INFLUENCE OF BUILDINGS ON HPEM VULNERABILITY OF IT INFRASTRUCTURES

Michael Joester [1], André Bausen [2], Stefan Pohlenz [3], Thorsten Pusch [4], Martin Schaarschmidt [5], Michael Suhrke [6]

[2] *AndreBausen@bundeswehr.org*
[3] *StefanPohlenz@bundeswehr.org*
[5] *MartinSchaarschmidt@bundeswehr.org*
Bundeswehr Research Institute for Protective Technologies and NBC Protection (WIS), Humboldtstraße 100, 29633 Munster (Germany)

[1] *michael.joester@int.fraunhofer.de*
[4] *thorsten.pusch@int.fraunhofer.de*
[6] *michael.suhrke@int.fraunhofer.de*
Fraunhofer Institute for Technological Trend Analysis INT,
Appelsgarten 2, 53879 Euskirchen (Germany)

Abstract

When evaluating the vulnerability of an electronic system against an external threat like High Power Electromagnetics (HPEM), its immediate surroundings have to be included. IT equipment will typically be located inside buildings, whose walls can considerably attenuate and deform electromagnetic waves. The layout of IT and supply cabling shapes the system response as well. A topological abstraction model renders analysis of our complex HPEM attack scenario possible. One can identify three topological zones: the outside as well as the inside of the building, and the IT equipment itself. We have performed radio frequency exposure experiments with reasonably simplified substitutes for the outer area, the building and a cabling scheme including two IT devices as the minimum IT system setup. The results give information about the key parameters of RF coupling from one zone to the next. Finally, some recommendations for protection measures at CI have been derived from the results.

Keywords: Critical Infrastructure, IT, HPEM, IEMI, Vulnerability, Protection, RF, Building.

1 INTRODUCTION

Electromagnetic waves of high frequency (Radio Frequency, RF) can carry electromagnetic energy into electronic systems over a distance. Thereby induced excess voltages and currents might influence device functionality. An attacker can exploit this effect to weaken electronic control or security systems by RF sources close to CI buildings, thus perpetrating a so-called Intentional Electromagnetic Interference (IEMI).

The residual amount of disturbance energy inside the target buildings is strongly related to reflections at large surfaces in the environment of the scenario location and the attenuation by materials located in the RF propagation path. The latter might include walls, windows, doors and holes in the outer walls. Furthermore, within the interior of buildings a complex electromagnetic field distribution establishes itself by a combination of internal reflections and attenuation.

In a last step of energy transfer, the electromagnetic field in the room enters the distributed electronic system by coupling into the mesh of cables and device nodes directly. The magazine article [1] describes the coupling into distributed systems with cable and reference ground loops.

The topology of the building defines clear boundary conditions between the outer electromagnetic field generated by an RF source in the outdoor environment and the electromagnetic field inside the building. Conceptually, the coupling from interior electromagnetic field into the distributed electronic system can be described in the same way.

To investigate these phenomena, it makes sense to define zones separated by boundary surfaces as a border between two zones with different characteristics, as described within the concept of Electromagnetic (EM) Topology [2].

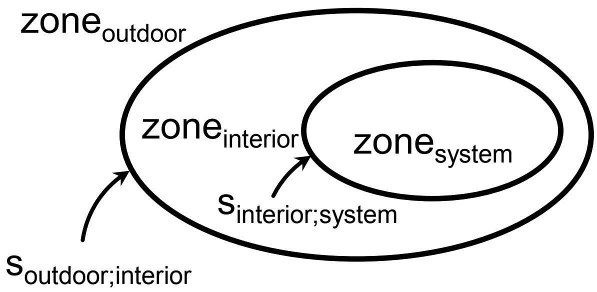

Fig. 1: The Zone / Boundary Surface model of EM Topology tailored to our scenario [2]

The boundary $s_{outdoor;interior}$ in Fig. 1 describes the influence of the building in this model of an HPEM attack scenario: an RF source is located outside the building in zone $zone_{outdoor}$, and the interior $zone_{interior}$ houses the distributed IT infrastructure defined as $zone_{system}$. The electromagnetic field in $zone_{outdoor}$ might be complex as scattering at surfaces in the environment leads to multi-path coupling into the building. The energy reaching $zone_{system}$ leads to an IT system response potentially including malfunction or even damage. Therefore, the injected energy as spread over a frequency range together with the characteristic system response describe the vulnerability of this system.

There are other unknown values in the chain of this model, the complex interior electromagnetic field in $zone_{interior}$ and the frequency-specific coupling into the distributed system represented by the boundary $s_{interior;system}$. The methodology to solve such a zone and surface model of EM Topology of an IEMI attack on CI in general is described in [3]. There are simulation works available describing a similar HPEM attack scenario on CI with multi-path coupling [4], including conducted coupling through cables into the building. The cable coupling as part of $s_{outdoor;interior}$ is investigated in [5] separately. The experimental work [6] determined RF transfer functions for the coupling between rooms within a building and outdoor with rooms in the building.

We will present in the following an experimental project of the Bundeswehr Research Institute for Protective Technologies and NBC Protection (WIS) together with the Fraunhofer Institute for Technological Trend Analysis INT, adhering to the zone and boundary model as presented above. All model components in Fig. 1 have been investigated separately by experiments with reasonable simplifications and predefinitions to reduce complexity and to get an overview on the key parameters of RF coupling. Apertures like windows and doors degrade the building walls’ attenuation, depending on the materials in use. Cable loops are the gateway for RF into distributed IT systems and should be avoided. These results are the base for protection measures recommendations.

2 COUPLING OF RF INTO A BUILDING

The characteristics of $zone_{outdoor}$ are mainly defined by the test site the experiment took place at. To get simple but realistic conditions, a free field test area has been chosen, without any buildings close-by, but with an RF-reflecting ground. The field generated by laboratory RF sources is well defined by geometries e.g. antenna height and polarization and the field strength is measured and adjusted in the frequency range of interest.

The representation of a building for determining the influence of boundary $s_{outdoor;interior}$ should be as simple as possible, but realistic. Therefore, the WIS has chosen a garage- sized reinforced concrete container module with windows and a door as a generic one-room office, denominated Electromagnetic Office Module (EMOM). Such a simple geometry can be easily simulated with 3D-solvers in parallel to the experiments. Fig. 2 shows the generic building placed on the test site at WIS.

Fig. 2: Generic WIS one-room office building at test site

The attenuation of the container's concrete walls with reinforcement is a rising function of frequency in the frequency range of interest and can be estimated based on the experiment results of Pauli and Moldan [7] and the work of Giri and Tesche [8]. They measured the RF behavior of different wall materials used in architecture. Apertures like windows and doors lessen this attenuation. Conventional insulated glazing features metal coating to reduce IR transmission and it has an RF attenuation in the same order of magnitude as the concrete walls [9]. The door and the window frames of the EMOM are made of plastic and therefore, the overall attenuation of the building is expected to be smaller than what the materials could obtain. On the other hand resonance effects within the building can be assumed. In that case, RF field amplitudes will vary over the volume due to superposition effects of RF waves.

During the experiments, a broadband pulse source generated RF waves with horizontal and vertical antenna polarization at the test site, cf. Fig. 2, left-hand side. The magnetic component of the RF field has been measured in all three axes, that is the X-, Y- and Z-direction, at a probe position defined for further investigations of coupling into distributed IT systems. By two test runs, the difference of field values with and without the generic building in place has been determined. The door of the building was directed towards the RF source.

Fig. 3 shows the transfer function of the magnetic field component H_y in the tested frequency range up to 4 GHz as a solid black line. The magnetic component of the outdoor RF field is generated horizontally. The blue curve is the expected attenuation of concrete with reinforcement according to [7] - apertures and window attenuation are neglected -, the red dashed curve is the linear fit of the result curve. The outdoor H_y

component might be transformed to some degree into the other two interior field directions, but this mechanism can be neglected for the attenuation discussion.

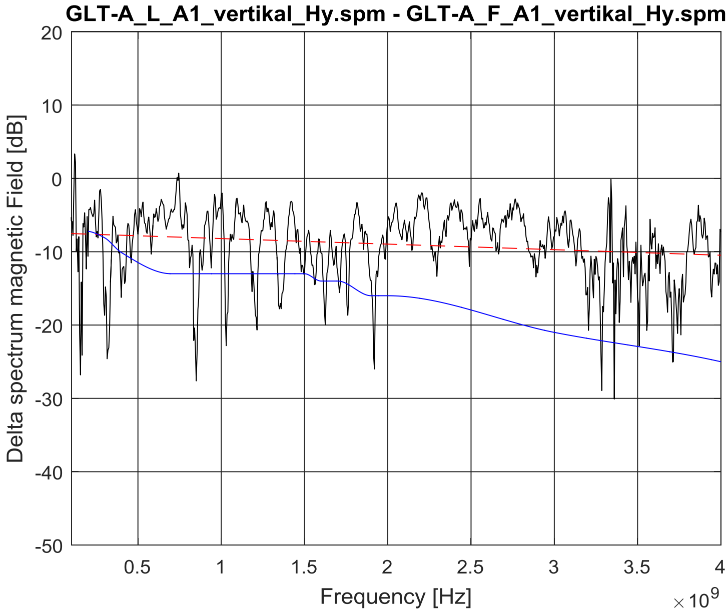

Fig. 3: Transfer function of magnetic field component H_y (black) of vertical polarized RF waves at a fixed probe position with and without generic building, together with a linear fit (red) and the estimation for attenuation by concrete [7] (blue).

As a result, one can see the degradation of wall attenuation with rising frequency by the apertures for windows and the door. The attenuation of the window glass might partly be suspended by the plastic frame. Anyhow, the door made of plastic is a large aperture without significant attenuation.

Also, the resonance behaviour of the volume versus frequency can be observed as characteristic dips in the field difference curve in Fig. 3. Simulations of the EMOM-shaped reinforcement as a simplified model validate the experimental evidence. As an example the result of the prominent resonance at 73 MHz is illustrated in x-/y-plane and in x-/z-plane in Fig. 4.

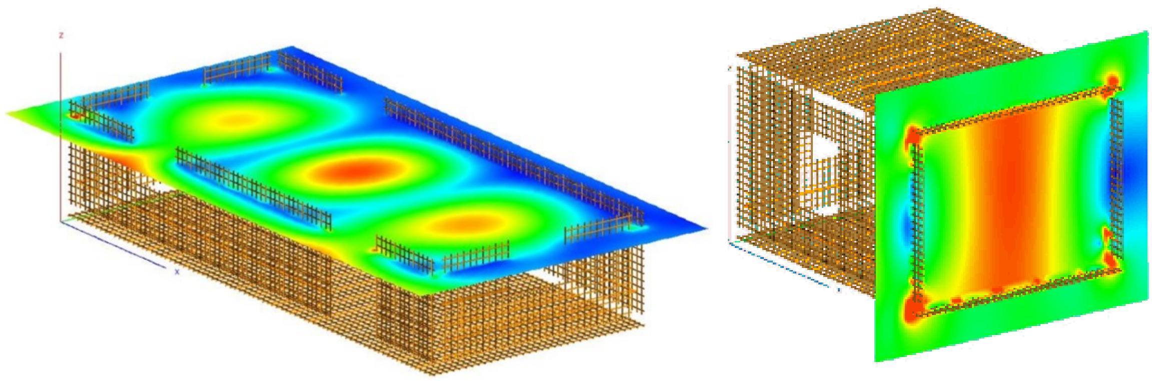

Fig. 4: Numeric simulation result of EMOM at 73 MHz as an example, the field amplitude is color-coded.

At each of the observed resonance dips, such spatially modulated field distributions will be established, leading to varying degrees of exposure depending on the position within the room.

3 COUPLING OF RF INTO A DISTRIBUTED IT SYSTEM

To investigate the RF coupling from the building's interior $zone_{interior}$ into the distributed IT system characterized by $zone_{system}$, the model representative $s_{interior;system}$ for this coupling has to be determined. Again, a preferably simple, but realistic test setup has been chosen for the experiments.

Today, an office IT system consists of a desktop tower PC, commonly placed under a table, a computer monitor, a mouse and a keyboard on the table, and the connections to mains and LAN. As an abstraction, one can find two overlaid meshes of copper wires, connected in loops with the devices PC, monitor, and a LAN router as nodes, illustrated in Fig. 5.

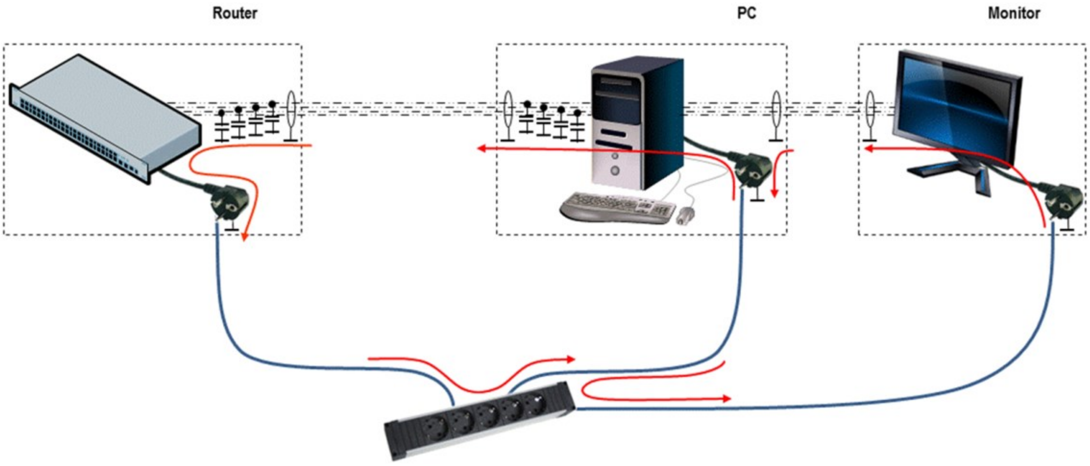

Fig. 5: Wire loops of a typical office workplace

Within the loops RF currents can flow, indicated by the red arrows in Fig. 5. The abstraction down to one loop and two devices leads to the following simplified test setup as shown in Fig. 6a.

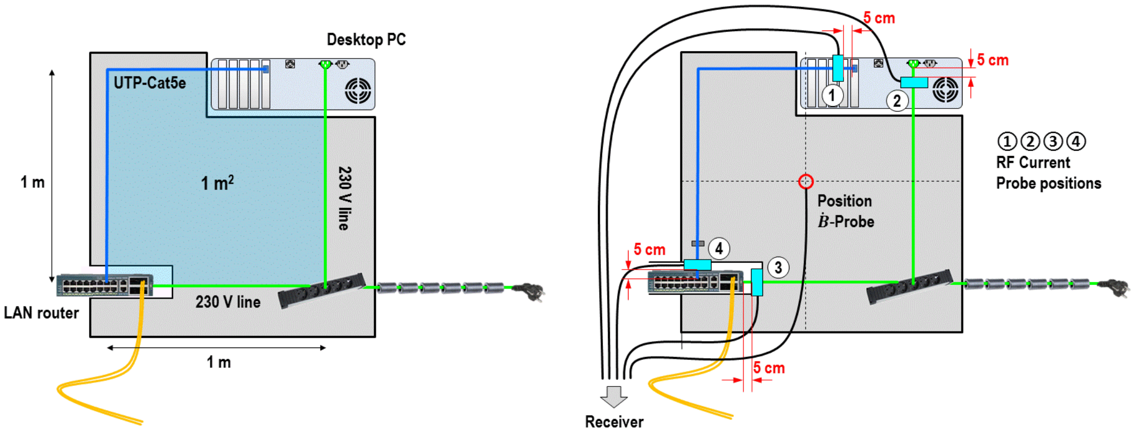

Fig. 6: a) Simplifed distributed IT system with one wire loop and two devices as nodes, propped up by a Styrofoam stand.
b) Measuring the RF currents on the IT system lines during testing

The goal of the experiments is to investigate the magnetic and electrical coupling of RF fields into this setup. During the tests, the RF currents on the wires close to the connectors of the devices and the magnetic component of the RF field in the middle of the square meter loop have been recorded. The monitoring setup is illustrated in Fig. 6b.

The coupling function of this setup can be determined with a transfer function measurement, performed in a TEM waveguide up to 2,5 GHz. Fig. 7 shows the maximum of the four RF currents on the wires at each frequency, normalized to an RF field strength of 1 V/m. The setup was placed into the TEM waveguide in the position illustrated in Fig. 6b.

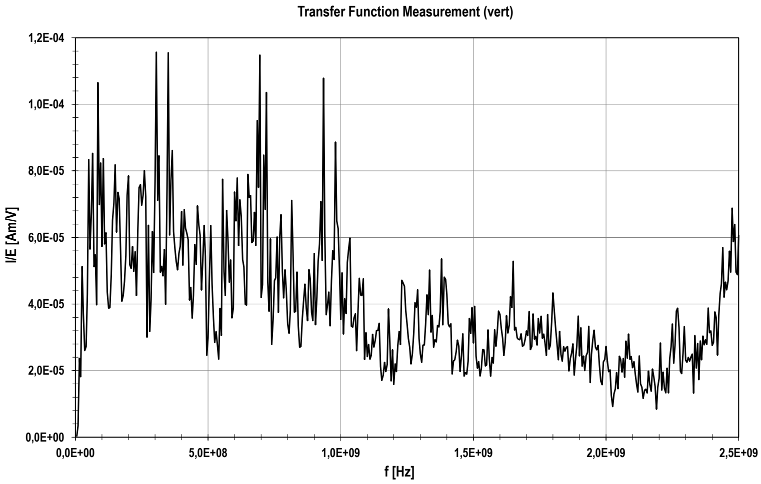

Fig. 7: Result of transfer function measurement

As expected, the magnetic coupling is effective up to approximately 1 GHz, beyond this frequency the impedance of the wires is too large for a magnetic RF field to couple into the loop. In that case the meshed characteristic of the distributed IT system dissolves into separate and independently susceptible sub-parts with rising frequency beyond 1 GHz.

4 COUPLING RF INTO A DISTRIBUTED IT SYSTEM WITHIN A BUILDING

For the prediction of failures in an IT system, additional information has to be considered: The RF susceptibility test results for each IT component, where functional failures are determined in dependence on the RF fields. In further experiments the overall coupling from $zone_{outdoor}$ to $zone_{system}$, implicitly including $s_{outdoor;interior}$, $zone_{interior}$, and $s_{interior;system}$, and the susceptibility of IT devices were investigated. The simplified test loop and a real office workplace were placed into the generic building, as shown in Fig. 8. The two PCs interacted via LAN, an RF hardened video camera was aimed at the computer monitor of the office workplace.

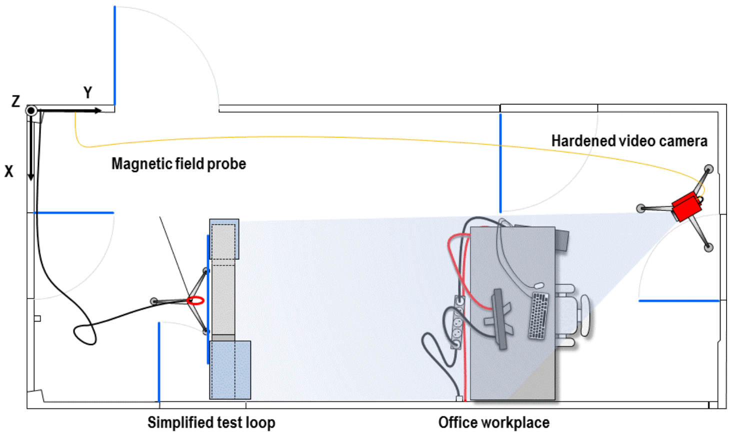

Fig. 8: Experimental setup for combined coupling in the generic building

Different program applications generated LAN traffic in both directions between the test loop PC and the workplace PC, passing the test loop router. The transmission has been evaluated for throughput and the hardware has been monitored for functionality, e.g. computer monitor display failures. Again, the magnetic RF field in the middle of the loop and the currents in the test loop have been recorded during the tests.

As a last experiment an attack scenario has been defined using this setup. A High Power Microwave (HPM) source was placed in front of the building similar to the setup shown in Fig. 2. This RF source generated pulsed RF in the frequency range from 150 MHz to 3400 MHz with a pulse power of maximum 35 kW. At each test frequency, the source increased the output power from start level to maximum level in a certain time.

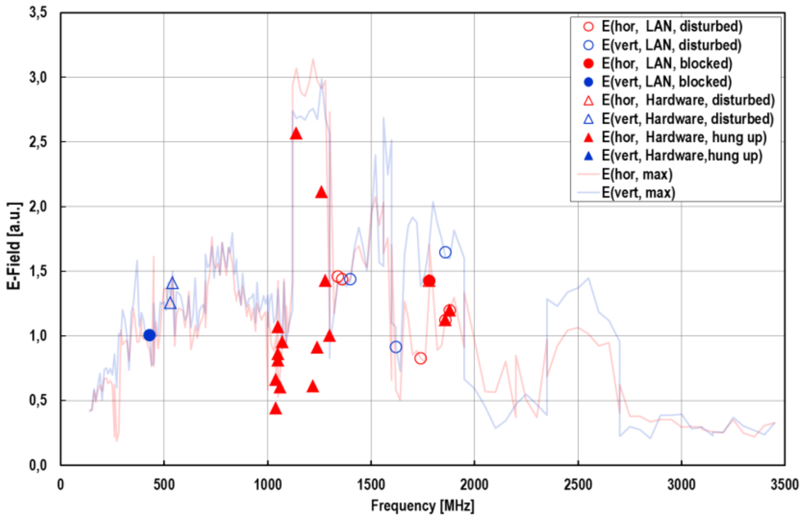

Fig. 9: Test result of HPM attack scenario on generic building with office desk and test loop inside

As a result the majority of failures occurred above 1 GHz and with horizontal field polarization (Fig. 9). In that frequency range, mainly the PC of the test loop hung up suddenly without any disturbance phenomena in advance. According to the transfer function result shown in Fig. 7 the coupling mechanism seems to be direct coupling into the housings of IT equipment. Only a few failures occurred with vertical polarization. Summing up the result of this experiment, the distributed IT system seems to be more susceptible in this frequency range, where it already split into individual devices.

5 CONCLUSIONS

In general, many CI buildings will be made of concrete with reinforcement and one expects a certain RF attenuation. Apertures like windows and doors degrade this attenuation, depending on the materials in use. RF experiments with a simplified building showed the degradation of the expected attenuation by apertures fitted with cost-effective materials.

Once the RF is inside a building, the rooms act as resonating cavities with RF field superposition leading to a stationary 3D-pattern of different field strengths. The RF field distribution with areas of higher and lower field strengths depends on the RF frequency and the dimensions of the room as well as on the interior (in particular metallic parts).

The placement of distributed IT systems within the rooms spatially related to the aforementioned RF field distribution influences the amount of RF energy coupled into the IT system. Experiments with a simplified test loop made of IT components showed a frequency limit where the distributed IT system initially considered as a single influenced unit transforms into a set of independent IT devices, influenced individually by the RF. Below frequencies of approximately 1 GHz, wiring loops formed by mains and LAN cables allow RF to couple into the wiring, which can disturb the functionality of the IT. At higher frequencies, the impact on IT devices is independent of the wiring mesh due to direct coupling into housings. The individual IT devices are roughly of the size of the higher field strength areas in case of cavity resonances above 1 GHz.

Summarizing, the individual frequency depending HPEM susceptibility of the involved IT devices completes the total picture of IT vulnerability. The complex two-stage transfer function couples RF energy from outside the building into a room and then into the distributed IT system. In case the amount of RF energy inside the IT system exceeds the susceptibility threshold levels system failures will occur.

Some protective measures recommendations for operators of CI can be derived from the experiments. Besides keeping distance to CI buildings realized with fences as part of a basic counter-IEMI practice, windows frames, doors, ventilation and similar openings in the walls and roof should be made of metal. Window glass should be selected with RF rejection capabilities. The layout of distributed IT systems should be planned before realization. The goal is to avoid cable loops, especially in the overlay of mains and LAN meshes. This will lead to device cable bundling and device clusters as well as a star-shaped routing. The work [10] gives additional hints for cable managing in trays, earthling and bonding. Finally, the CI IT devices themselves should be hardened against RF, in addition to the general EMC performance.

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