solutions at the beginning ($z = 0$) and at the end ($z = \mathcal{L}$) of the line are

$$V(0,t) = V^+(t) + V^-(t) \tag{7.9}$$
$$Z_c I(0,t) = V^+(t) - V^-(t) \tag{7.10}$$
$$V(\mathcal{L},t) = V^+(t - T_d) + V^-(t + T_d) \tag{7.11}$$
$$Z_c I(\mathcal{L},t) = V^+(t - T_d) - V^-(t + T_d) \tag{7.12}$$

where $T_d = \mathcal{L}/v = \mathcal{L}\sqrt{lc}$ is the time delay of the entire TL. The proper combination and time shifting of the last equations give

$$V(0,t) = Z_c I(0,t) + Ec_1(\mathcal{L}, t - T_d) \tag{7.13}$$
$$V(\mathcal{L},t) = -Z_c I(\mathcal{L},t) + Ec_2(0, t - T_d) \tag{7.14}$$

with two Voltage-Controlled Voltage Sources (VCVSs) Ec_1 and Ec_2. This circuit based analytical solution of the lossless TL equations has been derived in 1967 by Branin [106] and is already implemented in the Simulation Program with Integrated Circuit Emphasis (SPICE) (e.g. [112]) and can be used for transient and frequency domain analysis. This SPICE model that is specified by only Z_c and T_d is in Figure 7.3 with the two VCVSs:

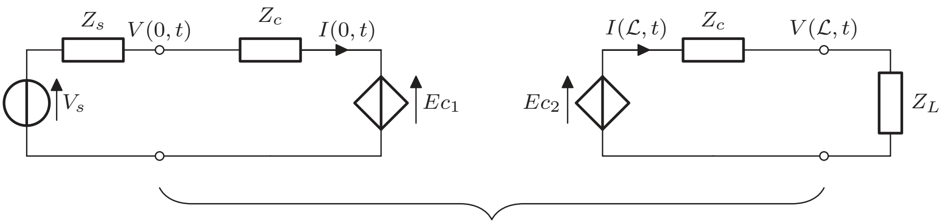

Figure 7.3: SPICE equivalent of a two conductor transmission line: Branin model [106].

$$Ec_1(\mathcal{L}, t - T_d) = V(\mathcal{L}, t - T_d) + Z_c I(\mathcal{L}, t - T_d) \tag{7.15}$$
$$Ec_2(0, t - T_d) = V(0, t - T_d) - Z_c I(0, t - T_d) \tag{7.16}$$

7.2 Three conductor transmission line

Crosstalk between cables can be calculated by the MTL model. The equations in this section are derived for three conductors as in Figure 7.4 but can easily be expanded to any number of conductors. The near-end crosstalk ($NEXT$) and far-end crosstalk ($FEXT$) are defined as

$$NEXT = V_2(0)/V_1(0) \tag{7.17}$$
$$FEXT = V_2(\mathcal{L})/V_1(0) \tag{7.18}$$

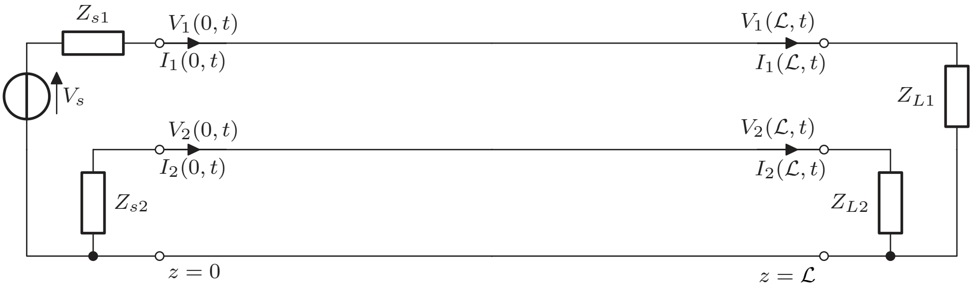

Figure 7.4: A three conductor transmission line configuration for crosstalk analysis.

The small section of the MTL in Figure 7.5 give the Kirchhoff's relations

$$V_1(z+\Delta z,t) = V_1(z,t) - l_1\Delta z\partial_t I_1(z,t) - l_{12}\Delta z\partial_t I_2(z,t) \tag{7.19}$$
$$V_2(z+\Delta z,t) = V_2(z,t) - l_2\Delta z\partial_t I_2(z,t) - l_{12}\Delta z\partial_t I_1(z,t) \tag{7.20}$$
$$I_1(z+\Delta z,t) = I_1(z,t) - [c_1+c_{12}]\,\Delta z\partial_t V_1(z+\Delta z,t) + c_{12}\Delta z\partial_t V_2(z+\Delta z,t) \tag{7.21}$$
$$I_2(z+\Delta z,t) = I_2(z,t) - [c_2+c_{12}]\,\Delta z\partial_t V_2(z+\Delta z,t) + c_{12}\Delta z\partial_t V_1(z+\Delta z,t) \tag{7.22}$$

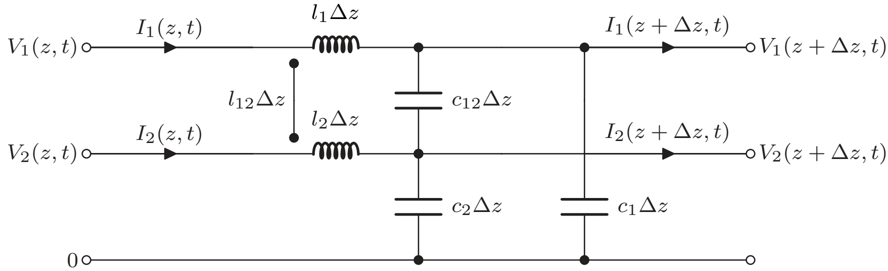

Figure 7.5: Three conductor transmission line of length Δz.

Taking the $\lim_{\Delta z \to 0}$ gives the set of differential equations

$$\begin{aligned}
\partial_z V_1(z,t) &= -l_1 \partial_t I_1(z,t) - l_{12} \partial_t I_2(z,t) && (7.23)\\
\partial_z V_2(z,t) &= -l_{12} \partial_t I_1(z,t) - l_2 \partial_t I_2(z,t) && (7.24)\\
\partial_z I_1(z,t) &= -\left[c_1 + c_{12}\right] \partial_t V_1(z,t) + c_{12} \partial_t V_2(z,t) && (7.25)\\
\partial_z I_2(z,t) &= +c_{12} \partial_t V_1(z,t) - \left[c_2 + c_{12}\right] \partial_t V_2(z,t) && (7.26)
\end{aligned}$$

which can be written in matrix notation

$$\begin{aligned}
\partial_z \mathbf{V} &= -\mathbf{L} \partial_t \mathbf{I} && (7.27)\\
\partial_z \mathbf{I} &= -\mathbf{C} \partial_t \mathbf{V} && (7.28)
\end{aligned}$$

where the voltages $\mathbf{V}$ and currents $\mathbf{I}$ have become vectors

$$\mathbf{V} = \begin{bmatrix} V_1(z,t) \\ V_2(z,t) \end{bmatrix} ; \mathbf{I} = \begin{bmatrix} I_1(z,t) \\ I_2(z,t) \end{bmatrix} \quad (7.29)$$

and the inductances $\mathbf{L}$ and capacitances $\mathbf{C}$ have become matrices

$$\mathbf{L} = \begin{bmatrix} l_1 & l_{12} \\ l_{21} & l_2 \end{bmatrix} ; \mathbf{C} = \begin{bmatrix} c_1 + c_{12} & -c_{12} \\ -c_{21} & c_2 + c_{21} \end{bmatrix} \quad (7.30)$$

where $l_{12} = l_{21}$ and $c_{12} = c_{21}$, which makes both matrices positive definite. The equations (7.27) and (7.28) look similar to (7.3) and (7.4) but all voltages and currents in $\mathbf{V}$ and $\mathbf{I}$ are related. To solve this system of MTLs, $\mathbf{V}$ and $\mathbf{I}$ are transformed into mode voltages and currents $\mathbf{V}_m$ and $\mathbf{I}_m$ by

$$\begin{aligned}
\mathbf{V}(z,t) &= \mathbf{T}_V \mathbf{V}_m(z,t) && (7.31)\\
\mathbf{I}(z,t) &= \mathbf{T}_I \mathbf{I}_m(z,t) && (7.32)
\end{aligned}$$

based on the yet unknown mode transformation matrices $\mathbf{T}_V$ and $\mathbf{T}_I$. Substitution of $\mathbf{V}_m$ and $\mathbf{I}_m$ in equations (7.27) and (7.28) give

$$\begin{aligned}
\partial_z \mathbf{V}_m &= -\mathbf{L}_m \partial_t \mathbf{I}_m && (7.33)\\
\partial_z \mathbf{I}_m &= -\mathbf{C}_m \partial_t \mathbf{V}_m && (7.34)
\end{aligned}$$

with

$$\begin{aligned}
\mathbf{L}_m &= \mathbf{T}_V^{-1} \mathbf{L} \mathbf{T}_I && (7.35)\\
\mathbf{C}_m &= \mathbf{T}_I^{-1} \mathbf{C} \mathbf{T}_V && (7.36)
\end{aligned}$$

Suppose that $\mathbf{L}_m$ and $\mathbf{C}_m$ are diagonal, i.e.

$$\mathbf{L}_m = \begin{bmatrix} l_{m1} & 0 \\ 0 & l_{m2} \end{bmatrix} ; \quad \mathbf{C}_m = \begin{bmatrix} c_{m1} & 0 \\ 0 & c_{m2} \end{bmatrix} \quad (7.37)$$

then the modal MTL equations (7.33) and (7.34) can be simulated by the Branin model as in Section 7.1. The complete model in Figure 7.6 shows these modal TLs in the middle and the transformations on the left and right. The transformations are realised with extra VCVSs (Ec_{i0j}) and Current-Controlled Current Sources (CCCSs) (Fc_{i0j}).

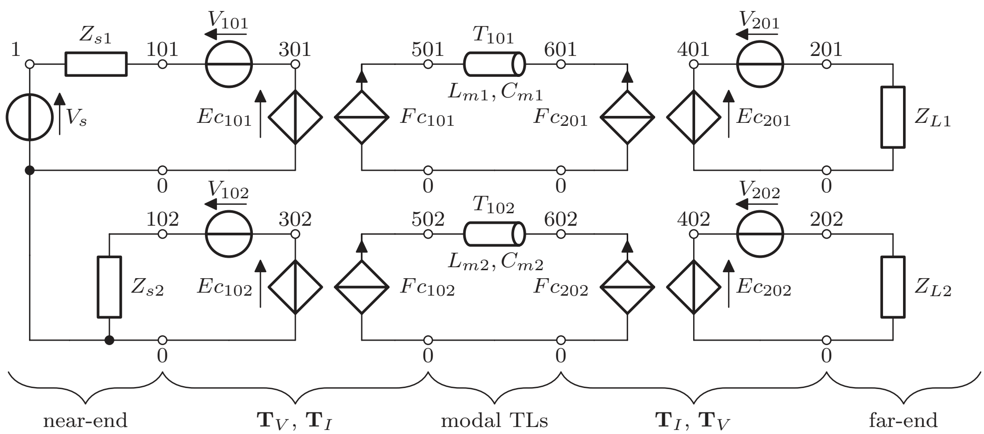

Figure 7.6: SPICE equivalent of a three conductor transmission line [107], [108], with the modal TLs as in Figure 7.3.

$$
\begin{aligned}
Ec_{101} &= T_{V11}V_{501} + T_{V12}V_{502} && (7.38)\\
Ec_{102} &= T_{V21}V_{501} + T_{V22}V_{502} && (7.39)\\
Ec_{201} &= T_{V11}V_{601} + T_{V12}V_{602} && (7.40)\\
Ec_{202} &= T_{V21}V_{601} + T_{V22}V_{602} && (7.41)\\
Fc_{101} &= T_{I11}^{-1}I(V_{101}) + T_{I12}^{-1}I(V_{102}) && (7.42)\\
Fc_{102} &= T_{I21}^{-1}I(V_{101}) + T_{I22}^{-1}I(V_{102}) && (7.43)\\
Fc_{201} &= T_{I11}^{-1}I(V_{201}) + T_{I12}^{-1}I(V_{202}) && (7.44)\\
Fc_{202} &= T_{I21}^{-1}I(V_{201}) + T_{I22}^{-1}I(V_{202}) && (7.45)
\end{aligned}
$$

7.3 The per unit length parameters

The MTL model needs the per unit length parameters l and c including the mutual variants l_{ij} and c_{ij} as input. This section will give the basic relations, but they can also be derived from measurements on actual cables. Assuming lossless lines in homogeneous media, $lc = \varepsilon\mu$, which will be used to calculate the per unit length parameters in several cases.

7.3.1 Two wires

Wires are circular-cylindrical conductors. For two wires with equal radii r, the l and c, defined in Section 7.1 are

$$l = \frac{\mu}{\pi}\text{acosh}\left[\frac{s}{2r}\right] \quad \text{[H/m]} \tag{7.46}$$

$$c = \frac{\pi\varepsilon}{\text{acosh}\left[s/2r\right]} \quad \text{[F/m]} \tag{7.47}$$

as in [105, eq. (4.41) and (4.38)], where r is the radius of the wire and s the separation between the wires as in Figure 7.7. The characteristic impedance becomes

$$Z_c = \sqrt{\frac{l}{c}} = \frac{\text{acosh}\left[s/2r\right]}{\pi}\sqrt{\frac{\mu}{\varepsilon}} \quad [\Omega] \tag{7.48}$$

In free space, where $\sqrt{\mu/\varepsilon} = 120\pi$, $Z_c = 60\ \Omega\ \text{acosh}\left[s/2r\right]$.

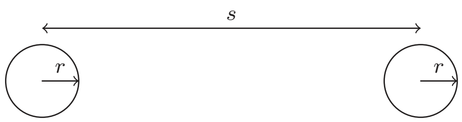

Figure 7.7: Geometry definition for two wires.

7.3.2 One wire above a ground plane

A wire above an infinite, perfectly conducting ground plane has capacitance c [105, eq. (4.44)] and the derived l and Z_c

$$l = \frac{\mu}{2\pi}\text{acosh}\left[\frac{h}{r}\right] \quad \text{[H/m]} \tag{7.49}$$

$$c = \frac{\varepsilon\mu}{l} = \frac{2\pi\varepsilon}{\text{acosh}\left[h/r\right]} \quad \text{[F/m]} \tag{7.50}$$

$$Z_c = \sqrt{\frac{l}{c}} = \frac{\text{acosh}\left[h/r\right]}{2\pi}\sqrt{\frac{\mu}{\varepsilon}} \quad [\Omega] \tag{7.51}$$

where r is the radius of the wire and h is the height above the ground plane as in Figure 7.8. In free space, $Z_c = 60\ \Omega\ \text{acosh}\left[h/r\right]$.

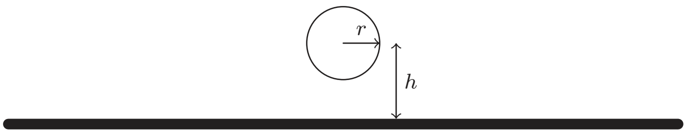

Figure 7.8: Geometry definition for one wire above a ground plane.

7.3.3 Multiple wires above a ground plane

Wires above an infinite, perfectly conducting ground plane (Figure 7.9) have inductance l_i and mutual inductance l_{ij}, defined in Section 7.2. These are approximated for a wide separation, i.e. $h_i \gg r_i$, $s_{ij} > h_i$, and $s_{ij} > h_j$ [105, eq. (5.25a) and (5.25b)]

$$l_i = \frac{\mu}{2\pi}\text{acosh}\left[\frac{h_i}{r_i}\right] \cong \frac{\mu}{2\pi}\ln\left[\frac{2h_i}{r_i}\right] \quad \text{[H/m]} \tag{7.52}$$

$$l_{ij} \cong \frac{\mu}{4\pi}\ln\left[1+\frac{4h_ih_j}{s_{ij}^2}\right] \quad \text{[H/m]} \tag{7.53}$$

where the acosh(x) function is approximated by ln($2x$). This approximation is accurate up to 5 % if $x > 2$. In homogeneous media, c_i and c_{ij} follow from l_i and l_{ij} by

$$\mathbf{C} = \varepsilon\mu\mathbf{L}^{-1} \tag{7.54}$$

A useful parameter is the coupling factor $k_{ij} = l_{ij}/\sqrt{l_il_j}$ between wires i and j:

$$k_{ij} = \frac{\ln\left[1+4h_ih_j/s_{ij}^2\right]}{2\sqrt{\ln\left[2h_i/r_i\right]\ln\left[2h_j/r_j\right]}} \tag{7.55}$$

For two wires with equal radii r at equal height h this becomes:

$$k = \frac{\ln\left[1+\left(2h/s\right)^2\right]}{2\ln\left[2h/r\right]} \tag{7.56}$$

which is a function of the ratios h/r and h/s.

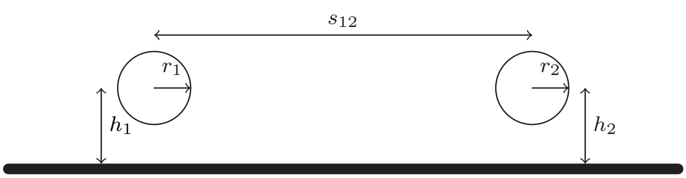

Figure 7.9: Geometry definition for multiple wires above a ground plane.

7.3.4 Twisted pair cables

The three conductor transmission line model works also for twisted pair cables. In the model, both cables share a common, ideal reference conductor. The geometry is defined in Figure 7.10. The inductance l_i and mutual inductance l_{ij} are defined by

$$l_i = \frac{\mu}{\pi} \ln \left[\frac{s_i}{r_i} \right] \quad \text{[H/m]} \tag{7.57}$$

$$l_{ij} = \frac{\mu}{\pi} \ln \left[1 + \frac{s_i s_j}{s_{ij}^2} \right] \quad \text{[H/m]} \tag{7.58}$$

and **C** follows from equation (7.54).

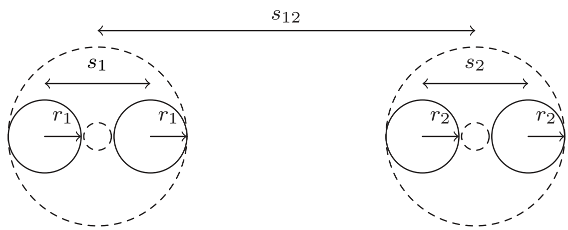

Figure 7.10: Geometry definition for two twisted pair cables.

7.4 Generic results for unscreened cables

Figure 7.11 shows the near-end crosstalk between two wires above an infinite perfectly conducting ground plane, calculated with the model as in Figure 7.6, implemented in SPICE [112]. The result always follows the same shape with the first peak at the frequency where $\mathcal{L} = \lambda/4$ and the first dip for $\mathcal{L} = \lambda/2$. All peaks are at the level

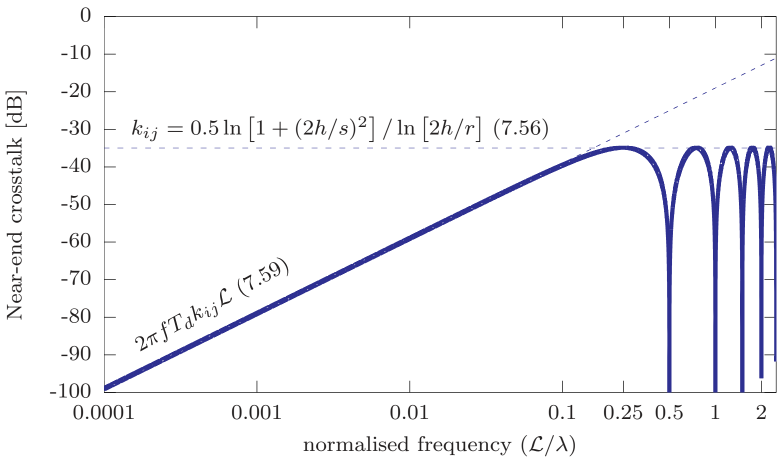

Figure 7.11: Near-end crosstalk between two wires above a ground plane. All terminations are matched loads. (r = 1 mm, h = 1.5 mm, s = 15 mm).

of k_{ij} as in equation (7.56), plotted as horizontal dashed lines and also plotted in Figure 7.12 as function s for two values of r and four values of h. The low frequency behaviour appears to be

$$NEXT_{ij}(f) = 2\pi f T_d k_{ij} \ , \quad \text{for } f \ll 1/T_d \tag{7.59}$$

which is also plotted in dashed lines in the results. For matched loads, the $FEXT$ is not present.

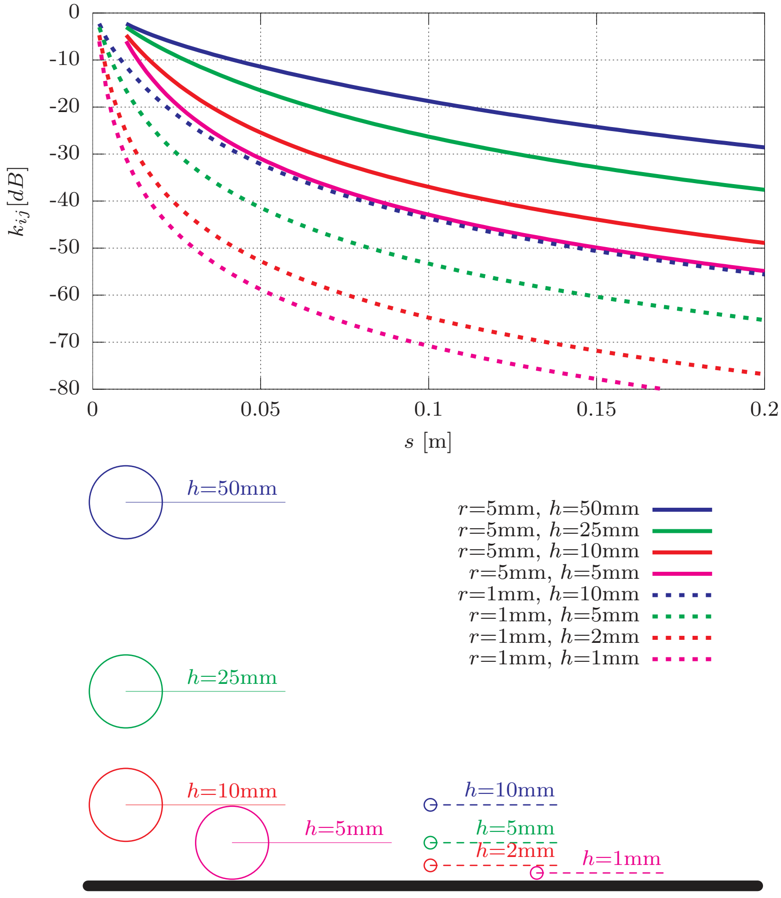

Figure 7.12: Values of k_{ij} which are the peaks of near-end crosstalk as function of separation distance s as in equation (7.56).

7.5 Transmission line model for screened cables

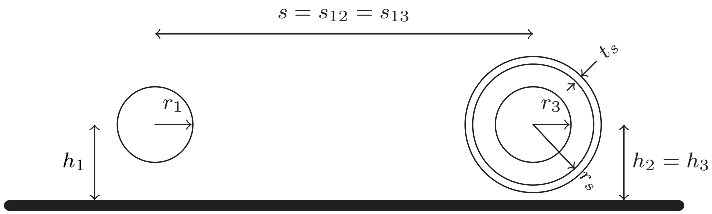

Figure 7.13: Geometry definition for a wire and a screened cable above a ground plane.

For the analysis of the crosstalk between a wire and a screened cable, the cross section in Figure 7.13 is modelled with a four conductor TL as in Figure 7.14.

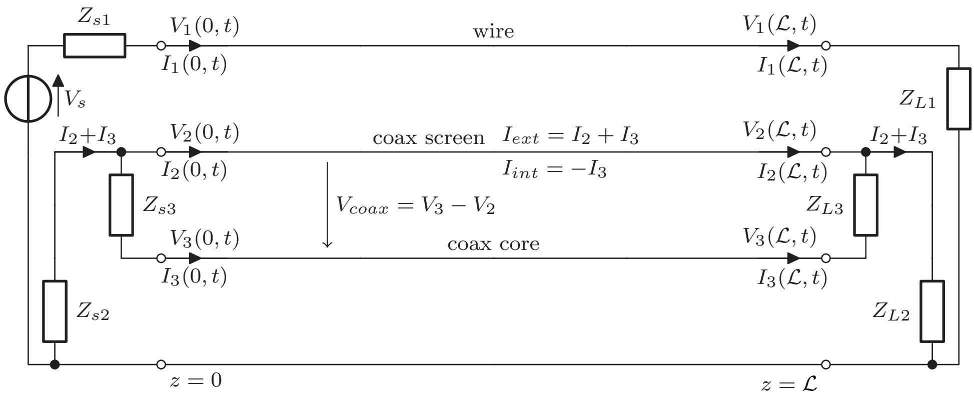

Figure 7.14: A four conductor transmission line configuration for crosstalk analysis of screened cables.

The differential equations for this set of MTL are in matrix form

$$\partial_z \mathbf{V} = -\mathbf{L}\partial_t \mathbf{I} - \mathbf{Z}\mathbf{I} \tag{7.60}$$

$$\partial_z \mathbf{I} = -\mathbf{C}\partial_t \mathbf{I} \tag{7.61}$$

where $\mathbf{Z} = \mathbf{Z_t} + \mathbf{R}$, the sum of the transfer impedance $\mathbf{Z_t}$ and the common impedance screen resistance

$$\mathbf{R} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \rho_s & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{7.62}$$

External part

First, the per unit length parameters for the external part of this configuration, i.e. between the wire and the screen, are considered. These are the same as in Section 7.3.3 for multiple wires above a ground plane [110], [111]:

$$l_1 = \frac{\mu_0}{2\pi}\text{acosh}\left(\frac{h_1}{r_1}\right) \tag{7.63}$$

$$l_2 = \frac{\mu_0}{2\pi}\text{acosh}\left(\frac{h_2}{r_s + t_s}\right) \tag{7.64}$$

$$l_{12} = l_{21} = \frac{\mu_0}{4\pi}\ln\left(1 + \frac{4h_1h_2}{s^2}\right) \tag{7.65}$$

$$\begin{bmatrix} c_1 + c_{12} & -c_{12} \\ -c_{21} & c_2 + c_{21} \end{bmatrix} = \varepsilon_r\varepsilon_0\mu_0 \begin{bmatrix} l_1 & l_{12} \\ l_{21} & l_2 \end{bmatrix}^{-1} \tag{7.66}$$

which are based on equations (7.52)-(7.54) for two wires above a ground plane.

Internal part

Second, the parameters for the internal part of the coaxial cable are [110], [111]

$$l_3 = \frac{\mu_0}{2\pi}\text{acosh}\left(\frac{h_2}{r_3}\right) \tag{7.67}$$

$$c_{23} = c_{32} = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\left(r_s/r_3\right)} \tag{7.68}$$

$$l_{23} = l_{32} = l_2 \tag{7.69}$$

where l_3 is obtained from equation (7.52), l_{23} is equal to l_2 assuming an ideal coupling between the core and the inside of the screen, c_{23} is the internal capacitance of a coax cable, which is typically 100 pF/m for 50 Ω coax cable with polyethylene as dielectric ($\varepsilon_r = 2.25$).

Ideal screening between external and internal part

Third, the coupling between the outer and inner parts has to be determined:

$$l_{13} = l_{31} = l_{12} \tag{7.70}$$

$$c_{13} = c_{31} = 0 \tag{7.71}$$

$$c_3 = 0 \tag{7.72}$$

where the mutual inductance from the wire to the core is equal to that to the screen, causing a cancellation by the ideal screen, c_{13} and c_3 are zero, because there is no capacitance between the core and the wire nor between the core and the ground plane. With this ideal screening, there is no coupling through the screen.

Account for the coupling through the screen

If the TL model would be modelled for the ideal case above, i.e. assuming only lossless conductors, an ideal screen, and uniformly distributed currents, this would result in zero crosstalk. To account for the coupling of field through the screen, three physical phenomena have to be accounted for:

1. The resistance of the screen, which is a common impedance between the screen and inner wire.
2. The skin effect that lowers the crosstalk for higher frequencies. This will not be modelled here, because this effect becomes negligible when imperfections are present.
3. The imperfections of the screen, like holes, through which inductive coupling takes places.

The first two phenomena are included as a common impedance screen resistance per unit length ρ_s in Ω/m that causes a ground bounce. This is already included by equation (7.62). The third phenomenon is described in 1972 [113] and later called transfer impedance, Z_t, and also has the dimension Ω/m. To include Z_t, the MTL model will be modified first.

Modified MTL for external and internal part

The current I_2 on the screen is split into an external part $I_{ext} = I_2' = I_2 + I_3$ and an internal part $I_{int} = -I_3$. Instead of the voltage V_3 on the core wire relative to the ground plane, the internal coax cable voltage $V_{coax} = V_3' = V_3 - V_2$ will be used. This results in variable transformations: [109]

$$\mathbf{I}' = \mathbf{T}_{I,s}\mathbf{I} \quad : \quad \begin{bmatrix} I_1' \\ I_2' \\ I_3' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \tag{7.73}$$

$$\mathbf{V}' = \mathbf{T}_{V,s}\mathbf{V} \quad : \quad \begin{bmatrix} V_1' \\ V_2' \\ V_3' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \tag{7.74}$$

and $\mathbf{I} = \mathbf{T}_{I,s}^{-1}\mathbf{I}'$, $\mathbf{V} = \mathbf{T}_{V,s}^{-1}\mathbf{V}'$. The result is the system in Figure 7.15. The inductive coupling through the imperfections in the screen causes the inside and outside currents to induce fields on the outer (E_{ext}) and inner (E_{int}) surfaces of the screen [109]:

$$\begin{bmatrix} E_{ext} \\ E_{int} \end{bmatrix} = \begin{bmatrix} 0 & l_t\partial_t \\ l_t\partial_t & 0 \end{bmatrix} \begin{bmatrix} I_{ext} \\ I_{int} \end{bmatrix} \tag{7.75}$$

where l_t is the transfer inductance in H/m, $I_{ext} = I_2'$ and $I_{int} = -I_3'$. A small section of the modified MTL in Figure 7.16 includes this inductive coupling.

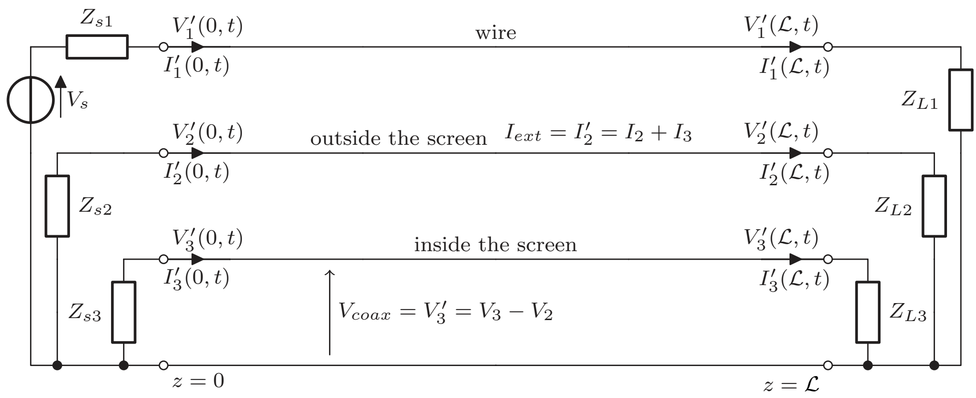

Figure 7.15: A four conductor transmission line equivalent for external and internal parts.

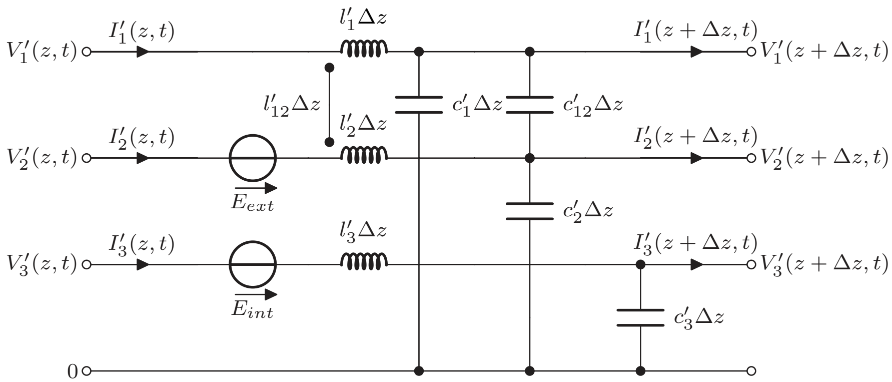

Figure 7.16: Transformed section of a four conductor transmission line of length Δz with a screened cable.

Using the conversions $\mathbf{I} = \mathbf{T}_{I,s}^{-1}\mathbf{I}'$, and $\mathbf{V} = \mathbf{T}_{V,s}^{-1}\mathbf{V}'$ the MTL equations (7.61) and (7.60) become

$$\mathbf{T}_{V,s}^{-1}\partial_z\mathbf{V}' = -\mathbf{L}\mathbf{T}_{I,s}^{-1}\partial_t\mathbf{I}' - \mathbf{Z}\mathbf{T}_{I,s}^{-1}\mathbf{I}' \tag{7.76}$$

$$\mathbf{T}_{I,s}^{-1}\partial_z\mathbf{I}' = -\mathbf{T}_{V,s}^{-1}\mathbf{C}\partial_t\mathbf{V}' \tag{7.77}$$

Multiplication by $\mathbf{T}_{V,s}$ and $\mathbf{T}_{I,s}$ give

$$\partial_z\mathbf{V}' = -\mathbf{T}_{V,s}\mathbf{L}\mathbf{T}_{I,s}^{-1}\partial_t\mathbf{I}' - \mathbf{T}_{V,s}\mathbf{Z}\mathbf{T}_{I,s}^{-1}\mathbf{I}' \tag{7.78}$$

$$\partial_z\mathbf{I}' = -\mathbf{T}_{I,s}\mathbf{C}\mathbf{T}_{V,s}^{-1}\partial_t\mathbf{V}' \tag{7.79}$$

and finally

$$\partial_z\mathbf{V}' = -\mathbf{L}'\partial_t\mathbf{I}' - \mathbf{Z}'\mathbf{I}' \tag{7.80}$$

$$\partial_z\mathbf{I}' = -\mathbf{C}'\partial_t\mathbf{V}' \tag{7.81}$$

The transformed matrices $\mathbf{L}'$, $\mathbf{Z}'$ and $\mathbf{C}'$ are obtained by the next transformations, with relations (7.69) to (7.72) filled in:

$$\mathbf{L}' = \mathbf{T}_{V,s}\mathbf{L}\mathbf{T}_{I,s}^{-1} = \begin{bmatrix} l_1 & l_{12} & 0 \\ l_{12} & l_2 & 0 \\ 0 & 0 & l_3 - l_2 \end{bmatrix} \tag{7.82}$$

$$\mathbf{Z}' = \mathbf{T}_{V,s}\mathbf{Z}\mathbf{T}_{I,s}^{-1} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \rho_s & -\rho_s \\ 0 & -\rho_s & \rho_s \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -l_t\partial_t \\ 0 & -l_t\partial_t & 0 \end{bmatrix} \tag{7.83}$$

$$\mathbf{C}' = \mathbf{T}_{I,s}\mathbf{C}\mathbf{T}_{V,s}^{-1} = \begin{bmatrix} c_1 + c_{12} & -c_{12} & 0 \\ -c_{12} & c_{12} + c_2 & 0 \\ 0 & 0 & c_{23} \end{bmatrix} \tag{7.84}$$

The modified per unit length parameters become

$$l_1' = \frac{\mu_0}{2\pi}\operatorname{acosh}\left(\frac{h_1}{r_1}\right) \tag{7.85}$$

$$l_2' = \frac{\mu_0}{2\pi}\operatorname{acosh}\left(\frac{h_2}{r_s + t_s}\right) \tag{7.86}$$

$$l_{12}' = \frac{\mu_0}{4\pi}\ln\left(1 + \frac{4h_1h_2}{s^2}\right) \tag{7.87}$$

$$\begin{bmatrix} c_1' + c_{12} & -c_{12}' \\ -c_{21}' & c_2' + c_{21}' \end{bmatrix} = \varepsilon_r\varepsilon_0\mu_0 \begin{bmatrix} l_1' & l_{12}' \\ l_{21}' & l_2' \end{bmatrix}^{-1} \tag{7.88}$$

$$\begin{aligned} l_3' &= \frac{\mu_0}{2\pi}\left[\operatorname{acosh}\left(\frac{h_2}{r_3}\right) - \operatorname{acosh}\left(\frac{h_2}{r_s + t_s}\right)\right] \\ &\cong \frac{\mu_0}{2\pi}\ln\left(\frac{r_s + t_s}{r_3}\right) \end{aligned} \tag{7.89}$$

$$l_{13}' = 0 \tag{7.90}$$

$$l_{23}' = -l_t \tag{7.91}$$

$$c_{13}' = 0 \tag{7.92}$$

$$c_{23}' = 0 \tag{7.93}$$

$$c_3' = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln\left(r_s/r_3\right)} \tag{7.94}$$

where l_t is included in $\mathbf{L}'$. For coaxial cables with a characteristic impedance of 50 Ω, $l3' = 0.25$ µH/m, and $c_3' = 100$ pF/m typically. Figure 7.17 shows the SPICE equivalent on this model that is based on [109]. The common impedance screen resistance ρ_s has not been included as a lossy TL but as one lumped element with resistance $\rho_s\mathcal{L}$ that is placed in front of the TL. The negative R_{23} and R_{32} has been

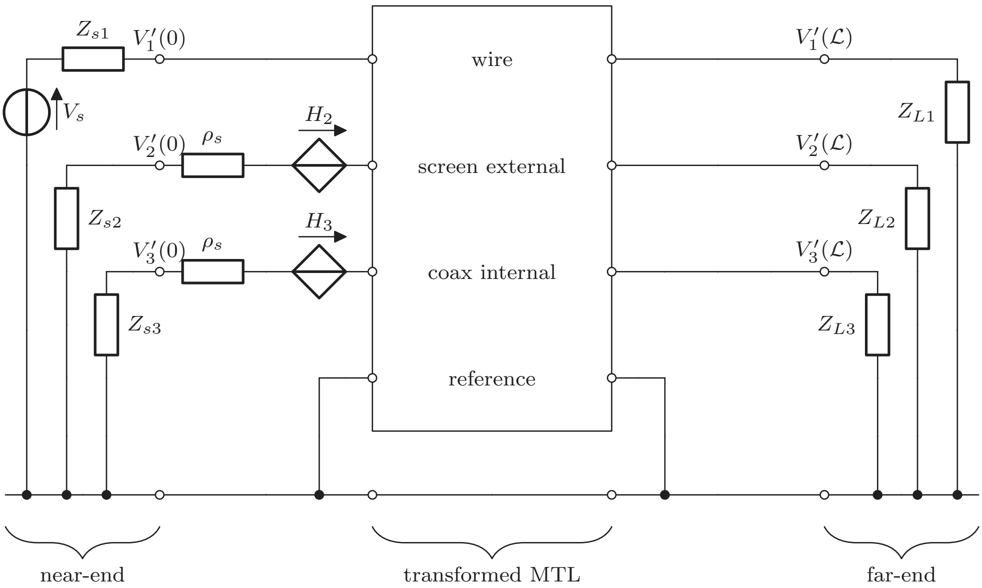

Figure 7.17: SPICE equivalent of a four conductor transmission line with a screened cable, with the MTL as in Figure 7.6.

implemented as Current-Controlled Voltage Sources (CCVSs) H_2 and H_3

$$H_2 = -\rho_s I_3' \tag{7.95}$$
$$H_3 = -\rho_s I_2' \tag{7.96}$$

The low frequency response accounting for ρ_s and not l_t goes to [110, eq.8c]

$$NEXT = \frac{V_3'(0)}{V_1'(0)} = \frac{Z_{s3}}{Z_{s3} + Z_{L3}} \frac{\jmath\omega l_{12}\mathcal{L}\rho_s\mathcal{L}}{\rho_s\mathcal{L} + \jmath\omega l_2\mathcal{L}} \frac{1}{Z_{s1} + Z_{L1}} \frac{Z_{L1}}{Z_{s1}} \tag{7.97}$$

For comparison, the same configuration as in [110] and [111] is calculated, where the screen is bonded to the ground plane on both sides and the core terminals are terminated to the screen with 50 Ohm or 1 kOhm. In this example, $l_t = 0$. The result is in Figure 7.18. The low frequency response from Equation (7.97) is in dashed lines. To include the magnetic coupling effect, modelled in l_t, the variable ρ_s in Equation (7.97) could be replaced by $Z_t = r_s + \jmath\omega l_t$ [114] to get

$$NEXT = \frac{V_3'(0)}{V_1'(0)} = \frac{Z_{s3}}{Z_{s3} + Z_{L3}} \frac{\jmath\omega l_{12}\mathcal{L}\left(\rho_s\mathcal{L} + \jmath\omega l_t\right)}{\rho_s\mathcal{L} + \jmath\omega(l_2 + l_t)\mathcal{L}} \frac{1}{Z_{s1} + Z_{L1}} \frac{Z_{L1}}{Z_{s1}} \tag{7.98}$$

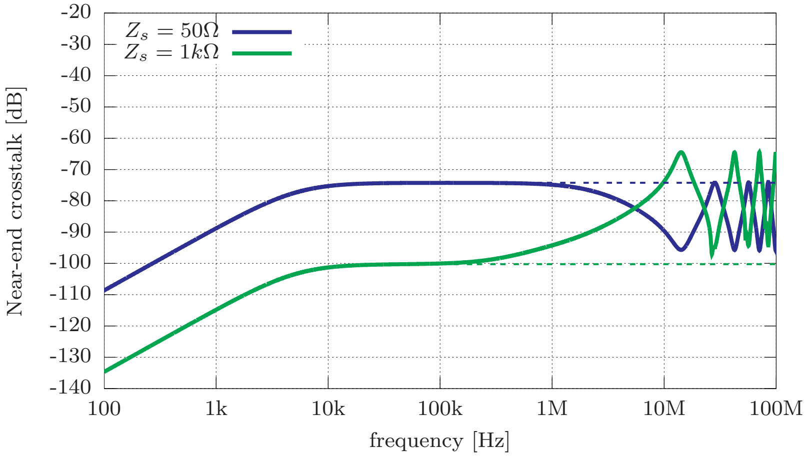

Figure 7.18: Near-end crosstalk for screened cable as in [110] and [111].

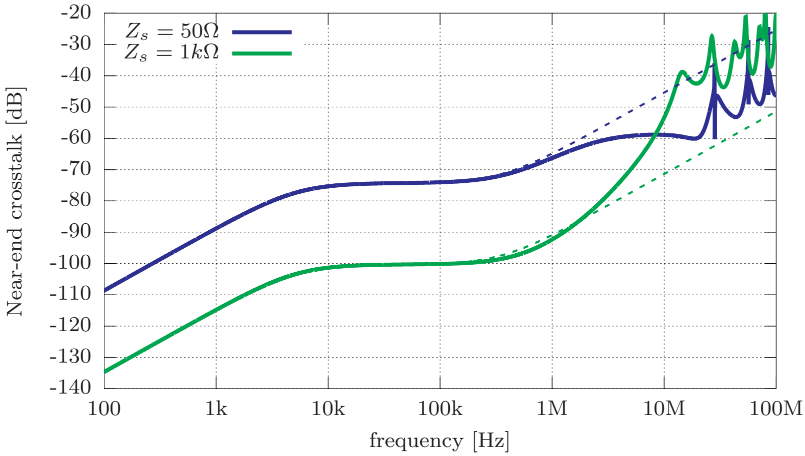

Figure 7.19: Near-end crosstalk for screened cable with $l_t = 10$ nH/m.

7.6 Crosstalk measurement set-up

Numerous measurements have been performed between different types of cables to analyse various parameters. Some of these results are used in this Chapter to compare them with the described theory. The used equipment is shown in Figure 7.20. The analysis has been done with the Rohde & Schwarz ESS measurement receiver as a scalar network analyser. The receiver was controlled from a laptop that also performed the data acquisition. Every frequency sweep has 379 logarithmically distributed frequency points from 10 kHz to 1 GHz. The measurement bandwidth is 1 kHz. The output signal was amplified with a Kalmus 706FC amplifier. For the lowest frequencies, very low crosstalk values could not be properly measured, because the amplifier was not designed for use below 0.5 MHz. Figure 7.21 shows the perforated cable tray that was used as a ground plane for the measurements.

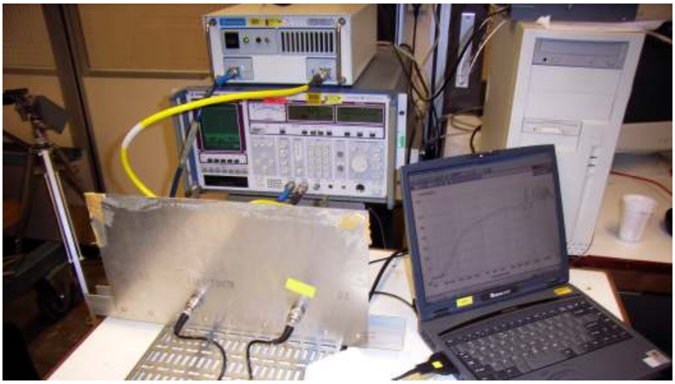

Figure 7.20: Used equipment for crosstalk measurements.

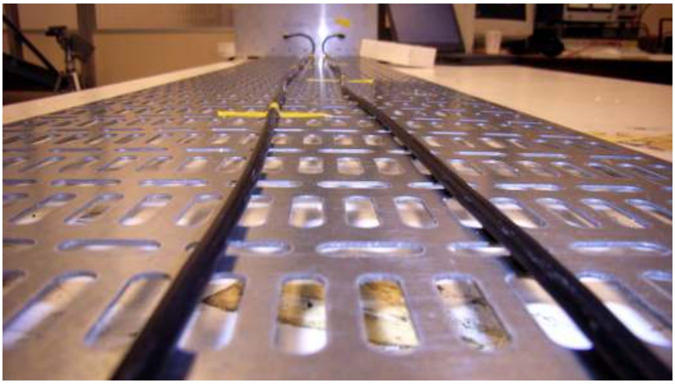

Figure 7.21: Set-up with ground a plane for crosstalk measurements.

7.7 Results of crosstalk analysis

7.7.1 Wires above a ground plane, matched loads

Calculations are performed for different s in Figure 7.22, different r in Figure 7.23, different h in Figure 7.24, and different $\mathcal{L}$ in Figure 7.25, all for matched load impedances, i.e. $Z_c = 60\ \Omega\ \text{acosh}[h/r]$. All results are plotted for the $NEXT$ only, since the $FEXT$ is not present for matched loads.

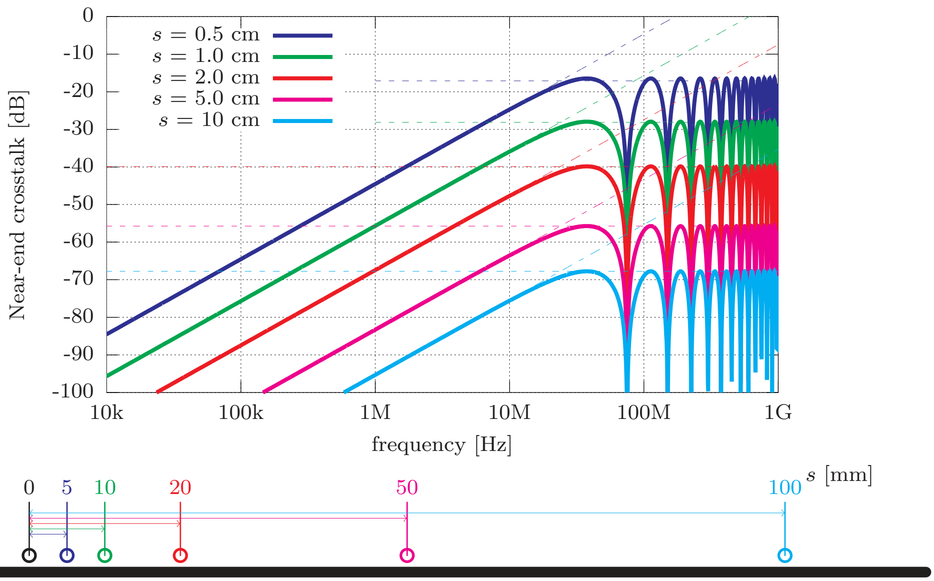

Figure 7.22: Near-end crosstalk between two wires above a ground plane for different separation distances s. All terminations are matched loads. (r = 1 mm, h = 1.5 mm, $\mathcal{L}$ = 2 m)

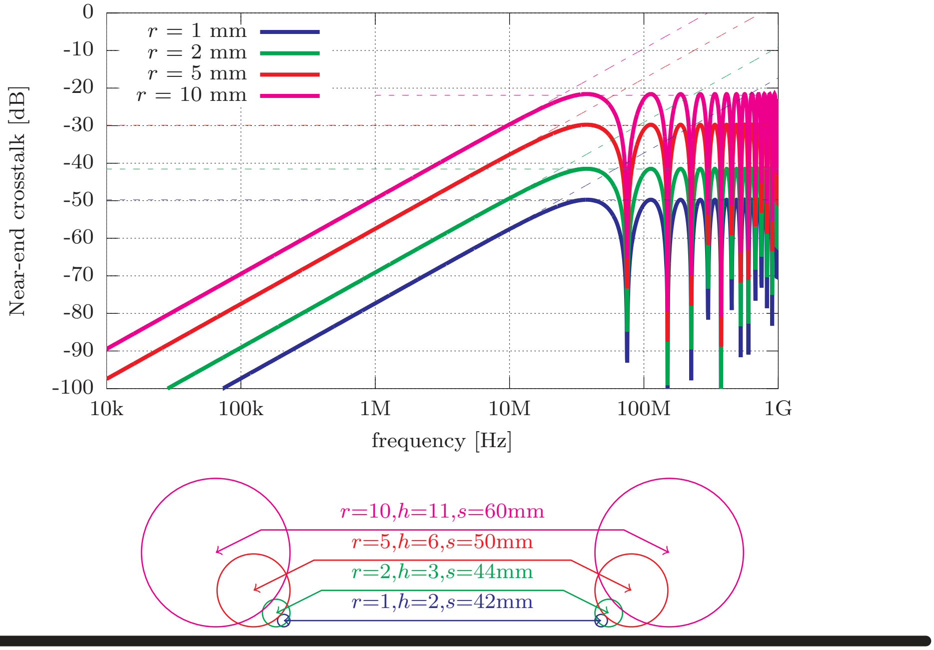

Figure 7.23: Near-end crosstalk between two wires above a ground plane for different radius r. All terminations are matched loads. ($\mathcal{L}$ = 2 m)

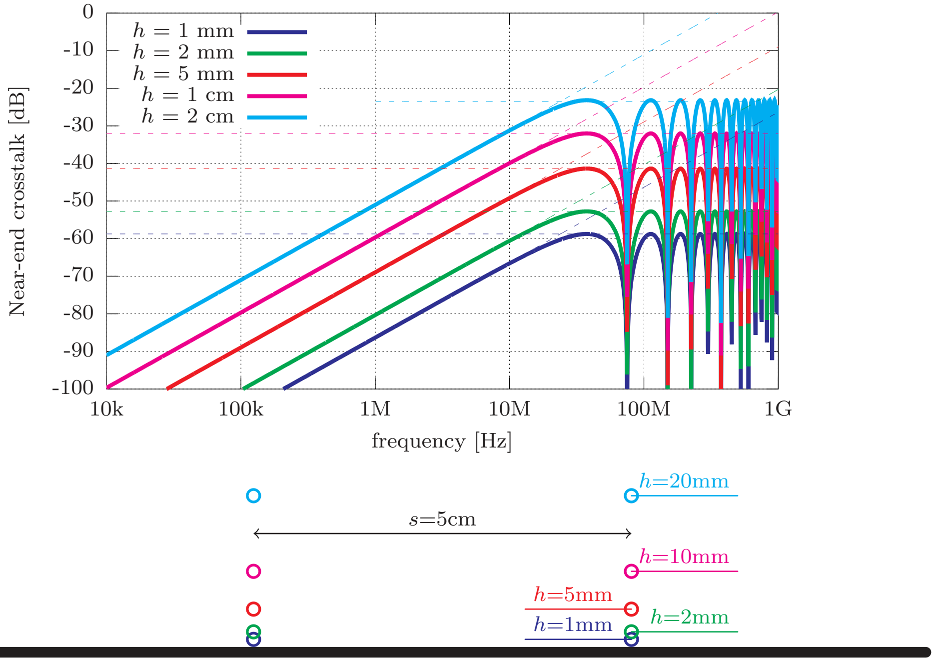

Figure 7.24: Near-end crosstalk for different heights h.
All terminations are matched loads. (r = 1 mm, s = 5 cm, $\mathcal{L}$ = 2 m)

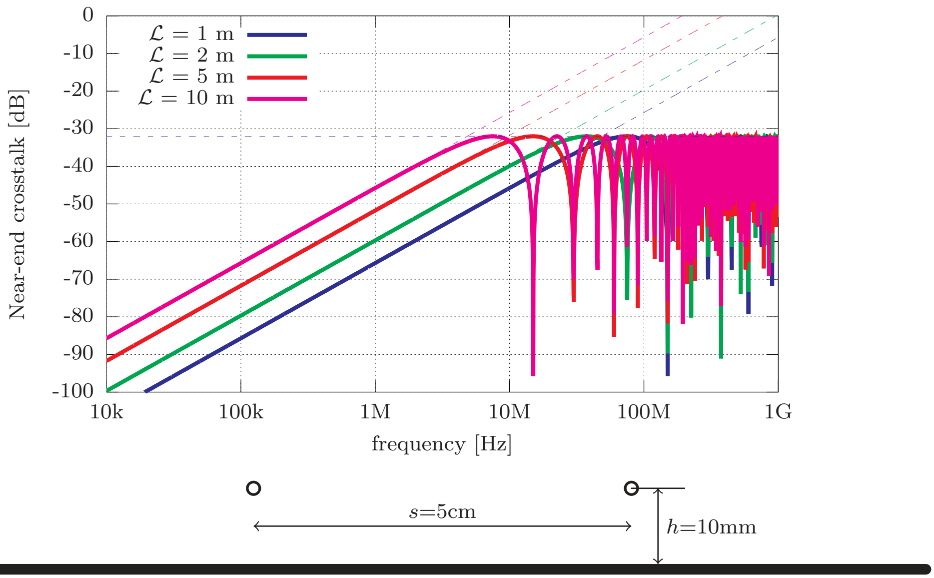

Figure 7.25: Near-end crosstalk for different lengths $\mathcal{L}$.
All terminations are matched loads. (r = 1 mm, h = 1 cm, s = 5 cm)

7.7.2 Wires above a ground plane, loads not matched

Figure 7.26 shows the near-end crosstalk for different values of all loads, i.e. Z_s, Z_{s2}, Z_{L1}, and Z_{L2} in Figure 7.6. Due to the mismatch, the peaks can be up to 6 dB higher. The low frequency behaviour can be highly affected.

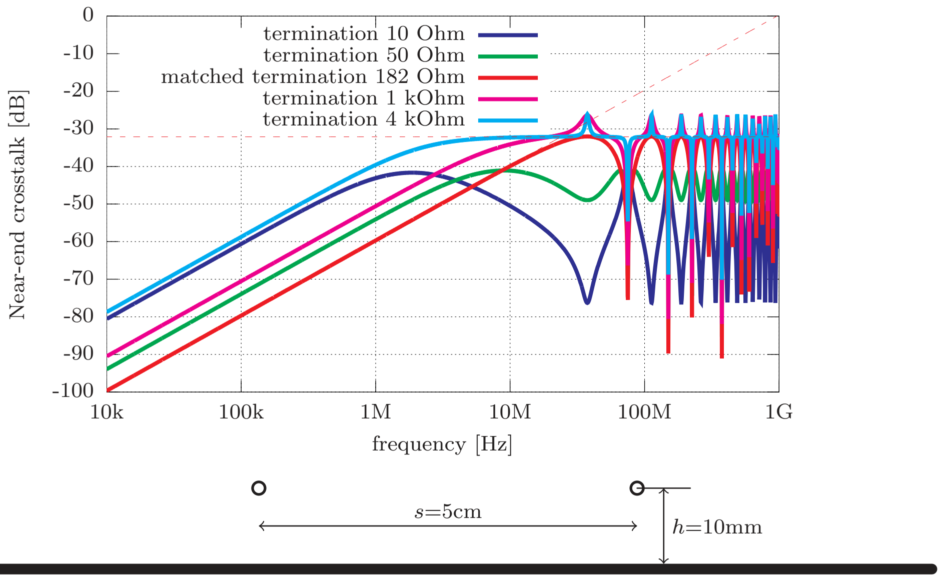

Figure 7.26: Near-end crosstalk for different terminations $Z_{s,i}$ and $Z_{L,i}$.
(r = 1 mm, h = 1 cm, s = 5 cm, $\mathcal{L}$ = 2 m)

7.7.3 Measured crosstalk between twisted pair cables

Figure 7.27 shows the near-end crosstalk between two twisted pair cables, based on the parameters in equations (7.57) and (7.58), with r_i = 0.5 mm, s_i = 1.25 mm. The dashed lines are results from measurements. **C** in the model is obtained by equation (7.54), with $\varepsilon = 1.5\ \varepsilon_0$ to fit the calculations on the measurement data. This ε_r reflects the insulation material of the twisted pair cable.

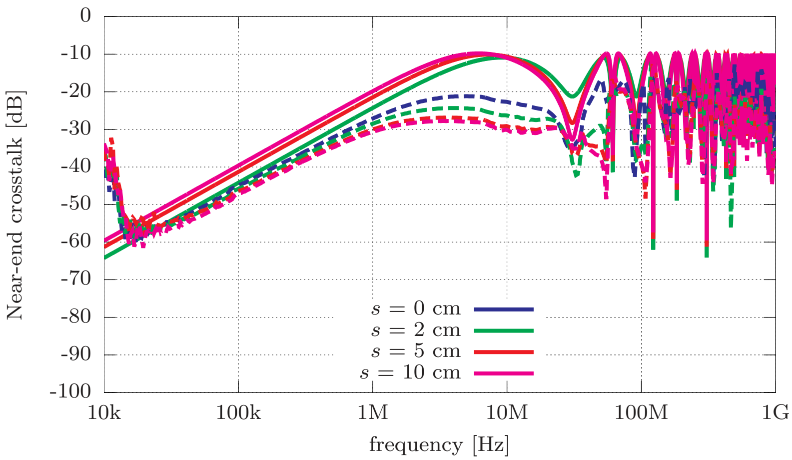

Figure 7.27: Near-end crosstalk between twisted pair cables, including measurements in dashed lines. (r = 0.5 mm, $\mathcal{L}$ = 2 m, Z_1 = 100 Ω)

7.7.4 Crosstalk to screened cables

Figure 7.28 shows the geometry that is used for the $NEXT$ from an unscreened cable to a screened cable in the next four figures for different values of ρ_s and l_t. The screened cable has the dimensions of an RG-58 cable ($r_3 = 0.4$ mm, $r_s = 1.45$ mm, $t_s = 0.1$ mm) and the screen is bonded to the ground plane at both sides. The RG-58 cable is chosen, because it is representative for any well screened multi-core cable. The unscreened cable is excited with a voltage source between the cable and the ground plane and is terminated at both sides with $Z_1 \approx 50\ \Omega$. Both cables have the same radii ($r_1 = r_s + t_s$) and are placed at the same heights $h_2 = h_1 \approx 2$ mm above the ground plane, tuned to get a Z_c of 50 Ω. The length of both cables are $\mathcal{L} = 2$ m and are separated by $s = 5$ cm. In the next figures, the $NEXT$ is shown, i.e. the voltage in Z_{s3} due to V_s in Figure 7.14.

Figure 7.28: Geometry of an unscreened and screened cable.

Figure 7.29 shows the $NEXT$ on the coaxial cable for different ρ_s, whereas $l_t = 0$. In Figure 7.30 l_t is varied with $\rho_s = 0.1$ mΩ/m.

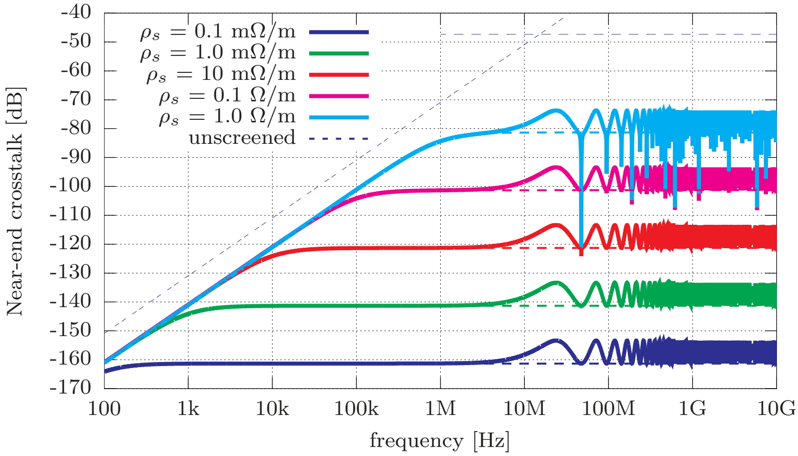

Figure 7.29: Near-end crosstalk from unscreened to screened cable, $l_t = 0$
($\mathcal{L} = 2$ m, $r_1 = 1.55$ mm, $r_s = 1.45$ mm, $t_s = 0.1$ mm, $h_1 = h_2 = 2.12$ mm, $s = 5$ cm).

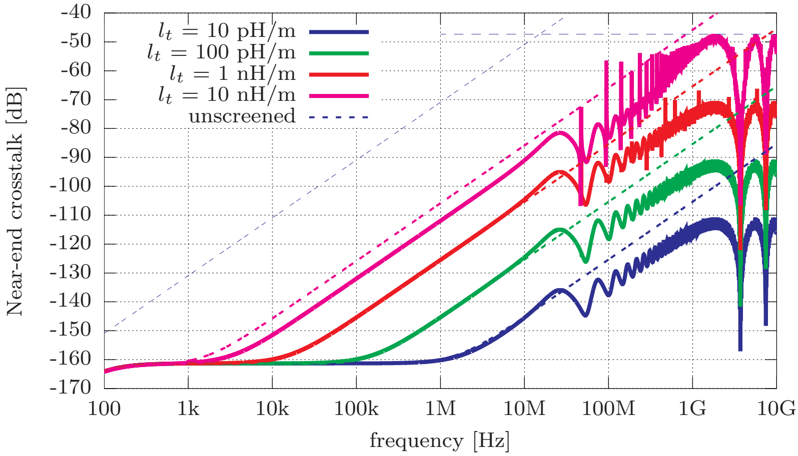

Figure 7.30: Near-end crosstalk from unscreened to screened cable, $\rho_s = 0.1$ mΩ
($\mathcal{L} = 2$ m, $r_1 = 1.55$ mm, $r_s = 1.45$ mm, $t_s = 0.1$ mm, $h_1 = h_2 = 2.12$ mm, $s = 5$ cm).

In Figure 7.31 l_t is also varied, but with $\rho_s = 20$ mΩ/, a typical value for RG-58. Figure 7.32 shows the result for varying ρ_s with $l_t = 1$ nH/m, a typical value for RG-58.

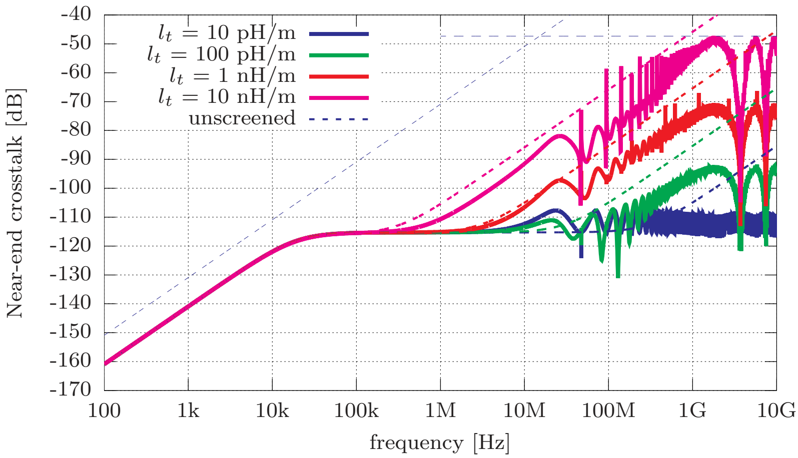

Figure 7.31: Near-end crosstalk from unscreened to screened cable, $\rho_s = 20$ mΩ/m ($\mathcal{L} = 2$ m, $r_1 = 1.55$ mm, $r_s = 1.45$ mm, $t_s = 0.1$ mm, $h_1 = h_2 = 2.12$ mm, $s = 5$ cm).

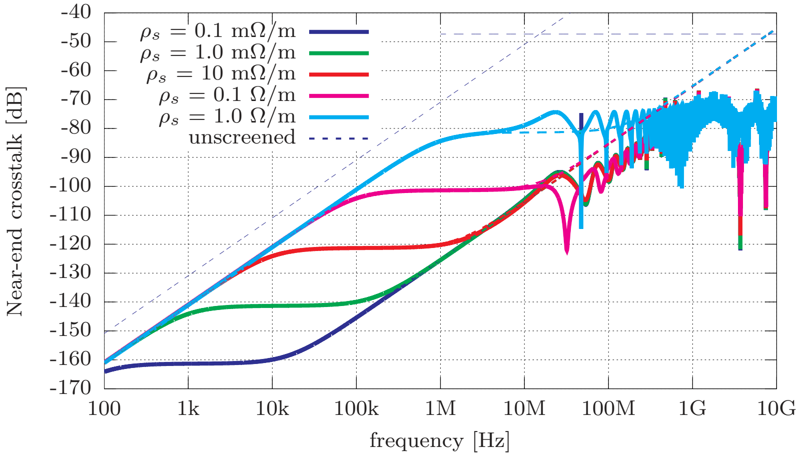

Figure 7.32: Near-end crosstalk from unscreened to screened cable, $l_t = 1$ nH/m ($\mathcal{L} = 2$ m, $r_1 = 1.55$ mm, $r_s = 1.45$ mm, $t_s = 0.1$ mm, $h_1 = h_2 = 2.12$ mm, $s = 5$ cm).

7.7.5 Measured crosstalk between screened cables

Figure 7.33 shows the $NEXT$ from a wire to an RG-58 cable, placed close to each other, i.e. at $s = 5$ mm. Figure 7.34 shows the $NEXT$ from a wire to an RG-214 cable for different h and s. All cables in this section have a length $\mathcal{L} = 2$ m.

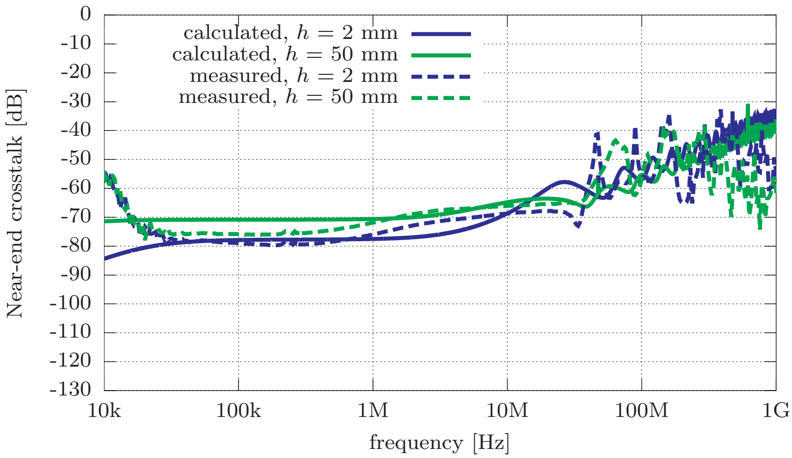

Figure 7.33: Near-end crosstalk measurements from a wire to an RG-58 cable ($h \approx 2$ mm, $s = 5$ mm).

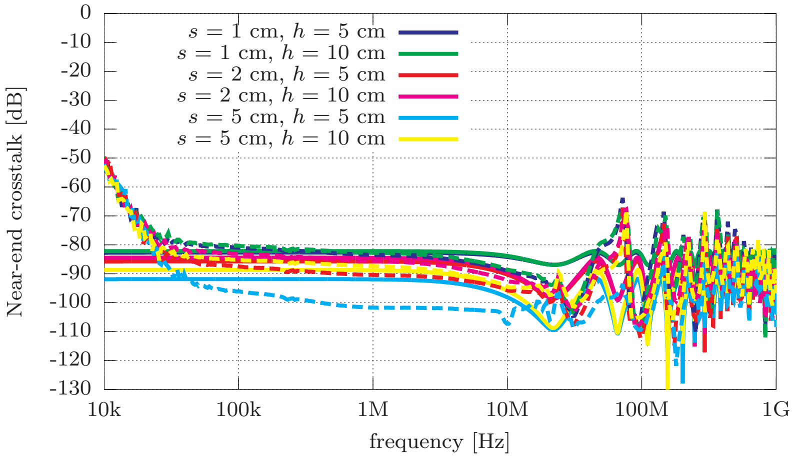

Figure 7.34: Near-end crosstalk measurements from a wire to an RG-214 cable at various h and s.

7.8 Ethernet Susceptibility to Electric Fast Transients

The most used medium for data communication nowadays is Ethernet, for which affordable, yet high quality screened cable is used for throughput reasons. The screen has a huge benefit for EMC as well resulting in low crosstalk levels if the finishing at connectors and feed-throughs is done properly as well. The study on crosstalk in Sections 7.1 to 7.7 showed that Electric Fast Transients (EFT) bursts on nearby power lines are very effective in causing interference and loss of data on Ethernet cables. Transient disturbances on the mains supply voltage originate from switch operations on low-voltage supply networks [115] and was observed before [25]. The effects of EFT bursts in an Ethernet set-up have been investigated in order to get more insight in coupling and interference mechanisms in a typical Ethernet installation. It is expected that digital circuits are more likely to exhibit non-linear failure characteristics compared to the gradual degradation of analogue signals with increasing noise. Part of this section is published in [92].

7.8.1 Set-up

Since the electrical properties of real-life transients are known, the EFT phenomena including the crosstalk has been simulated by a standardised test set-up, generating a common mode current [41]. One advantage of this standard is the availability of an easy set-up for repeatable experiments. EFT tests also have the advantage of a quick general impression of EMC of equipment. Similar work found in literature shows that an external overall braid additional to the existing screen on the standard cables are necessary for compliance in their set-up [116]. The purpose is not to do compliance tests on Ethernet equipment. Therefore, the electronic equipment in the test set-up has been decoupled from the EFT signals. Each pulse from the EFT burst generator has a rise time and duration of approximately 5 ns and 50 ns respectively, see Figure 7.35. Pulses are repeated with frequency f in one burst of duration t_d and bursts are repeated with repetition interval t_r as defined in Figure 7.36. Table 7.1 shows the adjustable EFT burst parameter with their possible ranges. The Cable Under Test (CUT) is excited by EFT pulses from an EFT burst generator using a capacitive coupling clamp (CCP) from IEC 61000-4-4, [41].

Table 7.1: Parameters for the EFT burst

parameter & range			description
V	0.2 - 4.4	[kV]	Applied voltage
f	0.1 - 1000	[kHz]	Pulse repetition rate in one burst
t_d	0.10 - 999	[ms]	Duration of one burst
t_r	10.0 - 9999	[ms]	Repetition time of the burst
T	1 - ∞	[s]	Total time of the bursts

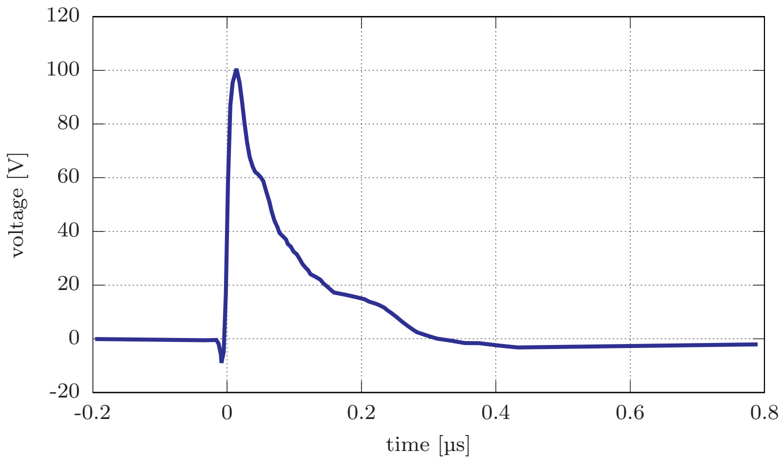

Figure 7.35: Measured single EFT pulse

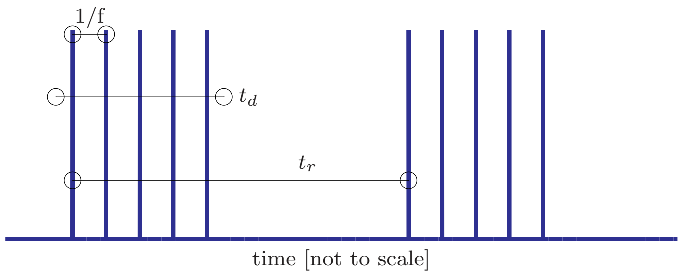

Figure 7.36: EFT bursts definition

Two types of cables have been tested: Unscreened Twisted Pair (UTP) and Screened Twisted Pair (STP) and the measurements are done in two different set-ups. One set-up is without feed-through, where the cable is terminated by a commercially available network switch for home or office use. In the other set-up the CUT is terminated by cable feed-throughs on either side. Whilst the cable is exposed by EFT bursts for 10 seconds for each experiment, the network throughput bandwidth is continuously monitored with the program Iperf [117], giving an average value every second. The nominal throughput is 650 Mbps. The impact on the throughput is taken as the disturbing effect in these measurements. The registered throughput is translated into an disturbing effect by

$$\{disturbing\ effect\} = \frac{650 - \{throughput\}}{650} \times 100\% \tag{7.99}$$

As an example, Figure 7.37 shows the throughput during a series of five experiments.

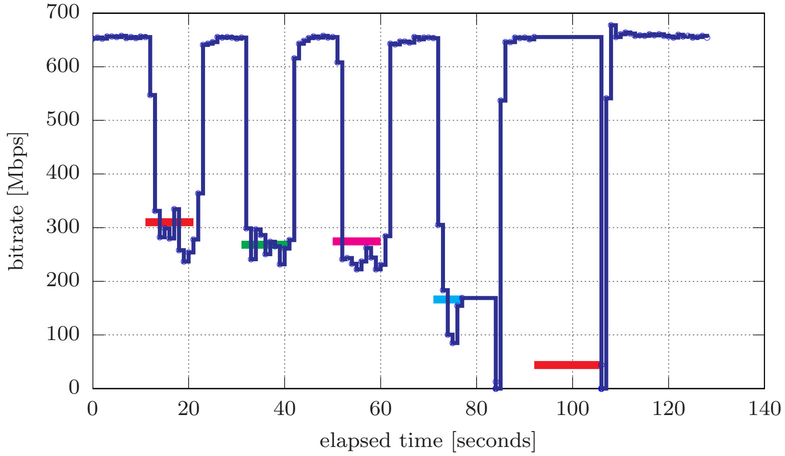

Figure 7.37: Example of resulting loss in throughput (3x) and complete disconnect (2x) for different applied voltages (0.2, 0.5, 1, 2 and 3 kV) (sequence: utp7)

7.8.2 Results

Several series of experiments have been carried out for two types of cables, for both set-ups, each with different burst parameters. Within each series, the applied voltage has been varied to get the threshold value for the disturbance. Table 7.2 shows the parameters of all series. Note the very low duty cycle of the pulses. Most experiments have been done with only one pulse of 100 ns every 30 ms. Observed effects are partial or complete loss in throughput during exposure and complete loss of connection. Recovery from the latter usually lasts longer than the 10 seconds exposure. The resulting disturbing effects of all experiments are plotted as function of the applied voltage. For the set-up without feed-through this is shown in Figure 7.38 for the UTP

Table 7.2: Burst parameters in each measurement

name	f[kHz]	t_d[ms]	t_r[ms]	name	f[kHz]	t_d[ms]	t_r[ms]
utp1	1.0	1.00	30.0	stp2	1.0	1.00	30.0
utp2	1.0	1.00	30.0	stp4	1.0	0.75	30.0
utp6	1.0	1.50	30.0	stp5	1.0	0.75	30.0
utp7	1.0	3.00	30.0	stp6	1.0	1.50	30.0
utp8	1.0	1.00	10.0	stp7	1.0	1.50	30.0
utp13	7.5	0.10	10.0	stp8	1.0	3.00	30.0
utp14	10.0	0.10	10.0	stp9	1.0	1.00	10.0
utp15	400.0	0.10	10.0	stp13	0.8	1.00	10.0
utp16	100.0	0.10	10.0	stp14	0.7	1.00	10.0
utp17	10.0	0.10	10.0	stp15	0.6	1.00	10.0
utp18	20.0	0.10	10.0	stp16	0.7	1.00	10.0
utp19	50.0	0.10	10.0	stp17	5.0	1.00	10.0
utp20	75.0	0.10	10.0	stp18	20.0	1.00	10.0
				stp19	75.0	1.00	10.0
utp	1.0	1.00	30.0	stp20-34	1.0	1.00	30.0

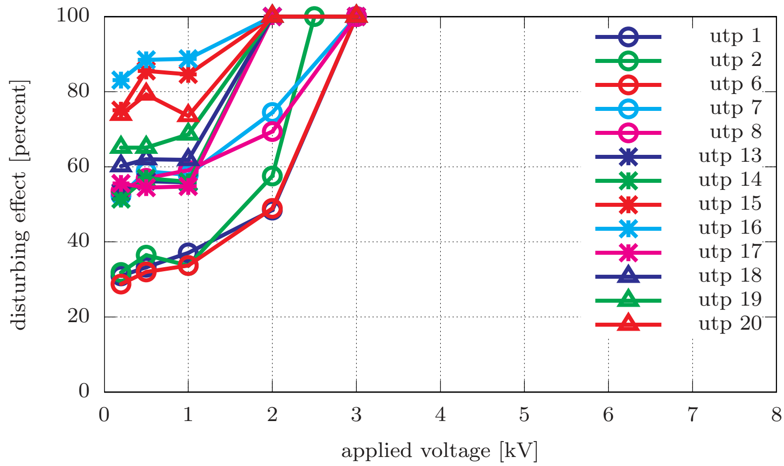

Figure 7.38: Disturbing effect on a UTP cable without feed-through.

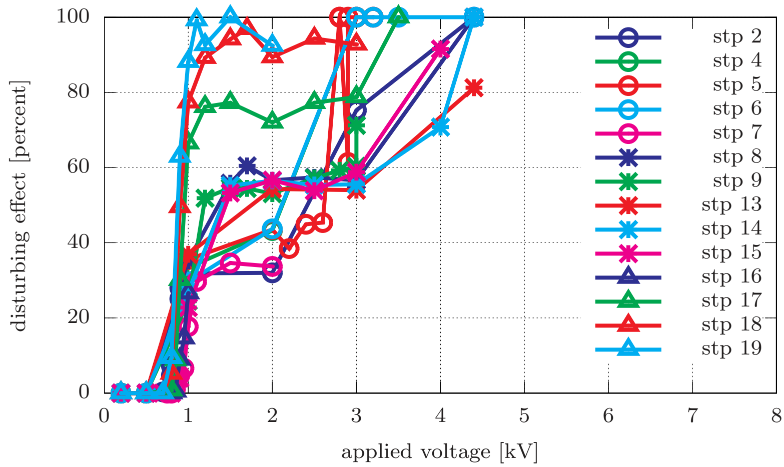

Figure 7.39: Disturbing effect on an STP cable without feed-through.

and in Figure 7.39 for the STP cable. All results for the set-up with feed-through are in Figure 7.40.

For the first set-up it is observed that the STP cable exhibits a threshold of approximately 900 Volt for any disturbance, but the interference increases rapidly above 900 Volt excitation. The UTP cable in this set-up also exhibits a non-linear behaviour, but the threshold appears to be under 200 Volt. Figure 7.40 shows a significant improvement for the STP cable in the second set-up, but not for the UTP cable. Apparently, in the first set-up the EFT pulses are coupled into the network switches directly, having an adverse effect on the throughput, whereas the feed-throughs give protection in the second set-up. The results in Figure 7.40 also show that a not properly bonded screen on an STP cable makes the system even slightly more susceptible

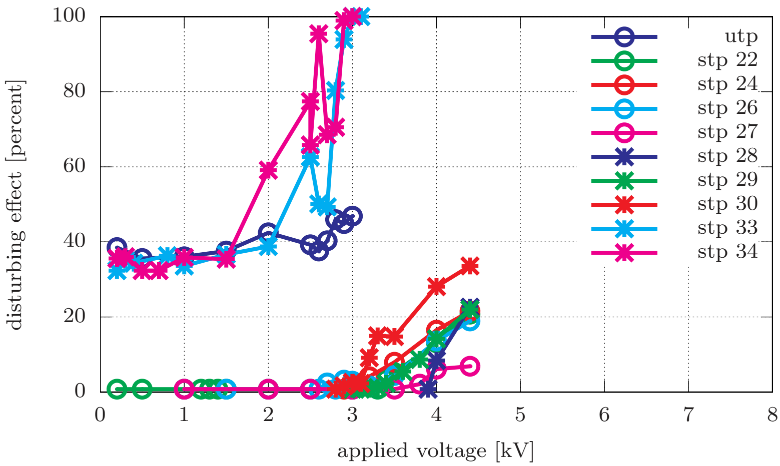

Figure 7.40: Disturbing effect with feed-through
utp: unscreened cable (without feed-through),
stp 33: screened cable, screen interrupted both sides,
stp 34: screened cable, screen interrupted on one side,
other: screened cable, bonded both sides.

to EFT than using a UTP cable.

Figures 7.41 and 7.42 show the measured Differential Mode (DM) voltage on the Ethernet line between one feed-through and a switch. Although this measurement is under-sampled (500 Msps), it shows two different, but reproducible responses of an EFT pulse. The signals represent communications between the two switches and are independent from other Ethernet peripherals that may be connected to these

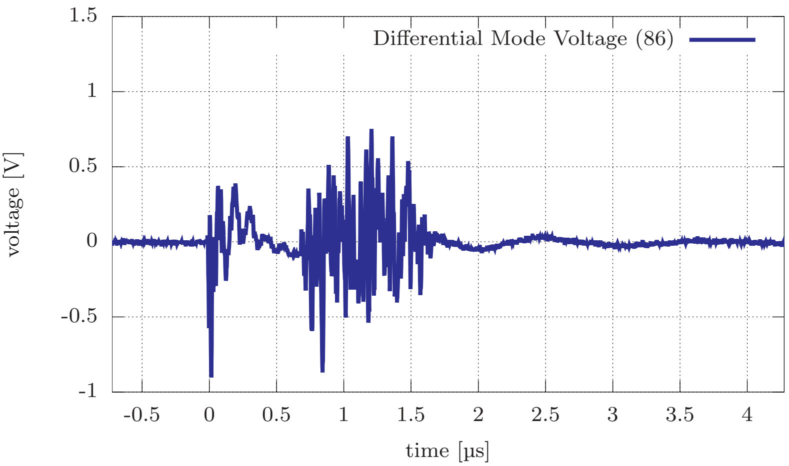

Figure 7.41: Effect on data traffic (undersampled):
small effect (recovery by 1 µs data traffic)

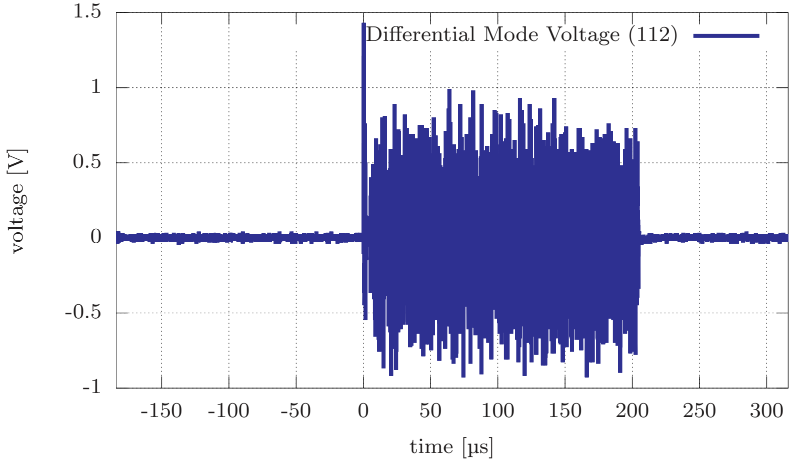

Figure 7.42: Effect on data traffic (undersampled):
larger effect (recovery by 200 µs data traffic)

switches. For lower pulses, this communication always lasts 1 µs (Figure 7.41) whereas for higher pulses it always lasts 200 µs (Figure 7.42). The disturbing effect on the throughput is approximately 50 percent for the 1 µs communication, whereas it is much more for the 200 µs.

7.9 Conclusion

Comparison of some installation rules show that there is a huge difference between these rules both in quantities and in definitions and that different mitigation measures are recommended. The rationale behind these rules is lacking and these rules appear not to be written for state of the art complex installations on nowadays naval vessels. This makes it impractical for system integrators to implement these rules and there is a need for an update.

Calculations and measurements are performed that give more insight in cable crosstalk in complex installations. One result from this analysis is a numerical evaluation of the coupling between two wires above a ground plane as function of frequency. This rises with 20 dB per decade with the first peak at a quarter wavelength. For higher frequencies there are peaks every half wavelength with all peaks at the constant level from equation (7.56) which is a function of the ratios h/r and h/s. This is a generic relation between cable separation and the maximum expected crosstalk, relative to cable radii and height above a ground plane. It accounts either for unscreened cables or for the outer screen of screened cables, i.e. the Common Mode (CM) currents and voltages.

For screened cables, the crosstalk is determined by the screen resistance ρ_s and transfer inductance l_t, besides h, r, and s.

A measurement set-up has been made and some modelling tools are developed to measure and calculate the crosstalk between commercially available cables. Results from the measurements show that cable type selection is the most important factor for cable coupling. Using a properly mounted high quality screened cable has more effect on crosstalk mitigation than cable separation. The measurements show that increasing a cable separation above approximately 5 cm has very little effect.

The most used medium for data communication nowadays is Ethernet. The state of the art cable, CAT7A, has multiple screens to permit high data rates up to 40 Gbit per second. This cable is commercially available and affordable. This high quality screening, for throughput reasons, has a huge benefit for Electromagnetic Compatibility (EMC) as well. Crosstalk is very low if the finishing at connectors and feed-throughs is done properly as well. Commercially available Information and Telecommunication Equipment (ITE) equipment for office use, a protected environment, is not suited for industrial environments, expected on parts of a ship, because normal Ethernet connections will be susceptible for transients causing disruptions in data transfer [92]. Therefore, a proper zoning implementation should create well defined industrial and protected (office) environments.

Different equipment that is designed for the intended use in the same environment, e.g. residential or office use, will be compatible and therefore the risk of crosstalk between cables from these equipment is low.

The study on crosstalk showed that Electric Fast Transients (EFT) bursts on nearby power lines are very effective in causing interference and loss of data on Ethernet cables. The effects of transient disturbances on the mains supply voltage bursts in an Ethernet set-up have been investigated in order to get more insight in coupling and interference mechanisms in a typical Ethernet installation.

It is shown that already a small EFT pulse is capable of disturbing or disrupting Ethernet communication at protocol level, which makes this not just a matter of signal integrity. It seems that the protocol is not designed to handle EFT phenomena in an efficient way. whereas affordable high quality cable is readily available, it is more difficult to find low cost and robust connectors without a large variability in performance for EMC, but to decouple data handling electronics from disturbing transients is of paramount importance for interference free data communication. As expected, screened cables help to mitigate the interference, but only when the screens are properly connected on both sides. The focus should be on the quality of the cable terminations, i.e. cable transits, connectors, feed-throughs, and other screen terminations. This will be the topic of the next chapter.

Chapter 8

Cable terminations

It is unnecessarily expensive to put all equipment in perfectly shielded cabinets. In certain environments [46], the radiated fields from high power transmitters can be low, and equipment can be placed in rather simple, regular cabinets with limited Shielding Effectiveness (SE). This means also not using highly qualified cable terminations entries, such as Multi Cable Transits (MCTs), connectors with 360° EMI backshells as in Figure 8.1, or Electromagnetic Compatibility (EMC) cable glands as in Figure 8.2. But when cable screens are not present, not mounted at all, or in huge pigtails, as in Figure 8.3, interference is likely to occur. Transient disturbances originating from switch operations on low voltage supply networks [115] appear as Common Mode (CM) currents on all cables entering equipment, and are very effective in causing interference and data loss [93] after mode conversion between CM and Differential Mode (DM). EMC is achieved by the decoupling of the CM current loops at the inside and outside of an equipment cabinet. This can even be realised by cable terminations instead of shielding walls, to create a boundary for CM currents, for example as in Figure 8.4. In this case, the loops will still be magnetically coupled. It is a best practice to bond all cable screens at the current boundary by a metal-to-metal contact over 360° avoiding pigtails. This requirement is called a circumferential

Figure 8.1: EMC connectors with 360° EMI backshells.

Figure 8.2: EMC cable glands at the entry of a shielded cabinet.

bond in many standards and installation guidelines.

In the next sections, the coupling between the loops will be discussed, based on measurements, calculations with Numerical Electromagnetics Code (NEC) [118] as a thin wire model, and calculations on an equivalent circuit model that will be developed. The performance of cable terminations will be quantified. Part of this section is published at the Asian Pacific International Symposium on Electromagnetic Compatibility (APEMC) in 2015 in Taipei [85].

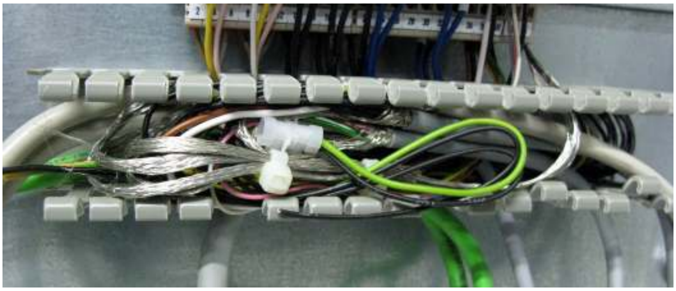

Figure 8.3: Pigtail connected cable screens.

Figure 8.4: Stainless steel tie wraps.

8.1 Calculations

8.1.1 Impedance of a loop

When a closed loop is placed in a time variant magnetic field, this field is equivalent to a voltage source in series with that loop [87, Section 2.3]. When a current injection clamp is used to induce a current in a loop, in fact a voltage is applied to that loop. A small circular loop with radius a and a small square loop with sides b that consist of a cable or wire with radius r have inductances [119, Equation 5.37]

$$L_{\text{circular}} = \mu_0 a \left(\ln \frac{8a}{r} - 2 \right) \tag{8.1}$$

$$L_{\text{square}} \approx \frac{2\mu_0 b}{\pi} \left(\ln \frac{b}{r} - 0.774 \right) \tag{8.2}$$

The radiation resistances R_r of a small circular loop and a small square loop are

$$R_{r,\text{circular}} = 320\pi^4 \left(\frac{\pi a^2}{\lambda^2} \right)^2 \tag{8.3}$$

$$R_{r,\text{square}} = 320\pi^4 \left(\frac{b^2}{\lambda^2} \right)^2 \tag{8.4}$$

which are a square function of the loop area (πa^2 and b^2) and fourth order function of frequency. The total impedance Z of a loop is composed of a resistive part R and a reactance X. For a small loop this becomes

$$Z_{\text{loop}} = R_{\text{loop}} + \jmath X = R_{\text{loss}} + R_r + \jmath\omega L \tag{8.5}$$

where R_{loss} is the resistive loss of the wire or cable, including the skin effect. The tool NEC [118], based on the Method of Moments (MoM) to solve an Electric Field Integral Equation (EFIE) model of thin wires, is used for the calculation of the impedance of a lossless circular loop. The results of this calculation in Figure 8.5 show a correspondence with equations (8.1) and (8.3) for frequencies where the circumference is much smaller than the wavelength λ. This analysis also shows that the radiation resistance R_r of a small loop is negligible compared to the loop inductance as long as the loop circumference is much smaller than the wavelength. A loop becomes a good radiator when its circumference is almost half a wavelength.

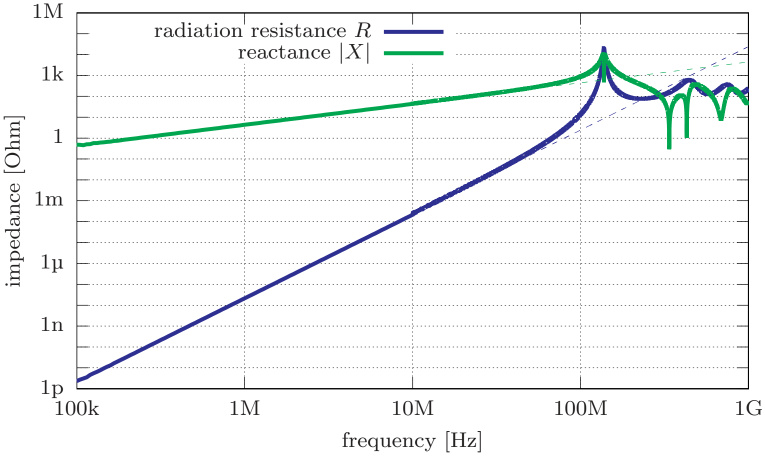

Figure 8.5: Impedance of a lossless circular loop of a thin wire, radius $r = 5$ mm, circumference $2\pi a = 1$ m. Calculations are done using NEC with 10 segments below and 50 segments above 10 MHz. The first resonance occurs at 136 MHz, i.e. 0.45λ. The derived loop inductance is 0.7µH.

8.1.2 Magnetically coupled loops

Common Mode (CM) disturbances are prevented from entering equipment cabinets by breaking up the current loops at the boundary with cable terminations and bond them together, i.e. all cable screens and earth leads are connected to each other at the cable entry points. The CM current path is broken up into two loops, I_1 and I_2 in Figure 8.6 without a ground plane and in Figure 8.7 with a ground plane.

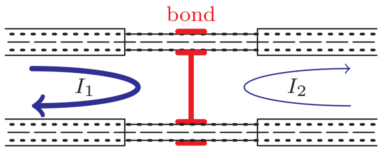

Figure 8.6: Magnetically coupled CM loops without ground plane.

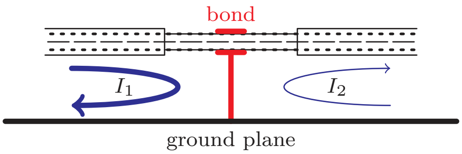

Figure 8.7: Magnetically coupled CM loops with ground plane.

If these connections are based on a good electrical bond, and if the dimensions are small compared to the wavelength, then the CM current in two adjacent loops is purely caused by their magnetic coupling and can be determined by their geometry. This magnetic coupling is represented as an equivalent circuit in Figure 8.8, including the bonding resistance R_b.

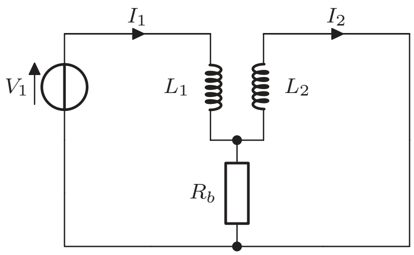

Figure 8.8: Equivalent circuit of two magnetically coupled CM loops with a bonding resistance at the current boundary.

From this equivalent circuit it follows that

$$V_1 = \jmath\omega L_1 I_1 - \jmath\omega M I_2 + (I_1 - I_2) R_b \tag{8.6}$$

$$0 = \jmath\omega L_2 I_2 - \jmath\omega M I_1 + (I_2 - I_1) R_b \tag{8.7}$$

$$\frac{I_2}{I_1} = \frac{\jmath\omega M + R_b}{\jmath\omega L_2 + R_b} \tag{8.8}$$

For a perfect bond, $R_b = 0\ \Omega$, the coupling I_2/I_1 becomes

$$\frac{I_2}{I_1} = \frac{M}{L_2} \tag{8.9}$$

i.e. the coupling is equal to M/L_2, where M is the mutual inductance between the loop inductances L_1 and L_2, and L_2 is the worst case impedance of the secondary loop. V_1 is an arbitrary source that causes the current I_1. In Section 8.2.2 the values of L_2, M, and R_b will be derived from the measurements as well as calculations with NEC. Figure 8.9 shows the coupling between two loops with a perfect bond, measured and calculated with NEC. As described in [84], the mutual inductance can be lowered by placing the cables over a ground plane.

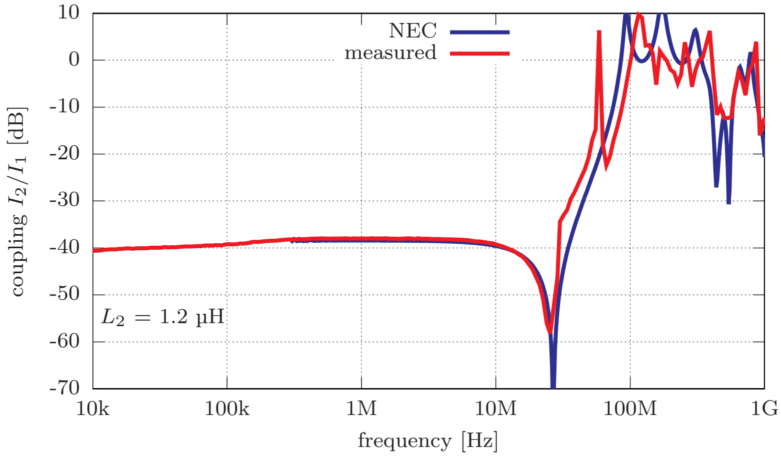

Figure 8.9: Magnetic coupling between two loops.

8.2 Measurements

8.2.1 Set-up

To investigate the effectiveness of cable terminations, two types of cables are used in the measurement set-ups: coaxial RG-58 cable with BNC connectors and CAT 7A Ethernet cable. The RG-58 is representative for any well screened multi-core cable. Measurements have been performed with and without ground plane and using two different bonding techniques. The RG-58 is analysed without a ground plane as in Figure 8.10, where the current boundary is created by feed-throughs for the BNC connectors. The RG-58 cables without ground plane with stainless steel tie wraps are in Figure 8.11, whereas Figure 8.12 shows the RG-58 cables over a ground plane with BNC feed-throughs. The Ethernet cable is analysed over a ground plane as in Figure 8.13, with stainless steel tie wraps as in Figure 8.14.

Figure 8.10: RG-58 and BNC feed-throughs without a ground plane.

Figure 8.11: RG-58 and stainless steel tie wraps without a ground plane.

Figure 8.12: RG-58 and BNC feed-throughs over a ground plane.

Figure 8.13: Ethernet with stainless steel tie wraps over a ground plane.

Figure 8.14: Detail of stainless steel tie wrap.

8.2.2 Results

A current is injected in the first loop by a current clamp (Eaton 91550-1). The current is measured in the first and second loop subsequently by another current clamp

(Eaton 91550-2B). The results show an increased coupling for the lower frequencies, compared to Equation (8.9). This increase is caused by the DC bonding resistance R_b. The results in Figure 8.15, 8.16, 8.17, and 8.18 belong to the set-ups in Figure 8.10-8.13 respectively and show the currents I_2 in the second loop, relative to the currents I_1 in the first loop.

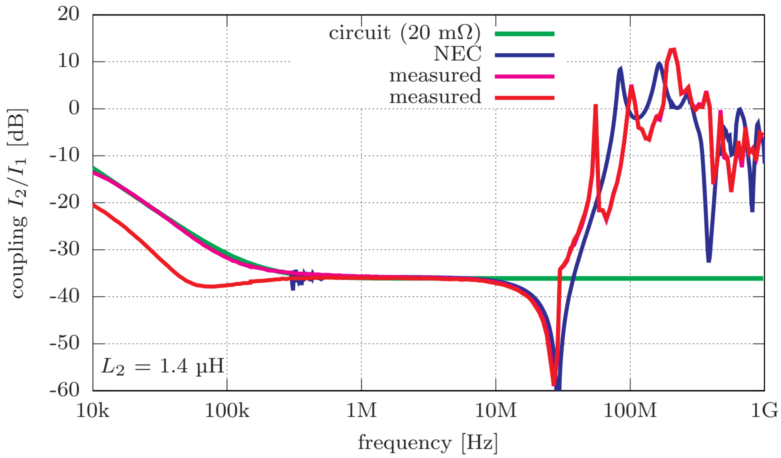

Figure 8.15: RG-58 and BNC feed-throughs without a ground plane.

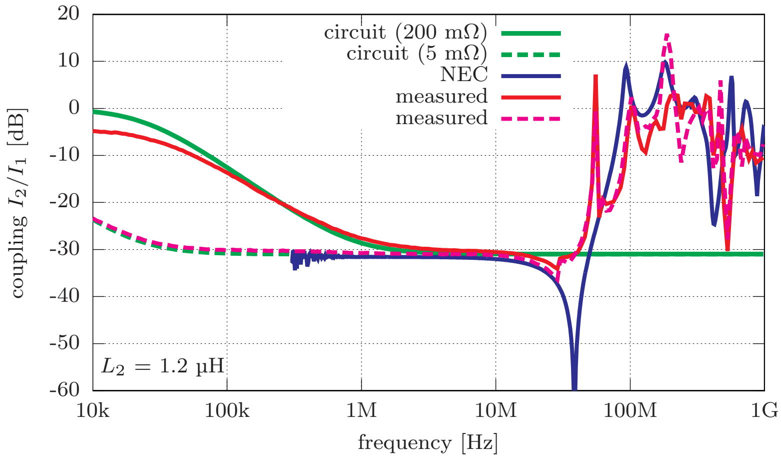

Figure 8.16: RG-58 and stainless steel tie wraps without a ground plane.

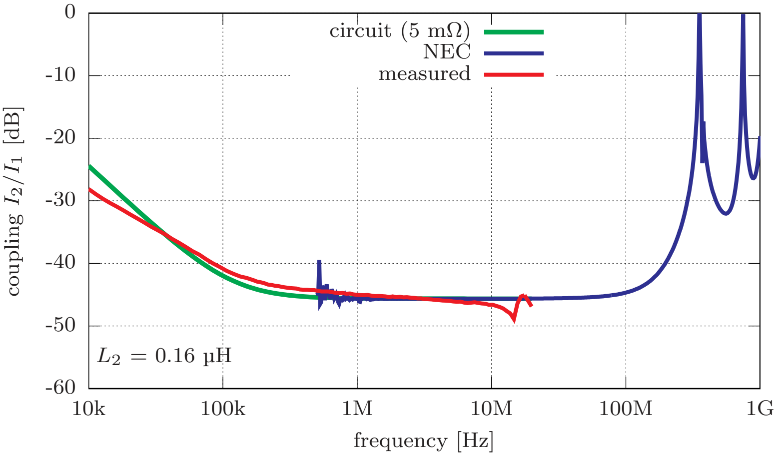

Figure 8.17: RG-58 and BNC feed-throughs over a ground plane.

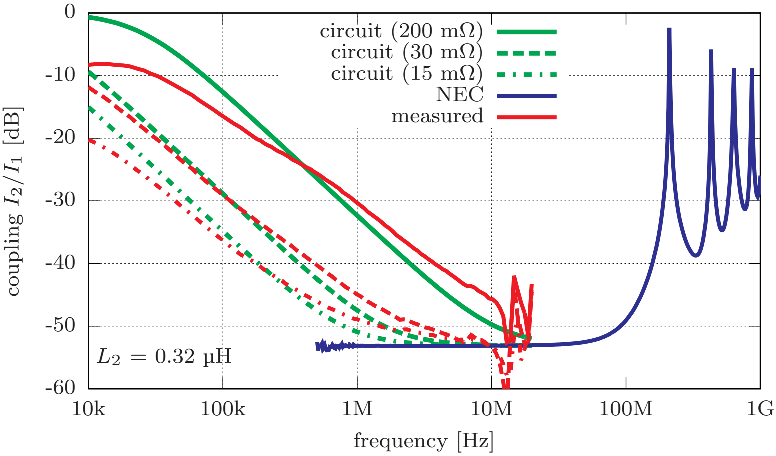

Figure 8.18: Ethernet with stainless steel tie wraps over a ground plane.

The NEC results for lower frequencies, below 300 kHz, are omitted, since NEC is not suitable for small segments and large wavelengths. In the set-ups with a ground plane, measurement results above 20 MHz are omitted, since the measured current I_2 is below the noise floor of the measurement receiver (R&S ESS). At the higher frequencies, above 10 MHz, measurements and NEC output follow the same trend. Differences are caused by the fact that cables are bent, unlike the straight wires in NEC wire model. In the medium frequencies, 1-10 MHz, there is a good agreement between the measurements, NEC calculations and the equivalent circuit from Equation (8.9), assuming a perfect bond. At the lower frequencies, below 1 MHz, the measurements follow the equivalent circuits results including the bonding resistance

R_b from Equation (8.8). The bonding resistance is not measured but obtained by curve fitting.

8.3 Quantification

In the previous sections, cable terminations have been modelled as magnetically coupled loops with a bonding resistance and this model has been validated. In this section, the minimal needed bonding resistance will be established based on this model.

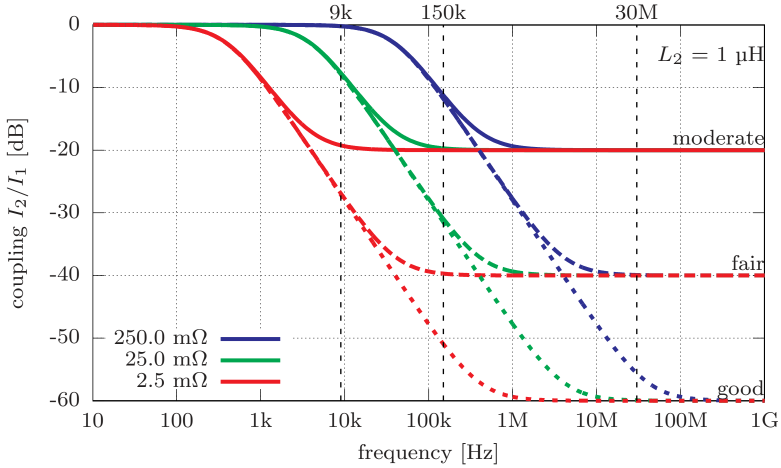

Figure 8.19: Effect of R_b on the current boundary performance for different magnetic coupling grades M/L_2, whereas L_2=1 µH.

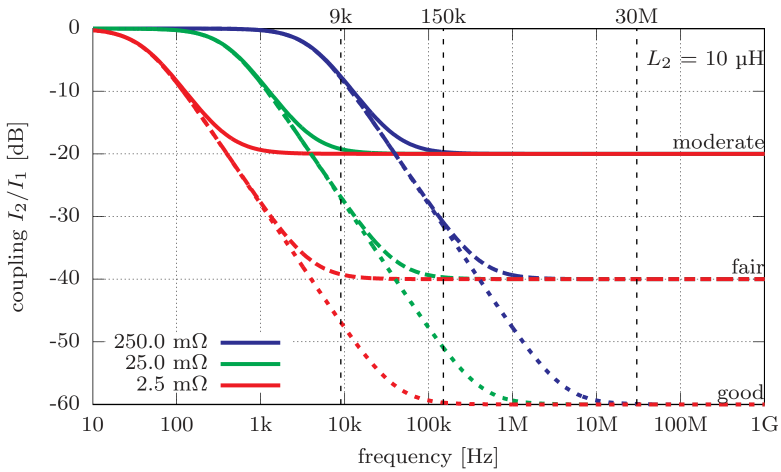

Figure 8.20: Effect of R_b on the current boundary performance for different magnetic coupling grades M/L_2, whereas L_2=10 µH.

The frequency range from 9 to 150 kHz is important for conducted Electromagnetic Interference (EMI), since the immunity of Commercial off the Shelf (COTS) equipment might not be guaranteed due to this gap in civil standards [62]. Some Power Drive Systems (PDSs) may cause conducted emissions that exceed the conducted immunity levels of light-industrial or even industrial equipment [56]. State of the art power electronics can cause transients up to 30 MHz and above with future developments.

Figure 8.19 and 8.20 show the magnetic coupling as derived in Equation (8.8) for different values of R_b (different colours), different magnetic coupling grades M/L_2 (moderate: -20 dB, fair: -40 dB, and good: -60 dB), and different values of the secondary loop impedance L_2 (in separate figures). The impact of the bonding resistance seems to be dependent on the coupling grade as well as the secondary loop impedance.

Therefore, the class R bond of 2.5 mΩ should be required in combination of a fair or good magnetic isolation. This requirement could be relaxed if the secondary loop inductance is kept high, for example with a CM choke, or if multiple moderate implementations of the current boundary principle are used.

8.4 Conclusions

To mitigate conducted interference, CM current loops at the inside and outside of an equipment cabinet can effectively be decoupled. At the absence of shielding walls, these loops are magnetically coupled. This coupling can be minimised by lowering the loop areas through a proper layout of the cables and the use of a ground plane, e.g. from a cable tray, for all cable entries. Cable screens must be bonded to this ground plane, creating a boundary for the CM currents. These current boundaries have been evaluated by a model, which has been verified by measuring the CM currents with current clamps. The DC bonding resistance is an important characteristic of a cable termination. The analysis has shown that this bonding resistance must be less than a few milli-Ohm. The class R bond of 2.5 mΩ has long been recognised as an indication of a good bond across a metallic interface and being realistic for a single joint. This is difficult to achieve with a tie wrap for these thin cables, because such a low bonding resistance requires a certain mechanical pressure between two conducting metal surfaces. A low bonding resistance will be easier to obtain with thicker cables.

Chapter 9

Protection of Exposed Cables

Part of this chapter is a summary of a publication at EMC Europe in 2015 in Dresden with a Symposium Best Paper Award Honorable Mention [120] and is published in [121] after extension with a time domain analysis for the risk assessment of Nuclear Electromagnetic Pulse (NEMP).

Systems and cables on naval ships act as antennas and are susceptible to the external Electromagnetic Environment (EME), which may cause Electromagnetic Interference (EMI). Signals, radiated from above deck cables, may also be of a concern for a possible increase of the noise floor of on-board receivers, as well as leaking information or detection by third parties. To prevent these problems, it is a best practice to avoid the installation of cables in the exposed upper-deck environment of naval ships, but that is not always practical and sometimes inevitable. Cables are necessary to feed auxiliary equipment, such as lighting, switches, auxiliary craft, general purpose power outlets, Replenishment at Sea (RAS) installations, etc. Cables can be protected by placing them in metallic trays or conduits [100] with proper bonding at all ends. Also this is not always practical. Lights are often non-conducting and long cables feeding auxiliary vessels are not always properly screened. To allow these situations, there is a need for a risk analysis of exposed cables as well as general quantified guidelines on how to install and protect them. A similar problem set-up with a chain of: wires acting as unwanted antennas, exposed cable shields, and unexposed cables is examined in [122]. In that paper, fields on the entire structure of an airplane are computed. This paper discusses design rules for the layout of unprotected cables above deck, assuming a well protected environment below deck of a ship. Unprotected cables are unscreened cables that are not properly protected by cable trays or metal pipes and therefore exposed to external fields.

The external EME on naval ships can be defined by four categories of electromagnetic threats. Protection against lightning [123], [124] and Intentional Electromagnetic Interference (IEMI) [125] are out of the scope of this research. Two other categories of environments will be defined in Section 9.1. One is the High Intensity Radiated Fields (HIRF) from powerful communication and radar transmitters, either on the own ship, or a nearby ship, sailing in convoy. The other environment is a Nuclear Electromagnetic Pulse (NEMP) also known as High Altitude Electromagnetic Pulse (HEMP). Conventionally, NEMP immunity is assessed by a NEMP simulator as in [126] that fires a full or reduced threat pulse and illuminates a system or a platform. Effects on the Equipment Under Test (EUT) are measured as voltages or currents on power or signal ports. This way of testing is time consuming and expensive. Therefore, a valid risk assessment based on calculations is beneficial in the development of quantitative design rules for Electromagnetic Compatibility (EMC).

The exposed cable will be characterised and modelled as a monopole antenna in Section 9.2.1, and a lossless transmission line over a perfect ground in Section 9.2.2. The results will be used in Section 9.3 for a risk analysis to the environment in Section 9.1. A recommendation for the layout of exposed cables will be given in the conclusion.

9.1 The environment

Two types of environments will be defined in this section: The frequency domain HIRF environment in Section 9.1.1 and the time domain NEMP in Section 9.1.2.

9.1.1 High Intensity Radiated Fields above deck (skyline)

The exposed environment on naval ships varies from a baseline of 200 V/m as described in several military test standards to several kV/m for powerful radar transmitters and is called the "skyline" [20] as in Figure 9.1. This skyline is based on the calculated field at 50 m distance in the bore-sight from a set of transmitters and must be tailored to each platform or fleet. For antennas that are large compared to the wavelength, i.e. radar systems operating above 1 GHz, the field strengths have their maximum around this distance of 50 m and are much lower near the antenna due to near field effects. High Frequency (HF) antennas have higher peaks at locations near the antenna. The actual field strength will be lower on many places of the ship

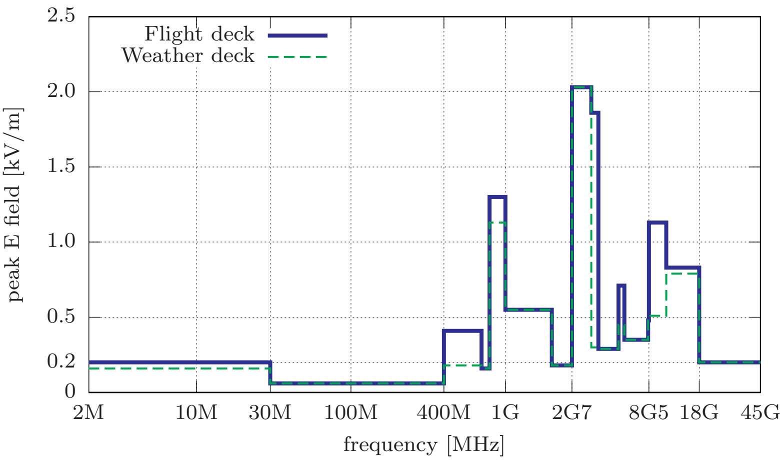

Figure 9.1: Maximum expected exposed environment on a naval ship, AECTP 250, Table 258-1A [20], to be tailored for each ship.

and can be much higher in the main beam of a radar. Mil-Std 464 [21] has different definitions of the skyline levels, see Section 3.4.1.

9.1.2 Nuclear Electromagnetic Pulse (NEMP)

Another threat for naval ships that will be analysed is the early-time HEMP waveform or NEMP, defined in Leaflet 256 of AECTP 250 [20] as:

$$E(t) = \begin{cases} 0 & t \leq 0 \\ E_0\, k_1 \left(\mathrm{e}^{-\alpha t} - \mathrm{e}^{-\beta t}\right) & t > 0 \end{cases} \tag{9.1}$$

where: $E_0 = 50\,000$ [V/m]
$k_1 = 1.3$
$\alpha = 4 \cdot 10^7 \left[\mathrm{s}^{-1}\right]$
$\beta = 6 \cdot 10^8 \left[\mathrm{s}^{-1}\right]$

This waveform is identical to the IEC standard [127] and plotted in Figure 9.2. The energy density of this pulse is 0.11 J/m^2, the rise-time is 2.5 ns, the fall-time or decay-time is 55 ns, the pulse-width or full-width-half-maximum is 23 ns.

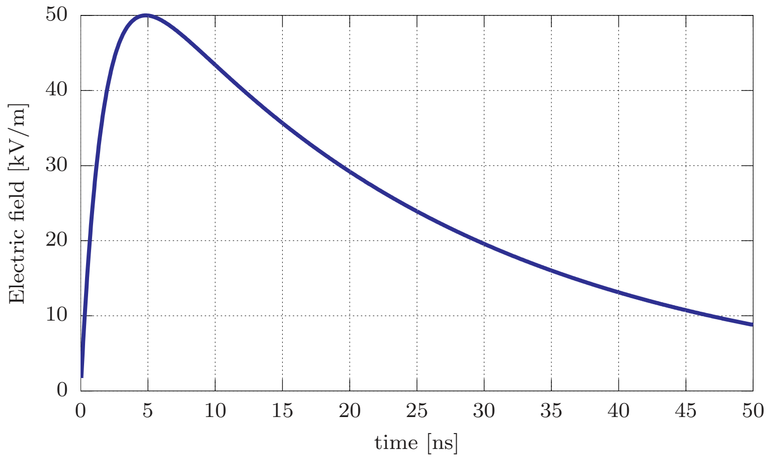

Figure 9.2: Unclassified Free-Field NEMP Environment [20, Figure 256-6].

9.2 Modelling of exposed cables

The exposed cable will be characterised and modelled as a monopole antenna in Section 9.2.1, and a lossless transmission line over a perfect ground in Section 9.2.2.

9.2.1 The exposed cable as a vertical monopole

The exposed cable acts as an unwanted wire antenna that puts a Common Mode (CM) signal on that cable with its antenna feed-points at the point where it enters the metal hull of the ship. Examples are power outlets for general purpose or to feed auxiliary craft, or complete installations, such as for RAS (Figure 9.3), etc. These examples have in common that there is an unprotected exposed part above deck, without an outer screen that can be properly bonded at hull penetration. Not all auxiliary equipment is made of metal with screened cables and steel cables may run

Figure 9.3: Power outlet and installation for Replenishment at Sea (RAS).

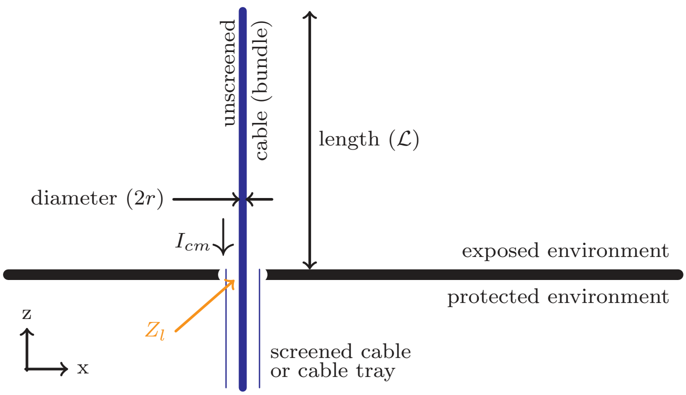

Figure 9.4: Exposed cable configured as a vertical monopole above a ground plane.

through openings to the winches below deck. These examples are considered as a worst case situation where the cable, perpendicular to the hull, is illuminated with an incident plane wave that matches this orientation as in Figure 9.4. It is assumed that the generated CM signals propagate inside the ship in a cable tray or screened cable and may be re-radiating.

Any thin wire-antenna is characterised by the Thévenin equivalent voltage, or electromotive force (e.m.f.) V_i and internal complex impedance Z_i as in Figure 9.5, for which the CM current I_{cm} through a load Z_l can be calculated. The tool Numerical Electromagnetics Code (NEC) [118], based on the Method of Moments (MoM) to solve an Electric Field Integral Equation (EFIE) model of thin wires, is used for the characterisation of this equivalent circuit. The impedance $Z_i = R_r + \jmath X$ in Figure 9.6, and voltage V_i in Figure 9.7, are calculated for a monopole of length $\mathcal{L} = 0.5$ m and radius $r = 0.005$ m that is illuminated by an incident plane wave with amplitude $E_i = 1$ V/m. The resonance frequency, approximately 141 MHz, is slightly lower than for an ideal quarter wavelength monopole due to the finite radius. The maximum e.m.f. voltage occurs at a considerably higher frequency than resonance.

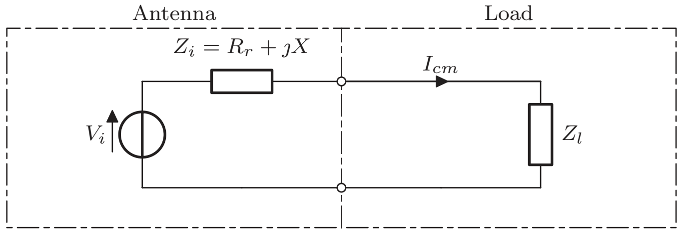

Figure 9.5: Equivalent circuit of the illuminated monopole antenna.

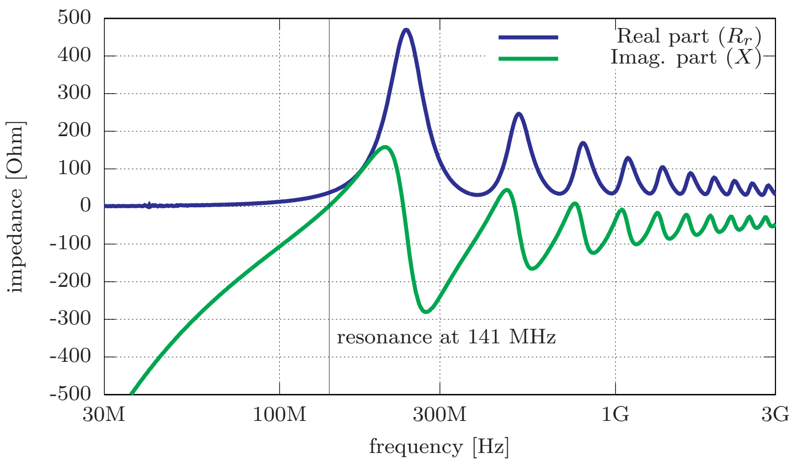

Figure 9.6: Antenna impedance Z_i ($\mathcal{L} = 0.5$ m, $r = 0.005$ m)

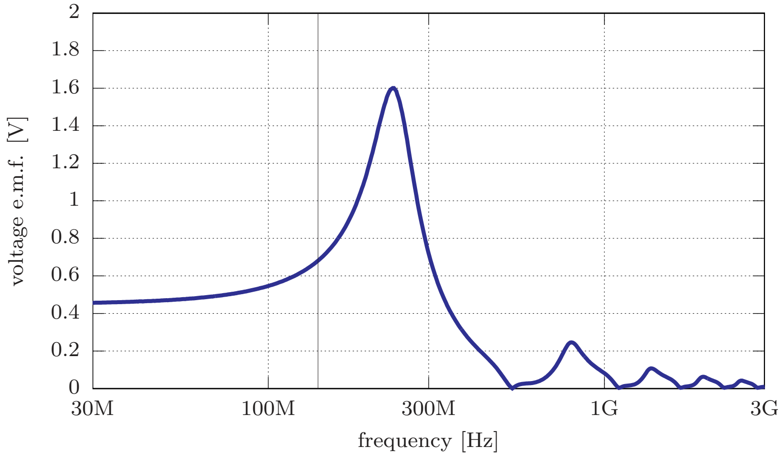

Figure 9.7: Induced voltage V_i ($\mathcal{L} = 0.5$ m, $r = 0.005$ m, $E_i = 1$ V/m)

The current I_{cm} has been calculated for different values of connected loads, using basic Kirchhoff's laws, based on these V_i and Z_i. These current values are in Figures 9.8. and match with the rule of thumb that an incident field of 1 V/m results in a CM current of 5 to 10 mA. Whereas the current increases for a decreasing load, the pertaining power in Figure 9.9 shows a maximum for a matched load.

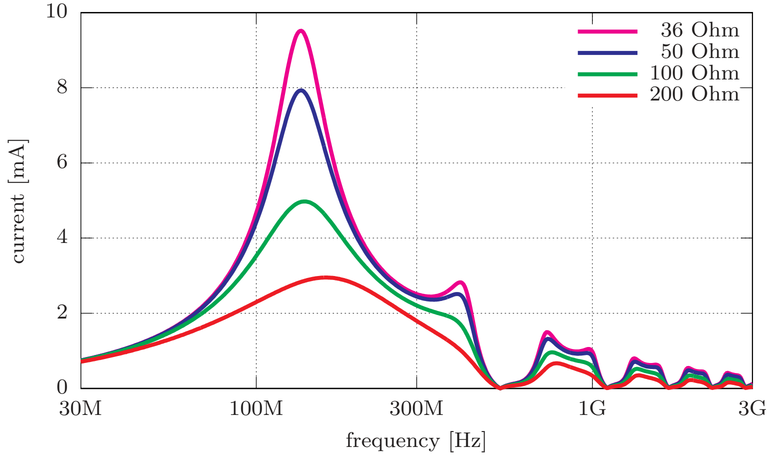

Figure 9.8: Induced current for different real values of Z_l
($\mathcal{L} = 0.5$ m, $r = 0.005$ m, $E_i = 1$ V/m)

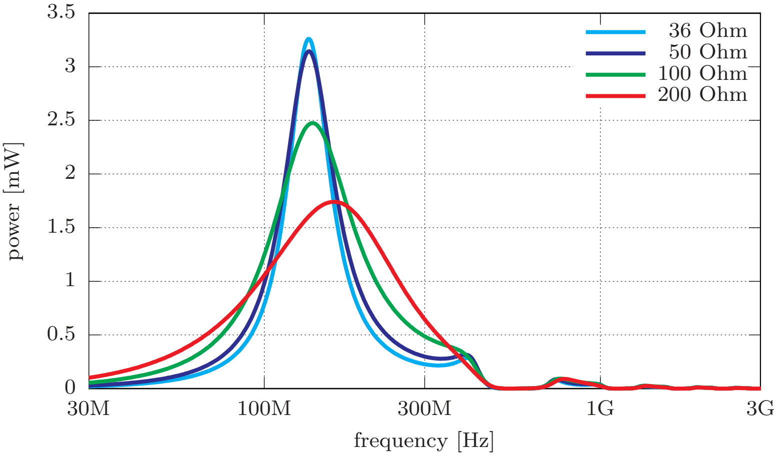

Figure 9.9: Induced power for different real values of Z_l
($\mathcal{L} = 0.5$ m, $r = 0.005$ m, $E_i = 1$ V/m)

All following results will show the induced voltage in a load $Z_l = 100\ \Omega$, which is representative for the characteristic impedance of a power cable. Figure 9.10 shows that the radius of the cable has not a strong effect on the induced voltage, whereas the length does in Figure 9.11. This plot shows two interesting phenomena: For lower frequencies the induced voltage goes up with length until the maximum just under the resonance frequency, i.e. a quarter wave length. Above this frequency the length of the exposed cable has no influence on the induced voltage any more.

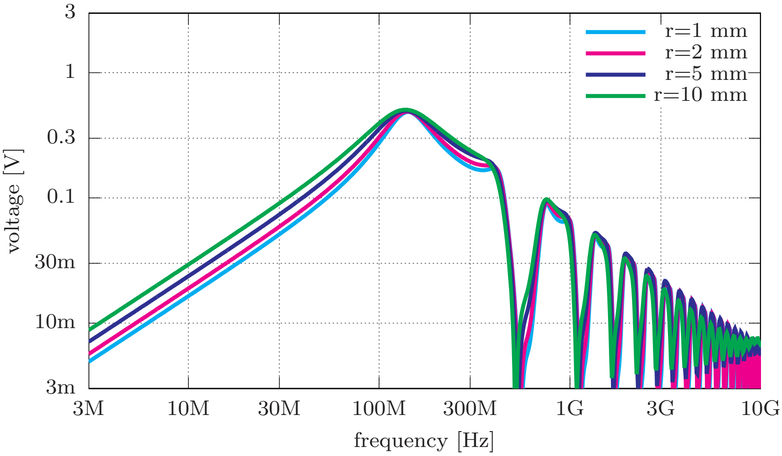

Figure 9.10: Induced voltage for different radius
($\mathcal{L} = 0.5$ m, $Z_l = 100\ \Omega$, $E_i = 1$ V/m)

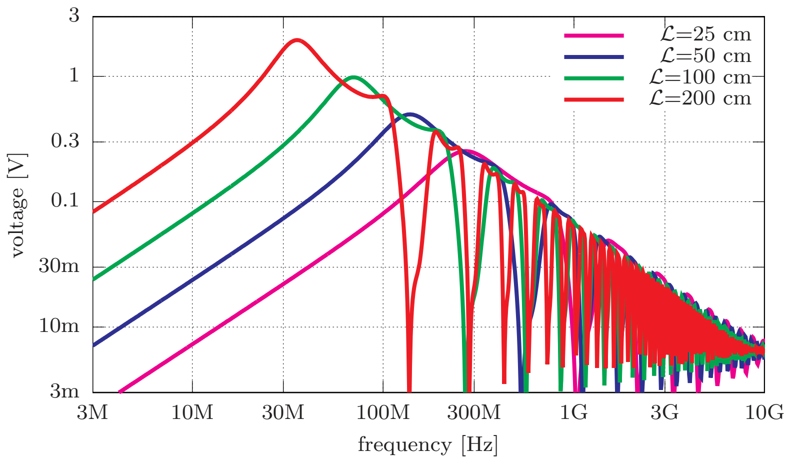

Figure 9.11: Induced voltage in Z_l for different lengths (monopole) ($r = 0.005$ m, $Z_l = 100\ \Omega$, normalised to $E_i = 1$ V/m).

9.2.2 Transmission line over a perfect ground plane

It is a best practice to route cables close to a metal ground plane wherever possible to avoid coupling of electromagnetic fields into the cable. There is a need for a more quantitative design rule, knowing the amount of coupled energy. The light in Figure 9.12 is an example of an exposed conductor close to a ground plane. The response of an illuminated cable, that is placed close to a perfect ground plane as in Figure 9.13 is calculated. The cable is modelled as a lossless Transmission Line (TL) above a perfect ground plane. The cable is characterised by the length $\mathcal{L}$, radius r, height h above a perfect ground and the terminations Z_1 and Z_2 (defined in Figure 9.14) at the near and far-end respectively. The per-unit-length parameters are dependent on h and r, which result in a characteristic impedance $Z_c = 60\Omega\ \mathrm{acosh}\,(h/r)$, if losses are negligibly small and neglecting the proximity effect. This TL model is only valid for heights h that are much smaller than the wavelength. As a rule of thumb, a cut-off frequency where $\lambda = 4h$ is chosen in the results. Since the cables are placed in the proximity of the ground plane, currents will not be uniformly distributed but flow close to the ground plane, resulting in a slightly better protection by this ground plane compared to the transmission line model used. For the highest frequencies it is better to use a full wave method, such as implemented in NEC and used for the monopole model above, whereas NEC gets inaccurate for conductors that are placed too closely in parallel to a ground plane. This TL is terminated at both sides with loads Z_1 and Z_2 and can be illuminated from different sides and polarisations. Figure 9.14 shows the four independent, non-zero, illuminations. The currents I_1 and I_2 at the loads Z_1 and Z_2 are based on the well known equations from Section 11.2.4 in [105]. The TL is terminated at the far-end with Z_2, that is modelled as very high (1 MΩ) because the cable is not connected, and terminated with $Z_1 = Z_l = 100\ \Omega$ at the near-end, representing protected power cables inside the ship.

Figure 9.12: Lighting in an exposed environment.

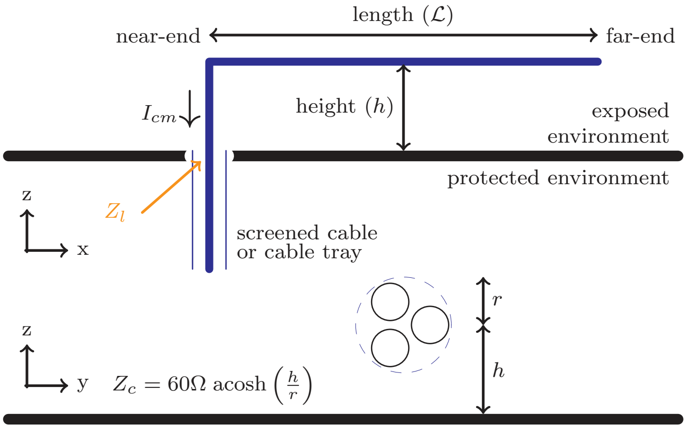

Figure 9.13: Exposed cable configured as a transmission line above a ground plane with cross section.

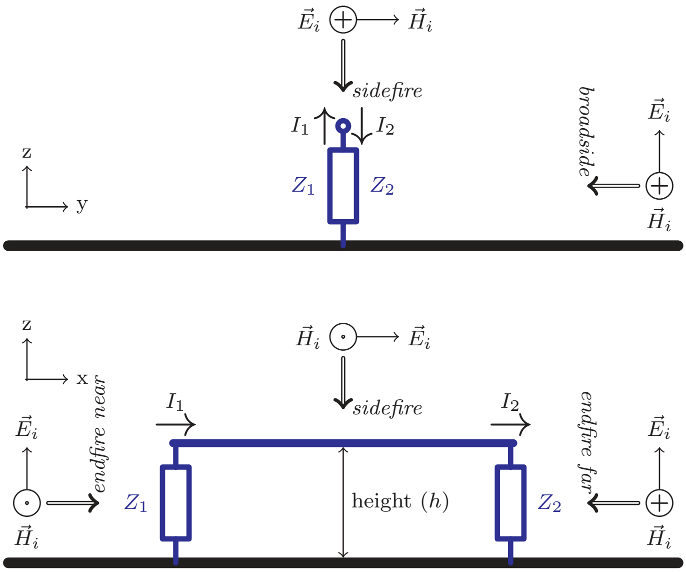

Figure 9.14: Definitions of a transmission line above a ground plane with terminations at both sides and four incident directions and polarisations.

The current I_1 for the four illuminations becomes:
Endfire far, equation (11.86a) in [105]:

$$I_{1,\text{endfire far}} = \jmath\frac{2hE_i}{D}\sin(\beta\mathcal{L})\left(1+\frac{Z_2}{Z_c}\right) \tag{9.2}$$

Endfire near, based on equation (11.86b) in [105]:

$$I_{1,\text{endfire near}} = -\frac{hE_i}{D}\left(1-\cos(2\beta\mathcal{L})+\jmath\sin(2\beta\mathcal{L})\right)\left(1-\frac{Z_2}{Z_c}\right) \tag{9.3}$$

Sidefire, equation (11.90a) in [105]:

$$I_{1,\text{sidefire}} = \frac{2hE_i}{D}\frac{\sin(\beta h)}{\beta h}\left(\frac{Z_2}{Z_c}\left(\cos(\beta\mathcal{L})-1\right)+\jmath\sin(\beta\mathcal{L})\right) \tag{9.4}$$

Broadside, equation (11.94a) in [105]:

$$I_{1,\text{broadside}} = \frac{2hE_i}{D}\left(\cos(\beta\mathcal{L})-1+\jmath\sin(\beta\mathcal{L})\frac{Z_2}{Z_c}\right) \tag{9.5}$$

where D is given by equation (11.70c) in [105]:

$$D = \cos(\beta\mathcal{L})(Z_1+Z_2)+\jmath\sin(\beta\mathcal{L})\left(Z_c+\frac{Z_1Z_2}{Z_c}\right) \tag{9.6}$$

where the incident field has an intensity E_i, and $\beta = \omega/c_0 = 2\pi f/c_0$. For an open TL at the far-end, the termination Z_2 can be chosen high, e.g. 1 MΩ. Alternatively, for $Z_2 \to \infty$, these equations reduce to:

$$\lim_{Z_2\to\infty} I_{1,\text{endfire far}} = 2hE_i\frac{\jmath\sin(\beta\mathcal{L})}{Z_c\cos(\beta\mathcal{L})+\jmath Z_1\sin(\beta\mathcal{L})} \tag{9.7}$$

$$\lim_{Z_2\to\infty} I_{1,\text{endfire near}} = hE_i\frac{1-\cos(2\beta\mathcal{L})+\jmath\sin(2\beta\mathcal{L})}{Z_c\cos(\beta\mathcal{L})+\jmath Z_1\sin(\beta\mathcal{L})} \tag{9.8}$$

$$\lim_{Z_2\to\infty} I_{1,\text{sidefire}} = 2hE_i\frac{\cos(\beta\mathcal{L})-1}{Z_c\cos(\beta\mathcal{L})+\jmath Z_1\sin(\beta\mathcal{L})} \tag{9.9}$$

$$\lim_{Z_2\to\infty} I_{1,\text{broadside}} = 2hE_i\frac{\jmath\sin(\beta\mathcal{L})}{Z_c\cos(\beta\mathcal{L})+\jmath Z_1\sin(\beta\mathcal{L})} \tag{9.10}$$

Difference between the four incident angles

The next figures show the voltage picked up by a cable for four different incident angles. The incident field has an intensity of E_i=1 V/m. For the calculation in Figure 9.15 both ends are terminated with 100 Ohm, representing cables that are connected at both sides. The four independent incident angles give different results.

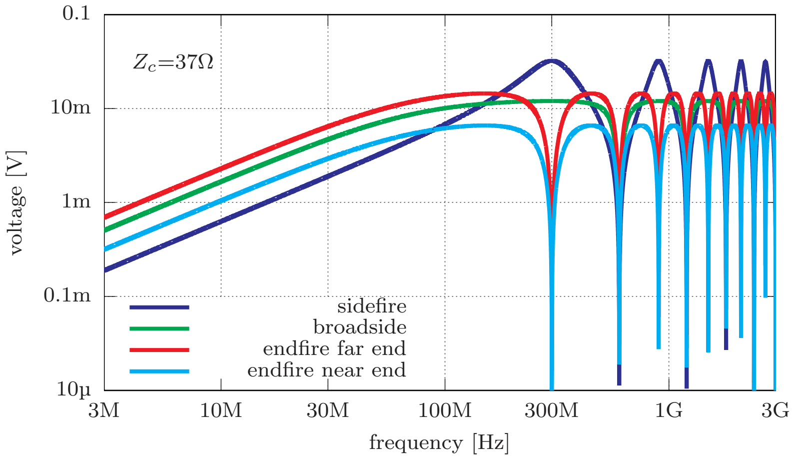

Figure 9.15: Induced voltage for $Z_s = Z_l = 100\ \Omega$
($\mathcal{L} = 0.5$ m, $r = 0.005$ m, $h = 0.006$ m, $E_i = 1$ V/m)

In Figure 9.16 the far-end is open, modelled by $Z_l = 1$ MOhm, and therefore an ideal reflector on the transmission line. In this situation only two independent illuminations remain: the sidefire illumination and all other.

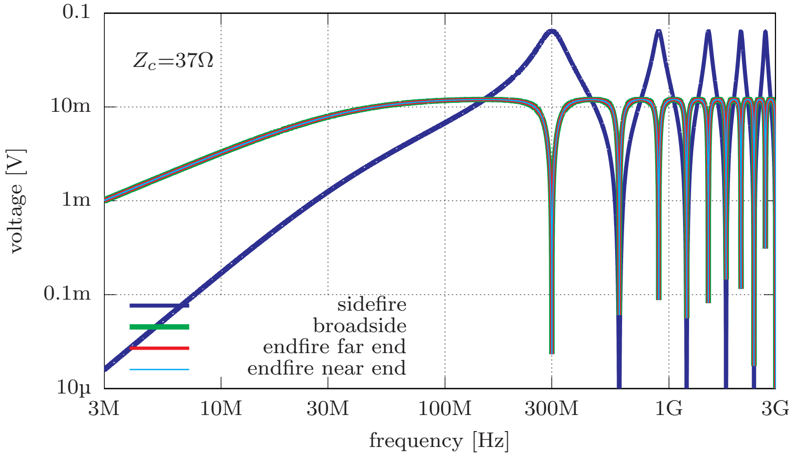

Figure 9.16: Induced voltage for $Z_s = 100\ \Omega$, $Z_l \to \infty$
($\mathcal{L} = 0.5$ m, $r = 0.005$ m, $h = 0.006$ m, $E_i = 1$ V/m)

Different heights to the ground plane

Figure 9.17 shows the response from a sidefire illumination for different heights of the cable. This figure also shows agreement between the TL equations and the results from NEC, which is known to be less accurate for wires that are very close to the ground plane. The coupling is a little higher for the higher cable.

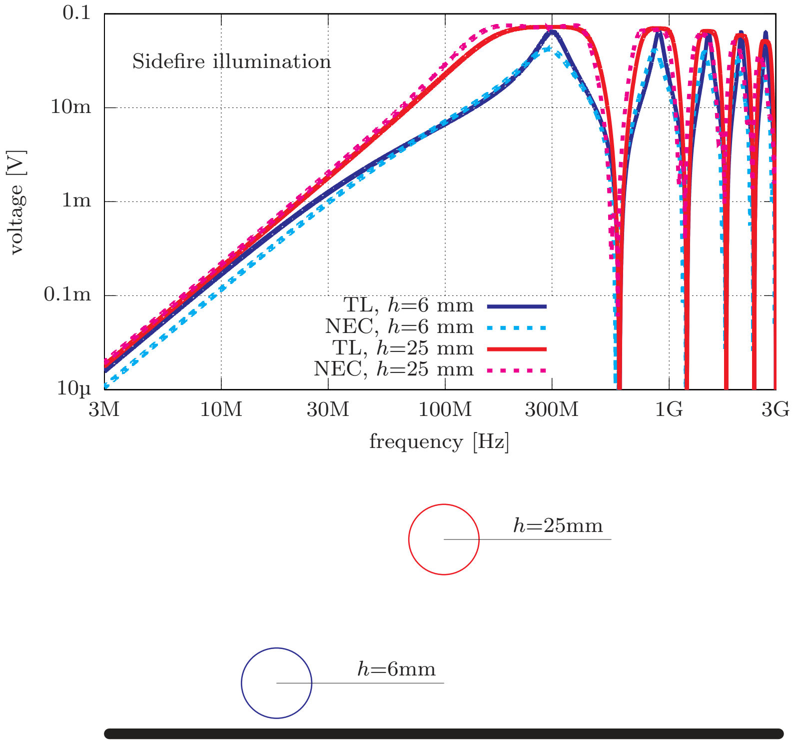

Figure 9.17: Induced voltage in Z_l for different heights ($\mathcal{L} = 0.5$ m, $r = 0.005$ m, $Z_1 = 100\ \Omega$, $Z_2 \to \infty$, $E_i = 1$ V/m).

Different radii at same height to the ground plane

Figure 9.18 shows that thicker cables pick up more field than thin cables. The NEC result for the thick cable close to the ground plane is less accurate that the TL result.

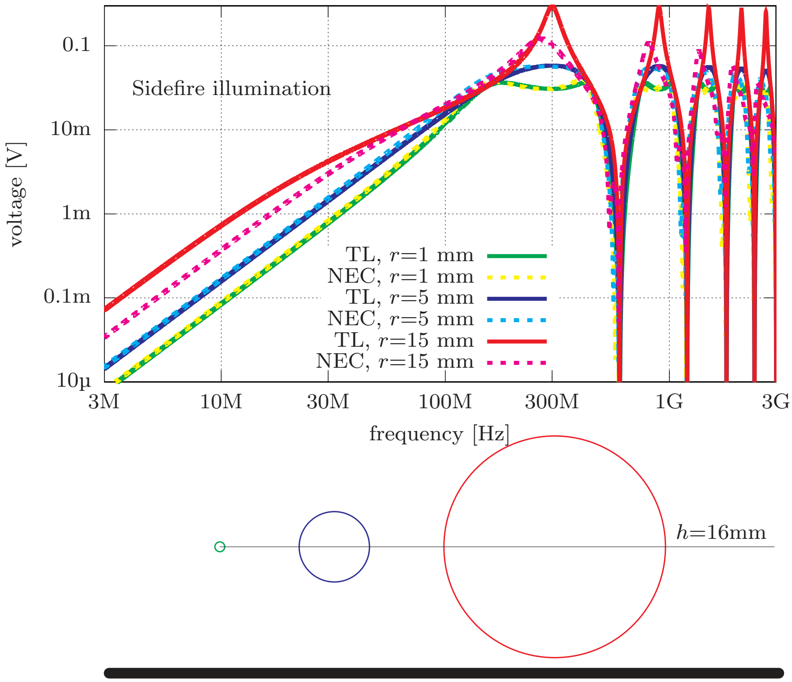

Figure 9.18: Induced power for different radii at same height ($\mathcal{L} = 0.5$ m, $h = 0.016$ m, $Z_1 = 100\ \Omega$, $Z_2 \to \infty$, $E_i = 1$ V/m)

Different radii close to the ground plane

Figure 9.19 for the same radii as in Figure 9.18 shows that thin cables close to the ground plane are protected best by that ground plane.

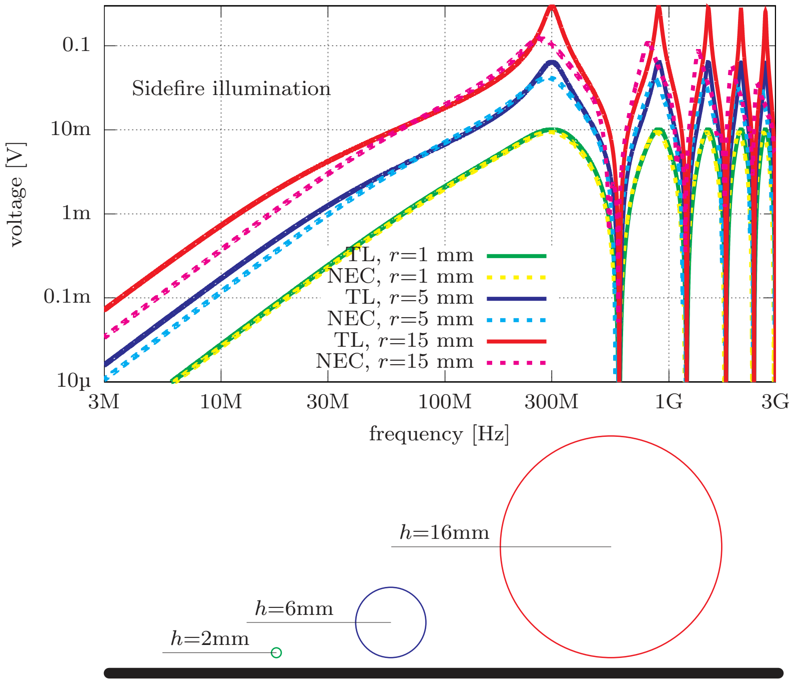

Figure 9.19: Induced voltage in Z_l for different radii close to ground plane ($\mathcal{L} = 0.5$ m, $Z_1 = 100\ \Omega$, $Z_2 \to \infty$, $E_i = 1$ V/m).

Different lengths

Figure 9.20 shows the induced voltage in the exposed cable above ground plane for variations in the length $\mathcal{L}$. Comparing these results with the monopole configuration in Figure 9.11, it can be concluded that placing a cable close to a ground plane reduces the induced voltage for long lines at the lower frequencies, but the decrease at the higher frequencies for the monopole is absent. Therefore the best practice of just placing a cable against the deck must be followed very carefully. It is better to put it in a cable tray or place it under an overhanging deck or in the corner of a beam where it is not directly illuminated by a HIRF. Cables can be protected by a conductive structure (ground plane) if the geometry and layout are chosen carefully [100], [84], resulting in a low transfer impedance between the induced CM current through the structure and an induced voltage in the cable [128].

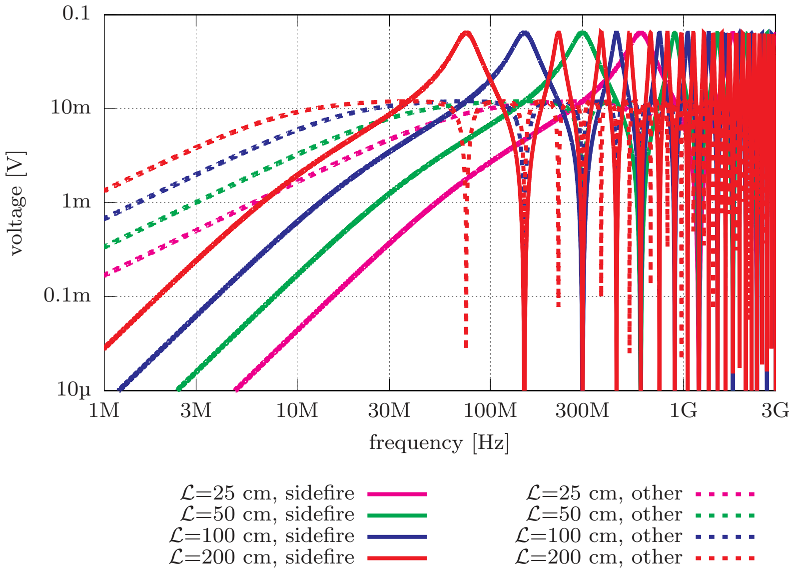

Figure 9.20: Induced voltage in Z_l for different lengths (transmission line) ($r = 0.005$ m, $h = 0.006$ m, $Z_1 = 100\ \Omega$, $Z_1 \to \infty$, normalised to $E_i = 1$ V/m).

9.3 Maximum allowable exposed length

The results from the models of exposed cables are the response of the monopole model in Section 9.2.1 and transmission line model in Section 9.2.2 in frequency domain for an incident field that is normalised to 1 V/m. To do an interference based risk analysis, these responses will be adapted to the HIRF values in Section 9.3.1 and NEMP field strengths in Section 9.3.2 environments. A possible filter is analysed in Section 9.3.3. The risk from radiated emissions will be addressed in Section 9.3.4.

9.3.1 Exposure to HIRF

Electrical installations are in general more immune against HIRF disturbances than electronic circuits. But to get a quantitative rule, the immunity levels of the generic limits will be taken as the basis for a risk analysis in a worst case situation. If only electrical installations are connected to the grid to which the exposed cable belongs rather than electronics, the field levels that couple with this cable can be somewhat higher. The limits for conducted immunity below 80 MHz are 3 Volt for residential and light-industrial equipment [43] and 10 Volt for industrial equipment [44]. The corresponding limits for radiated immunity above 80 MHz are 1 to 3 V/m [51] and 3 to 10 V/m [53].

The conducted immunity voltages are defined as an e.m.f. with an internal impedance of 150 Ω including a Coupling Decoupling Network (CDN) and a 150 Ω termination in another CDN, according to the set-up in [17, Figure 1]. To generate the same CM current as in this set-up, the allowed voltage at a cable of 100 Ω is the limit divided by 3, i.e. 1 and 3.3 Volt. This provides the worst case situation that all disturbing current is absorbed by one piece of equipment on that cable.

A disturbing CM current that is picked up by an exposed cable could be re-radiated below deck by an unprotected cable, i.e. without an additional screen or cable tray. To prevent re-radiated electromagnetic field strengths above the generic limits, the coupled energy on the exposed cable has to be limited. The MoM calculation results in Figure 9.21, where monopoles of different lengths are excited by a voltage source of 1 Volts, give a rule of thumb that 1 V produces about 0.3 V/m at 3 m distance. This will be used to set the residential and industrial risk levels in the next results. The calculated fields at lower frequencies and the peaks at higher frequencies are constant for a constant voltage source. This behaviour would be different for a constant current or constant power source.

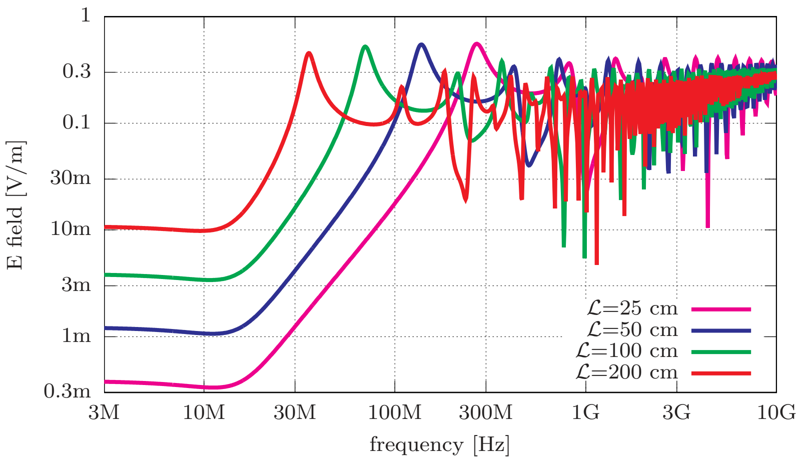

Figure 9.21: Radiated field at 3 m distance for different lengths ($r = 0.005$ m, $V = 1$ V).

Figure 9.22 and 9.23 show the induced voltages that are picked up by the exposed cable. These voltages are obtained by multiplying the results in Figure 9.11 and 9.20 by the so-called “skyline” for the flight deck [20] from Figure 9.1. Compared to the risk levels as defined above, it can be concluded that exposed and unprotected cables are a potential risk for conducted interference as well as re-radiation below deck.

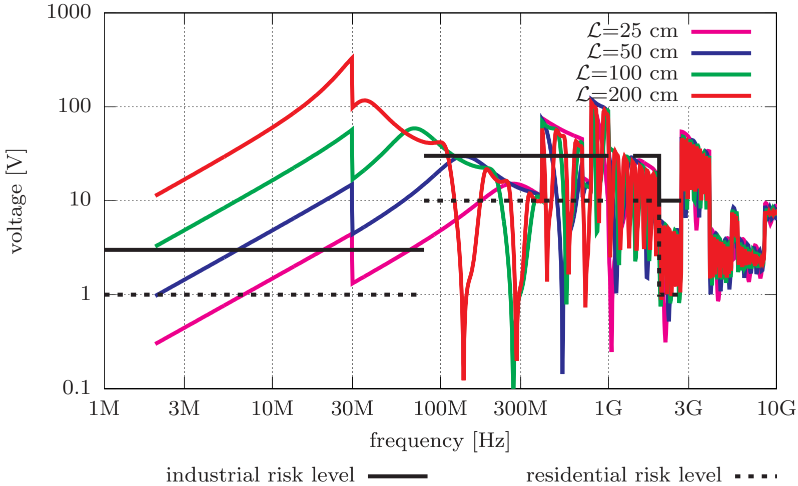

Figure 9.22: Induced voltage in Z_l for a monopole of different lengths $\mathcal{L}$ and scaled to the skyline.

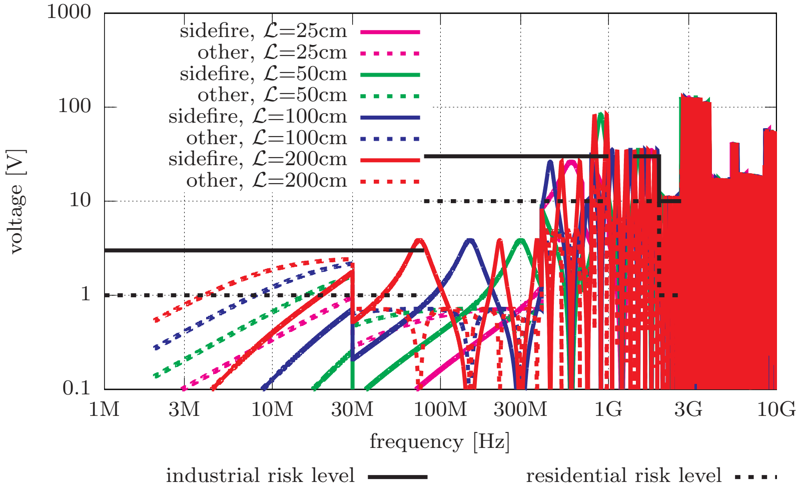

Figure 9.23: Induced voltage in a transmission line for different lengths $\mathcal{L}$ and scaled to the skyline.

This is a worst case situation and requires a cautious interpretation for several reasons:

- Much connected equipment will have a higher immunity limit than assumed here.
- As mentioned in Section 9.1.1, this skyline is based on calculated field on 50 m distance in the boresight from a set of transmitters and must be tailored to each platform or fleet.
- The actual field strength will be lower than the worst case on many places of the ship. For example, there are Radiation Hazards (RadHaz) safe zones for personnel on naval ships, where the expected maximum field strengths are lower than the skyline mentioned before. In these zones, the risk from unprotected exposed cables is also lower.
- The placement of an illuminated cable close to the deck is a good protection measure for long cables at low frequencies. For higher frequencies, such as Ultra High Frequency (UHF) communication and radar, coupling can be further reduced by using a cable tray or even a metal pipe [100], [84] with proper bonding at all ends.
- It is a best practice to assume that if a cable is not directly illuminated by a transmitter above roughly 400 MHz, the exposure can be neglected.

9.3.2 Exposure to NEMP

The results for the monopole and transmission line models in Section 9.2 give the coupled energy in a load for a plane wave illumination normalised to 1 V/m as a function of frequency. These results are the complex transfer functions from incident field to induced voltage. The Discrete Fourier Transform (DFT) of the time-domain NEMP waveform in Section 9.1.2 is multiplied with these complex transfer arrays. The inverse DFT of the obtained complex arrays give the real valued time domain waveforms that are present on the exposed cables. These are the currents I_{CM} at the feed-points of both models in Figure 9.4 and 9.13. The imaginary parts of the resulting time domain waveforms vanish, because the discrete frequency domain results consists of an even real part and an odd imaginary part as a result from a real valued time domain waveform and a causal system. An alternative method is an analytical calculation as in [129].

Monopole model

Figure 9.24 and 9.25 show the time and frequency domain results for the monopole model for different lengths. It is observed that the pulse rises with approximately 6 kV/ns, regardless the length of the antenna. There is an increase in the lower frequency parts with increasing lengths as is the case in the HIRF configuration. The amount of energy absorbed increases with the third power of the length increase, i.e. 10 dB increase for each doubling of the length. Figure 9.26 and 9.27 show that thicker cables absorb more, but this effect is not enormous.

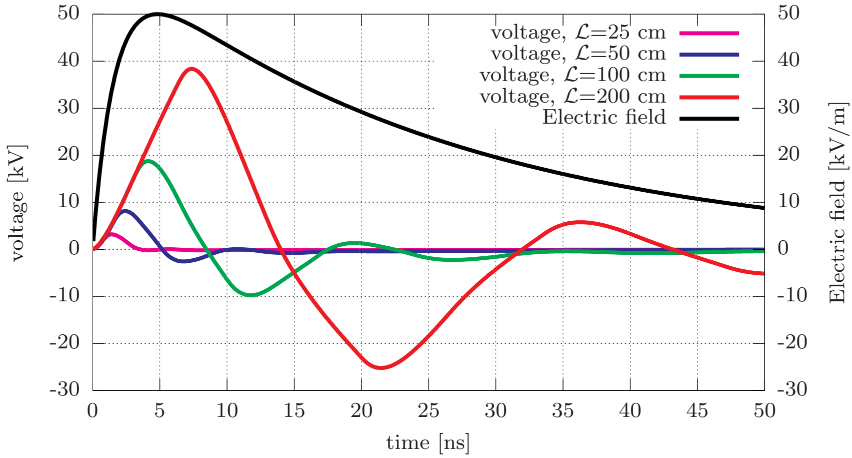

Figure 9.24: Time domain response of NEMP by a monopole with different lengths ($Z_l = 100\ \Omega$, $r = 0.005$ m).

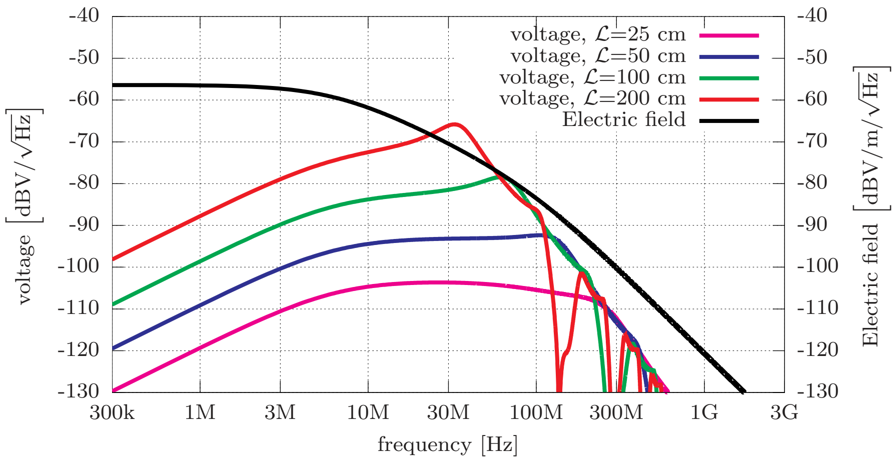

Figure 9.25: Frequency domain response of NEMP by a monopole with different lengths ($Z_l = 100\ \Omega$, $r = 0.005$ m).

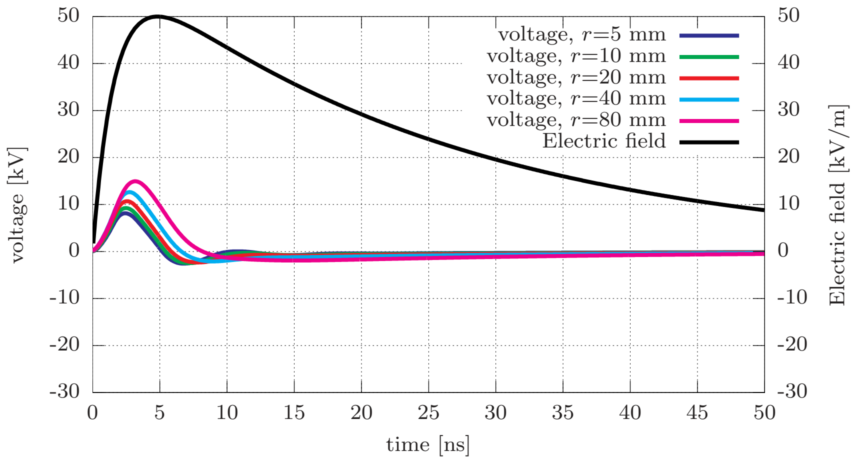

Figure 9.26: Time domain response of NEMP by a monopole with different radii ($Z_l = 100\ \Omega$, $\mathcal{L} = 0.5$ m).

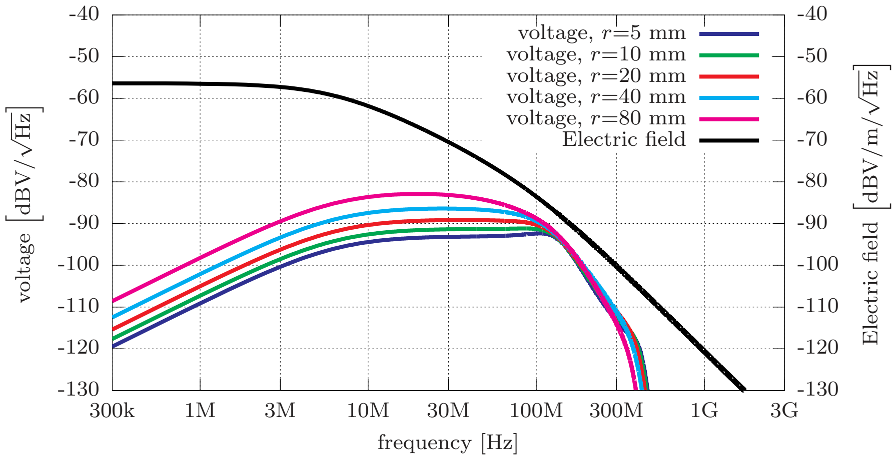

Figure 9.27: Frequency domain response of NEMP by a monopole with different radii ($Z_l = 100\ \Omega$, $\mathcal{L} = 0.5$ m)

Transmission line model

Figures 9.28, 9.29, 9.30 show the result for a transmission line of varying length that is illuminated from endfire far, endfire near, and sidefire respectively. Broadside illumination, Equation (9.10), has the same results as endfire far, Equation (9.7). The maximum induced voltage and energy are 1.12 kV and 0.34 mJ for the sidefire illumination and is reached from about 10 metres length. For the other three illuminations, the maximum induced voltage and energy saturate at 0.56 kV and 0.10 mJ. Compared to [130], which is a study to the coupling into long lines that are much higher above the ground plane, the impact of NEMP is much lower in the case of cables that run very close to the ground plane. In our case, the ground plane helps in the protection against NEMP, which appears to be a lower frequency problem compared to UHF communication and radar, where the protection does not work sufficiently.

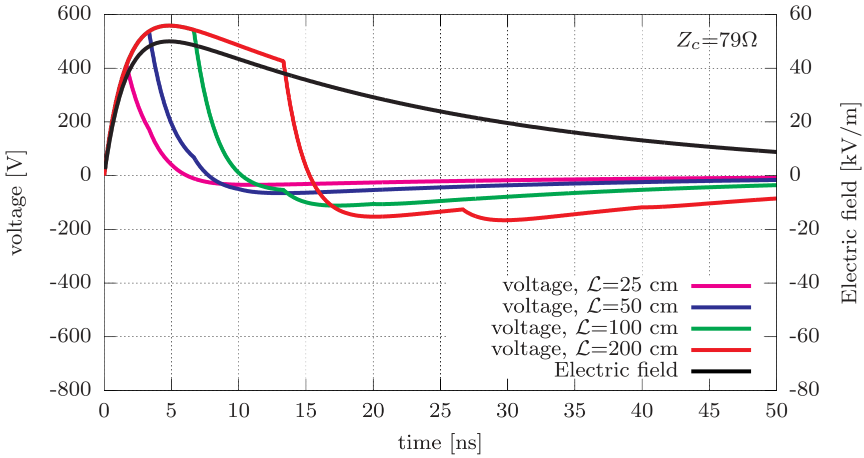

Figure 9.28: Response of NEMP by a transmission line with different lengths ($Z_1 = 100\ \Omega$, $Z_2 \to \infty$, $r = 0.005$ m, $h = 0.01$ m), endfire far and broadside.

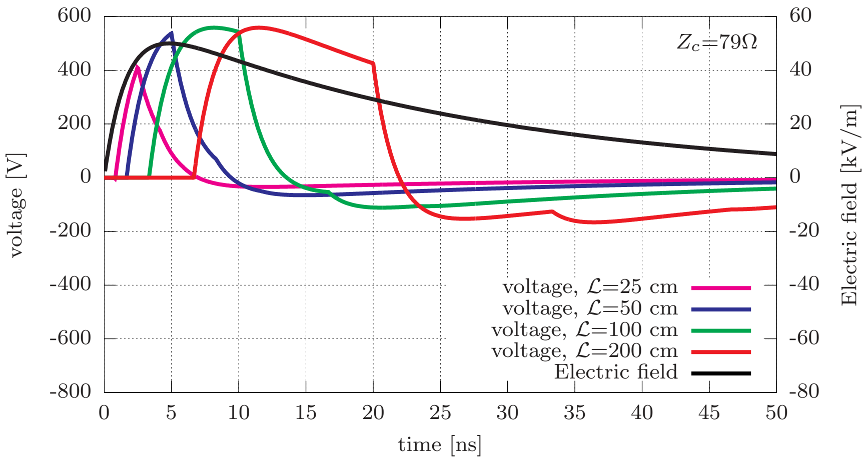

Figure 9.29: Response of NEMP by a transmission line with different lengths ($Z_1 = 100\ \Omega$, $Z_2 \to \infty$, $r = 0.005$ m, $h = 0.01$ m), endfire near.

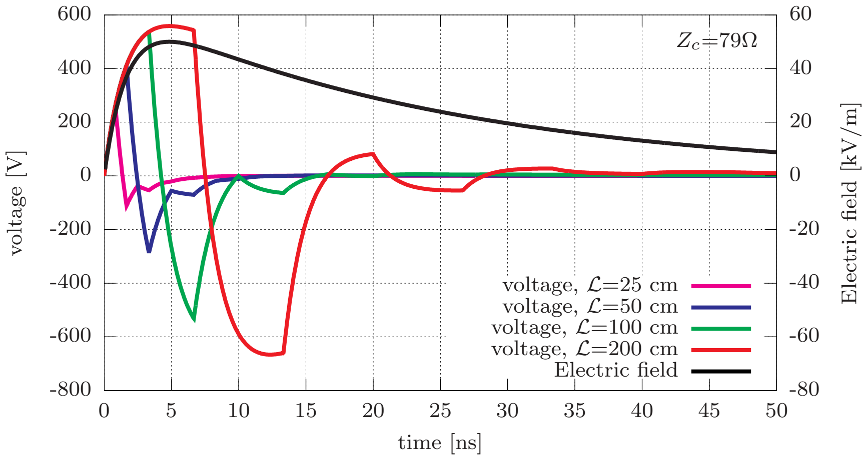

Figure 9.30: Response of NEMP by a transmission line with different lengths (Z_1=100Ω, $Z_2 \to \infty$, $r = 0.005$ m, $h = 0.01$ m), sidefire.

Effective coupling length

Figures 9.31 and 9.32 show the maximum voltage and the absorbed energy as function of $\mathcal{L}$. These two quantities do not increase above a certain length of the TL. This length is called the Effective Coupling Length (ECL), which appears to be different for maximum voltage and absorbed energy. These results show that sidefire illumination is the worst case.

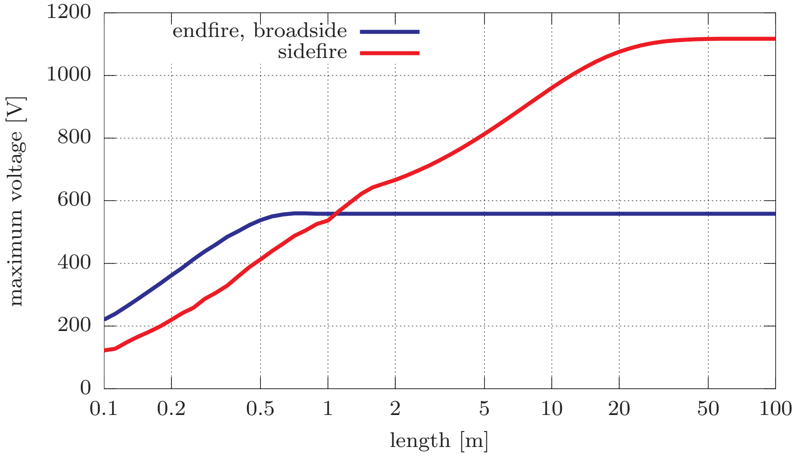

Figure 9.31: Voltage amplitude at a transmission line due to NEMP as function of the length $\mathcal{L}$ ($Z_1 = 100\ \Omega$, $Z_2 \to \infty$, $r = 0.005$ m, $h = 0.01$ m).

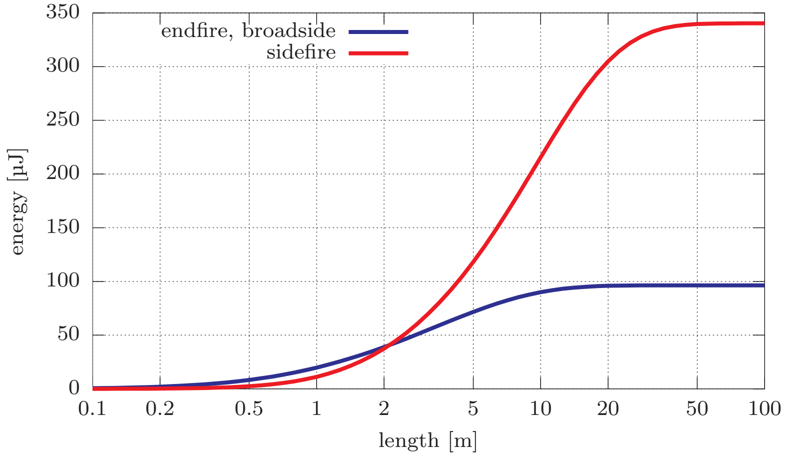

Figure 9.32: Absorbed energy by a transmission line due to NEMP as function of the length $\mathcal{L}$ ($Z_1 = 100\ \Omega$, $Z_2 \to \infty$, $r = 0.005$ m, $h = 0.01$ m).

Figures 9.33 and 9.34 show the maximum voltage and the absorbed energy as function of $\mathcal{L}$ for different heights, for sidefire illumination only. It is observed that the ECL for the maximum voltage and for the absorbed energy have a different meaning. This is because the waveform is deformed resulting in different pulse-widths due to the reflections on the line, as seen in Figures 9.31 and 9.32.

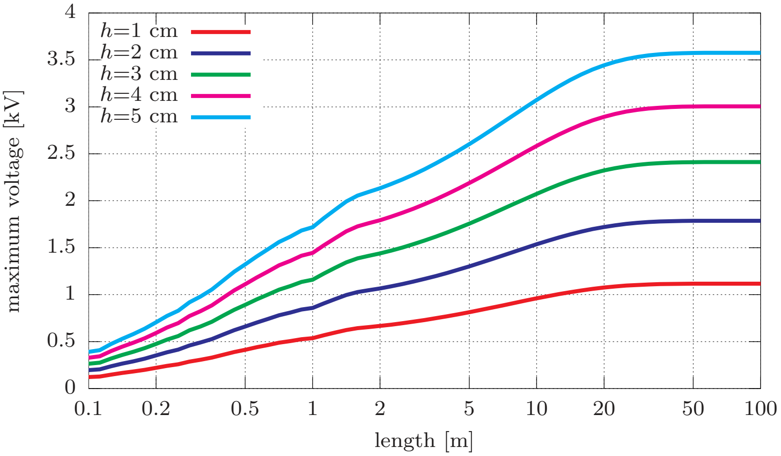

Figure 9.33: Voltage amplitude at a transmission line due to NEMP as function of the length $\mathcal{L}$ ($Z_1 = 100\ \Omega$, $Z_2 \rightarrow \infty$, $r = 0.005$ m), sidefire illumination

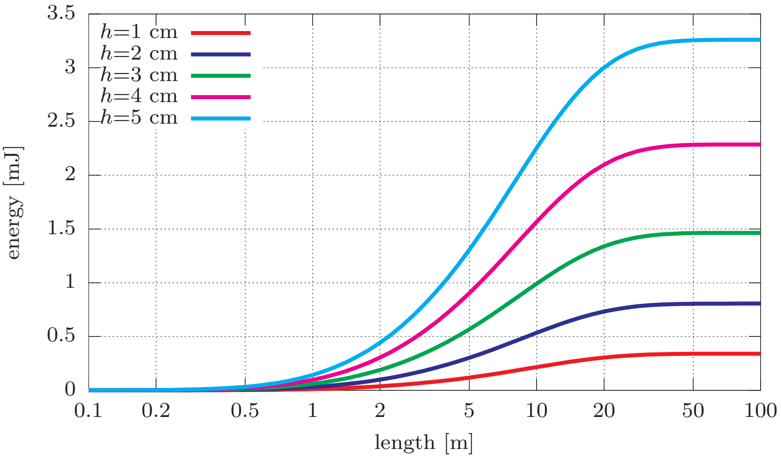

Figure 9.34: Absorbed energy by a transmission line due to NEMP as function of the length $\mathcal{L}$ ($Z_1 = 100\ \Omega$, $Z_2 \rightarrow \infty$, $r = 0.005$ m), sidefire illumination

9.3.3 Filtering

The effect of an additional filter to avoid electromagnetic signals to propagate into the hull of the ship is analysed. This filter is placed at the point where the cable penetrates the hull as in Figure 9.35. This filter is applied to each wire in the cable, i.e. one capacitor for each wire and either a Common Mode Choke (CMC) or one ferrite on the cable.

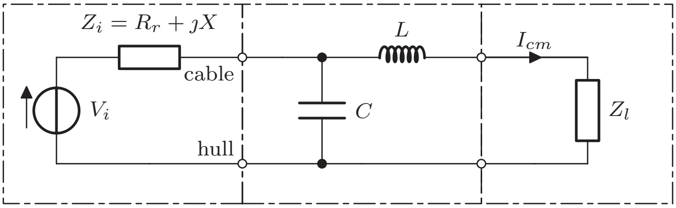

Figure 9.35: Equivalent circuit of an illuminated exposed cable with filter.

$$I_{cm} = \frac{1}{Z_l + \jmath\omega L + Z_i\left(1 + \jmath\omega C\left(Z_l + \jmath\omega L\right)\right)} V_i \tag{9.11}$$

Equation (9.11) shows the resulting current I_{cm} that flows into the load Z_l and is plotted in Figure 9.36 after conversion to voltage. The internal impedance Z_i of the antenna is included in the characterisation of the filter, which is important because it varies much as function of frequency. Analysis on different configurations of the filter,

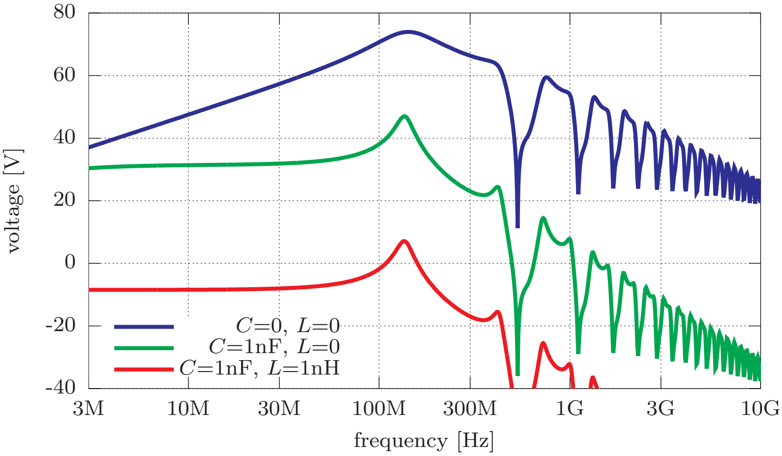

Figure 9.36: Induced voltage for different C and L
($\mathcal{L} = 0.5$ m, $r = 0.005$ m, $E_i = 1$ V/m, $Z_l = 100\ \Omega$).

not included here, show that the positions of C and L in this filter are important, i.e. the capacitor must be on the exposed side and the CM inductance on the protected side of the filter. The green line in Figure 9.36 already shows an improvement by using just a capacitance C of 1 nF without the inductance L. Further improvement is achieved by adding a small inductance L. The chosen values of C and L are small, but sufficient in a worst case scenario. The capacitance to earth of 1 nF will cause a negligible leakage current at 60 Hz on a naval IT-grid, defined in Section 2.3.1. An inductance of 1 nH can easily be achieved by a standard ferrite around the cable. Possible parasitic capacitance between windings of the inductance, in fact due to saturation of the coil [131], will be compensated by the capacitor as well.

9.3.4 Radiated emissions

CM conducted signals from below deck are radiated by cables in the exposed environment in the same way as exposed cables pick up field. These two mechanisms are reciprocal. The rationale behind immunity and emission limits are very different and so are the levels of the limits. Although it is difficult to compare military with civil standards [59], Commercial off the Shelf (COTS) equipment intended for use in a residential and light-industrial environment will produce a level of radiated emissions that will not have a great impact on the noise level of receivers used in a naval environment. Radio Frequency (RF) protection is covered well in the commercial standard and it is assumed that there is sufficient distance and hull attenuation between this kind of equipment and the receive antennas above deck. This is analysed in Chapter 10.

9.4 Conclusion

It is shown that High Intensity Radiated Fields (HIRF) from the above deck naval environment or a Nuclear Electromagnetic Pulse (NEMP) may cause conducted interference and generate electromagnetic fields below deck via unprotected cables that are inevitable above deck. Unprotected cables in an exposed environment are modelled and characterised both as a monopole antenna perpendicular to the deck and as a transmission line, representing a cable close to the deck. The length of the cable has no effect on the induced voltage if this length is more than a quarter wavelength for the monopole configuration and a half wavelength for the transmission line configuration. Long monopole configurations are a threat for low frequencies, such as HF (2-30 MHz) and NEMP. The placement of an illuminated cable close to the deck is a good protection measure for long cables at low frequencies, which includes NEMP protection. This measure does not show much improvement at higher frequencies, such as UHF communication and radar, in which case it is better to hide these cables from this illumination.

A risk analysis shows that the induced voltages may exceed the generic limits for Commercial off the Shelf (COTS) equipment in a worst case situation. If only electrical installations are connected to the grid to which the exposed cable belongs rather than electronics, the field levels that couple with this cable can be somewhat higher. Electrical installations are in general more immune against HIRF disturbances and NEMP than electronics. It appears that NEMP poses a low risk if exposed cables are kept short or placed against a protective ground plane. The coupled pulse from a high intensity NEMP illumination is comparable to Electrostatic Discharge (ESD) or Electric Fast Transients (EFT) and are not expected to cause damage on electric installations. It is recommended to limit the length of an exposed cable to 25 cm and to place exposed cables not in the Line of Sight (LoS) of transmitters above 400 MHz. For extreme cases, a simple Common Mode (CM) filter can be effective if it is placed at the point where each cable penetrates the hull.

Design rule

On the above deck of a naval ship with the worst case expected High Intensity Radiated Fields (HIRF),

1. limit the length of an exposed cable to 25 cm, and
2. do not place exposed cables in the Line of Sight (LoS) of transmitters above 400 MHz.

– If this rule can not be met, a common mode filter can be applied at the entry point of the cable.
– If the exposed cable is in a Radiation Hazards (RadHaz) safe zone for personnel, and Nuclear Electromagnetic Pulse (NEMP) protection is not required, the length can be extended to 50 cm.

Chapter 10

RF Protection of maritime VHF radio

Part of this chapter is submitted for publication in [132].

Widely available Commercial off the Shelf (COTS) equipment is integrated on naval ships for cost reduction as well as the ability to implement the newest technology into dedicated military applications. These products are normally not certified against military, nor maritime standards for Electromagnetic Compatibility (EMC). In Chapter 4 and [59] it was shown that a strict use of military equipment standards is a pitfall in procurement that makes naval shipbuilding unnecessarily expensive. Extensive testing and modification of COTS equipment against a specific standard is a cost-driver. A better approach is a risk assessment and the application of tailored measures if needed [8], [9]. Also the civil maritime industry faces the problem that affordable new technology is hardly tested against the maritime product standards, such as the IEC 60533 [63] and IEC 60945 [14], except for dedicated bridge equipment. One aspect from both IEC 60533 and IEC 60945 is the low emission limit in the Very High Frequency (VHF) radio telephony band. This specific limit is the highest constraint for the use of generic COTS equipment designed for residential [43], [51] or industrial [44], [53] use. The specific emission limit is formulated to guarantee the availability of VHF radio telephony as part of the Global Maritime Distress and Safety System (GMDSS), i.e. essential equipment to receive a distress call.

The rationale behind the requirements in the maritime standards must be analysed. The background of the actual requirements and their interpretation will be compared with functional requirements from the International Maritime Organization (IMO). The goal is to find a way to integrate COTS equipment in a cost-effective way and guarantee the reception of a GMDSS distress call. The basis for standardisation is formed by functional requirements, for example to guarantee the availability of essential functionality. Compliance with harmonised standards provides a presumption of conformity with the corresponding legal requirements. For example, the European Union (EU) has essential requirements in the EMC Directive [2], and requires limited generated disturbance from equipment and a level of immunity. The Radio Equipment Directive [3] supports the efficient use of radio spectrum in order to avoid harmful interference and to ensure access to emergency services. The third Directive of interest for VHF radiotelephony is for Marine Equipment [4] that for EMC points to the International Convention for the Safety of Life at Sea (SOLAS), the IMO, the European Telecommunications Standards Institute (ETSI), and the International Electrotechnical Committee (IEC). These functional requirements leave room for alternative implementations as long as these are substantiated by proper research.

Both maritime standards are analysed in Section 10.1 in an attempt to get the rationale behind some choices that are not explicitly written in the standards. The various regulations will be analysed and interpreted in Section 10.2 in an attempt to formulate an alternative requirement that is in line with the functional requirements. Section 10.3 will cover the technical analysis of the interference risks, including the minimum specifications of a radio, external noise, and propagation. Tests are performed on an actual radio receiver, as well as propagation measurements.

10.1 Two commercial maritime standards analysed

This section addresses two commercial standards for the maritime environment:

IEC 60945: Maritime navigation and radiocommunication equipment and systems - General requirements - Methods of testing and required test results [14]

This is a standard with requirements and test methods for maritime navigation and radio communication equipment and systems. For EMC, it also puts requirements on other bridge equipment in close proximity that can interfere with these systems. Its scope is to assist in meeting the requirements of the SOLAS through the IMO resolution A.694 [133], which gives requirements for equipment as a part of the GMDSS system and navigation equipment. The standard is prepared by the IEC technical committee 80: "Maritime navigation and radiocommunication equipment and systems". This standard is a product family standard that is adopted by the European Committee for Electrotechnical Standardization (CENELEC) and harmonised by the EU, referred to by the EMC Directive [2]. An ETSI standard [134] was found, harmonised by the EU, and referred to by the Radio Equipment Directive [3]. This document is almost identical to the EMC part of IEC 60945.

IEC 60533: Electrical and electronic installations in ships - Electromagnetic compatibility (EMC) - Ships with a metallic hull [63]

This is an EMC standard for electrical and electronic installations in ships. Its scope is to assist in meeting the requirements of IMO resolution A.813 [64], which "**invites** Governments to ensure that all ship's electrical and electronic equipment is tested to the relevant electromagnetic compatibility standards". The document contains a normative part with requirements for an EMC test plan, both for emissions (see Section 10.1.1) and immunity (see Section 10.1.2). The informative annexes give useful background information and guidance for achieving EMC in a maritime environment. The standard is prepared by the IEC Technical Committee 18 (TC18): “Electrical installations of ships and of mobile and fixed offshore units”. The first edition was published in 1977. The second [135] and third [63] editions are technical revisions and were published in 1999 and 2015. The addition “Ships with a metallic hull” in the title of the last edition is made anticipating a new standard for “Ships with a non-metallic hull” (IEC 62742). IEC 60533 is a product family standard but **not** harmonised by the EU.

In Sections 10.1.1 and 10.1.2, the requirements for EMC are analysed for their rationale, usability, and implications. One publication [80] is found that describes the rationale of IEC 60945 in 1994. Recent correspondence with the author of this article confirmed that this is the rationale and a long standing practice.

10.1.1 Emission requirements

Figure 10.1 shows the emission limits according to IEC 60533 for radiated emissions. The conducted emission limits from 10 kHz to 30 MHz are not shown, but they overlap with the radiated limits, whereas IEC usually defines all conducted emissions below 30 MHz and all radiated emissions above 30 MHz. Both radiated and conducted emission requirements serve for the protection of the Radio Frequency (RF) spectrum. The blue line in Figure 10.1 from IEC 60945 is identical to the requirements for the deck and bridge zone in IEC 60533. Considering that radar systems have very directional antennas, the frequency range of 10 kHz to 2 GHz for the emission limits is a consequence of the list of systems in [14, Table C.1]. With the obsolescence of Omega and Decca and the possible future obsolescence of Loran navigation, this frequency range could be revised.

Noteworthy is the low radiated emission limit between 156 and 165 MHz at 9 kHz bandwidth to protect the maritime VHF radio telephone band, which is the subject of Section 10.2. As a comparison, Figure 10.2 shows the emission limits for COTS equipment scaled to 3 m according to the generic standards ([51] and [53]) and the emission limits from the military standard [5, NRE02] (different bandwidths, also scaled to 3 m). Some observations with respect to these standards, compared to the generic standards:

- The radiated emission requirements, i.e. RF emissions at the enclosure port, in the frequency range 150 kHz - 30 MHz are not present in the generic standards for industrial [53] nor for residential, commercial, and light-industrial [51] equipment. The generic standards are based on the assumption that emissions below 30 MHz should be measured as conducted emissions to cover the protection of the RF spectrum.

- A rationale for the values of the RF emission limits has not been found. The only rationale in [80] is “based on established values”. In edition 3 of IEC 60533 it is mentioned that the radiated emission limits, which are the same as in

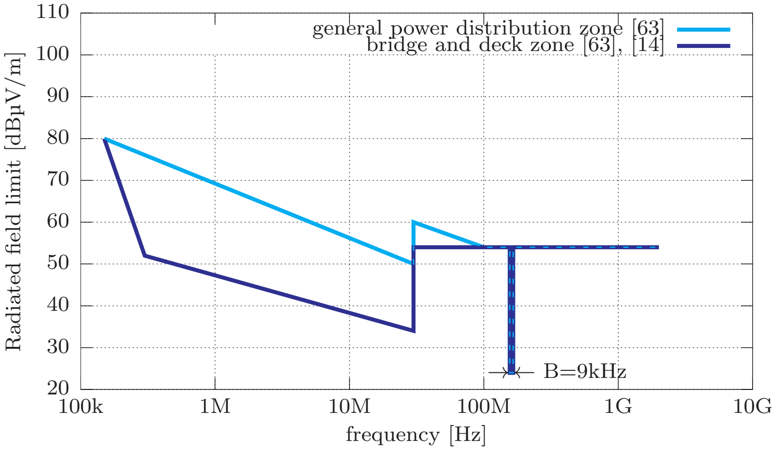

Figure 10.1: Emission limits for RF protection in a maritime environment. Limits are quasi peak and defined at 3 m distance.

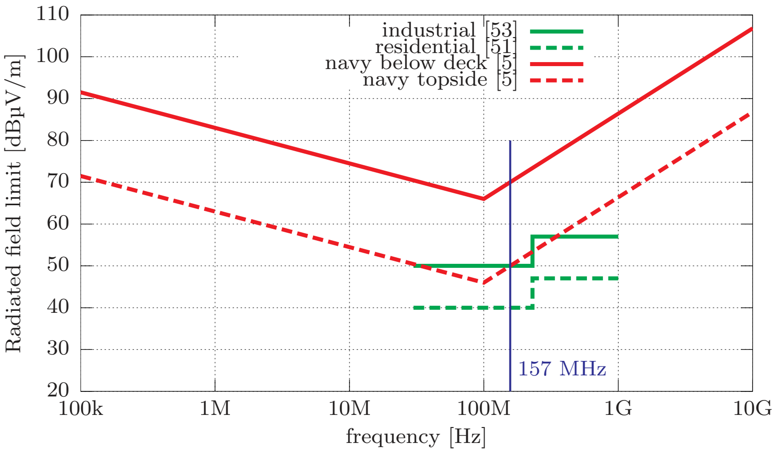

Figure 10.2: Emission limits for RF protection from generic COTS and military equipment. Industrial and residential limits are quasi peak; navy limits are peak and range from 10 kHz to 18 GHz. The different measurement distances (1 m and 3 m) have been compensated allowing a rough order of magnitude comparison.

IEC 60945, are in accordance with International Association of Classification Societies (IACS) [136, requirement E10], which does not give a rationale for these values either, but notes that it is harmonised with IEC 60533. So this seems a circular reference.

- The radiated emission tests have to be performed at a distance of 3 meters, whereas the generic standards allow these also at 10 meters distance.
- The radiated emission limits extend to 2 GHz, whereas the generic standards

[51] and [53] stop at 1 GHz. The measurement bandwidth is 120 kHz, whereas the CISPR bandwidth is 1 MHz above 1 GHz. [137].

– The extra radiated emission requirement from 156 to 165 MHz to protect the reception of the maritime VHF band is copied from IEC 60945. This will be discussed in more detail in Sections 10.2 and 10.3.

Commercial ships have systems with typical receiver sensitivities and transmitter powers as characterised by the set of radio equipment in Table 10.1 [14]. In the past there were also Omega and Decca navigation, starting at 10 kHz with a sensitivity of 5 µV/m [80]. The receiver sensitivity is the minimum required magnitude of the input signal to receive that signal with a specified Signal to Noise and Distortion ratio ($SINAD$) or Signal to Noise ratio (S/N), mostly 20 dB, where

$$S/N = \frac{S}{N} \tag{10.1}$$

$$SINAD = \frac{S+N+D}{N+D} \tag{10.2}$$

and is determined by the internal noise from the first amplifier stage in the receiver front-end. This makes the sensitivity an equipment parameter, independent from any external noise.

Table 10.1: Characteristics of radio equipment in a maritime environment [14, Table C.1]

Frequency band	**Equipment type**	**Rx sensitivity**	**Tx power**
90 - 110 kHz	LORAN navigation	20 µV/m	Rx only
283.5 - 325 kHz	Navigation differential corrections	5 µV/m	Rx only
415 - 535 kHz	MF radiotelegraphy	50 µV/m	150 W
490, 518 kHz	NAVTEX	2 µV e.m.f.	Rx only
1605 - 3800 kHz	MF radiotelephony	25 µV/m	400 W p.e.p.
4 - 27.5 MHz	HF radiotelegraphy radiotelephony	25 µV/m	1500 W p.e.p.
121.5 - 243 MHz	EPIRB/ELT	Tx only	0.5 W
156 - 165 MHz	VHF radiotelephony	2 µV e.m.f.	25 W
406.025 MHz	COSPAS-SARSAT EPIRB	Tx only	5 W
1525 - 1544 MHz	Inmarsat	0.03 µV	Rx only
1575.42 ±1.023 MHz	GPS navigation	0.07 µV	Rx only
1602 - 1615 MHz	GLONASS navigation	0.07 µV	Rx only
1626.5 - 1646.5 MHz	Inmarsat	Tx only	25 W
2.9 - 3.1 GHz	S band radar	1.4 µV	25 kW peak
9.3 - 9.5 GHz	X band radar	1.4 µV	25 kW peak
9.3 - 9.5 GHz	SART	-80 dBW	400 mW

IEC 60533 defines four zones, based on emission limits:

1. **Bridge and deck zone**, with emission limits that are the same as in IEC 60945, the blue line in Figure 10.1;
2. **General power distribution zone**, with higher emission limits, the cyan line in Figure 10.1. The standard requires a Radio Frequency Interference (RFI) decoupling device of about 30 dB in the frequency range of 10 kHz to 30 MHz in the power supply circuit between the general power distribution zone and the bridge and deck zone;
3. **Special power distribution zone**, without emission limits, but with the requirement of an "adequate" RFI decoupling device in the power supply circuit between the special and general power distribution zone, where adequate means equivalent to the difference of the relevant limits;
4. **Accommodation zone**, without requirements for non-permanently installed, i.e. non-essential equipment. The IEC 60533 gives room for use of generic COTS equipment in the accommodation zone for passengers and crew, provided that "Precautions should be taken for a sufficient decoupling of the accommodation zone from all other zones". It is left to the reader to determine how much is sufficient.

10.1.2 Immunity requirements

The RF immunity limits in IEC 60945 are based on Medium Frequency (MF) and High Frequency (HF) radio transmitters on board, as well as portable VHF radios that are expected to be used anywhere on the ship, including the bridge. Radar transmitters have very directional antennas and are therefore considered as a low risk for Electromagnetic Interference (EMI) [80]. The immunity limits and test specifications are comparable to those in the generic standards [43], [51], [44], [53]. But there are many differences in limits and the details about test set-ups, which are too minor to contribute to EMC, yet strictly inhibit the integration of generic COTS equipment.

Some differences are addressed here:

- For RF immunity tests (IEC 61000-4-3 [18] and IEC 61000-4-6 [17]), the prescribed modulating frequency is 400 Hz instead of the customary 1 kHz. The reason for this is to distinguish between this disturbance of 400 Hz and the wanted pilot tone signal of 1 kHz, which is normally used to monitor the performance of all radio communication equipment.
- The frequency band for RF immunity on the enclosure port is a continuous band from 80 MHz to 2 GHz, whereas the comparable generic standard (IEC 61000-6-2 [44]) has a gap from 1 to 1.4 GHz. The rationale for this particular gap, nor for the continuous band in IEC 60945, is clear. Possible powerful transmitters in the maritime environment in this band are military:
  * LINK-16: 960 - 1215 MHz, up to 200 Watt peak power
  * Identification Friend or Foe (IFF): 1030 MHz, up to 4 kW peak power
  * L-band radar: 1200 - 1400 MHz, many kW peak power, even many MW Effective Isotropic Radiated Power (EIRP)

- The IEC 60945 puts higher requirements on voltage dips and interruptions compared to the generic standards. Issues on not meeting these requirements could be solved by the use of Uninteruptible Power Supplies (UPSs) near bridge equipment.
- IEC 60533 requires the same immunity limits and test specifications for equipment in all zones. The rationale for this could be an observed low shielding effectiveness by the superstructure [80], which was the rationale to skip the differentiation above and below decks from the first to the second edition of IEC 60945. This does not comply with the new statement in the third edition of IEC 60533: "It is based on the assumption that the ship is constructed in such a way that metallic hull and structure parts will significantly attenuate electromagnetic disturbance from the outer deck environment to the inner deck environment and vice versa".
- In IEC 60533 there are two exceptions to the immunity limits:
    1. There are no immunity requirements for induction motors/generators, synchronous machines, DC-machines, transformers, circuitbreakers/contactors without electronics, and relay operated control devices.
    2. There are no immunity requirements for equipment in the accommodation zone. The IEC 60533 gives room for use of generic COTS equipment in the accommodation zone for passengers and crew, provided that "Precautions should be taken for a sufficient decoupling of the accommodation zone from all other zones".
- Without a rationale given, IEC 60533 adds IEC 61000-4-16 [54], a test for immunity to conducted Common Mode (CM) from 50 Hz to 10 kHz. This test is not in IEC 60945, nor in the generic standards and the test levels that are not compatible with the definitions in IEC 61000-4-16.
- In the same way a conducted RF immunity test is added for a frequency of 10 kHz, for which no test procedure is given.
- The surge immunity requirement is compatible to IEC 61000-6-1 [43], except for the line-to-earth limit on Direct Current (DC) power ports (1 kV instead of 0.5 kV).
- The Electrostatic Discharge (ESD) immunity test is specified at 6 and 8 kV (level 3 in [45]) instead of 4 and 8 kV in the generic standards.
- For the RF immunity tests, the frequency sweep rate shall not exceed 1.5×10^{-3} decades/s in order to allow for the detection of any malfunction of the EUT [14]. This requirement is unnecessary, since the requirement in IEC 61000-4-3 [18] is even stricter.
- The Electric Fast Transients (EFT) burst test has to be done with a capacitive coupling clamp on all applicable ports, whereas it is common to use a Coupling Decoupling Network (CDN) on power ports.

10.2 Interpretation of the regulations

The strict emission limit of 24 dBµV/m (quasi peak, measured at 3 m distance from the Equipment Under Test (EUT)) as mentioned above is established to insure the availability of VHF radio telephony as part of essential equipment to establish a distress call. The rationale behind this limit will now be analysed.

10.2.1 Minimum performance of radio equipment

All commercially available VHF radio installations are type approved and have a minimum performance as required by the 1988 amendments of the SOLAS from 1974. These minimum performance specifications follow from the Annex of IMO Resolution A.803(19) [138] from 15 December 1995, which "recommends" among other things:

7.1 "The transmitter output power should be between 6 and 25 W". (same as in [139])

8.1 "The sensitivity of the receiver should be equal to or better than 2 µV e.m.f. for a signal-to-noise ratio of 20 dB". (similar as in [140])

8.2 "With a Digital Selective Calling (DSC) modulated input signal having a level of 1 µV e.m.f. to its associated VHF receiver, the DSC equipment should be capable of decoding the received message with a maximum permissible output character error rate of 10^{-2}".

8.3 "The immunity to interference of the receiver should be such that the wanted signal is not seriously affected by unwanted signals".

The receiver sensitivity is determined by the internal noise from the first amplifier stage in the receiver front-end, which is normally White Gaussian Noise (WGN) quantified with the Noise Figure (NF) of the receiver. This makes the sensitivity an equipment parameter.

The above recommendations define exact requirements for the receiver sensitivity and functional requirements for immunity, where the wanted signal in 8.3 should not be confused with the sensitivity in 8.1 and 8.2. Note that 2 µV electromotive force (e.m.f.) means 1 µV at the antenna feed-points. This requirement can be translated to a receiver NF of 8.2 dB at a bandwidth of 9 kHz, or a noise level at the receiver input of 0.2 µV e.m.f., which is 7.4 dB above kT_0B. This sensitivity requirement is not derived from the distance at which a radio signal should be received. The range at which a distress call must be able to be received is not specified in any document, with the exception of one IMO resolution [141], which requires a detection range of 5 Nautical Mile (NM) for AIS Search and Rescue Transmitters (AIS-SART). Results of range performance assessments were found in [142, Table 1] and [143, Annex A] and will be further discussed in Section 10.3.

The above outlined minimum performance requirements are complemented with technical characteristics and methods of testing in two IEC [144], [145] and three ETSI [146], [147], [148] standards, which are almost identical. One remarkable requirement in these standards is the spurious receiver emission limits of 2 nW below

1 GHz and 20 nW above 1 GHz. This requirement with slightly different frequency specifications can be found in many standards from IEC, ETSI, and International Telecommunication Union (ITU). It is even found in a previous version of [140] from 1978, without a rationale to the value.

Except for GPS and Inmarsat, these VHF systems are the most sensitive radios on ships. As a comparison, Ultra High Frequency (UHF) combat radios [149] have a recommended minimum sensitivity of 5 µV at 10 dB S/N.

10.2.2 Minimum performance of bridge equipment

The minimum performance specifications for all bridge equipment follow from the Annex of IMO Resolution A.694(17) [133] from 6 November 1991, which "recommends" about interference among other things:

6.1 "All reasonable and practicable steps should be taken to ensure electromagnetic compatibility between the equipment concerned and other radiocommunication and navigational equipment carried on board in compliance with the relevant requirements of chapter IV and chapter V of the 1974 SOLAS Convention". (with a footnote to IEC Publications 533 and 945)

This does not give any quantitative requirement but refers to the two IEC standards for that.

10.2.3 Interpretation of IEC 60945

Figure 10.1 showed a tighter emission limit in the maritime frequency band between 156 and 165 MHz. The rationale behind this 24 dBµV/m quasi-peak limit in IEC 60945 is illustrated in Fig. 10.3 and can be found in [80]:

> "For the VHF band IMO requires a receiver sensitivity of 2 µV e.m.f. which equates to a field strength of 3 µV/m at the antenna. For a typical separation of 15 m between the bridge and the VHF antenna, the free space field strength at 3 m is 15 µV/m (23.5 dBµV/m) to give 3 µV/m at the antenna, so a tighter limit is a requirement for operation of VHF communications".

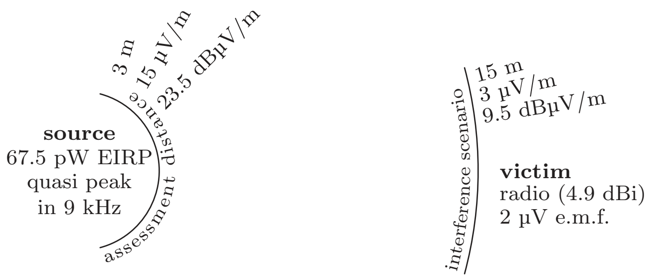

Figure 10.3: Interpretation of the IEC 60945 emission limits.

- The relation between 3 µV/m at the antenna and 2 µV e.m.f. or 1 µV at the receiver input port implies an antenna gain minus the losses of 4.9 dBi, but this is nowhere explicitly mentioned. This value will be used for further analysis, although most commercial antennas have a gain of 2 to 5 dBi.
- Apparently, an assumption is made that the distance between disturbing equipment on the bridge and the VHF receive antenna is 15 m and is placed in the main beam of that antenna. If possible disturbing equipment is placed in the protected environment below deck, the emission limit could be higher. This is a best practice on naval ships.
- In the placement in the above rationale, a disturbance signal is generated that is equal to the receiver sensitivity, which results in a S/N of 0 dB (assuming N and D the same) or $SINAD$ of 3 dB. In this case, the minimum receivable signal strength S_d increases from 2 to 20 µV e.m.f., maintaining a S/N of 20 dB as required by IMO Resolution A.803(19) [138].

From this reconstruction it is inferred that the emission limits are not established to protect radio transmissions at the receiver sensitivity level, but are 20 dB higher. The emission limit of 24 dBµV/m for equipment at 3 m distance is equivalent to 67.5 pW EIRP, which is 15 dB lower than the spurious emission limit (2 nW) of any receiver. The choices and assumptions made in the past put a restriction on the use of widely available, high quality COTS equipment, that complies to the generic EMC standards [43], [51].

Table 10.2 shows a summary of the requirements in the standard including the derived quantities. The last line in this table can be translated to an equivalent functional requirement for the emission requirement in the VHF band:

equivalent functional requirement

The maximum allowed distortion D at the receiver input is 1 µV, measured quasi peak in a bandwidth of 9 kHz.

which translates to 3 µV/m if the receiver gain is 4.9 dBi, or 3 dB more for most maritime VHF antennas that are specified at 0 dBd (2.15 dBi). Note that D has the same value as S. In other words, the maximum allowed distortion level D is the same as the sensitivity level S, which is 20 dB higher than the maximum noise level N in the receiver, which is a choice from IEC 60945.

Table 10.2: Summary of assumptions and interpretations

var.	description		value	unit
S	Rx sensitivity	$\leq$	1	µV (2 µV e.m.f.)
		$\leq$	−107	dBm in 50 Ω
S_d	receivable signal	$\geq$	−87	dBm in 50 Ω
E_S	Rx sensitivity	$\leq$	3	µV/m
		$\leq$	9.5	dBµV/m
E_d	receivable field strength	$\geq$	29.5	dBµV/m
B	channel bandwidth		9	kHz
N	Rx internal noise	$\leq$	0.1	µV
		$\leq$	−127	dBm in 50 Ω
		$\leq$	7.4	dB above kT_0B
NF	Rx Noise Figure	$\leq$	8.2	dB
G	Rx gain in standards		4.9	dBi
d_3	distance for emission		3	m
d_{15}	distance for interference		15	m
E_{15}	interference @Rx	$\leq$	3	µV/m
		$\leq$	9.5	dBµV/m
D	distortion @Rx	$\leq$	1	µV
		$\leq$	−107	dBm in 50 Ω

10.3 Technical analysis of the interference risks

To be able to establish emission limits for RF protection, the cause of interference and the range limiting factors of a radio communication link are investigated in this section.

10.3.1 Interference mechanisms

Electromagnetic disturbances can cause interference in RF front-ends via the antenna in a number of interference mechanisms. The most severe, where the first amplifier stage is burnt out by enough power or energy, causes permanent damage. This power level is not expected in a commercial maritime environment. Not permanent, so less severe, is desensitisation, where the first amplifier stage gets saturated, maybe by an off-channel disturbing signal. This can be in-band or out-of-band. These two mechanisms are covered by the design of the radio equipment (selectivity), frequency management by the ITU, and the properly designed antenna plan, creating sufficient isolation between antennas.

The interference mechanism that will be investigated here is caused by an in-band, on-channel disturbing signal that directly affects the wanted signal, decreasing the S/N. To define a limit of this disturbance, one can relate this to the actual signal level, the background noise, or to the noise floor of the receiver front-end.

10.3.2 External noise

The performance of radio systems is limited by radio noise [13]. Figure 10.4 shows the radio noise external to the radio receiving system according to the ITU [13], based on models from measurements in the past. The noise is quantified in dB above the Gaussian thermal noise, $N_0 = kT_0B$ at room temperature ($T_0 = 290$ K). There is a distinction between galactic noise, man-made noise (MMN), and atmospheric noise. Athmospheric noise is dependent on the location on earth, time of day, and the season of the year. MMN is usually not WGN, but impulsive in nature, Impulse Noise (IN), or found to be as Single Carrier Noise (SCN). It is strongly dependent on the presence of nearby activities, which have changed in the last decades from combustion motor ignition pulses to RF emissions from electrical equipment [47]. ITU incorporates four environment classes: quiet rural, rural, residential, business. The standardised cyan lines in Figure 10.4 are based on measurements in the 1970s, and are not a usable absolute quantity, but gives a very rough estimate of what could be expected. The circles S (27.4 dB above kT_0B) and N (7.4 dB above kT_0B) in Figure 10.4 are based on the minimal receiver sensitivity requirements by IMO, as discussed in Section 10.2.1. D is introduced in Section 10.2.3.

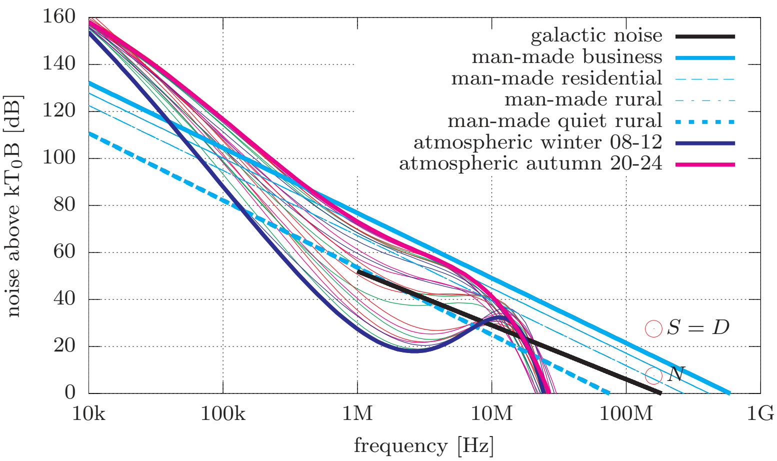

Figure 10.4: Radio noise external to the radio receiving system according to recommendation ITU R P.372 [13].
S and N are based on the minimal receiver sensitivity requirements by IMO, as discussed in Section 10.2.1
D is introduced in Section 10.2.3.

10.3.3 Measurement of noise and sensitivity

Measurements have been performed with an actual radio and a radio test set, and were carried out on several locations in Rotterdam, Gorinchem, and IJmuiden in the Netherlands. The radio test set is a communications service monitor and functions as an RF signal generator, spectrum analyser, and S/N-meter. In set-up 1, shown in Figure 10.5, the radio receiver is directly connected to the transmitter via a cable to measure the radio sensitivity without influences from the external environment. In set-up 2, shown in Figure 10.6, the direct connection is replaced by two whip antennas that are placed about 10 meters apart. The attenuation between the two antennas is measured. The received signal strength at the radio receiver is calculated by subtraction of this attenuation from the transmitted power by the radio test set.

Figure 10.5: Test set-up 1: Measurement of the radio receive characteristics.

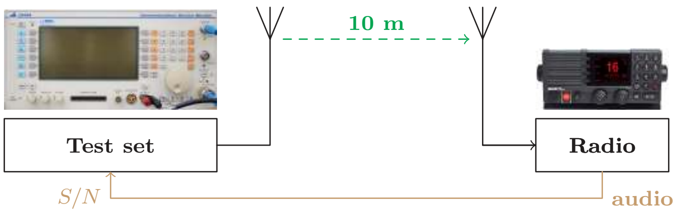

Figure 10.6: Test set-up 2: Measurement of the effect of external influences.
VHF radio: Thrane & Thrane Sailor 6222 VHF DSC.
Antennas: AC Marine CX4 (gain: 0 dBd).
Radio test set: Marconi 2945A.

Figure 10.7 shows the S/N that is measured by the radio test set as function of the received signal. From the results of set-up 1 (five blue curves) it follows that the radio meets the sensitivity requirement with a S/N of 36 dB (required 20 dB) at a received signal of 0 dBμV ($\sim$ 1 μV $\sim$ 2 μV e.m.f.). The measurements from set-up 2 show that more power is necessary to get the same S/N values in different cases. In other words, extra power is needed to compensate for external influences, such as added noise or other radio signals that cause desensitisation of the receiver. This excess power is shown in Figure 10.8. On the site in IJmuiden, a lot of marine radio traffic was going on, most likely causing desensitisation of the radio. From these measurements it can be concluded that external factors adversely affect the sensitivity of the receiver and therefore the range at which a distress call can be received.

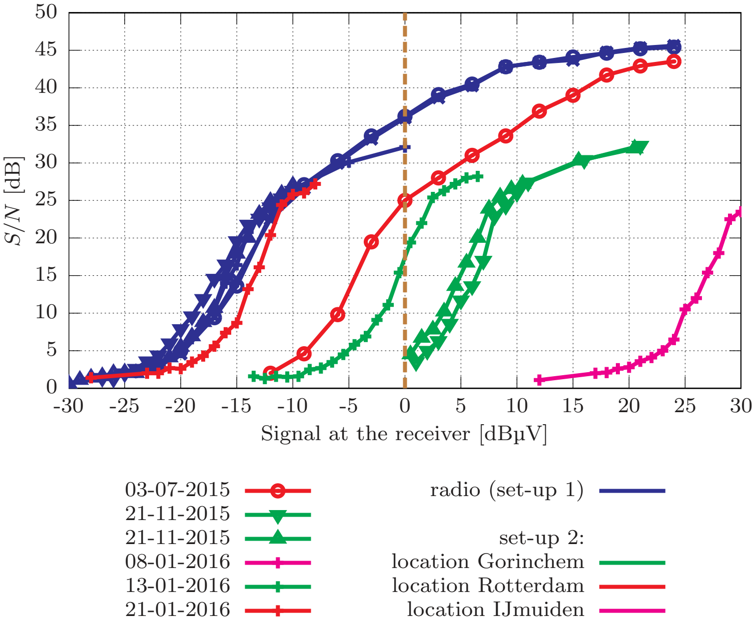

Figure 10.7: Measured S/N as function of received signal.

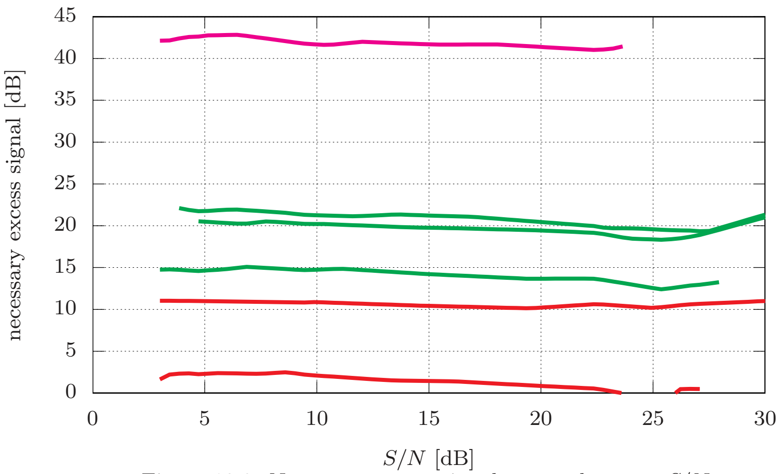

Figure 10.8: Necessary excess signal to get the same S/N.

10.3.4 Propagation

At VHF, it is generally assumed that propagation requires a Line of Sight (LoS) between the transmitter and the receiver. This very simplified assumption, based on free space propagation only, could be used to calculate the link budget from the transmitted power, the transmit-antenna gain, the distance, receive-antenna gain, receiver sensitivity, and the level of disturbances. But other propagation effects also play an important role also. Figure 10.9 shows the necessary height h of an antenna above sea level to reach the geometric horizon at a certain range d, which follows from.

$$d \approx \sqrt{2Rh} \tag{10.3}$$

where the radius R of the earth is 6371 km (d, R, and h in the same length units). For example, a transmit antenna at 12 m height (12 km range) and a receive antenna at 45 m height (24 km range) results in a maximum range of 36 km.

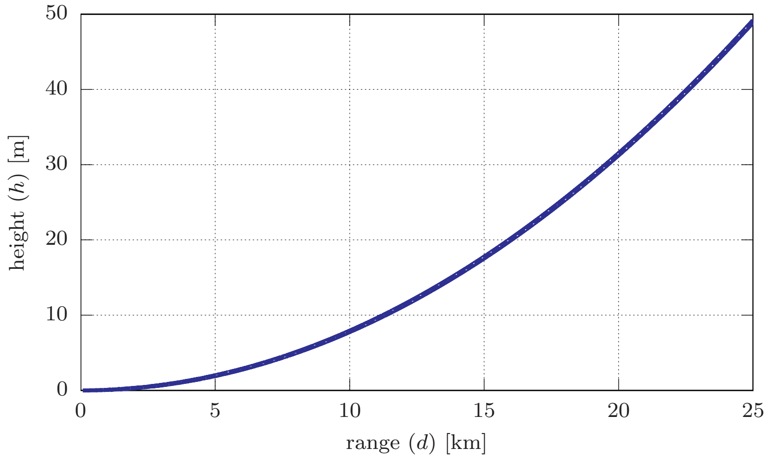

Figure 10.9: Geometric horizon as function of height above sea level.

For larger distances at sea, propagation characteristics differ from the free space model and a propagation loss has to be subtracted from the expected field level. Figure 10.10 shows the received field level from a transmitted power of 25 Watt and an antenna gain of 4.9 dBi for different propagation models. There is a variation between the model results, but there is also a variability in the actual values due to a statistical distribution of weather parameters. A good illustration of this can be found in [150, Figure 4-13]. The red line at 9.5 dBµV/m is the sensitivity level S, assuming no distortion. Propagation plays an important role in the link budget. It causes a significant attenuation and also introduces a considerable uncertainty.

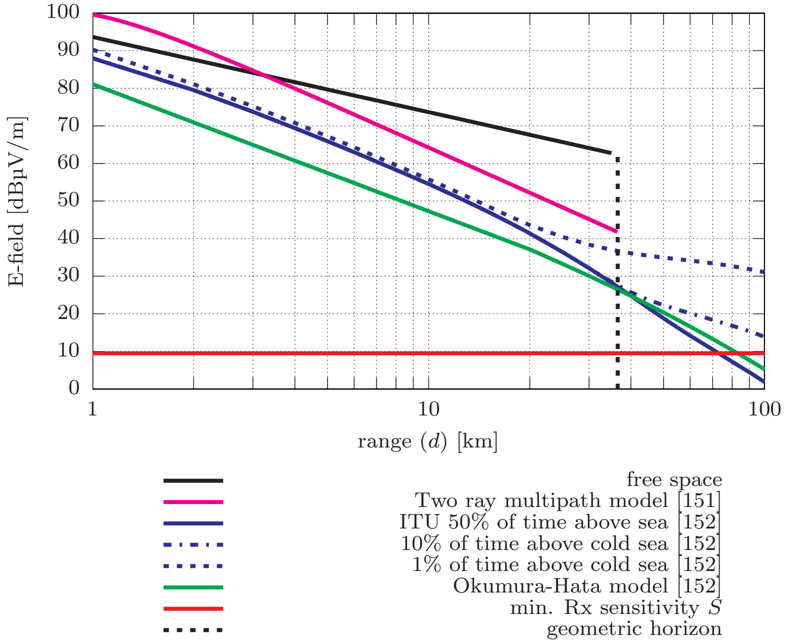

Figure 10.10: Field after propagation losses
(h_t=10 m, h_r=50 m, power 25 Watt, gain 4.9 dBi).

10.3.5 Propagation measurements

Propagation measurements were carried out by the Royal Netherlands Navy (RNlN) to ensure coverage of two coast stations on request of the Dutch Coastguard. Two Rigid Hulled Inflatable Boats (RHIBs) sailed a route as shown in Figure 10.11, transmitting at 22 W (measured). The received signal that is measured at the coast stations Hoorn and Wezep is plotted against the distance in Figure 10.12 and compared with the power that would be received in free space conditions. This free space link budget is based on 22 W power, 8 dB system loss at the shore station, and antenna gains of 2 and 5 dBi. The measurement results that are below the required receiver sensitivity S are outside the service area of that coast station.

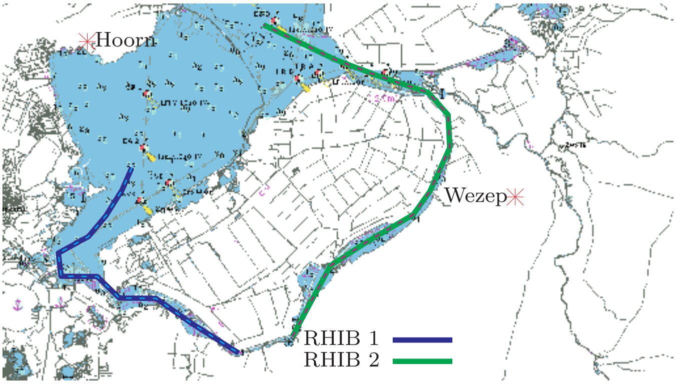

Figure 10.11: Map with the routes of the RHIBs on 27 November 2013 and the position of the coast stations at 79 m height.

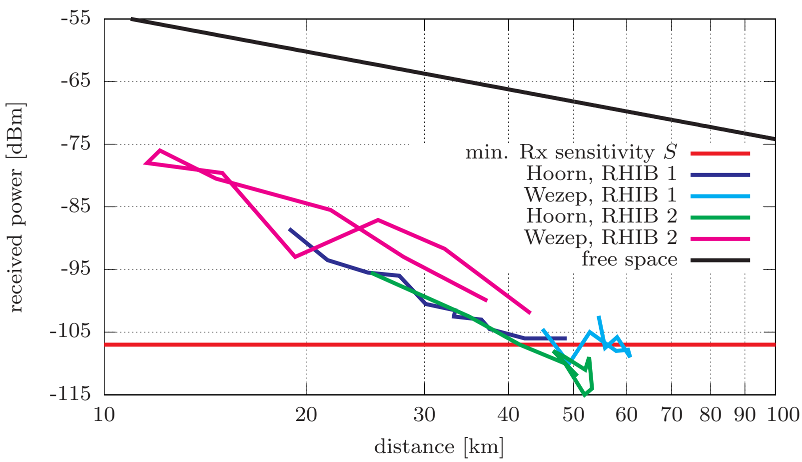

Figure 10.12: Measured received power on channel 67 at the coast stations Hoorn and Wezep.

10.4 Conclusion

Specific requirements in IEC 60533 and IEC 60945 to insure the availability of GMDSS inhibit the general integration of COTS equipment on ships. Compared to the basic and generic IEC standards, emission and immunity limits as well as test methods deviate so much that implementation of COTS equipment without retesting and maybe modifications is impossible when these standards are strictly enforced.

Analysis of several standards showed that many details are copied from other documents, pointing at each other to justify the rationale. So this seems a circular reference, hiding the real rationale. Many requirements have no or little added value to the essential requirements, which the standards should help to achieve. The observed lack of rationale and superfluous requirements make compliance of generic COTS equipment unnecessarily expensive. The rationale behind the requirements in the maritime standards have been analysed. Reconstruction of the rationale behind the standards and calculations have shown that an equivalent functional requirement is a maximum allowed distortion of 1 µV (quasi peak in 9 kHz bandwidth), which can give the system integrator more flexibility in choosing equipment and achieving the same interference free environment. A protected environment below deck is an instrument that is a best practice on naval ships.

Technical analysis of the interference risks has shown that the range for maritime VHF radio communications is dependent on propagation characteristics, the radio horizon, and the amount of man-made noise (MMN) in close proximity. Propagation causes significant attenuation and also introduces considerable uncertainty. But with the exception of AIS Search and Rescue Transmitters (AIS-SART), no standard or IMO resolution has been found that specifies a minimum range at which a distress call must be able to be received, nor a minimum EIRP of a distress call.

Chapter 11

Conclusions

The strict use of military equipment standards is a pitfall in procurement that makes naval shipbuilding unnecessarily expensive and might give a false presumption of compliance for Electromagnetic Compatibility (EMC). Nowadays, state of the art technology is integrated on naval platforms conform standards with legacy rationale. Therefore there is a need for a better rationale that fits more to the state of the art technology. Some addressed aspects of the effects of a military naval environment on civil Commercial off the Shelf (COTS) equipment show that a careful design with properly engineered EMC protection measures can be an alternative for the hardening and compliance required for all integrated equipment. This is called the risk based approach in contrast to the traditional rule based approach. Integration of the newest components from the civil market into highly specialised, dedicated military applications is only possible by replacing the traditional rule based approach at equipment level by a risk based approach with functional requirements at ship level.

Equipment is designed to operate in a certain intended environment, which is the basis of all EMC standards, as well as the risk based approach. This environment is defined by all kinds of electromagnetic disturbances and interference mechanisms. Based on these electromagnetic phenomena, a classification of electromagnetic environments with disturbance levels, compatibility levels and possible performance criteria is made. Not all electromagnetic disturbances will be present on all kinds of vessels. This approach starts with the specification of the electromagnetic environment in which the system or platform is going to operate together with functional performance requirements on equipment level. In the risk-based approach, measures to be taken to achieve EMC must be tailored to the customer's need, i.e. the contractual environment, that is based on the anticipated external exposure and the purpose of the ship.

Instead of hardening equipment to military standards, specific environments are created by zoning and proper installation measures at zone boundaries. In this way, the created zones on a naval ship below deck is not so different from an office environment, a communication centre, or light industrial site. If the immunity limits are low, compared to the voltage and signal levels at which the equipment itself operates, then hardening efforts can be small and good design practice with a sense for EMC will be a good start. In that case, immunity compliance testing can easily be replaced by an analysis or demonstration. If the immunity limits go up to above the equipment's own signal and power levels, hardening demonstration gets less evident and especially for military limits, an acceptance test becomes inevitable.

The goal is to protect equipment against environmental effects that it is not intentionally designed for and to protect radio services and sensor performances against possible interferences from equipment that is allowed to emit in its intended environment. It is important to create a current boundary for all conductive parts, such as cables and pipes, that penetrate a zone boundary.

Whereas military standards traditionally prescribe various measures against all possible electromagnetic threats for all equipment, the risk based approach allows to tailor these efforts to the difference between the actual and intended environment for each class of equipment. One of the sources for Electromagnetic Interference (EMI) that remains to require attention is not the outside harsh military environment from powerful transmitters, but fast transients from all kind of switch events, causing conducted interference and loss of data throughput from within the ship.

To meet the EMC challenges in Part I, a clear and uniform approach with verification and control is needed including requirements with clear rationale, put in today's perspective, and installation guidelines with quantitative rules. This has been provided in Part II.

Crosstalk between cables is one of the oldest types of interference. Cable separation rules have been in use for over five decades and were derived in an era where equipment did not meet legal or contractual requirements, where signals in the cables where analogue and knowledge on EMC was still in development. Different equipment that is designed for the intended use in the same environment, e.g. residential or office use, will be compatible and therefore the risk of crosstalk between cables from these equipment is low. Calculations and measurements in Chapter 7 have shown that commonly used qualitative cables can be put close together for most of the systems on a ship, provided that these cables are properly installed.

To mitigate conducted interference, Common Mode (CM) current loops at the inside and outside of an equipment cabinet can effectively be decoupled. At the absence of shielding walls, these loops are magnetically coupled. This coupling can be minimised by lowering the loop areas through a proper layout of the cables and the use of a ground plane, e.g. from a cable tray, for all cable entries. Cable screens must be bonded to this ground plane, creating a shortcircuit for the CM currents. These current boundaries, defined in Section 5.2, have been evaluated in Chapter 8 by a model, which has been verified by measuring the CM currents with current clamps. The Direct Current (DC) bonding resistance is an important characteristic of a cable termination. The analysis has shown that this bonding resistance must be less than a few milli-Ohm. The class R bond of 2.5 mΩ has long been recognised as an indication of a good bond across a metallic interface and being realistic for a single joint. This is difficult to achieve with a tie wrap for these thin cables, because such a low bonding resistance requires a certain mechanical pressure between two conducting metal surfaces. A low bonding resistance will be easier to obtain with thicker cables.

High Intensity Radiated Fields (HIRF) from the above deck naval environment or a Nuclear Electromagnetic Pulse (NEMP) may cause conducted interference and generate electromagnetic fields below deck via unprotected cables that are inevitable above deck. In Chapter 9, unprotected cables in an exposed environment have been modelled and characterised both as a monopole antenna perpendicular to the deck and as a transmission line, representing a cable close to the deck. It has been shown that the length of the cable has no effect on the induced voltage if this length is more than a quarter wavelength for the monopole configuration and a half wavelength for the transmission line configuration. Long monopole configurations have shown to be a threat for low frequencies, such as HF (2-30 MHz) and NEMP. The placement of an illuminated cable close to the deck is a good protection measure for long cables at low frequencies, which includes NEMP protection. This measure does not show much improvement at higher frequencies, such as UHF communication and radar, in which case it is better to hide these cables from this illumination. A risk analysis shows that the induced voltages may exceed the generic limits for COTS equipment in a worst case situation. If only electrical installations are connected to the grid to which the exposed cable belongs rather than electronics, the field levels that couple with this cable can be somewhat higher. Electrical installations are in general more immune against HIRF disturbances and NEMP than electronics. It appears that NEMP poses a low risk if exposed cables are kept short or placed against a protective ground plane. The coupled pulse from a high intensity NEMP illumination is comparable to Electrostatic Discharge (ESD) or Electric Fast Transients (EFT) and are not expected to cause damage on electric installations. It is recommended to limit the length of an exposed cable to 25 cm and to place exposed cables not in the Line of Sight (LoS) of transmitters above 400 MHz. For extreme cases, a simple CM filter can be effective if it is placed at the point where each cable penetrates the hull.

Specific requirements in IEC 60533 and IEC 60945 to insure the availability of Global Maritime Distress and Safety System (GMDSS) inhibit the general integration of COTS equipment on ships. Compared to the basic and generic IEC standards, emission and immunity limits as well as test methods deviate that much that implementation of COTS equipment without retesting and maybe modifications is impossible when these standards are strictly enforced. An analysis of several standards in Chapter 10 showed that many details are copied from other documents, pointing at each other to justify the rationale. So this seems a circular reference, loosing the real rationale. Many requirements have no or little added value to the essential requirements in which the standards should help to achieve. The observed lack of rationale and superfluous requirements make compliance of generic COTS equipment unnecessarily expensive. The rationale behind the requirements in the maritime standards have been analysed. Reconstruction of the rationale behind the standards and calculations have shown that an equivalent functional requirement is a maximum allowed distortion of 1 µV (quasi peak in 9 kHz bandwidth), which can give the system integrator more flexibility in choosing equipment and achieving the same interference free environment. A protected environment below deck is an instrument that is a best practice on naval ships. Technical analysis of the interference risks has shown that the range for maritime Very High Frequency (VHF) radio communications is dependent on propagation characteristics, the radio horizon and the amount of man-made noise (MMN) in close proximity. Propagation causes a significant attenuation and also introduces a considerable uncertainty. But with the exception of AIS Search and Rescue Transmitters (AIS-SART), no standard or International Maritime Organization (IMO) resolution has been found that specifies a minimum range at which a distress call must be able to be received, nor a minimum Effective Isotropic Radiated Power (EIRP) of a distress call.

Recommendations

The research on crosstalk was limited to the CM crosstalk itself, which can be translated to Differential Mode (DM) with mode conversion and compared with actual signal levels. In future research, the minimum needed transfer impedance Z_t of cables and connectors for unbalanced interfaces should be further investigated, as started in [153], to achieve EMC without overprotection.

The general rationale behind emission limits to prevent Radio Frequency (RF) interference should be further analysed with a clear definition on RF disturbance for communication links, aimed at state of the art communication, including digital data transfer. One problem with digital communications, compared to analogue, is the abrupt disconnection when the link quality gets below a certain threshold. Another important factor in broadband communication, wireless as well as wired, is the pulse width, i.e. duration of one bit of information, which become narrower than transient disturbances.

The proposed risk based approach needs to be implemented into the design philosophy of future ships. The knowledge should be transferred to the involved project members. Since this approach relies upon installation measures and best practices to create a certain environment, supervision on the correct implementation of these efforts is of paramount importance.

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Abbreviations and Symbols

Abbreviations

AC	Alternating Current (pp. 53, 62)
AECTP	Allied Environmental Conditions and Tests Publication (pp. 4, 13, 18, 23, 24, 27, 37, 39, 40, 43, 59, 61)
AIC	Active In-feed Converter (pp. 34, 35)
AIS	Automatic Identification System (pp. 148, 158, 161, 162, 175)
AIS-SART	AIS Search and Rescue Transmitters (pp. 148, 158, 161)
APEMC	Asian Pacific International Symposium on Electromagnetic Compatibility (p. 104)
CCCS	Current-Controlled Current Source (p. 76)
CCVS	Current-Controlled Voltage Source (p. 86)
CDN	Coupling Decoupling Network (pp. 128, 147)
CEN	the European Committee for Standardization (p. 2)
CENELEC	the European Committee for Electrotechnical Standardization (pp. 3, 142)
CIC	Command Information Centre (pp. 49, 50)
CISPR	the International Special Committee on Radio Interference (pp. 4, 31, 32, 36, 41)
CM	Common Mode (pp. v, vii, 9, 14, 37, 38, 48, 49, 51–55, 60, 63, 64, 66, 67, 101, 103, 106, 112, 116–118, 127, 128, 138, 139, 147, 160–162)
CMC	Common Mode Choke (pp. 62, 137)
COTS	Commercial off the Shelf (pp. v, vi, 1, 4, 5, 7, 9, 16–19, 31, 36, 38, 40–43, 48, 49, 61, 112, 138, 141, 143, 146, 147, 150, 158, 159, 161)
CUT	Cable Under Test (pp. 96, 97)
DC	Direct Current (pp. 39, 66, 67, 147, 160)
Def-Stan	Defence Standard from the Ministry of Defence in the UK (pp. 39, 67)
DFT	Discrete Fourier Transform (p. 130)

DM Differential Mode (pp. 37, 38, 52, 53, 64, 100, 103, 162)

DSC Digital Selective Calling (pp. 148, 153)

E^3 Electromagnetic Environmental Effects (pp. 13, 66)

ECL Effective Coupling Length (pp. 135, 136)

EFIE Electric Field Integral Equation (pp. 105, 117)

EFT Electric Fast Transients (pp. 14, 24, 25, 27, 48, 49, 61, 62, 96, 97, 99, 100, 102, 139, 147, 161)

EIRP Effective Isotropic Radiated Power (pp. 40, 146, 150, 158, 162)

ELF Extremely Low Frequency (pp. 16, 40)

EM electromagnetic (pp. 5, 13, 17, 31, 51, 55)

EMC Electromagnetic Compatibility (pp. v, vii, 1–9, 13, 18, 22, 28, 31, 34–36, 38–43, 46, 51, 52, 57, 58, 60, 61, 63, 65–68, 71, 96, 102, 103, 114, 141–143, 146, 150, 159, 160, 162)

EMCON Emission Control (pp. 14, 28, 49)

EME Electromagnetic Environment (pp. 2, 3, 9, 13, 113)

e.m.f. electromotive force (pp. 17, 117, 128, 148–151, 153)

EMI Electromagnetic Interference (pp. v, vii, 2–5, 9, 13–15, 22, 40, 42, 43, 49, 55, 57, 58, 60, 61, 67, 71, 112, 113, 146, 160)

EMSEC Emission Security (pp. 28, 179)

ESD Electrostatic Discharge (pp. 14, 25–27, 49, 61, 139, 147, 161)

ETSI the European Telecommunications Standards Institute (pp. 3, 142, 148, 149)

EU European Union (pp. 2, 63, 141–143)

EUT Equipment Under Test (pp. 22, 113, 148)

EW Electronic Warfare (p. 29)

FLYCO Flying Control Centre (pp. 47, 59)

GMDSS Global Maritime Distress and Safety System (pp. 9, 141, 142, 158, 161)

HEMP High Altitude Electromagnetic Pulse (pp. 14, 26, 113, 115)

HF High Frequency (pp. 48, 67, 114, 146)

HIRF High Intensity Radiated Fields (pp. 13, 17, 18, 40, 49, 58, 113, 114, 127, 128, 131, 138, 139, 160, 161)

HPEM High Power Electromagnetics (p. 28)

HPM	High Power Microwaves (pp. 28, 29)
IACS	International Association of Classification Societies (p. 144)
IEC	the International Electrotechnical Committee (pp. 8, 13, 15, 17, 22–27, 31–34, 37, 38, 59, 61, 62, 65, 66, 96, 142, 143, 148, 149)
IEEE	the Institute of Electrical and Electronics Engineers (pp. 24, 27, 59)
IEMI	Intentional Electromagnetic Interference (pp. 28, 29, 49, 113)
IFF	Identification Friend or Foe (p. 146)
IMO	International Maritime Organization (pp. 2, 38, 141, 142, 148–150, 158, 162)
IN	Impulse Noise (p. 152)
ISM	Industrial Scientific and Medical (p. 32)
IT	Isolated Terra (pp. 18–21, 35)
ITD	Integrated Topside Design (pp. 8, 14, 18, 40, 58)
ITE	Information and Telecommunication Equipment (pp. 32, 49, 102)
ITU	International Telecommunication Union (pp. 149, 151, 152)
LEMP	Lightning Electromagnetic Pulse (pp. 14, 23, 27, 49)
LF	Low Frequency (pp. 48, 67)
LoS	Line of Sight (pp. 139, 155, 161)
LPS	Lightning Protection System (pp. 23, 50)
LPZ	Lightning Protection Zone (p. 50)
LV	Low Voltage (p. 35)
MCT	Multi Cable Transit (pp. 60, 103)
MF	Medium Frequency (p. 146)
Mil-Std	Military Standard from the Department of Defense in the USA (pp. 5, 18, 22, 23, 39, 40, 42, 43, 59, 66, 67, 115)
MMN	man-made noise (pp. 152, 158, 161)
MoM	Method of Moments (pp. 105, 117, 128)
MOTS	Military off the Shelf (p. 39)
MTL	Multiconductor Transmission Line (pp. 71, 74–76, 81, 83, 84)
NATO	North Atlantic Treaty Organization (pp. 18, 21, 39, 178)
NEC	Numerical Electromagnetics Code (pp. 104, 105, 107, 110, 117, 120, 124, 125)

NEMP	Nuclear Electromagnetic Pulse (pp. 13, 14, 26, 27, 39, 49, 59, 113–115, 127, 130, 133, 138, 139, 160, 161)
NM	Nautical Mile (p. 148)
ODVA	the Open DeviceNet Vendor Association Inc. (p. 67)
PCB	Printed Circuit Board (p. 45)
PDS	Power Drive System (pp. 34, 35, 48, 112)
PE	Protective Earth (pp. 25, 66)
PIM	Power Insulation Monitor (pp. 18–21)
PLC	Power Line Communication (p. 35)
PQ	Power Quality (pp. 14, 36, 49)
PS	Power Supply (p. 49)
PV	Photo Voltaic (pp. 34, 35)
RadHaz	Radiation Hazards (pp. 14, 18, 49, 58, 130, 139)
RAM	Radar Absorbing Material (p. 58)
RAS	Replenishment at Sea (pp. 113, 116)
RCD	Residual Current protection Device (pp. 20, 21)
RE	Radiated Emission (pp. 14, 35, 49)
RF	Radio Frequency (pp. 4, 13, 15, 17, 21, 31–33, 46, 48–50, 59, 61–63, 66, 67, 138, 143, 146, 147, 151–153, 162)
RFI	Radio Frequency Interference (p. 146)
RHIB	Rigid Hulled Inflatable Boat (p. 157)
RNlN	Royal Netherlands Navy (p. 157)
SCN	Single Carrier Noise (p. 152)
SEWACO	sensor weapon and communication (pp. 47, 58)
SME	Subject Matter Expert (p. 8)
SMPS	Switched Mode Power Supply (pp. 34, 35)
SOLAS	International Convention for the Safety of Life at Sea (pp. 2, 141, 142, 148)
SPD	Surge Protection Device (pp. 27, 34, 50, 62)
SPICE	the Simulation Program with Integrated Circuit Emphasis (pp. 73, 79, 85)
STANAG	NATO Standardization Agreement (pp. 18–21, 39)

STP Screened Twisted Pair (pp. 97, 99)

SV Source Victim (pp. 18, 58)

TEMPEST a codename for methods to spy upon others through leaking emanations as well as how to shield equipment against such spying, also referred to as Emission Security (EMSEC) (pp. 14, 28, 47–49)

TL Transmission Line (pp. 71–73, 75, 81, 83, 85, 120, 122, 124, 125, 135, 179)

TPD Transient Protection Device (p. 62)

UHF Ultra High Frequency (pp. 130, 149)

UPS Uninteruptible Power Supply (pp. 34, 147)

UTP Unscreened Twisted Pair (pp. 97–100)

VCVS Voltage-Controlled Voltage Source (pp. 73, 76)

VHF Very High Frequency (pp. 15, 141, 143, 145, 146, 148–150, 153, 155, 158, 161)

VLF Very Low Frequency (pp. 16, 40)

VoIP Voice over IP (p. 50)

WGN White Gaussian Noise (pp. 148, 152)

Symbols

c per-unit-length capacitance of a TL to a ground plane in F/m (pp. 72–74, 76–78, 82, 84, 85)

c_{ij} per-unit-length capacitance between two wires of a MTL in F/m (pp. 76, 78)

Δz section of a TL that is small compared to the wavelength (pp. 72, 74, 75, 84)

ε_r relative permittivity of a dielectric (pp. 82, 85, 91)

$FEXT$ far-end crosstalk (pp. 74, 80, 88)

h height of a wire above a ground plane in m (pp. 53, 77–82, 85, 88–95, 101, 120, 121)

k coupling coefficient for mutual inductance (pp. 78–80)

l per-unit-length series inductance of a TL in H/m (pp. 72–79, 82, 85, 86)

$\mathcal{L}$	length of a TL or exposed part of a cable in m (pp. 72–74, 79, 81, 84–86, 88–95, 116, 117, 120, 121, 127–129, 131, 133–135)
l_{ij}	per-unit-length mutual inductance between two wires of a TL in H/m (pp. 76, 78, 79)
l_t	per-unit-length screen transfer inductance of a TL in H/m (pp. 83, 85–87, 92–94, 101)
$NEXT$	near-end crosstalk (pp. 74, 88, 92, 93, 95)
NF	Noise Figure (p. 148)
r	radius of a wire in m (pp. 77–82, 85, 88–94, 101, 105, 117, 120, 121)
R_b	bonding resistance in Ohm (pp. 15, 66, 106, 107, 109, 111, 112)
R_r	radiation resistance in Ohm (pp. 105, 117, 137)
r_s	inner radius of a screen in m (pp. 81, 82, 85, 86, 92–94)
ρ_s	common impedance screen resistance per unit length in Ohm/m (pp. 81, 83, 85, 86, 92–94, 101)
s	separation between two wires in m (pp. 77–82, 88–95, 101)
SE	Shielding Effectiveness (pp. 15, 59–61, 64, 103)
$SINAD$	Signal to Noise and Distortion ratio (pp. 145, 150)
S/N	Signal to Noise ratio (pp. 145, 149–151, 153, 154)
t_d	burst duration in s (pp. 96–98)
T_d	time delay of a TL in s (pp. 72, 73, 79, 80)
$\mathbf{T}_I$	current transformation matrix for a MTL (pp. 75, 76)
t_r	burst repetition interval in s (pp. 96–98)
t_s	thickness of a screen in m (pp. 81, 82, 85, 92–94)
$\mathbf{T}_V$	voltage transformation matrix for a MTL (pp. 75, 76)
Z_c	characteristic impedance of a TL in Ohm (pp. 72, 73, 77, 88, 92, 120, 121)
Z_t	transfer impedance in Ohm (pp. 15, 60, 63, 64, 83, 86, 162)

Biography

Bart van Leersum received his M.Sc. degree in 1995 at the Eindhoven University of Technology. From 1995 to 2006 he was a research scientist in electromagnetics for defence, safety and security applications at TNO, the Dutch institute for applied sciences in Den Haag. In 1999/2000 he was an exchange engineer at Spawar Systems Center in San Diego. From 2006 he is employed by the Dutch Ministry of Defence in Den Haag as a specialist on electromagnetic effects and is tasked to set requirements for future Naval ships, responsible for knowledge management, and involved in finding solutions for complex problems. He also has been a part-time researcher at the Telecommunications Engineering group at the University of Twente, sponsored by industry to get the requirements with rationale and quantitative rules for EMC on future ships.

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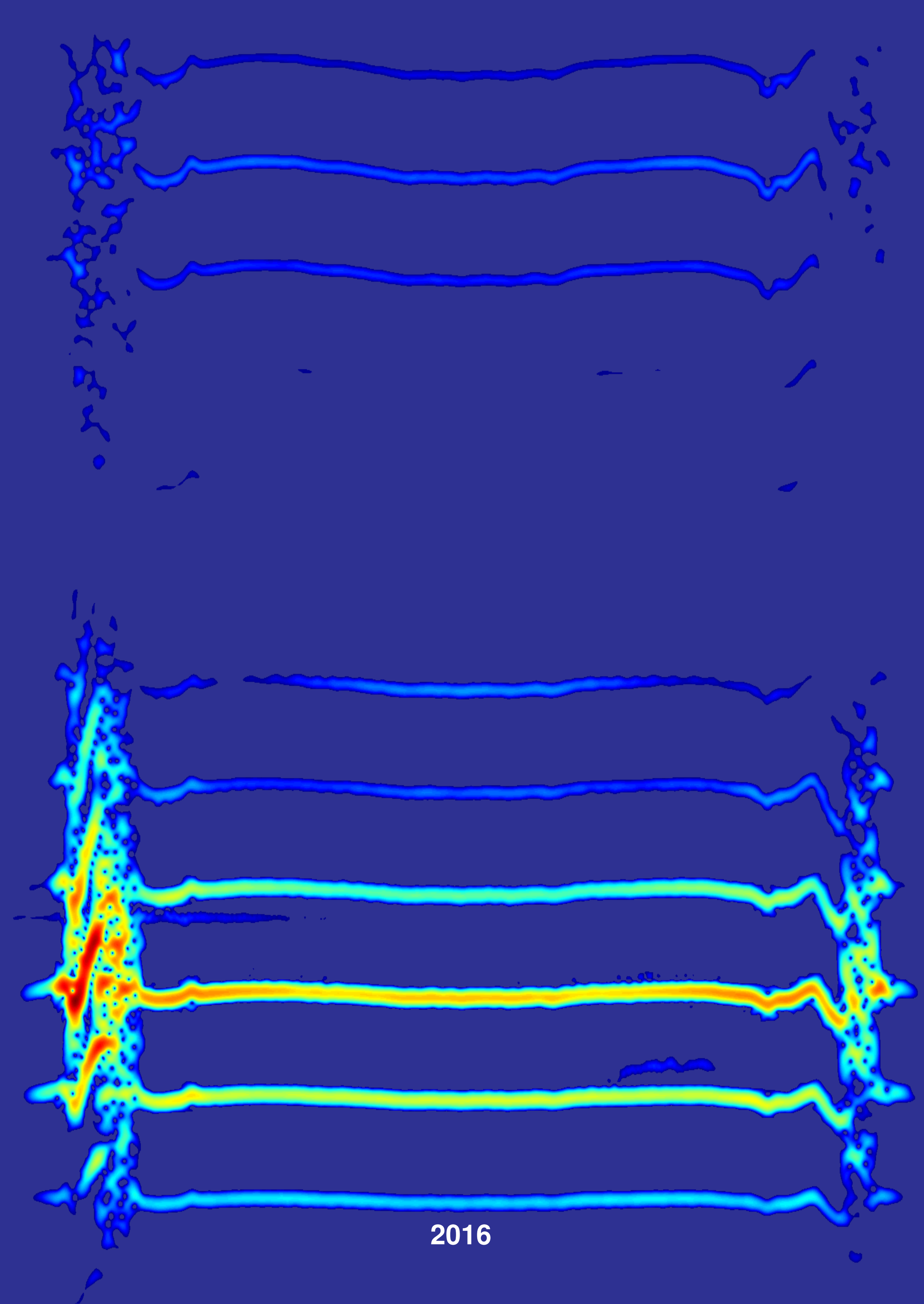
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