Protection Strategy against IEMI for Wireless Communication Infrastructures

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Abstract—In this paper, we present a methodology for estimating the protection levels of critical equipment against IEMI. We apply the method to a wireless communication infrastructure, but it can be applied to any critical infrastructure. The required protection levels that need to be implemented are determined by analyzing the susceptibility of the victim, and the threat level associated with a specific IEMI scenario. Based on the required protection levels, possible protection strategies are identified and the associated costs are evaluated. The total cost includes the monetary cost and the costs related to loss of performance. The method we present can be used for a quantitative comparison between different protection techniques in terms of monetary cost. The method is applied to develop a strategy for protecting a wireless receiver from damage due to in-band interference using an RF limiter. We also analyze the loss in performance due to the installation of a limiter. It is shown that the noise figure degradation is linearly dependent on the insertion loss of the limiter.

I. INTRODUCTION

The use of wireless communications has seen a steep increase over the recent decades. Large, distributed infrastructures provide wireless coverage over most parts of the world. The most widely used wireless infrastructure is the cellular radio network. This system finds its applications in many standards for radio communication, such as Terrestrial Trunked Radio (TETRA), Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), and Long Term Evolution (LTE). A variety of mission-critical communication applications, for example the public safety communications, are based upon the TETRA standard and, as such, it is considered to be a critical infrastructure.

A possible threat against critical infrastructures is intentional electromagnetic interference (IEMI) [1]. In [2], the wireless communication infrastructure was analyzed to find the most critical subsystems in case of an electromagnetic attack. The wireless link and the wireless receivers were recognized as the most vulnerable subsystems. The base station transceiver is particularly critical, since its failure can bring down a complete cell. Besides that, a base station is often an easy target since it is usually located at a fixed position on a tall mast, which provides a line-of-sight link to the attacker [3]. It is difficult to protect the receivers and the wireless link against IEMI for various reasons. First of all, due to the open access nature of

the shared medium, the wireless link can be easily jammed by interference within the frequency band of operation. Secondly, the electronics of the receiver are difficult to shield against IEMI since the antennas are intended as a point of entry for electromagnetic energy. The coupling of IEMI via the antenna is defined as front door coupling [4].

Several studies have been carried out to investigate the vulnerability of wireless communication systems against IEMI. In [5], the vulnerability of the GSM-R standard (global system for mobile communications (GSM) standard for railway usage) was studied, and in [6], the vulnerability of a TETRA base station was investigated. Both papers focused on the expected threat levels due to IEMI, and on the susceptibility levels of the equipment. In this paper, we extend the work in [5] by providing a systematic analysis to determine the required protection levels. This overall analysis methodology is applicable to any critical infrastructure, i.e., it is not restrained to the wireless communication infrastructure. Based on the required protection levels, we identify applicable protection techniques for wireless communication. Finally, we investigate the associated costs, both monetary and due to loss of performance, associated with the implementation of the protection techniques. The method to assess the monetary costs can be used for a quantitative comparison of different protection techniques that are suitable for protection of the infrastructure. We are mainly interested in presenting a method that can be used to compare different techniques and not in the exact assessment of the costs.

This paper is organized as follows. The expected power at the input of a base station receiver and its susceptibility levels are discussed in Section II. The procedure for estimating the protection levels is presented in Section III. The application of the methodology to the case of a base station is shown in Section IV. The possible protection schemes and their selection based on costs are discussed in Sections V and VI, respectively. Finally, conclusions and perspectives are given in Section VII.

II. VULNERABILITY ANALYSIS OF A BASE STATION RECEIVER

In this section, we analyze the vulnerability of a typical base station receiver against IEMI, based on information available in the literature and on previous research [6]–[9]. We start by analyzing the power transfer from the IEMI source to the susceptible electronics in the receiver. Then, we discuss the selectivity of receivers and interference mechanisms.

A. Transfer Function

Since it is directly connected to the antenna, the front end of the receiver is most susceptible to IEMI. Assuming far field conditions, the received signal power of the antenna equals [10]

$$P_{rx} = \frac{E^2 \lambda^2}{Z_0 4\pi} G(\theta, \phi) (1 - |\Gamma|^2) e_p, \quad (1)$$

where E is the RMS value of the electric field at the antenna, Z_0 is the wave impedance, λ is the wavelength, $G(\theta, \phi)$ is the gain of the antenna as a function of the polar and azimuthal angle, Γ is the antenna reflection coefficient, and e_p is the polarization mismatch.

From (1), we can make two important observations. Firstly, the received power is space-dependent and related to the antenna pattern. The maximum amount of energy is received if the direction of the interferer is along the boresight of the receiving antenna. This is one of the reasons why front door interference can be relatively easily achieved at a large distance. The gain of the receiving system can be used by the adversary to effectively couple IEMI into the system. Secondly, the received power is strongly frequency dependent due to the antenna reflection coefficient. An antenna is often designed such that the coefficient is below -10 dB for the desired frequencies, i.e. in-band frequencies. For out-of-band (OoB) frequencies the reflection coefficient can be higher, resulting in less received power. However, antennas can be very broadband or can have more resonating frequencies with a low reflection coefficient.

After the signal is received by the antenna, it is further processed by the front end of the receiver. The front end is almost always directly located at the antenna so that there is no need for a long cable. This improves the noise performance of the receiver [11]. Typically, the RF signal is first filtered by a front door filter which selects an entire band (the bandwidth typically ranges from a few MHz to 20 MHz). Next, the signal is fed to a low noise amplifier (LNA). Then, the mixer converts the amplified signal to a lower IF frequency where it is easier to implement a sharp analog filter to suppress out-of-channel interference. Finally, the signal can be amplified again and converted to the digital domain for further processing.

B. Selectivity

The selectivity of a receiver can be defined as the ability to correctly detect and decode a desired signal in the presence of unwanted signals close in frequency. The selectivity is achieved by implementing high quality filters that attenuates all other frequencies except those in the desired frequency channel. The channel-selection filtering is typically done at lower IF frequencies, since the required value of Q is then lower. Clearly, all stages in the receiver preceding the channel selection filter should be sufficiently linear, to avoid non-linear effects, such as compression and intermodulation, resulting from unwanted spectral components.

C. Interference Mechanisms

In [6], it is showed that there are three interference mechanisms: damage, saturation, and jamming.

1) *Damage*: Firstly, high-power interference can damage the LNA [5], leading to a permanent DoS. The typical destruction level of LNAs [7] is 34 dBm, in the case of a narrowband interference with a pulse width exceeding 1 μ s. OoB interference can be attenuated by a front filter and the damage can be avoided. However, in-band interference cannot be filtered out.

2) *Saturation*: Secondly, a high-power interferer (below damage levels) can saturate the receiver and as a result desensitize the receiver for the desired signal [8]. A highly selective receiver is not more robust against this interference mechanism: the degradation happens at the RF stage while the selectivity is at the IF stages. A high dynamic range of a receiver does improve the robustness against saturation. In [6], a particular base station was tested for saturation levels and it showed saturation starting from an input power at -4 dBm.

3) *Jamming*: Finally, a low-power interferer, i.e. with comparable power levels as the desired signal, can mask the desired signal [9] and cause temporary denial-of-service (DoS) in the wireless communication system. If the signal-to-noise ratio is too low, the receiver will not be able to detect and decode the signal. The effectiveness of a jamming attack depends on the jamming-to-signal ratio [12]. A highly selective receiver is more robust against jamming. For an in-channel interference, protection strategies lie in spread spectrum techniques, smart antennas, and error coding schemes.

To better understand these three mechanisms, one should analyze the frequency content of the radiated IEMI. A front door coupled IEMI can be defined as in-band if the frequency is within the pass band of the front end filter or of the antenna. Otherwise, it is an OoB interference. For example, the front end filter of a TETRA base station often has a bandwidth of 5 MHz, but the bandwidth of a TETRA communication channel is only 25 kHz. This means that in-band interference can be both in-channel or out-of-channel. In Fig 1, the various frequency domains of IEMI are graphically presented. The effect of out-of-channel interference on the performance of a receiver depends on its selectivity. A wideband interference can inject its energy over the whole channel. In case of wideband interference, the total power at the input of the LNA can be approximated by integrating the power density of the interference over the bandwidth of the front end filter.

III. PROCEDURE FOR ESTIMATING THE REQUIRED PROTECTION LEVELS

In this section, we set up a general procedure to assess the required protection levels for a critical infrastructure.

First, one has to collect relevant information regarding the infrastructure:

- 1) The typical configurations of the topological and interaction sequences diagrams of the infrastructures under study;
- 2) The typical attenuation levels imposed by the different EM barriers that will be encountered by a travelling wave while it propagates towards the infrastructure;
- 3) An estimation of the radiated and conducted susceptibility levels of the critical equipment according to what has been reported in the literature and standards.

Fig. 1. Graphical representation of the various frequency domains for IEMI with respect to the system transfer (from antenna to LNA). Adopted from [6].

In the previous section, we already provided part of this information concerning a wireless infrastructure. Then, one has to implement the following steps:

- (i) Create a possible scenario by choosing an IEMI source and the configuration of the EM topology; starting from the source up to the critical equipment (victim).
- (ii) Obtain the far voltage, that is, the product of the peak electric field measured in the far field and the range, of the IEMI source and its fundamental frequency.
- (iii) Obtain the typical transfer functions of the EM barriers found in the topological diagram.
- (iv) Obtain the susceptibility threshold of the equipment.
- (v) Calculate the total transfer function by adding the transfer functions of all the successive EM barriers.
- (vi) Estimate the total received voltage/field at the equipment level.
- (vii) Calculate the difference between the received voltage/field and the susceptibility threshold; and add the required extra protection in order to ensure compatibility.

In the first step of this procedure, the scenario is selected based upon a possible threat (realistic IEMI source) and a realistic source location. A list of potential IEMI sources can be found in [13], where the sources are assessed and characterized based on both technical and non-technical attributes. Non-technical attributes such as availability and portability help provide an estimate of the actual risk of the analyzed scenario. Given the source characteristics and its location, the procedure will result in an estimated total received voltage/field at the equipment level. If this exceeds the susceptibility threshold, the protection needed is calculated using the difference between the received signal strength and the susceptibility level. We suggest to add a 10 dB safety margin to ensure compatibility. The whole procedure can be iterated for different scenarios.

IV. REQUIRED PROTECTION LEVELS FOR TYPICAL BASE STATION

In this section, we calculate the required protection levels for a typical TETRA base station using the previously described procedure. The goal is to protect the wireless receiver against damage. The critical component is the LNA in the front end. We assume that its damage level is 34 dBm (in this case we use a threshold in terms of power rather than voltage). This is, clearly, an estimate. The LNA damage level can vary for different types of LNA.

Fig. 2. EM topological diagram of the front-door illumination of the base station receiver.

Fig. 3. Typical structure of the front end at a TETRA base station.

A. Topological Decomposition of the IEMI Scenario

The topological diagram of the proposed scenario is presented in Fig. 2 and is inspired by typical setup of a TETRA base station. A dipole antenna located on a tall mast is being used to receive the wireless communication signals. We assume it is at a height H of 10 meters above ground. The antenna is directly connected to a front end, whose typical structure is shown in Fig. 3. This structure can vary depending on the manufacturer. The base station, where the actual digital processing is done, is at ground level. The front end and the base station are connected via an RG214 cable. Finally, we assume the TETRA base station operates in the 380 to 385 MHz frequency band.

B. IEMI Source Description

To choose the sources for this case, we have considered transportable devices that could be brought close to the station by a person or by a vehicle. We specify the generated field strengths by the far voltage, which is defined as the product of the peak electric field measured in the far field and the range (distance). In this analysis we study the effect of two different sources assumed to be at a distance r of 20 meters (see Fig. 2). This implies that the separation between the source and the mast S is 17.3 m. The first source is a standard T DIEHL HPEM case [14]. It is a mesoband source and it can be tuned to operate at a frequency of 395 MHz providing a far voltage of 225 kV. The frequency was purposely chosen as an OoB frequency. The second source is the EPFL switching oscillator connected to a monopole antenna [15]. It is a mesoband

TABLE I. PARAMETERS OF THE CONSIDERED SOURCES

Source ID	Source type	Description	f (MHz)	Far voltage (kV)
Source 1	Mesoband	A standard T Diehl HPEM case.	395	225
Source 2	Mesoband	Switching oscillator + Monopole antenna	385	6.6

source that is tuned at the frequency of 385 MHz, in-band, and generates a far voltage of 6.6 kV. A summary of the parameters of the considered sources is presented in Table I.

C. Obtaining the Required Protection Level

At a distance of 20 m, the incident field strength of Source 1 and Source 2 will be respectively 11.25 kV/m and 0.33 kV/m. The received power is calculated using (1). As a receiving antenna we use a half-wave dipole antenna which is commonly used by TETRA networks [16]. It has an 8 % bandwidth from 380 MHz up to 410 MHz with a reflection coefficient Γ of 0.316 (-10 dB). The gain of an omnidirectional dipole antenna is only dependent on the angle θ , see Fig. 2, and is given by [10]:

$$G(\theta) = 1.64 \left[\frac{\cos\left(\frac{\pi}{2} \cos\theta\right)}{\sin(\theta)} \right]^2 \quad (2)$$

The maximal gain is at $\theta = 0$ and is 1.64 (2.15 dBi). Furthermore, we set Z_0 at 377 Ω and we assume the polarization mismatch e_p between the transmitter and the receiver to be 0.75.

The received power is attenuated by the BPF before the LNA. A typical filter characteristic of the band pass filter [6] is presented in Fig. 4. It shows an OoB attenuation of over 80 dB, and an in-band insertion loss of 1 dB. This means that Source 1 is attenuated by 80 dB and Source 2 only experiences a 1 dB insertion loss. As a result, the approximate input power at the LNA due to Source 1 and Source 2 is, respectively, -9 dBm and 39 dBm. The front end filter is successful in attenuating the OoB interference from Source 1 below the damage levels. However, the in-band interference of Source 2 exceeds the threshold by 5 dB. The results are summarized in Table II. It is important to understand that we purposely chose Source 1 to be OoB. If it was in-band, the received power would exceed the damage level of the LNA by 35 dB, so we can conclude that the front end filter is very effective in mitigating the impact of OoB interference.

V. IDENTIFICATION OF PROTECTION TECHNOLOGIES

There are few methods available for the protection of front-door coupling since the additional measures taken to attenuate the incoming interferences will also contribute to degrading the operation of the system in normal conditions. Therefore, the chosen methods need to provide a very low insertion loss.

A. Fencing

A possible way to diminish the amplitude of the incoming disturbance is to restrict the minimum distance to which a source could approach the communication tower. The minimum distance can be restricted with the use of a protection fence at a given radius from the tower, so as to increase the

Fig. 4. S-parameters of a BPF as a function of frequency. Adopted from [6].

TABLE II. REQUIRED PROTECTION LEVELS.

Source ID	Incident field strength E (kV/m)	Filter attenuation (dB)	Power at the LNA (dBm)	Required Protection (dB)
Source 1	11.25	80	-9	N/A
Source 2	0.33	1	39	5

separation distance S . The additional attenuation compared to $r=20$ m as a function of the radius can be estimated with the following formula:

$$Att = 20 \log_{10} \left(\frac{\sqrt{S^2 + H^2}}{20} \right) \quad (3)$$

where S is the separation and H the height of the base station as indicated in Fig. 2. The additional attenuation by installing a fence at a S of 35 m is 5.2 dB. However, if we would like to add a 10 dB safety margin, the fence would have to be at a distance of 112 m. In the previous derivation, we even neglected the fact that with increasing S , the IEMI gets closer to the boresight of receiving dipole, i.e. the gain of the dipole antenna increases (see (2)). If this is taken into account, the distance of the fence should be further increased. However, base station towers are often situated at populated areas and therefore it is not easy to put a fence with a large radius around a base station. This all shows that a fence is not a practical solution to protect the base station and is not further taken into account as a protection strategy.

B. RF Limiter

Perhaps the only effective (commercially available) measure against front-door attacks of LNAs is the use of RF limiters based on PIN diodes. Several vendors provide discrete pin diodes that can be used to limit the incoming power to an LNA. Typical limitation levels are about 20 dBm for input powers between 1W-1000W. The insertion loss of these devices can be typically between 0 to 3.5 dB which is a very good rating for the front-door protection.

For the application, the required pin diodes usually work in the band between 50 MHz and 4 GHz. Since the considered sources are pulsed sources, the CW power that the pin diodes should tolerate is low. Notice that the installation of an RF limiter will provide protection to the LNA from damage but will impede the operation of the system during an attack since communication is not possible if the limiter is active.

TABLE III. ELEMENTS PARTICIPATING IN THE COST OF IMPLEMENTING A PROTECTION METHOD.

Cost	Description
C_{INIT}	Initial cost
P	Price if protection elements are available for purchase (price per element times the number of protection elements).
H_{HW}	Hours of HW design (≥ 0).
PPH_{HW}	Price-per-hour of HW design.
H_{SW}	Hours of SW design (≥ 0).
PPH_{SW}	Price-per-hour of SW design.
C_{PU}	Cost of material per unit. One unit can be a surface unit, length unit, an element, etc.
U	Number of units (≥ 0).
H_{IN}	Hours of installation.
PPH_{IN}	Price-per-hour of installation.
C_{YOP}	Yearly operational cost (handling, power consumption, etc.).
C_{YM}	Yearly maintenance cost.
$H_{HW,YM}$	Hours of HW maintenance (≥ 0).
$PPH_{HW,M}$	Price-per-hour of HW maintenance.
$H_{SW,YM}$	Hours of SW maintenance (≥ 0).
$PPH_{SW,M}$	Price-per-hour of SW maintenance.
C_{YT}	Cost per yearly testing.

VI. EVALUATION OF THE PROTECTION TECHNOLOGY

A. Monetary Cost

To assess the monetary cost of implementing a protection scheme, we divide the total life-cycle expenditures into three main categories: initial cost, yearly operational cost, and yearly maintenance cost. The initial cost greatly depends on whether the required equipment and components are available for purchase or if they will need to be designed and manufactured. It also depends on the effort required for the installation of the protection scheme. A yearly operational cost exists if a protection scheme requires the presence of an operator to run it, or if it necessitates an energy supply or any other resources needed for its uninterrupted operation. A yearly maintenance cost is determined by the hardware and/or software maintenance costs, and the cost of yearly checks, if applicable. We propose here the following formulas for calculating the mentioned categories of the protection cost:

$$C_{INIT} = P + \{H_{HW} \cdot PPH_{HW} + H_{SW} \cdot PPH_{SW} + C_{PU} \cdot U\} + H_{IN} \cdot PPH_{IN} \quad (4)$$

$$C_{YM} = H_{HW,YM} \cdot PPH_{HW} + H_{SW,YM} \cdot PPH_{SW} + C_{YT} \quad (5)$$

The cumulative cost after N_Y years of use is given by:

$$C = C_{INIT} + (C_{YOP} + C_{YM}) \cdot N_Y \quad (6)$$

The variables in Eq. (4) to (6) are defined in Table III.

The costs of installing an RF limiter equals the initial costs, as there are no yearly operational or yearly maintenance costs. The hourly rates to be used in (4) depend not only on the type of work but also on the particular country where the work is carried out. For simplicity, and since it is not our goal here to calculate the required budget exactly, we will assume the following rates in Euros: $PPH_{HW} = 100$ and $PPH_{IN} = 50$. An approximate estimate of the costs of installing a limiter is presented in Table IV. The costs presented in Table IV are an educated guess based on experience and discussions with

TABLE IV. ESTIMATION OF THE COSTS OF IMPLEMENTING RF LIMITER PROTECTION SCHEME.

Description	P (€)	H_{HW}	C_{PU} (€)	U	H_{IN}	C_{INIT} (€)
RF limiter max. CW power 1000W	2000	20	500	1	20	5500
RF limiter max. CW power 100W	200	20	500	1	20	3700
RF limiter max. CW power 10W	100	20	500	1	20	3600

Fig. 5. Receiver configuration

TABLE V. TYPICAL VALUES FOR THE GAIN AND THE NOISE FIGURE OF RECEIVER COMPONENTS.

Component	Noise Figure (dB)	Gain (dB)
1. Filter	1	-1
2. Limiter	1	-1
3. LNA	2	20
4. Cable	4	-4

experts in this field. The price of adding an RF limiter to a base station is primarily influenced by the costs of material and personnel. However, these costs are fixed, whereas the price of the RF limiter itself depends on the power it should withstand: the higher the power, the higher the price.

B. Loss in Performance

Another cost of using an RF limiter as a protection scheme is the loss in performance. Let us investigate the receiver noise factor F (or noise figure when expressed in decibels) in the presence of an RF limiter. Fig. 5 shows a typical receiver configuration. The noise factor F equals

$$F = \frac{SNR_{in}}{SNR_{out}} \quad (7)$$

where SNR_{in} and SNR_{out} are the input and output signal-to-noise ratios (SNRs) of the receiver, respectively. The total noise factor, F_{total} , depends on the noise factor of individual components and on their respective gains, and can be estimated using the Friis' formula:

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} \quad (8)$$

Typical values of the gain and the noise factor are given in Table V. For the passive components, such as the filter, the limiter, and the cable, it is known that the noise factor equals the insertion loss of the component itself [11]. Without the limiter, F_{total} is 3 dB. Installing a limiter with an insertion loss L of 1 dB will degrade F_{total} by 1 dB. This results in 1 dB loss of sensitivity. From (8), we can see that F_{total} depends linearly on the noise factor of the limiter, as $F_2 = L_2$ and $G_2 = 1/L_2$. Fig. 6 shows F_{total} as a function of the limiter

Fig. 6. F_{total} as a function of limiter insertion loss.

insertion loss L_2 . We varied the insertion loss L_2 from 0.5 dB to 3.5 dB in steps of 0.1 dB. As expected, every additional dB of insertion loss affects F_{total} . This is one of the main reasons why limiters are not often present in a receivers.

VII. CONCLUSION

In this paper, we analyzed the susceptibility of a wireless infrastructure and presented a methodology to estimate the required protection levels. The focus in this paper was mainly on a communication infrastructure based on TETRA, but it can be applied to any critical infrastructure. We showed that available sources at a distance of 20 m can easily generate an input power at the LNA that exceeds the susceptibility level of the LNA. The best protection against OoB interference is a front end filter, which significantly reduces the vulnerability. However, wireless receivers showed to be highly vulnerable against in-band interference.

A possible protection technique is the installation of an RF limiter in the front end of the receiver. The possibility of restricting the minimum distance to which a source could approach the communication tower showed not to be effective. IEMI can effectively be coupled into the antenna at a large distance.

We presented a method to estimate the costs of a protection technique. We applied this method on the installation of an RF limiter in a wireless receiver. It showed that the price of adding an RF limiter to a base station is primarily influenced by the costs of material and personnel. The costs presented here are intended only to illustrate the methodology. The actual costs for any particular implementation will depend greatly on the detailed specification, quantities to be installed and whether the protection is installed as the infrastructure is built, or fitted to an existing installation.

Finally, we showed that the loss in performance of a wireless receiver can be expressed using the noise factor. It is essential to keep the insertion loss of the limiter as low as possible to mitigate the loss in performance of the wireless receiver.

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