Interaction Notes

Note 625

October 2014

APPLICATION OF ELECTROMAGNETIC TOPOLOGY AND POWER BALANCE CONCEPTS TO RADIO FREQUENCY COUPLINGS INTO BUILDINGS

I. Junqua – J.P. Parmantier - F. Issac - W. Quenum

DEMR/CEM
Onera – The French Aerospace Lab,
F-31055, Toulouse, France

Abstract

This paper focuses on the experimental and modelling work led in the context of the HIPOW European project that deals with the protection of critical infrastructures against IEMI/NNEMP attacks. The objective is to evaluate and analyze Radio Frequency transfer functions between different areas of a building and the exterior of a building in order to assess EM environment in potentially critical rooms submitted to an external EM threat.

At a first step, this analysis is purely based on experiments, which implies to develop an optimized experimental set-up. At a second step, Power Balance concepts initially developed for high-Q oversized systems have been evaluated in the case of Radio Frequency coupling in and through building rooms.

.

TABLE OF CONTENTS

Acknowledgements:

This work has been founded by the European project HIPOW under the grant agreement FP7-SEC-2011 284802.

1 INTRODUCTION

A "critical infrastructure" is a common term accepted by worldwide nations and governments which refer to any asset essential for the society and its economy including also health and security. Consequently, protecting critical infrastructures against any type of attack likely to jeopardize their normal operation has become a major concern addressed at the highest levels of all country organizations. Among the large set of possible attacks (explosive, chemical, biological, cyber-attack, armed attack…), the IEMI/NNEMP attack, as defined as the use of a radio frequency wave to induce possible disruption or destruction of electronics, is clearly identified and must be considered in a risk management process ([1], [2]). This is the reason why, for a few years, several projects in Europe and in the world have addressed this specific topic and its consequences on critical infrastructures.

The work presented here has been carried out in the context of a European project named "HIPOW" [3] and funded by European Commission (EC) under the grant agreement FP7-SEC-2011 284802. HIPOW stands for "protection of critical infrastructures against high power microwave threats" as mentioned in the description of work and aims at:

- *"Conducting a threat analysis and risk assessment of an IEMI/NNEMP attack onto critical infrastructures,*
- *Evaluating the efficiency of current protections,*
- *Investigating the feasibility of hardening measures,*
- *Developing detection and diagnosis systems,*
- *Proposing guidelines and inputs to standards for protection."*

In this work, we consider a building as an infrastructure hosting critical devices operating critical functions, as an hospital or a bank. Figure 1 shows such a building with an IEMI/NNEMP attack carried out at distance from a truck. The risk analysis from this EM threat will be then derived from:

- The critical functions included in the building, each of them having elementary levels of IEMI/NNEMP vulnerability,
- Their distribution, location and installation inside the building,
- The interdependencies between critical functions,
- The EM characteristics of the building in terms of Electromagnetic (EM) attenuation between the exterior and the interior and between different areas of the building,
- The attack scenario since the effect onto the internal functions of the building may significantly vary with the impact generated by the threat. According to the definition of IEMI/NNEMP (UWB and narrow band waveforms) given in IEC standard 61000-2-13, the frequency band of analysis considered in this work ranges from a few hundreds of MHz up to a few GHz (typically 300MHz-3GHz).

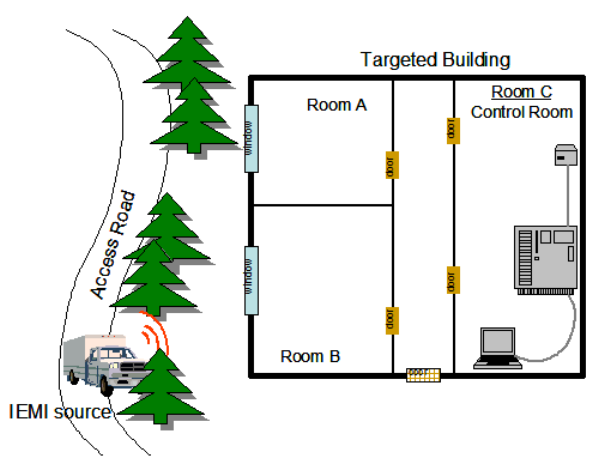


Figure 1 – IEMI/NNEMP attack of a building from outside

The building being seen as a passive envelope made of walls and containing several electrical/electronic functions; this envelope has a strong influence on how the incident EM threat generated from the outside will enter the building and how it will propagate inside the building rooms up to critical equipment. Several EM coupling phenomena are involved in this process together with the topology of the building: the attenuation of walls, the penetration through apertures and windows, the propagation along the conducts and electrical wires. All those EM phenomena contribute to the building attenuation or “shielding effectiveness” which relates the incident EM level produced by the EM source and the resulting EM level at critical test-points in the building. The knowledge of this information thereby becomes a key-parameter to evaluate possible effects of an IEMI/NNEMP on critical devices of a building and to derive the most appropriate protection measures. The scope of this work is deliberately restricted to the investigation of induced EM radiated observables in the high frequency range [over 1GHz] and does not consider any conducted observables on cable networks.

In this context, the focus of this paper will be on the analysis of EM interactions through and inside a building in order to propose a methodology to estimate this relevant transfer functions from which EM levels inside building-rooms induced by specific external or internal RF EM sources will be deduced. For this, we propose to apply the Electromagnetic Topology concepts and Power Balance concepts (EMT/PWB), even if those concepts have been initially developed for electrically large and high-Q-factor (Q=Quality) systems ([4], [5]) which is not the general case of buildings. Indeed this methodology has been largely validated for modeling and assessing EM coupling of a High Intensity Radiated Fields (HIRF) environment onto an aircraft/rotorcraft [4]. In other words, the objective is to see how the application domain of the EMT/PWB methodology can be extended to the evaluation of EM coupling in a low-Q factor system as this is the case in buildings.

Section 2 of this paper deals with experiments conducted in the authors’ premises in order to acquire a first set of data and to analyze EM interactions in their building. For experiments on such large scale systems, we will show how the test set-up needs to be optimized. Section 3 is dedicated to the EMT/PWB approach: Firstly, some recalls on the methodology are given. Then, the potentiality of the approach is evaluated. Finally, some conclusions and prospects are given about future applications of the EMT/PWB method for EM RF interactions in buildings.

2 ANALYSIS OF EM INTERACTION THROUGH AND INSIDE A BUILDING FROM EXPERIMENTAL DATA

At a first step, experiments have been conducted in ONERA premises in order:

- To analyse RF EM environment and RF EM interactions in buildings and to study to which extend they can be represented by pseudo random variables as in perfectly mode stirring reverberating chambers (MSRCs).
- To identify potential EM areas of confinement of EM energy inside building rooms and to evaluate the relevance of EM topology concepts based on volume decomposition of EM problems.

2.1 Test Site

Such transfer-function tests require realistic installation features in order to represent correctly the topology of most common critical building infrastructures as:

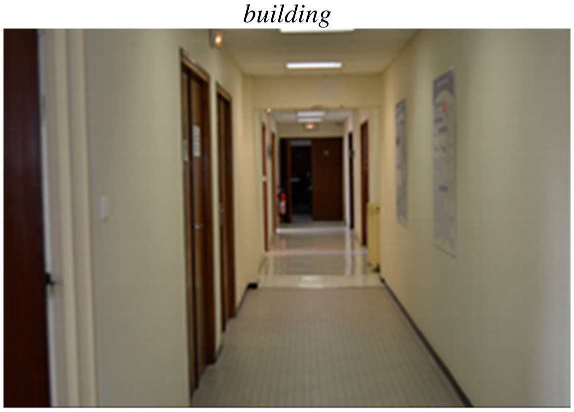
- Several rooms of several size and shapes
- Fully equipped building with windows, window shades, doors
- Fully electrical and water pipes installation

Transfer function measurements are low level measurements and do not require any safety management as real high level tests. The incident power at the transmitting antenna input is low enough to generate EM fields much below the safety levels given in IEEE standards with respect to human exposure to Radio Frequency EM fields.

However obtaining agreements to perform them is generally tedious. This is why, for flexibility and safety reasons, we have chosen to carry-out those tests at our ONERA premises located in Toulouse, France. The site is a civil multi-building site with buildings made of usual materials, including doors and windows and without any specific EM protection (Figure 3). In addition, this site hosts several laboratory rooms and one building aisle hosts the EM and Radar Department (DEMR) which means that EM tests are not an issue for this building. This building contains three floors levels. It has been chosen as our targeted building. Besides, since this building is made of several interconnected aisle-buildings, it is possible to make the illumination from one of these aisle buildings onto the DEMR building. Such a solution offers the possibility to keep using the Ethernet network of the site for transmission of data and commands of measurement equipment. Consequently, the "Spatial Environment" (DESP) building has been chosen as the illumination building (see Figure 2). In addition, Figure 3 presents several views of the neighboring of the targeted building and from its internal installation.

Figure 2 - ONERA's site in Toulouse with the DEMR aisle-building (targeted building) and the DESP aisle building (from which the EM external illumination is made) – Credits: Google Maps

View of the illumination building from the targeted building



Building corridor

Typical office room

Figure 3 – Targeted aisle building views

2.2 Test Set-Up

In the approach, the native experimental data that characterize EM interactions inside a system are transfer functions between a received power on a receiving antenna and the incident power injected in a transmitting antenna for a given geometry and location of both antennas and for given frequencies which implies that only linear EM mechanisms are taken into account.

These transfer functions have been directly measured with a network analyzer. Nevertheless, such measurements generally require connection of the transmitting and receiving antennas to the ports of the network analyzer using either long measurement cables or optic-fiber links. In case of a multi-room building, such measurement configuration is not possible from the practical point of view of the availability of long-enough measurement cables and deployment of those cables without generating any trouble in the normal operation of the building. This is the reason why, the measurement setup has been optimized according to the experimental protocol described below:

- On the transmitting side, the measurement equipment includes a frequency synthesizer and the transmitting antenna.
- On the receiving side, the measurement equipment includes a spectrum analyser and the receiving antenna.
- Both transmitting and receiving equipment (synthesizer, spectrum analyser, motor) are driven by a software program through a command PC. Instructions are carried via the built-in internal Ethernet network of the site.
- At each side of the link, both receiving and transmitting equipment are placed onto a trolley in order to allow easy displacement inside the building areas.

- A stirrer is installed in the room hosting the transmitting equipment in order to generate a pseudo-reverberating chamber environment. The stirrer is driven by a motor enabling a step-by-step rotation. Therefore, the transfer function between the reception point and the transmitting point could be measured on a frequency band from 300MHz up 6.3GHz for each position of the stirrer.
- In order to reinforce the stirring effect in the building rooms, the four polarisation combinations of transmitting and receiving antennas are considered: HH, VV, HV, VH (V=vertical; H=Horizontal).
- The whole set of experimental data has finally been post-processed for a given room-location of transmitting and emitting antennas in order to extract histograms and statistical parameters over a complete rotation of the stirrer and for all combinations of antenna polarisations.

A complete overview of the test set-up is illustrated in Figure 4. Antennas are classical double ridged guide antennas 3119 (from Ets Lindgren). The stirrer is a home-made stirrer.

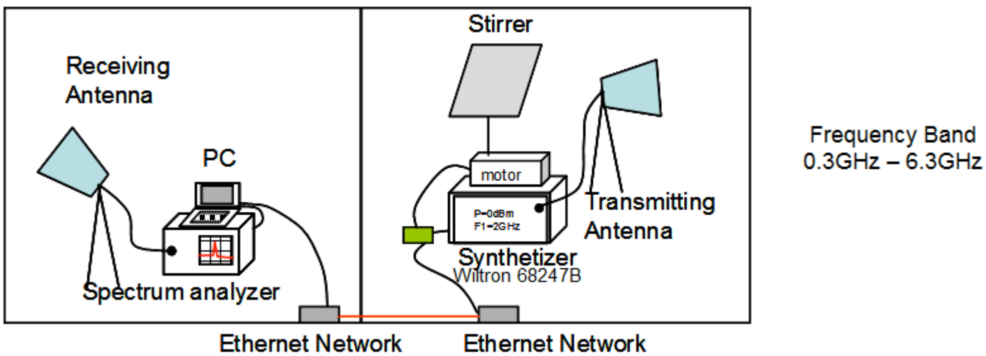


Figure 4 - Test set-up for transfer function measurements in a building

2.3 Test configurations

Three main configurations with different objectives have been considered:

- **"Intra" configuration**: the transmitting and the receiving antennas are located in the same building room. The measured experimental data provide assessment of equivalent losses in the room. According to the Power Balance Method, they can be expressed in terms of mean "Q factors" or so-called equivalent "coupling-cross-sections" (CCS) [4] (or equivalent areas) which fully characterize EM dissipative effects in a single room (see paragraph 3.1).
- **"Inter" configuration**: the transmitting and the receiving antennas are located in two different rooms of the same building. These measurements of transfer functions combined to previous "Intra" configurations give the equivalent coupling cross section of the propagation path between the two rooms.
- **"Ext/Int" configuration**: one of the antennas is outside the building and the other one is inside a building-room. For safety reasons and because of the reciprocity of the EM problem, the transmitting antenna has been positioned in the targeted room and the receiving antenna inside a room of the illumination building. This solution allows maintaining the emission within the targeted building and to keep using the Ethernet Network for data and command transfers. Both antennas are facing each other in front of two windows of the two buildings at a distance of 20m. Of course, the post-processing and measurements are analysed as if the transmitting antenna was in the illumination building and the receiving antenna was inside the targeted building (as in normal NNEMP/IEMI attack conditions).

Figure 5 illustrates the test setup in the room hosting equipment for emission.

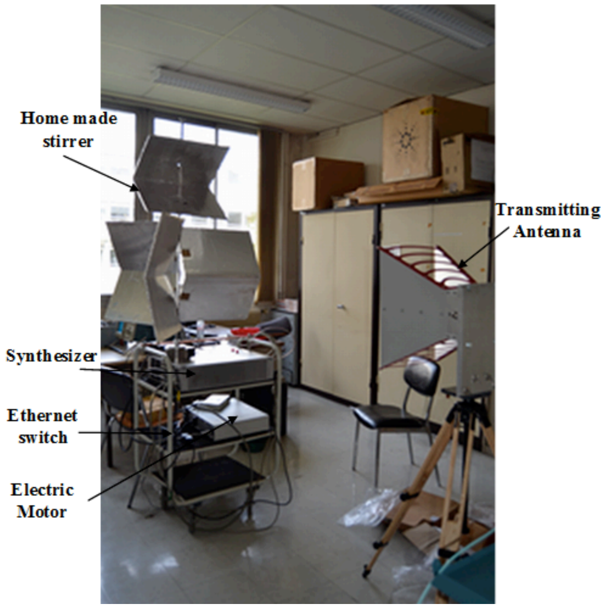


Figure 5 - Transmitting equipment in building room at emission side

In Figure 6, the red-coloured window indicates the window at which the receiving antenna is placed (second floor of the illumination building) in configuration "Ext/Int". The picture is taken from the window of the targeted building room at the first floor hosting the transmitting system (again using the property of reciprocity of the problem).

Figure 6 - Configuration "Ext/Int" – View from the targeted room under test

2.4 Test results and main conclusions

2.4.1 "Intra" measurements

Figure 7 illustrates a typical set of results obtained in an office room of 50m^3, in "Intra" configuration (we remind that the objective is to characterize EM environment in a room in terms of statistical distribution of the transfer function). In this configuration, the EM environment is expressed as the S_{21} parameter between the transmitting and the receiving antennas, both placed in the same room for each position of the stirrer and for each combination of polarization of the antennas. Figure 7 thereby presents the cumulative histogram of S_{21} measurements at a frequency equal to 2GHz. As seen in Figure 7 (but this result is also confirmed by all measurements), EM environment in building rooms cannot be characterized as in mode stirring chambers with Rayleigh probability functions because of their low Q factor (or high losses features). However a Weybull law can be a good approximation[6]. Nevertheless, Weybull laws are a 2-parameters functions which can be deduced from the average and standard deviation of the set of measurements. At this stage of the work and since the measurements have been carried out at ONERA's premises only, it is not possible to find general laws correlating these 2 parameters with typical characteristic features of buildings (such as materials, volumes,…).

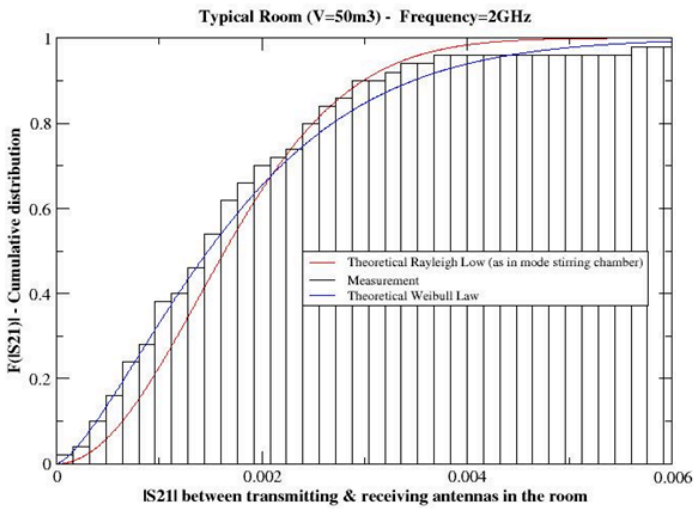


Figure 7 - Example of cumulative distribution obtained from "Intra" configuration measurements in a typical room of ONERA's building

At a second step, the S_{21} results obtained in "Intra" configuration in several typical rooms of the targeted building have been post-processed in terms of mean "Q factor" or in terms of mean "CCS" as in the Power Balance approach as follows ([4], [5]): .

$$Q = \frac{16\pi^2 V}{\lambda^3} E\left[\left|S_{21}\right|^2\right]$$
$$CCS = \frac{2\pi V}{\lambda Q} \qquad (1)$$

V is the volume of the room under test, λ, the wavelength, and $E[|S_{21}|^2]$ the statistical 2nd moment of S_{21} over a rotation of stirrer and combinations of antennas polarizations.

In Figure 8, the equivalent CCSs are deduced from the S_{21}-measurements and are drawn for several rooms of the targeted building in the whole frequency range of interest. In this figure, "reference" means CCS of ONERA's empty MSRC. This reference configuration in MSRC is overlaid in order to put to the fore the difference of EM physics in a reverberating chamber and in a standard building room. Note that the equivalent coupling cross-section of a common building room of about 50 to 60m^3 is relatively flat with respect to the frequency; the values varies between 100 and 500m^2, which is 20 to 30dB higher than in a MSRC of the same size. The comparison with the results of the MSRC with the open door is particularly interesting: they seem to indicate that EM scattering through windows or doors is not significant in buildings compared to other EM dissipative mechanisms such as classical "Joule" or absorption effects.

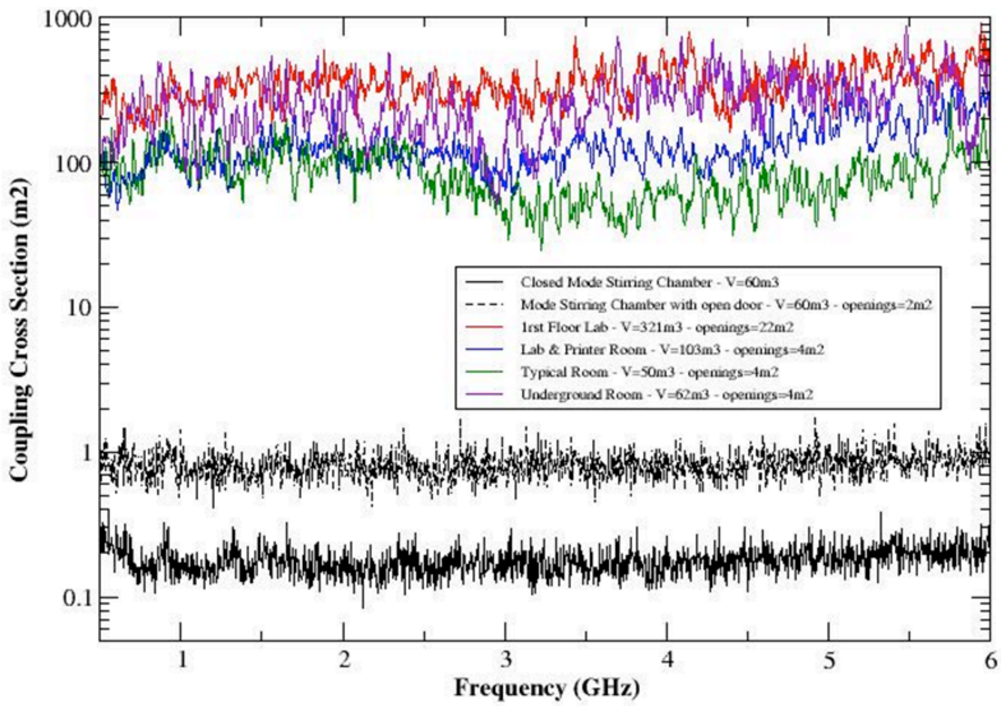


Figure 8 - Equivalent mean Coupling Cross-Sections of different rooms in the targeted building

2.4.2 "Inter" measurements

At a third step, EM coupling between several rooms of the targeted building has been measured in "Inter" configuration in order to characterize EM attenuation inside the building. Figure 9 presents a mapping of EM attenuation deduced from the measurements at a frequency of 5.2GHz between the "Emission" room, in which the transmitting antenna is placed, and neighbouring rooms hosting the receiving antenna. This figure shows that EM propagation in the building depends on EM dissipative mechanisms that are specific to each elementary room. Note that ergodicity between point locations in rooms and measured samples (including stirrer rotation and polarisation configuration) has been applied to obtain this mapping. Note that in similar office rooms, we almost obtain the same attenuation level. The measured data are finally post-processed to extract the transfer CCSs between the "Emission" room and the other elementary rooms.

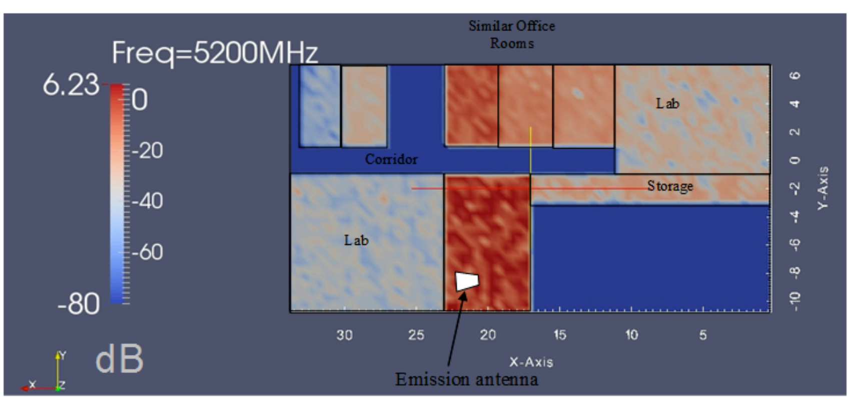


Figure 9 - Attenuation between an emission room and other neighbouring rooms in the targeted building (blue zones correspond to zones for which no measurement is available)

2.4.3 "Ext/Int" measurements

Finally, the last configuration intends to measure EM transfer functions between an incident external field and the resulting induced EM fields in several rooms of the targeted building ("Ext/Int" configuration). These data will be used later on as reference data for the validation of the PWB modelling of EM interactions with buildings.

"Ext/Int" measurement configurations:

We remind that the incident field is generated by the transmitting antenna (double ridge antenna) located at 20m far from the targeted room of the building as illustrated in Figure 10. The emission antenna is positioned in front of the window of the "targeted office room". Other observation rooms are the "Laboratory room" and two other "Office rooms", all of them located at the first floor of the targeted building.

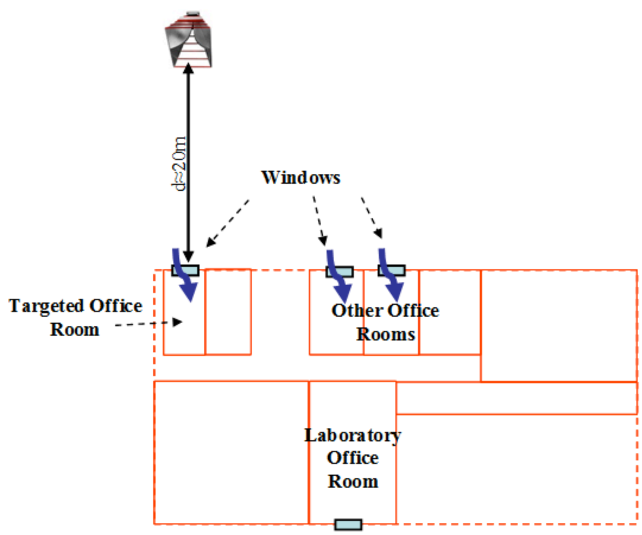


Figure 10 - Shielding effectiveness of targeted office and laboratory rooms for several open-closed configurations of offices

The windows of the office rooms are made of 4 glass panels, fully transparent to EM waves. Those windows can be considered as the only relevant Point of Entry (POEs) of EM energy for our problem. All the office room windows are equipped with metallic roller shades likely to provide a significant attenuation of the EM external interference and act as an EM protection against an external EM threat. The roller shades are made of metallic blades that can be set horizontally leaving 60 equivalent slots of 2cm width and 0.775m long in each of the four window panels. The dimensions of windows of the targeted office with open roller shades and half-open roller shades are illustrated in Figure 11.

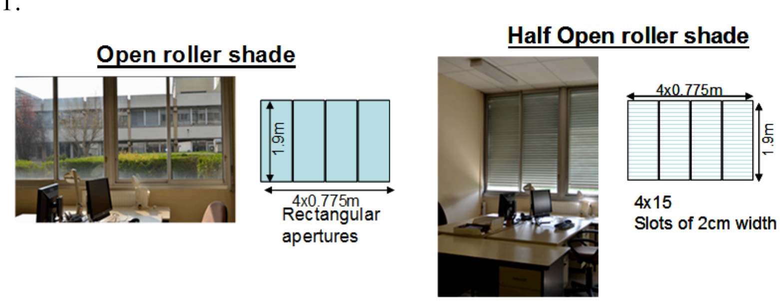


Figure 11 - Office-room windows and roller shade configurations

Therefore, 3 configurations of windows can be distinguished:

- "**Fully open**" when the roller shades are up
- "**Half open**" when the roller shades are down in "half open" position
- "**Closed**" when the roller shades are down in "closed" position

In addition, in order to evaluate the influence of the position of the blades of the roller shades, **horizontal** and **vertical polarizations** of the transmitting antenna have been considered.

<u>Influence of roller shades position:</u>

In order to evaluate the influence of the roller shades, various configurations of illumination of the targeted office have been considered depending on the position of the roller shades (open, half-open, closed), both in emission and reception rooms and depending also on the polarization of the external incident EM field:

i) Horizontal polarization – open roller shades in both rooms

ii) Horizontal polarization – half-open roller shades in both rooms

iii) Vertical polarization – half-open roller shades in both rooms

iv) Horizontal polarization – half-open roller shades in reception room (in targeted office room) – open roller shades in emission room

v) Horizontal polarization – closed roller shades in both rooms

In all configurations, the attenuation brought by the roller-shades is defined as the transfer functions measured between the transmitting and the receiving antennas and normalized to the reference configuration in which the roller shades are open in both rooms. The attenuations brought by the metallic roller shades (closed or half-open) depending on the polarization of the incident interference are plotted in Figure 12 up to 6GHz. The 0dB-level represents the reference configuration with open roller shades in both rooms. The reference configuration does not depend on the polarization of the external field.

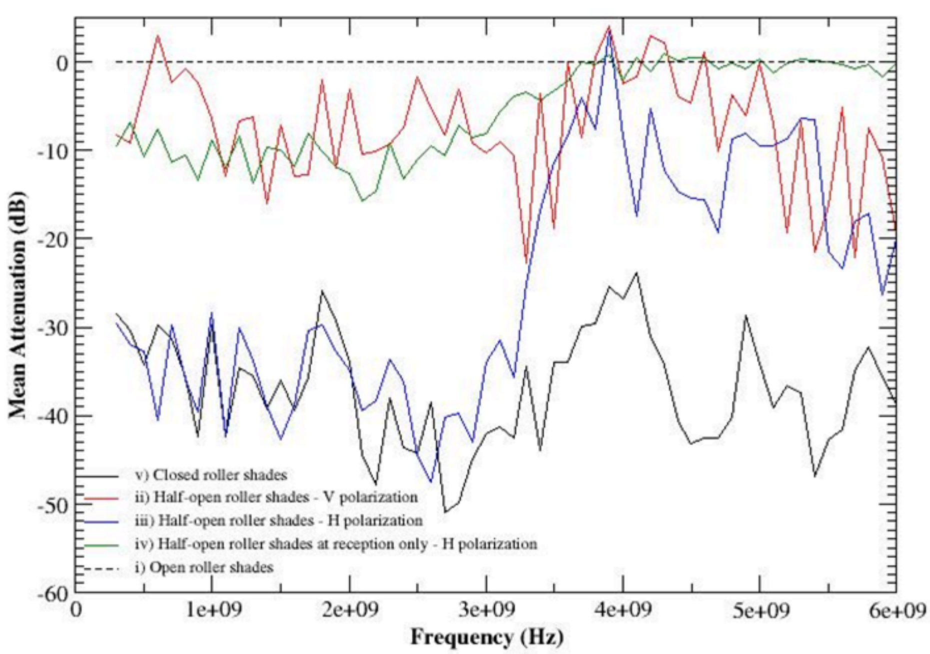


Figure 12 - Effects of metallic roller shades onto building attenuation in the targeted building room

The following conclusions can be drawn:

- Metallic roller shades when completely closed bring a significant attenuation of about 40dB in the whole frequency range onto the EM induced levels in the targeted office.
- When half open in both rooms, the attenuation of metallic roller shades depends on the polarization of the external EM interference.
- With incident vertical polarization, slots being horizontal, the attenuation is about 8dB less in the whole frequency range than the in full open configuration. This result is consistent with the fact that the equivalent area of the 60 slots is also about 8dB less than the open windows.
- With incident horizontal configuration and in half-open configuration of roller shades, the attenuation varies with frequency and the typical behaviour of slots corresponding to high-pass filters can be seen. The cut-off frequency depends on the dimensions of the slots. At high frequency (with respect to the dimensions of the slots) the slots (in half open roller shades configuration) let the EM energy penetrate through the window and the attenuation is the same in both polarizations of the incident external interference.
- With incident horizontal configuration, the effect of high pass filter is more obvious when both rooms have half-open roller shades which can be explained by the fact that both half open roller shades act as two successive high-pass filters. This is also why the variation with frequency between 2.5GHz and 4GHz is much more abrupt than with a single half open roller shade.

<u>Shielding effectiveness measurement results in targeted building:</u>

Figure 13 illustrates an example of shielding effectiveness deduced from experimental results. Here the shielding effectiveness is defined as the ratio between the incident electric field in free space at the level of the targeted room and the average electric field induced in another room. The incident reference electric field in free space is supposed to be the one induced by the transmitting antenna at the level of the targeted office. It is calculated analytically given the gain of the antenna, the distance antenna-targeted office and the incident power at antenna input.

The results have been obtained in two different rooms of the targeted building:

- The targeted office room of the building in two configurations of its window shades (metallic roller shades open or closed),
- The laboratory room for two configurations of window shades (metallic roller shades open or closed) of the neighbouring offices.

In this analysis, the roller shades in the targeted building-room are in “open” position but the roller shades of the two other building-offices are either open or closed.

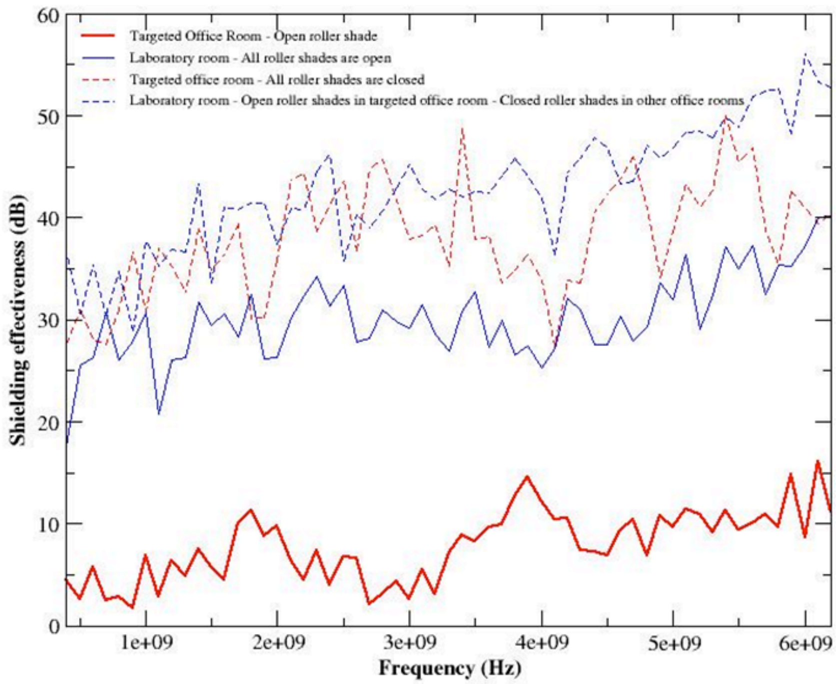


Figure 13 - Shielding effectiveness of targeted office and laboratory rooms for several open-closed configurations of office windows

The following conclusions can be drawn:

- In the targeted office, the shielding effectiveness is low when the roller shades are in open position because its window is in front of the illuminating antenna and constitutes the main POE of the EM energy in this room. Off course, when the roller shades are closed, the shielding effectiveness increases.
- In the laboratory-room, the shielding effectiveness has an average level of about 30dB when all the roller shades are open and 30dB when they are open in the targeted office only. This result clearly shows that the two windows of the two other building rooms also contribute to the penetration of EM energy inside this room.

Main lessons:

The lessons from analysis of the measurement results in various configurations of the illumination can be summarized as follows:

- EM coupling inside building-rooms is mainly due to internal losses. Leakages through openings (windows and doors) are not significant in terms of loss of EM energy. Such a situation contributes to the localization of the average EM energy in rooms.
- Openings are the main POEs for the transfer of EM energy from the outside or between rooms. The fact of opening or closing those openings clearly influences the transfer functions in logical additive way.

As a general conclusion, even if the field distribution in building rooms cannot be modeled with simple and efficient distribution laws as in MSRC, the coupling between each room and the coupling between rooms approach can be characterized by specific CCS. This situation seems favorable to the application of the network formulation of the EMT/PWB theory. This is the subject of the next section.

3 APPLICATION OF EMT/PWB METHODOLOGY

As previously mentioned, the idea is to use the experimental data base previously presented in order to validate EMT/PWB concepts applied to buildings by comparing them to numerical data resulting from the EMT/PWB modelling. Recalls on EMT/PWB methodology are given in paragraph 3.1. Paragraph 3.2 is dedicated to the validation of the EMT/PWB method when applied to modelling EM interactions in buildings. In paragraph 3.3, additional configurations of the building are simulated in order to demonstrate the potentiality of the modelling method for assessing EM environments in various building rooms induced by an IEMI/NNEMP attack.

3.1 Recalls on EMT/PWB methodology

3.1.1 General concepts

The principles and the theoretical formalism of the EMT/PWB methodology to model EM interactions in electrically large systems has been fully detailed in ([4],[5]). Let us recall that the modelling methodology consists in combining Electromagnetic Topology concepts (EMT) of a system decomposed in topological volumes [8] and a PoWer Balance (PWB) quantification of EM interactions inside and between those volumes. A qualitative analysis of the EM problem enables building an interaction diagram sequence in which nodes represent volumes in which dissipative mechanism happen and branches describing transfer-of-energy paths between volumes.

The quantitative analysis is made in two steps:

- The building of the topological network model
- The resolution of the topological model

3.1.2 Topological network models

The network model is made of tubes connecting junctions and derived from the interaction diagram sequence and is filled with relevant physical features of EM interactions using PWB concepts. Let us point out here the advantage of a network model compared to a simple transfer function model applied on the interaction diagram sequence. The network model includes in its formulation the fact that EM interactions are of course bi-directional since back-interactions of one volume on the other are possible. In a transfer function model, EM interactions are unidirectional and do not account for any back coupling. In EMT, this absence of reaction coupling is known under the Good-Shielding approximation but it must be applied with caution. The network formulation is also more general in the sense that sources can be applied anywhere on the network.

PWB concepts assume that the structure under test is large enough compared to the incident wavelength and complex enough to assume that the exact geometry of the problem is not fully controlled. Consequently, as in classical MSRCs, the induced EM environment can be modelled by pseudo-random variables and reduced to energetic (scalar) quantities such as mean power densities, mean dissipated power, equivalent CCSs. CCSs are defined as the ratio between the dissipated power and the incident EM power density. It has the property to be an intrinsic characteristic (in the sense that it does not depend on the excitation source and the test environment used to measure it). Two types of CCSs can be identified:

- EM energy dissipation in volumes (Joule losses, scattering through exterior openings…) described mathematically by a matrix or a scalar number
- Transfer of energy between volumes described mathematically by a matrix.

In the PWB network formulation we have chosen, the two types of CCSs are applied in junctions. Therefore, three types of junctions are defined:

- POA junctions that contain the CCS scalars number describing the dissipation of energy at POAs (Points Of Absorption).
- POE junctions that contain the matrices related to the transfer of external energy through POEs (Points Of Entry).
- POC junctions that contain the matrices related to the transfer of internal energy through POCs (Points Of Coupling).

- Volume junctions that sum-up the CCS from the POA, POE and POC junctions

The consequence of such a description is that the tubes are ideal connections that only carry a unit transfer functions. Nevertheless, they are the only elements of the network supporting the application of sources as in usual EMT network models [7]. This PWB network model description is the one chosen in the PWB computer code developed at ONERA and applied in the following for quantitative calculations.

As an example of EMT/PWB modelling of EM interactions inside a building, let us consider the case of a building made of three rooms as shown in Figure 1 at the beginning of this paper. Let us also assume the IEMI attack scenario in which the RF source is aiming at the building inside a van parked onto the access road (supposed to be the only possible access to the building from the exterior).

The topological decomposition of the problem can be summarized as follows:

- The building is along an access road,
- Two rooms (room A and room B) have windows facing the access road,
- The third room (room C) is a control room with no windows and is supposed to contain critical equipment.

To build the equivalent EMT/PWB network of this scenario of attack, it is necessary to first analyse from a qualitative point of view the propagation path of the RF incident EM energy from the source up to the internal rooms by considering all possible EM coupling paths. The analysis here is quite obvious:

- The RF energy can enter the building by both windows of rooms A and B (with possible different levels of EM fields at the levels of the windows depending on the relative positions between windows, road and EM source).
- Once in room A, RF energy can either dissipate in the room, go out through the window or go to room B and room C through the doors and the corridor.
- Once in room B, RF energy can either dissipate in the room, go out through the window or go to room A and room C through doors and the corridor.
- Once in room C, RF energy will dissipate in the room and interact with other rooms.

All these EM interactions are put together in the EMT/PWB network schemed in Figure 14. From a quantitative point of view, the CCSs are the relevant physical input parameters and they are assigned to each junction representing an elementary EM mechanism.

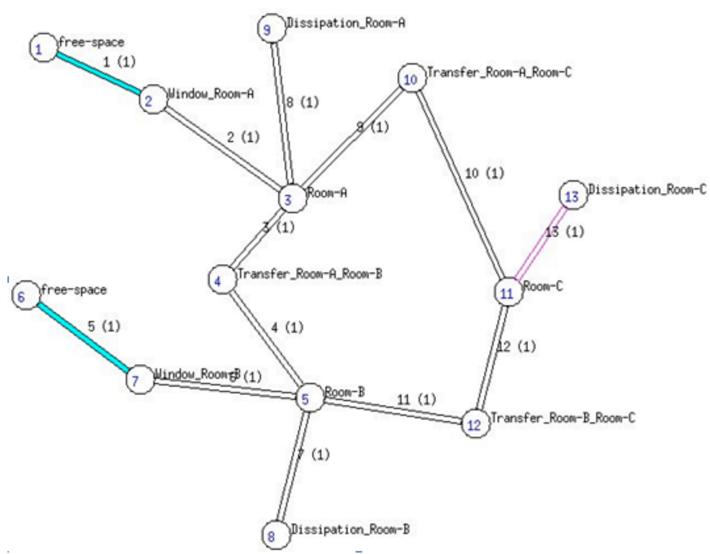


Figure 14: EMT/PWB network of the simple building

In this network model we can identify the following elements:

- Blue tubes indicated that an equivalent source (either an incident power or an incident power density) is applied to this access point.
- A red tube indicates the EM volume of interest (for us the room containing the critical equipment) in which EM levels must be evaluated.
- "Room-A", "Room-B" and "Room-C" junctions are volume junctions related to the 3 main rooms of the building.
- "Window-room A", "Window-Room-B", are POE junctions.
- "Transfer-Room-A_Room-B", "Transfer-Room-A_Room-C", "Transfer-Room-B_Room-C" are POC junctions.
- "Dissipation-Room-A", "Dissipation-Room-B" and "Dissipation-Room-C" are POA junctions.

3.1.3 EM resolution of topological models

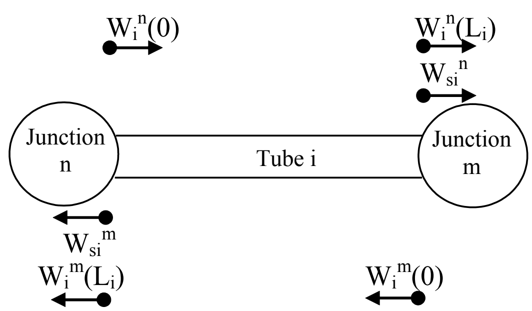
In the EMT formalism, the unknowns are defined as incoming and outgoing waves travelling along tubes. These waves are then gathered into the BLT network equations recalled hereafter where [W(0)], [W(L)] and [Ws] are respectively, the incoming, outgoing and source waves. [S] is the scattering matrix and [Γ], the propagation matrix along tubes. In this formation, no sources are applied on a port of a junction. If a source must be applied on a junction, it is applied on the tube connected to this port: this formalism is an analogy with what is done on multiconductor network formalism.

Propagation equation: $\left[W(L)\right]=[\Gamma].\left[W(0)\right]+\left[W_s\right]$

Scattering equation: $\left[W(0)\right]=[S].\left[W(L)\right]$ (2)

BLT equation: $\left([I]-[S].[\Gamma]\right).\left[W(0)\right]=[S].\left[W_s\right]$

Here, in order to match the EMT formalism with PWB concepts, two waves are applied on each tube in order to describe incoming and outgoing waves at junction level. They are defined as a linear combination of dissipated power "P" and power density "S" as illustrated in Figure 15. "Ac" is called the "characteristic" CCS chosen arbitrarily as the coupling cross section of a perfectly matched antenna and equal to $\lambda^2/8\pi$.



$$W_i^n(0)=A_c.S_i^n-P_i^n \qquad W_i^n(L_i)=A_c.S_i^m+P_i^m$$
$$W_i^m(0)=A_c.S_i^m-P_i^m \qquad W_i^m(L_i)=A_c.S_i^n+P_i^n \qquad (3)$$

Figure 15 – Definition of waves on a tube in EMT/PWB formalism

Junctions are characterized in our formalism by scattering parameters [S] linking at each junction incoming and outgoing waves. S-parameters are derived from the dual CCS matrix [A] of the junction. These relevant physical features can be either derived from analytical and theoretical expressions or deduced from measurements of Q factors in volumes or measurements of transfer functions between areas as presented in paragraph 2.4 in "Intra" and "Inter" configurations.

Let us finally note that in the BLT equation formulation of PWB, propagation of waves along tubes is taken into account in the super matrix [Γ] which is reduced to the unit matrix at this moment in the PWB formalism.

The EMT/PWB formalism as described above has been implemented at ONERA in a dedicated computer code named "PWB" [9]. It is based on the "CRIPTE" code initially developed at ONERA in the 90's to model and evaluate EM interactions on multiconductor cable networks [10]. The EMT/PWB formalism and its related numerical code "PWB" had been fully validated onto different test cases, from a generic simplified structure up to an aircraft [5].

3.2 Validation of EMT/PWB methodology

3.2.1 Topological network model of the 1st floor of the targeted building

The EMT/PWB network model corresponding to the configurations of illumination of ONERA's targeted building is deduced from the analysis of the topology of the building; the topological network model is illustrated in Figure 16 together with a geometrical scheme of the 1st floor of the targeted building. In this figure, we can identify the following PWB network elements:

- Blue tubes indicate coupling paths between the exterior and the building.
- Junctions 2, 10 and 15 represent windows (POEs). Let us recall that in the simulation, the windows are considered as four free apertures (1.9m x 0.775m) when there is no roller shade and as 60 slots of 2cm width and 0.775m when the roller shade is half-open. In configuration with closed metallic roller shades, the source terms on associated blue tubes will be removed in the EMT/PWB modelling.
- The room junctions (volume junctions 3, 6, 11 and 16). Such a junction corresponds to a so-called "Ideal junction" [11] which makes the ideal connection of all the ports of the junction (equivalent to sum-up all the powers on the connected tubes)
- The coupling paths between room junctions (POC junctions 5, 12, 18). The associated CCSs are deduced from the "Inter" configuration transfer function measurements presented in section 2.
- The various global intrinsic dissipative mechanisms (POA junctions 4, 8, 13 and 17) and the receiving antennas (POA junctions 7, 19 and 20) located in rooms under test (connected to purple tubes). As for POC junctions, the associated CCSs are deduced from the "Intra" configuration transfer function measurements presented in chapter 2.

Note that the whole building has been reduced to offices and corridor located next to the targeted office at the first floor in order to simplify the EMT/PWB modelling.

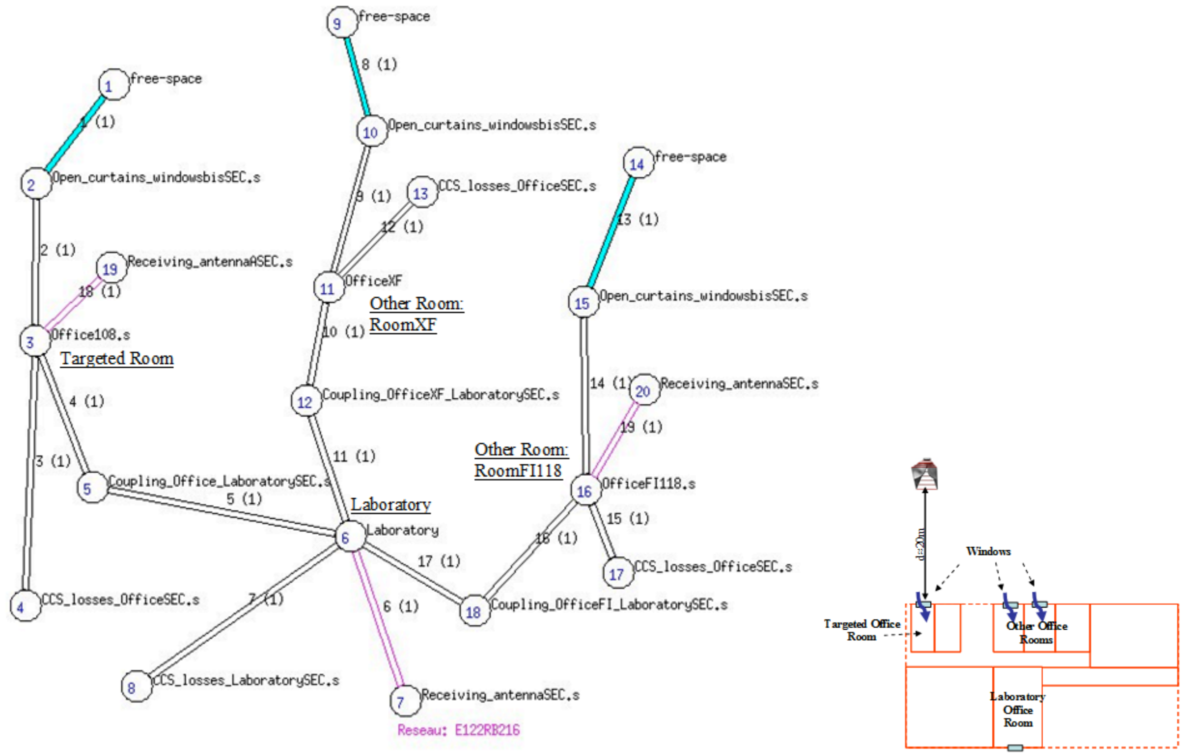


Figure 16 - EMT/PWB network model of the illumination configuration of ONERA's targeted building

Prior to model the entire building illumination and in order to validate the EMT/PWB approach applied on buildings, some specific experimental configurations with increasing levels of complexity have been considered and simulated. They are reported in the following paragraphs.

3.2.2 Basic configuration: EM environment modelling in the targeted office

This basic configuration consists in measuring and simulating the shielding effectiveness in the targeted office which is directly illuminated by the external incident EM field in horizontal polarization. For this we consider an ideal far field model of the antenna at a distance d=20m (distance between the illumination and targeted buildings as in Figure 6). In this configuration the main coupling path is the illuminated window of the targeted office with, in the one hand, no roller shades and, in the other hand, the half-open metallic roller shade. As far as the orders of magnitude and global frequency variation are concerned, Figure 17 shows that the PWB modelling gives a good agreement in the whole frequency range between the measured and simulated shielding effectiveness obtained in this basic configuration.

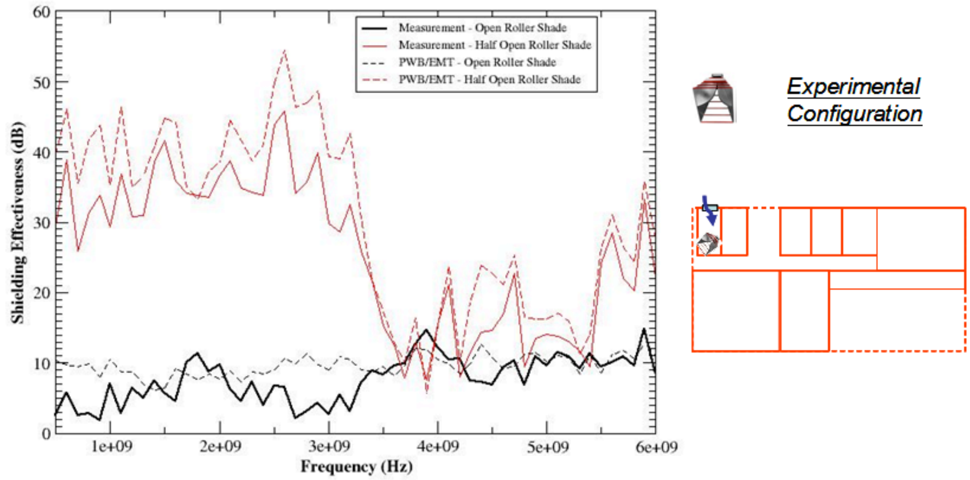


Figure 17 - Shielding effectiveness of targeted office – simulation and measurement – Horizontal polarization

3.2.3 More complex configurations: shielding effectiveness in the laboratory room

The next validation step consists in measuring and simulating the EM environment induced in the laboratory room which is not in the line of sight of the external illumination. Therefore, the path to reach the laboratory room is not direct and can be decomposed as follows: the external field penetrates in parallel in the building through the window of the targeted office room and through the windows of the neighbouring office room. Once inside, the EM energy scatters depending on dissipative mechanisms and internal coupling paths between elementary rooms of the building. Two configurations are considered:

- Configuration A: all roller shades are closed except the window of the targeted office
- Configuration B: all roller shade windows (targeted office and 2 neighbouring offices) are open.

Measured and simulated shielding effectiveness are drawn respectively in Figure 18 and Figure 19 in configurations A and B.

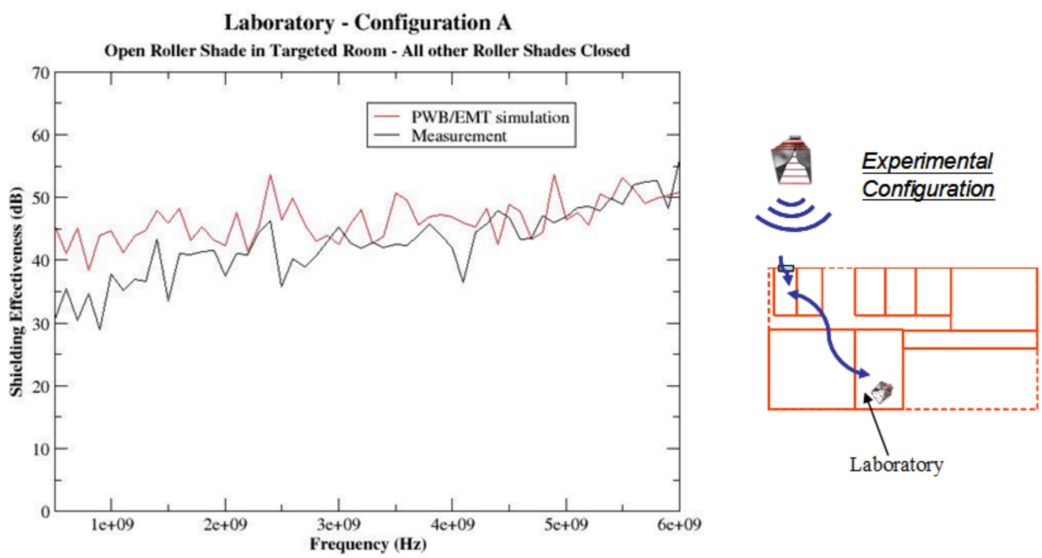


Figure 18 - Shielding effectiveness of laboratory room – configuration A

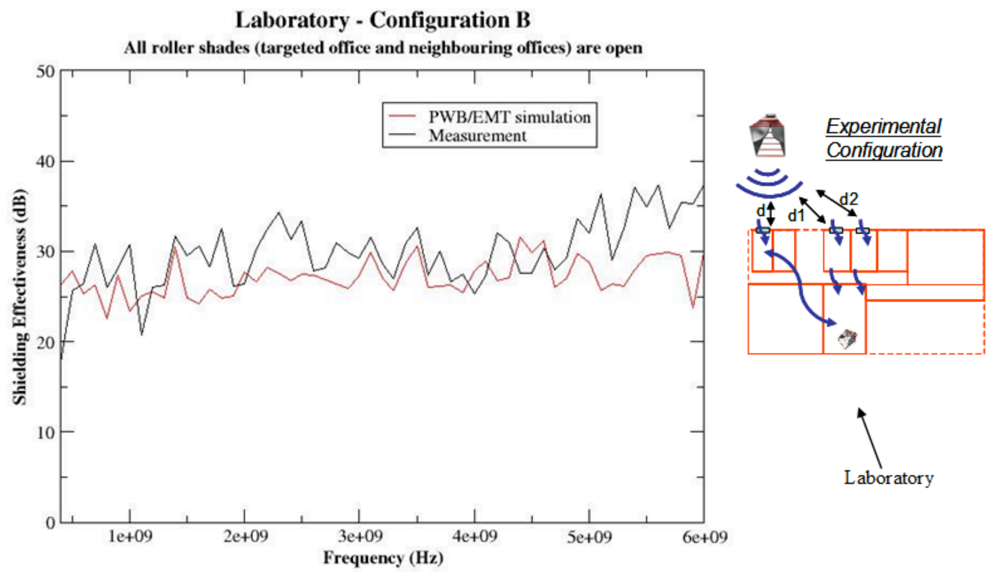


Figure 19 - Shielding effectiveness of the laboratory room – configuration B

The agreement between measurements and simulations is quite consistent in the whole frequency range if one considers the orders of magnitude and global frequency variation. Of course, some discrepancies can be noted. These discrepancies can be explained as follows:

- In both configurations, the EMT/PWB network has been reduced to the main coupling paths between the targeted room, two neighbouring offices and the laboratory. This representation may be insufficient and additional EM interaction paths might have been included in the model such as, for example, the coupling paths between neighbouring laboratory room or other rooms which can be in the radiation pattern of the illumination antenna.
- The external incident EM field has been also reduced in the EMT/PWB modelling to an ideal plane wave impinging globally onto all illuminated windows. The amplitude of the plane wave has been deduced analytically from experimental conditions as the distance between antenna and targeted room, the gain of the antenna. Therefore, scattering due to the building and due to the other surrounding buildings has been neglected and this assumption may be too simplified for our experimental setup.

3.3 EMT/PWB modelling of additional configurations – Efficiency of metallic roller shades for EM protection

The last step of this work consists in simulating additional configurations of IEMI/NNEMP attacks (for which no comparisons with measurement is available) onto the building in order to demonstrate how this modelling approach may be used in order to draw protection measures. We have chosen to analyse the efficiency of metallic roller shades as EM protection devices. Let us thereby assume the following attack scenario in which:

- The IEMI/NNEMP weapon is located outside the building facing the previously targeted office and radiates a plane wave with horizontal polarization,
- The targeted room is not equipped with metallic roller shade, the window is supposed to be free. This might be an operating constraint imposed to the building.
- The critical equipment is located in the laboratory room
- The neighbouring rooms are equipped with metallic roller shades which can be either open, half open or closed.

Let us suppose that we do not want to overcome the susceptibility level of the critical equipment in room C and we need to define the appropriate protection to be applied at the levels of the windows. For this we run different configurations of the metallic roller shades in the other office rooms in order to assess the level of protection brought by the roller shades:

- Configuration 1: metallic roller shades of both neighbouring rooms are closed,
- Configuration 2: metallic roller shades are half-open in both neighbouring rooms,
- Configuration 3: one open window in one neighbouring room and metallic roller shade are half-open in the other neighbouring room,
- Configuration 4: open roller shades in both neighbouring rooms.

The simulated EM levels induced in the laboratory room normalized to "Configuration 4" are drawn in Figure 20. The plots indicate the attenuation efficiency of metallic roller shades regarding the frequency of the IEMI/NNEMP attack of the building.

Depending on the level and frequency range of EM susceptibility of the equipment and the frequency of the IEMI/NNEMP attack, the user will be able to decide with these simulations which configuration is appropriate for EM protection and operational conditions. For example below 3GHz, metallic roller shades do not need to be completely closed to obtain a sufficient EM attenuation of 20dB. This conclusion is of course not valid anymore at higher frequency; for the same level of 20dB attenuation, metallic roller shades must be closed.

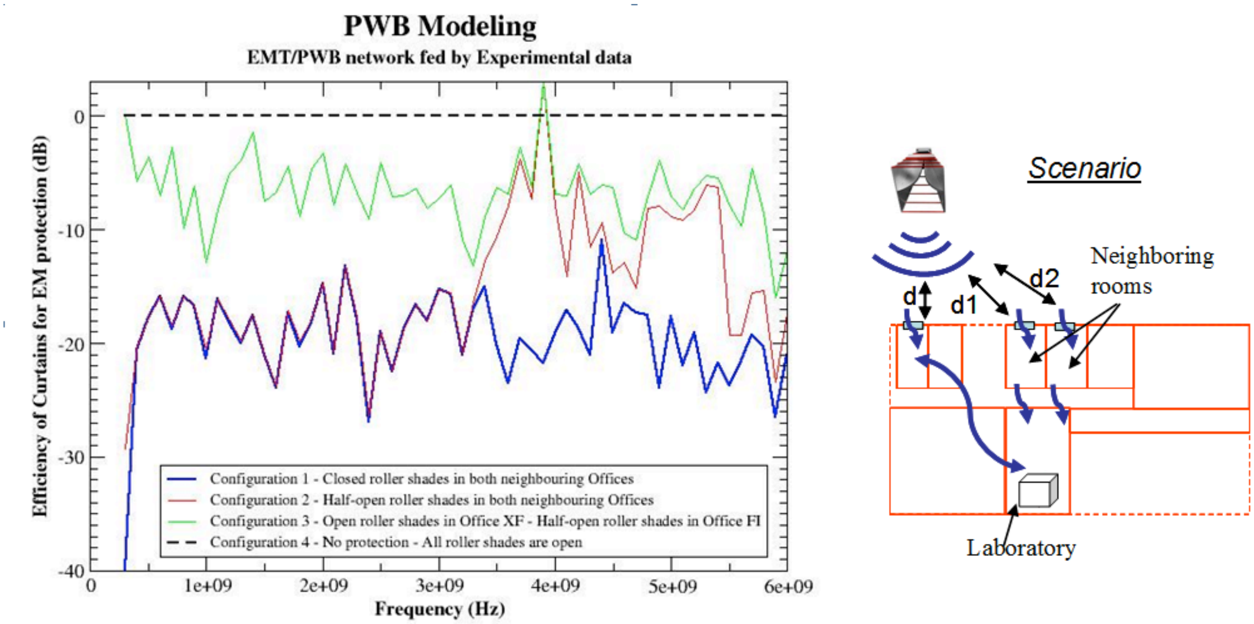


Figure 20 – Attenuation brought in the laboratory room by other rooms metallic roller shades

4 CONCLUSION

The work presented in this paper focused on the analysis of transmission of EM RF energy inside building rooms through building windows at which the first level of possible EM protection versus external attack can be performed. The paper also investigated the transmission of the EM energy inside a building.

In parallel to experiments carried out in ONERA's building in specific rooms, numerical modelling have been conducted in order to validate the relevance of EMT/PWB methodology to assess EM environment induced in a building by an IEMI/NNEMP attack. The modeling results are very encouraging but some additional experimentation in different types of buildings (with reinforced concrete walls for example) would be interesting in order to enlarge the conclusions on the scope of application of EMT/PWB concepts. In parallel, a specific work is required to obtain theoretical analytical models of losses in rooms depending on their main features (as volumes, materials, openings, ..) and of POEs.

Experimental characterization of EM losses and EM coupling paths in a given building can be made efficiently by using simple laboratory equipment and transmission of data onto the built-in Ethernet network. In the future, we can think of developing dedicated and lighter equipment in order to obtain those measurements. Especially transmission of data with RF signals may be of interest if the Ethernet access is not possible.

Once those measurements available (even partially), this methodology and the associated model can be now used to play various attack scenarios and obtain the induced EM levels at the level of critical equipment or internal functions inside a building.

From now on, EMT/PWB modeling of EM interactions in a building can also be used in order to help to the diagnosis of an IEMI/NNEMP attack. Two different ways can be proposed:

- Evaluation of critical EM environments for critical equipment inside the building rooms given the EM sources measured by detectors at POEs
- Evaluation of external incident EM source amplitude and frequency spectrum given the EM environment measured inside the building by detectors (inverse problem).

5 REFERENCES

[1] W. A. RADASKY, C. E. BAUM, *Introduction to the special issue on high-power electromagnetics (HPEM) and intentional electromagnetic interference (IEMI)*, IEEE Transaction on Electromagnetic Compatibility, Vol. 46, No. 3, pp 314-321, 2004

[2] R. HOAD, W. RADASKY, *Progress in IEC SC 77C standards addressing HPEM threats to systems and infrastructure*, EUROEM 2012, Toulouse, France, July 2012

[3] O-H. ARNESEN, *Protection of Critical Infrastructures against High Power Microwave Threats – HIPOW - An EU 7th framework project on protection of electronic systems against natural and manmade electromagnetic threats,* in AMEREM2014 proceedings, Albuquerque USA, July 2014

[4] I. JUNQUA, J-P. PARMANTIER, F. ISSAC, *A Network Formulation of the Power Balance Method for High-Frequency Coupling*, Electromagnetics 25:7-8, pp 603-622, or in Interactions Notes, Note 576, November 2002

[5] I JUNQUA, *High frequency coupling mechanisms in complex systems: analysis and assessment by the PoWer Balance method*, Ph.D. Dissertation of Lille University, June 2010 (in French)

[6] C. LEMOINE, P. BESNIER, M. DRISSI, *Investigation of reverberation chamber measurements through high power goodness-of-fit tests*, IEEE Transaction on Electromagnetic Compatibility, Vol. 49, No. 4, pp 745-755, 2007

[7] I. JUNQUA, J-P. PARMANTIER & Al, *Combining Asymptotic Methods and Power Balance Approach to simulate HIRF HF scenarios*, in EUROEM2012 proceedings, Toulouse France, July 2012

[8] C.E. BAUM, *The theory of electromagnetic interference control*, Interaction Notes Note 478, December 1989 also in modern radio science 1990, pp 87-101, Oxford University Press.

[9] I. JUNQUA, S. BERTUOL, J-P. PARMANTIER, *Power Balance TM User's Guide – Version 1.0 2008*, IDDN.FR.001.110011.000.S.P.2008.000.31235, October 2009

[10] J.P. PARMANTIER, X. FERRIÈRES, S. BERTUOL, C. E. BAUM, Various Ways to Think of the Resolution of the BLT Equation with an LU Technique. Interaction Notes. Note 535. January 1998

[11] J.P. PARMANTIER, An efficient technique to calculate ideal junction scattering *parameters in multiconductor transmission line networks*. Interaction Notes. Note 536. February 1998