**Article:**

van de Beek, Stefan, Dawson, John orcid.org/0000-0003-4537-9977, Flintoft, Ian David orcid.org/0000-0003-3153-8447 et al. (4 more authors) (2015) Overview of the European project STRUCTURES. Electromagnetic Compatibility Magazine, IEEE. pp. 70-79. ISSN: 2162-2264

https://doi.org/10.1109/MEMC.2014.7023202

# Strategies for the Improvement of Critical Infrastructure Resilience to Electromagnetic Attack: An overview

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Published in IEEE Electromagnetic Compatibility Magazine, vol. 3, no. 4, pp. 70-79, 4th Quarter 2014.

DOI: 10.1109/MEMC.2014.7023202

# Overview of the European Project STRUCTURES

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**Abstract: An overview of the European project STRUCTURES and its main challenges is given. Current and foreseen Intentional Electromagnetic Interference (IEMI) threats are classified according to their availability, their technical characteristics (such as bandwidth) and their portability. Critical infrastructures are identified and their most characteristic aspects are highlighted, from an electromagnetic point of view. These concepts are used to establish a set of reference threats to be investigated and possible techniques to handle simulations and measurements in this complex environment are explored, emphasizing the use of the topological approach.**

## *1. Introduction to the STRUCTURES project*

Security and quality of life in industrialized countries depend on the continuous and coordinated performance of a set of infrastructures that can therefore be defined as *critical*. Examples of critical infrastructures include, amongst others, electrical energy distribution networks, communication networks, transportation networks such as railways, motorways and airways, law enforcement structures and public health facilities. Their growing interdependency increases even more their vulnerability to external attacks aimed at interrupting some of their services.

Hampering the functionality of such infrastructures using electromagnetic fields to jam, damage, or shut down the electric and electronic systems instrumental to their good performance has becoming a more and more effective threat in the recent years [1], [2]. The targets could be very susceptible to such kinds of attack, as many of the critical infrastructures are civilian and protected by shielding which is neither designed nor tested to resist to high frequency and high power interference. On the other side, more portable and more powerful IEMI sources are becoming available, even "off the shelf". These devices can generate various kinds of electromagnetic waves, from narrowband to wideband, from low frequency (e.g. a few kilo-hertz) to high frequency (e.g. a few giga-hertz).

In the past 25 years, the study of electromagnetic fields produced from high-altitude nuclear detonations (known as HEMP) advanced technical knowledge and brought forward good protection strategies [3]–[5]. Another, relatively new, kind of attack to be studied, in order to design the proper countermeasures, is referred to as HPEM (see Table 2) [6], [7].

The European Commission opened a call in the context of the overall FP7 Security Call SEC-2011.2.2-2 *Protection of Critical Infrastructure (structures, platform and networks) against Electromagnetic (High Power Microwave (HPM)) Attacks*, to investigate such threats. The diversity of structures to be considered, the intrinsic complexity of the electromagnetic phenomena, the plethora of existing (and foreseen) attacks, the numerous and different issues to be studied (modelling of the attacks, design of sensors, design of shielding, etc.) required a multi-disciplinary approach from highly skilled partners.

The project STRUCTURES started on the 1 July 2012 to address the call. The Consortium is composed of 13 partners, from 5 countries:

1. IDS, Ingegneria Dei Sistemi
2. École polytechnique fédérale de Lausanne
3. Haute école spécialisée de Suisse occidentale

4. University of York
5. Montena
6. Helmut-Schmidt-Universität
7. Gottfried Wilhelm Leibniz Universität Hannover
8. Bergische Universität Wuppertal
9. Rheinmetall Waffe Munition GmbH
10. University of Twente
11. Istituto Superiore Mario Boella (together with the Politecnico di Torino)
12. Navigate Consortium

Its investigation is divided into three broad phases, described in Table 1. The project faces many issues in the field of electromagnetic compatibility, ranging from the problem of identifying reference configurations, taking into account all aspects relevant to electromagnetic modelling, to the problem of correctly modelling complex scenarios, composed of electrically large structures and many interacting elements, for a wide range of parameters. In the following sections, these points will be described in more detail. In particular, Section 2 presents a classification of IEMI threats; Section 3 describes the different critical infrastructures considered in STRUCTURES; Section 4 gives an account of the methods used to deal with electromagnetic modelling of complex scenarios, emphasizing the use of the topological approach adopted by STRUCTURES.

**Table 1 Project phase division**

**Phase 1** focuses on the assessment of the physical scenario concerning IEMI attacks:

## 2. Threat analysis of IEMI

The effect of an electromagnetic attack can be classified into four different classes: permanent damage, upset, interference, and deception. Classification schemes are described in [11]–[13]. The most severe effect is damage, where the system needs repair before it can function again. In the case of an upset, the system is temporarily disrupted, but not damaged. Interference degrades the functioning of the system only during the attack, i.e., once the attack stops the system functions as specified again. Another effect that can be realized with an electromagnetic attack is deception. The system can be spoofed by giving it false information, e.g., transmitting a false GPS signal. Several studies have investigated the impact of IEMI on individual electronic systems [14]–[19]. The effectiveness of an electromagnetic attack is dependent upon the victim susceptibility, the coupling path, and the electromagnetic weapon, i.e., the radio frequency (RF) source characteristics. The coupling path can be radiated or conducted and often the complete coupling path is a combination of both radiated and conducted. In this section we will focus on the RF source characteristics.

As mentioned in the introduction, STRUCTURES focuses on HPEM environments. Figure 1 is adopted from [6] and helps to understand the relationship of the HPEM environment to other EM environments, such as lightning and HEMP. See also Table 2. The difference is that HPEM extends to higher frequencies, up to 10 GHz, and the field levels exceed the typical civil protection levels. HPEM generators operating in the 200 MHz–5 GHz range are effective in disturbing electronics for several reasons:

1. Many antennas operate in this frequency range;

2. Physical dimensions of circuit boxes are resonant in this frequency range (1 to 2 GHz), and typical apertures have their resonances in this frequency range;

3. The inner system coupling paths are approximately a quarter to a full wavelength in this frequency range, resulting in effective field-to-wire coupling.

The RF sources creating HPEM environments can be classified by many attributes, including the frequency content, peak electric field, pulse repetition frequency (PRF), and pulse length. In [20], four categories based on the bandwidth of an IEMI source are distinguished; narrowband, moderate band, ultramoderate band, and hyperband. The classification is based on the *band ratio* defined as $b\text{r} = fh/fl$, where $fh$ is the upper frequency point and $fl$ the lower frequency point. The frequency points are defined such that 90% of the signal energy is contained within these frequency points. The frequency bandwidth classification adopted from [20] is presented in Table 3. As an example, in [21] an overview is given of narrowband sources and in [22] an overview is given of wideband sources.

Three different waveforms can be distinguished that are common for HPEM; a narrowband waveform, an ultrawideband (UWB) waveform, and a damped sinusoidal waveform. Most waveforms are similar to these waveforms or are a combination of them.

A narrowband waveform can emit a high amplitude burst of pulses at a carrier frequency, with each pulse containing many cycles, at a certain PRF, or a continuous signal. The majority of its energy is centred around a single frequency, i.e., the carrier frequency. The carrier frequency can be tuned to a vulnerable frequency of the intended target to increase the chance of a successful attack, but this implies that the vulnerable frequencies needs to be known a priori. In the case of wireless communication this can easily be determined, and the front door coupling can be maximized with a narrowband source tuned to the operating frequency of the communication system.

An UWB waveform is represented by a double exponential pulse with very low rise time and low full-width-at-half-maximum (FWHM) time. As opposed to the narrowband waveform, this waveform spreads its energy over a very wide frequency band, resulting in a relatively low power density. Since a UWB covers a large frequency band, it is likely to cover a vulnerable frequency of the victim system. However, as mentioned, the power density is relatively low, and the energy of a UWB pulse is very low because it is extremely short. This makes it less likely to cause damage to a system.

A damped sinusoidal waveform is a combination of the previous two waveforms. It has the short rise time of a UWB pulse and a carrier frequency carrying a large part of the energy. In Figure 2 the differences between the time and frequency content of the waveforms is emphasized.

As explained in [23], to analyse the risk an RF source poses it is necessary to not only take technical attributes into account, but also non-technical attributes. The risk of a source is also dependent on the likelihood of occurrence of an RF source attack. For this reason we also classify RF sources by the following non-technical attributes:

frequencies where the wavelength is comparable to or bigger than the size of the object being analysed. At high frequencies, their performance may be limited because of the large amount of computational resources required. Three main families of fully validated codes may be distinguished [38]: Volumetric codes, where the whole calculation volume is meshed into volume shells (Finite Difference Time Domain, for example); Surface codes, where only the surfaces of the diffracting object are meshed (Method of Moments, for example); and Asymptotic techniques which are based on an asymptotic formulation of Maxwell's equations (Physical Theory of Diffraction and Uniform Theory of Diffraction, for example).

*2) Cable network codes:* Cable network codes are used to solve the wiring coupling problem with a multi-conductor transmission line (MTL) model, with the previously determined field distributions in the local shielding level. With MTL models, several key aspects of the wiring in complex systems — such as cable shield properties, frequency dependent dielectrics, or inhomogeneous propagating media — can be included independently from the cable lengths because the bundles are only specified from their cross-section. It has been established that cable network codes are appropriate for describing the EM coupling in the frequency range between DC to about 1 GHz (the upper frequency limit depends on the cross section of commonly found cables) [38].

The MTL model sources stressing the network are described as a set of voltage and current generators distributed along the wires length and calculated from the incident electromagnetic fields. This is how the link between 3D full-wave codes and cable network codes is made. The largest advantage of such an approach is that the calculation of the incident fields, which takes time whatever the full wave technique is used, is made once for all in the absence of the cable bundles. Then, the MTL solution can be launched for various cable topologies, provided that the cable routes remain the same [34], [35].

Another important advantage of MTL models is that they can be used with an EMT formalism [43] in which the wiring network is decomposed as a set of tubes and junctions, respectively, representing the network branches and nodes. Currents on the branches are obtained from the frequency domain solution of the so-called Baum-Liu-Tesche (BLT) equations describing all the interactions to the network [34]. The junctions are described in terms of any type of Z, Y, or S matrices derived from the electric circuits modelling the wire connections or loads, or from measurements.

When dealing with shielded cables, the coupling between the external currents flowing on the cable screens and the internal induced voltages and currents is made through the so-called transfer impedance and admittance of the screens [32], [44]. The theoretical estimation and measurement of the transfer impedance of common cables at frequencies beyond hundreds of MHz become an issue, and poses a difficulty for implementing the MTL models. It is important to highlight that MTL models do not account for radiation and are based on a quasi-TEM field response the transmission lines. Such a condition is generally observed when the MTL height over the reference plane does not exceed a fraction of the minimum wavelength (one tenth or so) (one tenth or so) [30], [45]. Depending on the frequency regime, it may be desired to account for the backscattering of cables in order to identify resonant behaviours in the cavities containing the wires. However, as far as the TEM mode approximation is concerned, techniques are available to handle the field emission due to cable-network-induced currents with 3D codes or reciprocity-based approaches [32], [38].

Recent efforts to extend the cable models at higher frequencies have provided methods to generalize the MTL models to account for high frequency and radiation effects [45], [46].

*3) Electrical circuit codes:* Electrical circuit codes such as SPICE are used to solve the equipment response once the currents and voltages at the cable terminations (equipment inputs) are determined. The calculations are generally limited to the input of the equipment, and no internal electronic components or PCBs are taken into account [38].

## D. Simulation techniques at high frequencies

*1) Toward a statistical approach:* At high frequencies the use of the aforementioned tools for the analysis of critical infrastructure becomes complicated. Facilities are not generally conceived from an EMT viewpoint and some typically made assumptions (e.g. good shielding approximations, or small apertures) may lose their validity. Furthermore, high-frequency responses of systems are very sensitive to various parameters, some of which are not very well known [38]. Since the design and the placement of components in complex systems at high frequencies are not well controlled, statistical models appear to be more appropriate for obtaining the response of the system subject to random input parameters [47]. A commonly used approach to such a problem has been for years the well-known Monte-Carlo technique which requires a large number of deterministic simulations to obtain the probability density function (PDF) of the output of the system [48]. In the kind of models required for IEMI studies, where a single deterministic simulation is a major computational task, the preferred approach should allow to establish the PDF, or at least some of its moments, from a small number of simulations. Methods like the Unscented Transform [47] or the Stochastic Collocation method [49] among others, have recently been suggested to be accurate and faster than the Monte-Carlo approach. However, their capacities in terms of modelling real system configurations have yet to be demonstrated.

In the context of IEMI, a statistical approach provides estimates of mean coupling but it does not provide any "worst case" scenario. The definition of the worst case being unclear in the scientific community, this approach can be considered as useful since no deterministic method is currently available to perform such an analysis [47]. The definition of appropriate norms in terms of statistical quantities, as is done for EMT, should allow overcoming this drawback [35].

*2) The Power Balance (PWB) Method:* The PWB method [50] is another statistical macroscopic approach for the EM coupling into oversized complex systems. The PWB method is based on energy equilibrium and has been shown to provide satisfactory results at high frequencies. This approach is based on the assumption that the EM fields inside the enclosures of complex systems behave as random variables, as in a mode-stirred chamber (MSC) [51]. The mean dissipated power inside a cavity is calculated as the superposition of the losses arising from the coupling of the mean power density through the mean coupling cross-section (CCS) of all the dissipative mechanisms present in the cavity as [50], [52]: $\langle P\rangle=\langle\sigma\rangle\cdot\langle S\rangle$. It is shown in [50], [52] that the CCS of any dissipative mechanism $\sigma_i$ in the cavity is inversely proportional to its associated quality factor $Q_i$. Each CCS may be considered independently from other losses mechanisms, as long as the mean stored energy of the cavity is not significantly affected by each of the loss mechanisms separately. This allows the description of cavities as "current nodes", where $\langle S\rangle$ and $\langle P\rangle$ are analogous to voltages and currents, respectively [38]. A BLT-like equation can also be derived to solve for the power densities and dissipated powers at each node and as a consequence, the PWB method can also be described with an EMT formalism [52].

## 5. Summary

The European STRUCTURES project aims at investigating the issue of Intentional Electromagnetic interference to the services and infrastructures our lifestyle is based on. This study has a number of critical aspects, mainly related to the large size of the problem (both in terms of electrical dimensions and in terms of parameters and cases to be accounted for) and the complexity of the interconnections among the many parts. We briefly reviewed some topics addressed in the project so far, as classifying the different threats and the different targets from an electromagnetic point of view, and identifying the most efficient numerical tools and the way to couple them to simulate such complex scenarios.

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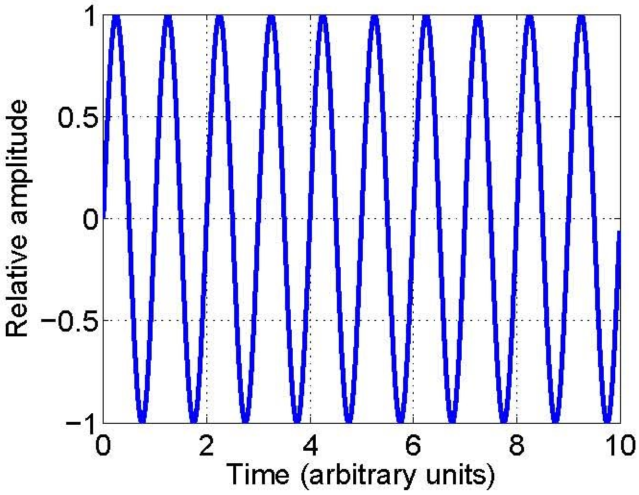
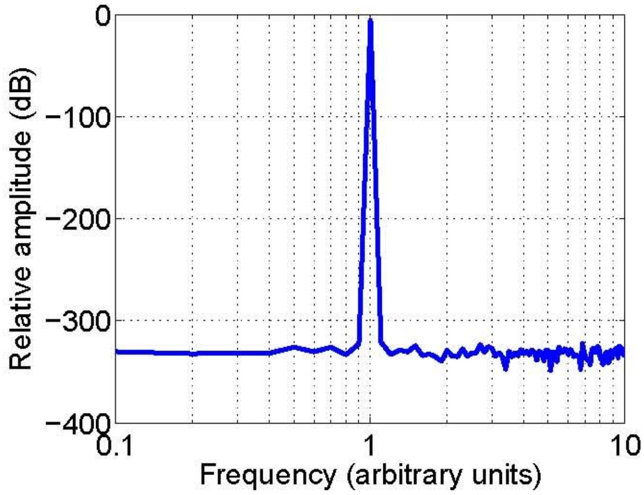
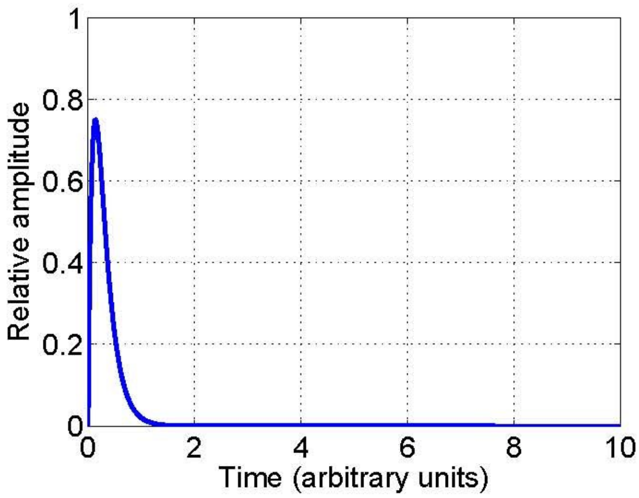
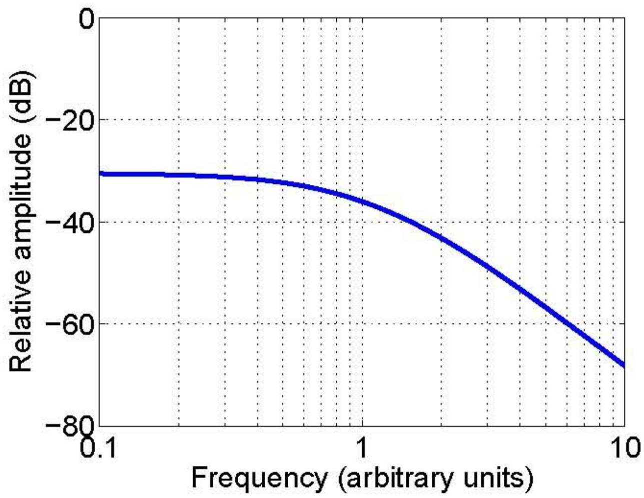


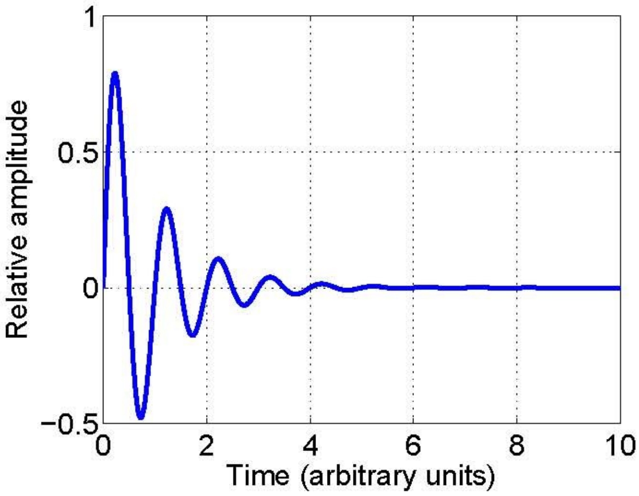



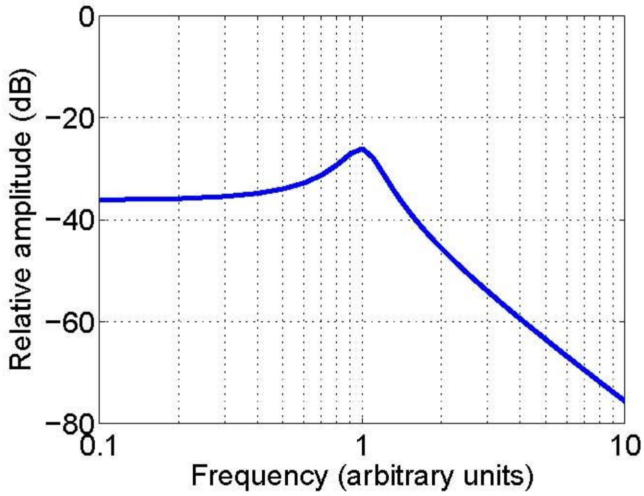

(a) Narrowband waveform. (b) Frequency content of the narrowband waveform.



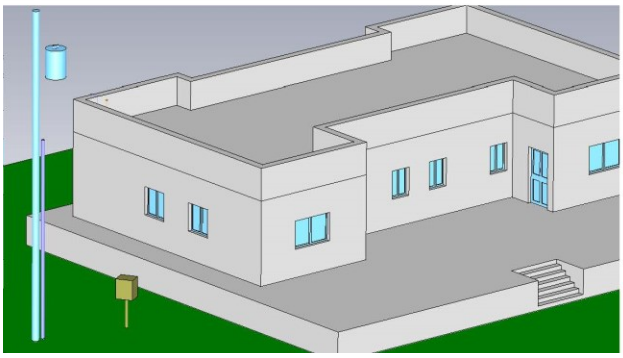

(c) UWB waveform (d) Frequency content of the UWB waveform.




(e) Damped sinusoidal waveform. (f) Frequency content of the damped sinusoidal waveform.

Figure 2: Time and frequency description of the three different waveforms.



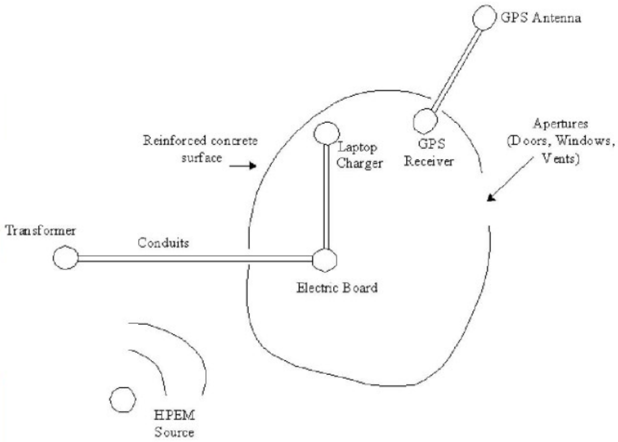



Figure 3: Electromagnetic Topology of a civil building.

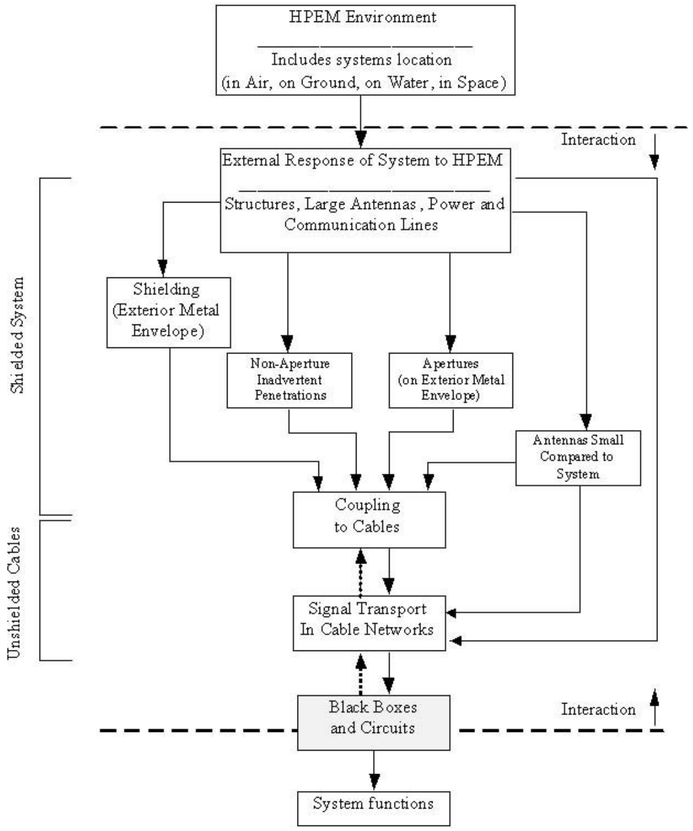



Figure 4: EMP interaction sequence for shielded systems with unshielded cables. (Figure edited from [30]).