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Effects of intentional RF interference on Optical Wireless Communication Systems

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Abstract— Optical Wireless Communication (OWC) has been always regarded as a technology guaranteeing a strong immunity to Radio Frequency electromagnetic interference. However, as a matter of fact, no accurate studies have been realized in low cost practical implementations of this technology. For the establishment of the OWC in real scenarios it is paramount to have an electromagnetic characterization of the environment, considering the effects of Radio Frequency interference on system performance. A proper analysis of interference prevents Electromagnetic Compatibility issues between a Visible Light Communication system (VLC) and the other components of the architecture and, overall, underline critical frequencies that could be potentially exploited by electromagnetic attacks. Based on these premises, an extended analysis of the effects caused by electromagnetic radiations on a typical VLC Tx-Rx pair has been realized in this work. In particular, two optical prototypes have been developed and tested in a controlled environment. Plane waves, generated at different power levels and in a wide frequency range, represent the intentional interference sources. The effects on data communication, considering Pulse Position Modulated (PPM) as useful optical signal, have been measured and shown. Effects on time domain and Bit Error Rate (BER) have been reported. In order to reduce the effects of the disturbing EM fields on the VLC system, we have integrated an electromagnetic shield and we have evaluated its impact through extensive measurements.

Keywords— Electromagnetic Interference, Visible Light Communication, Electromagnetic Compatibility, Environmental Tests, Denial of Service

I. INTRODUCTION

The reuse of existing infrastructures for adopting novel communication paradigms, allowing better performance and low environmental impact, is a hot theme in current research on wireless networks. Interest in Optical Wireless Communication (OWC), and in particular in Visible Light Communication (VLC), is more and more increasing. The relative low cost integration with existing lighting infrastructure in buildings [1], vehicle lights and, potentially, with each other entity providing illumination, makes VLC paradigm particularly attractive [2]. In big indoor areas, like hospitals or malls, VLC can represent an interesting way to smartly reuse the huge amount of power provided by illuminating sources. However, several issues have still prevented a massive development of VLC architectures, as the huge optical interference, mainly caused by sunlight. Anyway, several efforts have been made by the community in order to find novel strategies and proposing effective so-

lutions, to quantify and mitigate this problem. In [3], various parameters of the communication model have been investigated in order to understand their influence on the performance in terms of Signal to Interference Noise Ratio (SINR) of a generic VLC system. Different approaches for analyzing the noise and trying to reduce it are based on signal processing techniques. An anti-noise modem based on the improved M-ary position phase shift keying (MPPSK) for visible light communication (VLC) systems has been developed in [4], while a noise listening technique has been proposed in [5], for a partial cancellation of background noise. A noise measurement and mitigation scheme to reduce the noise influence on a Visible Light Positioning system, by introducing Allan Variance has been used in [6]. A similar technique, based on real time power spectral density measurements, has been provided in [7] and a Fingerprinting-Based Positioning Error Technique has been developed in [8]. In [9] environmental conditions, in terms of SINR, drive in real time the modulation through a dedicated feedback channel. An adaptive technique, based on color switching, has been proposed in [10], while a novel context aware modulation scheme has been implemented and tested in [11]. In [12], channel impairments in optical wireless networks have been estimated and mitigated through neural network and K-means algorithm. An Artificial Intelligence (AI) approach, based on multi-arm bandit formulation, for obtaining a low impact in both BER and goodput of the communication by properly modifying preamble length of the synchronization message, has been proposed and experimentally validated in [13]. However, most of relevant works in current literature focusing on optical noise mitigation in VLC, mainly analyze internal effects of the devices, artificial and natural light sources. Very few papers focus on the electrical interaction between VLC driving circuits and external non optical sources. However, this aspect is essential for an effective deployment of this technology in real scenarios, like Vehicular Communication. External RF sources, as well as intentional RF interference, could significantly prevent the functionality of the system. A proper analysis of interference prevents Electromagnetic Compatibility issues between VLC system and the other components of the architecture and, overall, underline critical frequencies that could be potentially exploited by electromagnetic attackers (Jamming, Side channel

etc.). Authors in [14] and [15] address the extra power losses due to the data modulation if a traditional buck converter LED driver is adapted for VLC. In [16] authors consider the effect of external interference on the receiver filter, quantifying, in terms of Bit Error Rate (BER), the effect of ripple interference on the system and proposing a mitigation technique based on the introduction of a proper filtering stage. The effects of radiated emission by other devices on VLC circuits have been almost neglected by current literature. However, this aspect will be absolutely crucial in the integration of VLC paradigm in real applications, where the coexistence of different technologies in the same environment could potentially cause a malfunctioning of optical transmitters, receivers and their drivers. As far as we know, the only analysis properly quantifying the effects of electromagnetic interference on Visible Light Communication front-end, has been provided in [17]. A VLC prototype with a Software Defined approach has been developed in this work in order to evaluate the interference immunity of the communication system, different index of Pulse Position Modulation Technique have been developed and tested, by spanning on different frequency values and different power levels. In our work, we quantify in a rigorous way the effects of radiated electromagnetic interference on a common VLC architecture, in order prevent the possibility of intentional denial of service (DoS) and guaranteeing an adequate compatibility with other devices. In particular:

- We developed and tested a common circuit architecture for both transmitter and receiver, avoiding any additional processing block or particular filtering and conditioning stage, in order to have easily repeatable results.
- We tested a wider range of disturbing electric field amplitudes, with respect to [17]. This aspect is particularly important in most of practical applications and real use cases. Many electromagnetic compatibility standards, indeed, impose an interference immunity threshold, in terms of radiated electric field intensity, higher than 50V/m.
- We developed and built proper metallic shields around the transmitter and the receiver, in order to mitigate interference effects. We repeated all the measurement campaign, testing the shield prototypes and we compared experimental results, in order to validate the effectiveness of the approach.

The paper is organized as follows. In Section II, we provide a detailed description of the communication context and the main motivations of our work. In Section III, a detailed description of optical prototypes and related driving circuits is provided, as well as a description of the architecture developed for measurement campaign. In Section IV, we further describe the experimental setup, the main system parameters and we discuss the experimental results in terms of Bit Error Rate (BER) by considering different power levels. Therefore, a description of the shielding structure and its effect on system performance have been provided. Conclusions have been provided in Section V.

II. MOTIVATIONS AND CONTEXT

The enormous spread of various wireless communication technologies in the recent few years, has led to an ubiquitous communication certainly, but also to create a complex radiated Electromagnetic (EM) environment. An accurate characterization of such a complex environment is necessary, to ensure the operability of the wireless devices and networks. Such a kind of study has been led for the $2.4GHz$ frequency band, where the emission level and the susceptibility level have been analyzed [18]. In particular, different environments spanning from commercial environment, airport environment, coffee bar environment have been considered and analyzed for considering all the devices operating at this frequency. This environmental analysis revealed some important information on interfering devices, also used for different applications (e.g., microwave ovens). In [19], authors demonstrated the importance of the electromagnetic characterization of industrial environments, to improve the comprehension of the performance limits of the wireless applications in the factories. In particular, they noticed the importance to develop a method to evaluate the effect of electromagnetic interference in factory automation. Previous analysis were performed by members of the National Institute of Standards and Technology (NIST) to characterize the wireless environment in automotive manufacturing facilities [20]. The authors of this report noticed how the improvement of the implementation of wireless networks and control at automotive manufacturing facilities is strictly related to the evaluation of the propagation environment by carrying out precise measurements at appropriate frequencies. The results of these studies have permitted to advance in the understanding of key factors that can complicate the reliable performance of wireless communication systems. The main objectives of this work are exactly in the same direction. We aim to provide a detailed analysis of the RF propagation environment of a VLC system, by focusing on the interference aspects. In this work, we aim to deal a down-scale analysis of the environment, with VLC devices and test antennas. In practice, one of the first objective is to expand the results obtained in [17]. This analysis aims to move the first steps towards the VLC environmental characterization from an electromagnetic point of view. Similarly as in [18], we aim to establish the operating work conditions. Differently from this previous work on $2.4GHz$, we deal a completely controlled analysis, in a well established and isolated setup, for confirming and characterizing the no complete RF immunity of VLC. The RF interference characterization is particularly important in the context of mobile communication systems, as the vehicular networks, where the communication protocols have to be highly adaptive guaranteeing a reliable communication. In this work, based on the interference analysis, we propose some suitable metallic shield design for reducing the effects of the interference.

III. SYSTEM MODEL

A detailed description of optical prototypes and related driving circuits, system setup and measurement environment

is provided in this section. In order to provide a measurement campaign that can be useful in many real designs, a typical LED driver has been designed and fabricated on a 10x10cm PCB (Fig. 1).

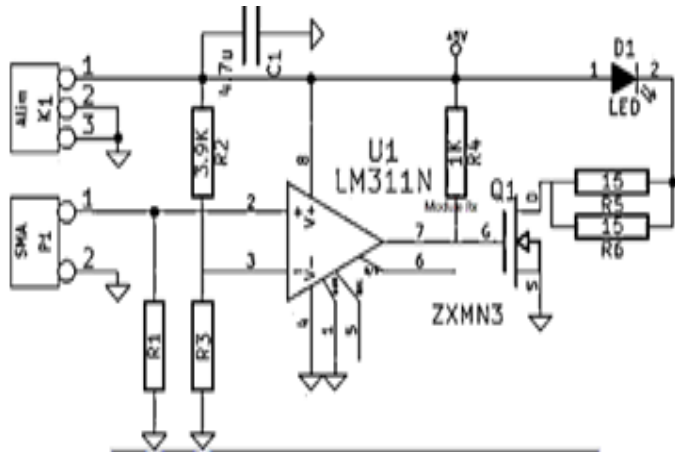


Fig. 1. Visible Light Transmitter: main scheme of Optical and electrical connections

A simple amplifying network has been employed to allow the led to work in the correct voltage range and SMA connectors have been used to connect the driver to the signal processing unit. An optical concentrator has been used for improving the directivity of the light path and the overall circuit is fed with a 5V battery, to avoid additive effects due to the 50Hz power network. The optical receiver is based on a double stage Trans Impedance Amplifier, as shown in Fig. 2. The current signal produced by the photodiode is converted into a voltage signal by the first network and the overall network allows to avoid the saturation of the second amplifier, which guarantees the correct voltage sweep for data elaboration. A further comparative network has been included for cleaning the amplified signal from unwanted ripples. At the same way as in the receiver, signal is transferred to the elaboration unit through a SMA cable and a 5V battery is used for feeding the amplifiers. The components type, as well as the value of resistance and capacitance of passive elements, are provided in Fig. 1 and Fig. 2, in order to make the experiments repeatable. However, a full description of design criteria for LED driver and, overall, for receiving amplifying network, is not provided in this work for lack of space, but is extensively described in [21]. A simplified block diagram of the overall measurement system is shown in Fig. 3. Two NI USRP2920, connected by Gigabit Ethernet cables to the respective PCs, have been used for data signal processing. Low frequencies daughterboards have been employed in both transmitting and receiving path in order to allow the USRP to manage relative low frequency driving signals, up to some MHz. Signal generation, conditioning and further elaboration processes have been carried out using the software Labview.

A Gigahertz Transverse ElectroMagnetic cell (GTEM) has been employed for guaranteeing a controlled environment. A

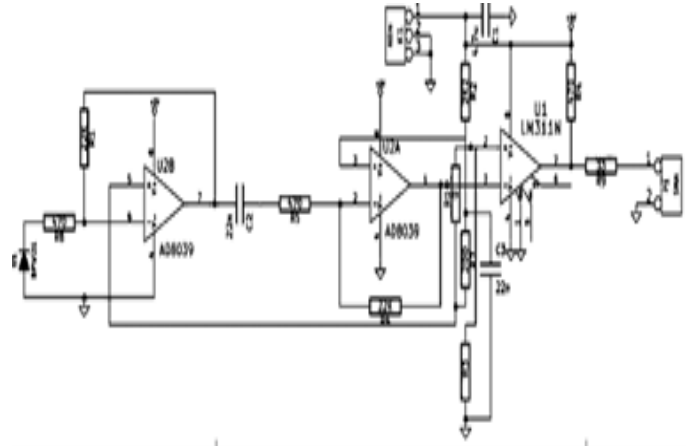


Fig. 2. Visible Light Receiver: main scheme of Optical and electrical connections

HI-6005 Electric field probe, connected to a PC, has been located in the GTEM, and employed for monitoring the correct level of interfering emissions. The probe has been located in the middle of the cell, in order to measure a correct value of Electrical Field, not affected by edges effects. A stripline antenna, integrated in the top side of the GTEM has been connected to an external RF waveform generator in order to produce the interference. In order to avoid unwanted field perturbations due to reflections, the end of stripline has been connected to a 50 Ohm load. To guarantee a disturbing electromagnetic wave following Transverse ElectroMagnetic (TEM) propagation, and avoiding different field distributions at the corners of the cell, the transmitter and receiver are placed along the transverse axis. In this way, tests performed are in

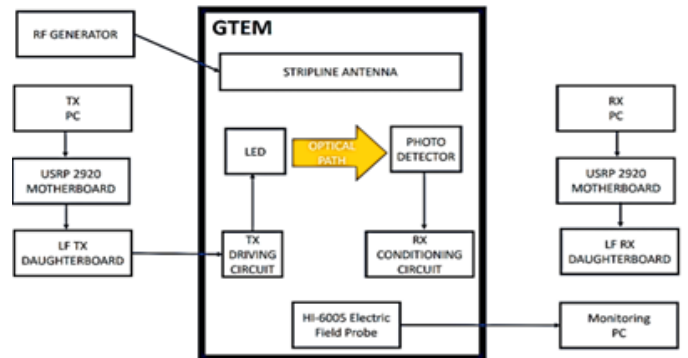


Fig. 3. System Setup

Far-field conditions with a plane wave propagation along the transverse axis of the GTEM.

IV. MEASUREMENTS AND PERFORMANCE DISCUSSION

In this section, we provide quantitative results on the measurements. In particular, we registered received time domain signals and we experimentally verified the effects of interfering signal on Bit Error Rate. Finally, we repeated the

same measurement campaign using a proper EM shield and we compared the results in order to validate the effectiveness of the protection. We use a known sequence, based on the first symbol of a 16PPM modulation, with 500ns pulse duration and 2Msamples/s sampling rate. Transmitted waveform, indeed, can be considered as a train of rectangular pulses, with duty cycle equal to 1/16.

A. Measurement without shielding

A first experimental campaign has been carried out, testing the electromagnetic compatibility of the two VLC prototypes at low frequencies, namely in LF and HF radio spectra. Prototypes have been placed in the test volume in between the septum and the cell floor, 1m away each other, along the z axis of the GTEM camera. A further series of measurements, using the same prototypes and the same test conditions, has been performed using interfering signals in the HF-UHF range. No metallic structures have been employed to shield the prototypes from external electromagnetic interference. A picture of the measurement campaign, including the two prototypes and the Electric Field Probe, is provided in Fig. 4

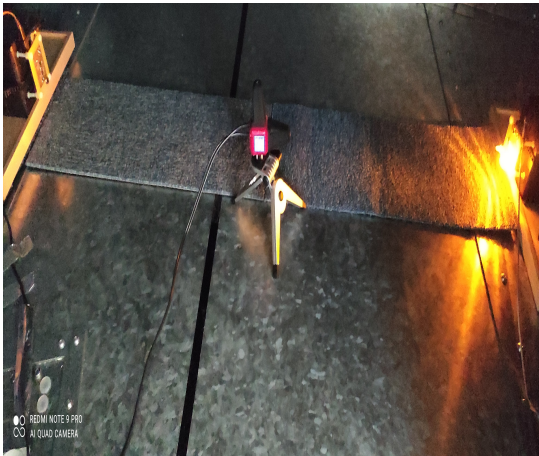


Fig. 4. Receiving and Transmitting Prototypes during the tests

In Fig. 5 are shown received waveforms according to one of the external frequencies affecting in a most significant way the communication, namely at 450kHz. Similar degradation has been obtained at 390 KHz and 650 KHz. The intensity of the electric field associated to the test interfering signal has been varied between 0 and 50 V/m.

For sake of clarity, time domain signals have been plotted just up to the interference intensity of 20V/m, since after these values, original signals start to appear completely indistinguishable from the interference effect. A significant impact on received waveform even at quite low levels of interference ($> 10V/m$). Since navigation signals, AM long-wave broadcasting and amateur radios normally operate in this frequency range, these effects could seriously impact on VLC performance in real scenarios.

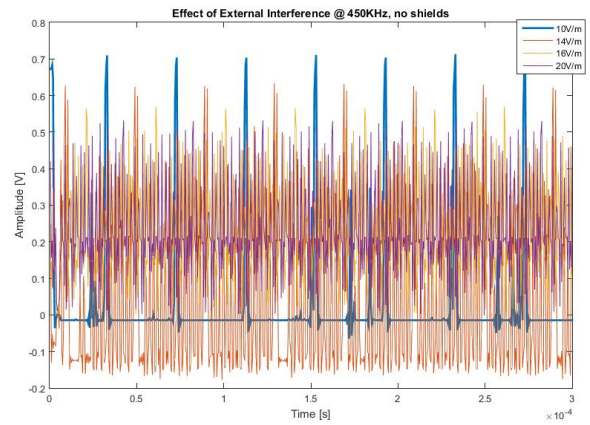


Fig. 5. Effects of 450KHz interference on Visible Light Communication without EM shielding

At higher frequencies, significant effects have been noticed in the frequency range between 525MHz and 532MHz. Corresponding receiving waveforms at 525 MHz are shown in Fig.6.

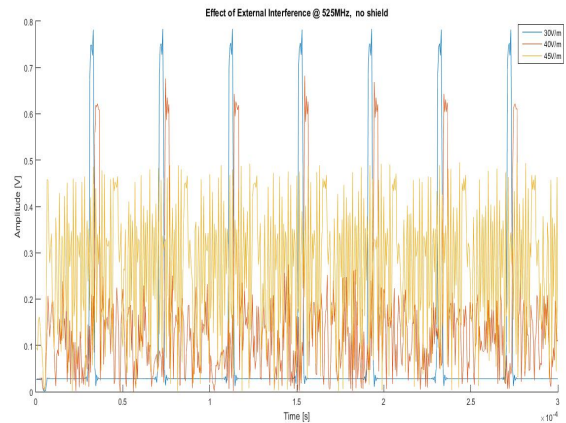


Fig. 6. Effects of 525MHz interference on Visible Light Communication without EM shielding

Differing from the tests performed at low frequencies, in this case received signals are less affected by low intensity fields up to 30V/m. However, starting from this value, received signals significantly suffer EM interference. Since the specifications in terms of EM compatibility, for many scenarios, impose an interference immunity higher than 50V/m or more, also in this case external interference could prevent the employment of a VLC system without considering some techniques for avoiding, or at least mitigating this effect. Several military applications and TV broadcast, indeed, operate in this range and could hugely affect the system. In addition, these frequencies are easy to be reproduced by a potential attacker using low cost equipment.

B. Measurement with metallic shielding

In order to mitigate the effect of electromagnetic interference on VLC prototypes, a metallic box has been placed around the transmitter and the receiver, completely covering the whole driving circuitry, but allowing the correct propagation of optical signals. The size of the aperture and its position towards the photodiode have been properly set in order to guarantee the propagation of the light path. Proper transitions, allowing the connection of SMA cables, and the aperture for the feeding network have been chosen in order to avoid the penetration in the box, and consequently in the driving circuit, of RF signal. This aspect is particularly important at higher frequencies, with a progressive reduction of the wavelength of the interfering signal. A picture of the receiving prototype, shielded by the metallic box, is provided in Fig. 7.

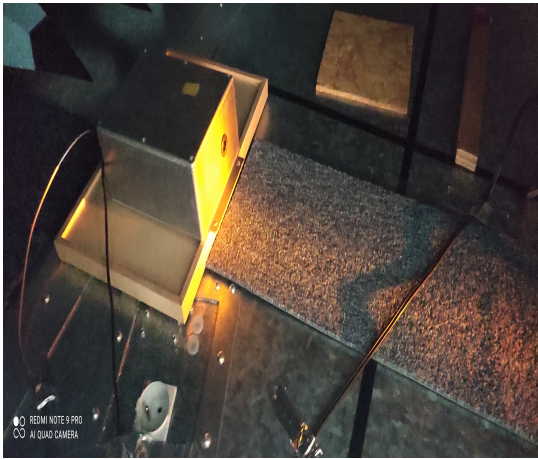


Fig. 7. Shielded receiving prototype

We repeated the same experimental tests, in the same conditions, for all the interfering signals previously mentioned. Results are shown in Fig. 8 - 9.

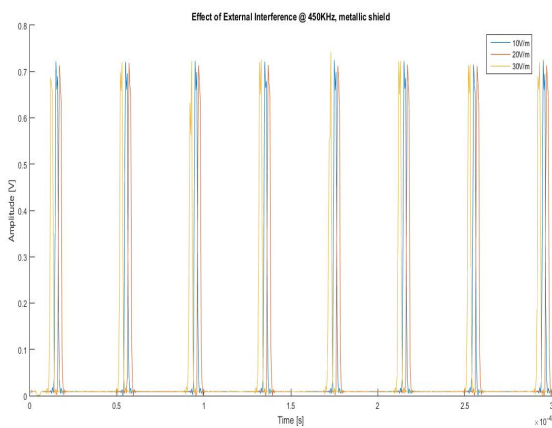


Fig. 8. Effects of 450KHz interference on Visible Light Communication using a metallic shield covering prototypes

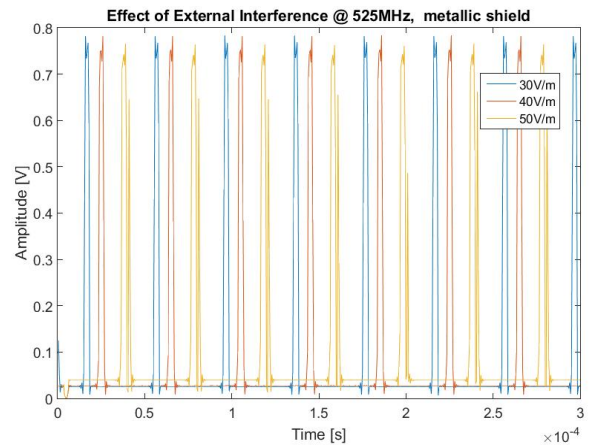


Fig. 9. Effects of 525MHz interference on Visible Light Communication using a metallic shield covering prototypes

Time domain results clearly show how the employment of a proper metallic shield around prototypes significantly improves waveform shape even when the interfering signal reaches high levels of electrical field intensity. However, in order to quantify these effects, a quantitative analysis on system performance has been provided in next section.

C. Effects on System Performance

In order to quantify the impact of external interference on system performance, and the mitigation effect due to the employment of a metallic shield around the prototypes, Bit Error Rate has been quantified, starting from the received waveforms, according to the analytical calculation provided by authors in [17]. Results for low frequencies are shown in Fig. 10.

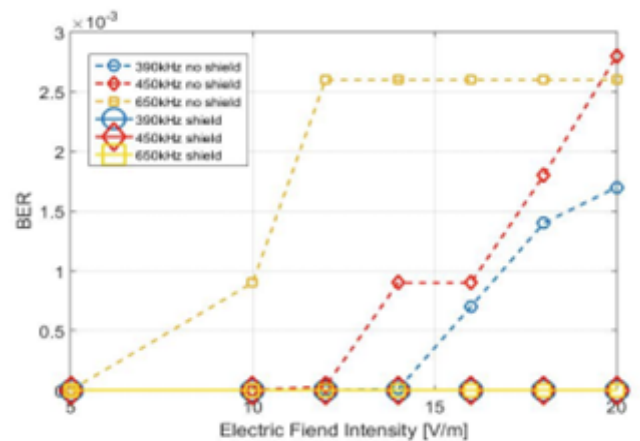


Fig. 10. Effects of EM interference on BER, and mitigation through metallic shield

We notice how the BER in the non shielded version reaches very high levels, even for low level of electrical field intensity, which could represent a problem in many applications. However, a proper shield dramatically decreases BER, which

achieves negligible values even for high levels of interference. All noise or interfering external sources, except interfering test signal, have been avoided performing the test in a controlled environment. Small oscillations in BER, in the case of shielded testbed, are due to thermal and shot noise endemically affecting the VLC system. Anyway, these variations are not statistically relevant in our measurements. Results for high frequencies are shown in Fig. and 11.

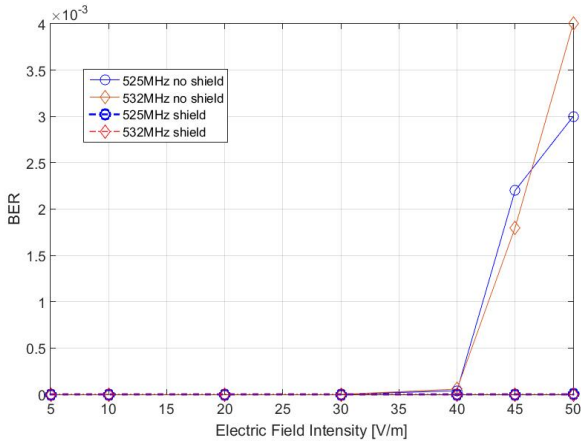


Fig. 11. Effects of EM interference on BER, and mitigation through metallic shield

Also in this case, the metallic protection around the prototypes prevent unwanted effects on system performance and BER levels dramatically decrease. However, it is worth to notice how, in this case, the protection does not completely eliminates the effect of external interference. We notice how for very high level of electric field intensity, BER starts to weakly increase even in the case of shielded prototypes. This effect is frequency dependant and it is probably due to a small quantity of energy penetrating in the hole of the metallic box, which is necessary for allowing the optical path between transmitter and receiver. However, in these measurements, the effect is not so significant to prevent to satisfy most of EM specifications and employment in real scenarios, like vehicular applications.

V. CONCLUSIONS

The interference immunity of a VLC system has been deeply studied in this work. We have considered a wide range of frequencies and amplitudes in terms of interference, approaching real values suggested by EM compatibility guidelines for Vehicular applications. Two prototypes have been designed and fabricated for these tests. Measurements and performance evaluations show how, neglecting EM interference impacts on the system, the communication between optical devices could be easily degraded. Indeed, a heavy loss of data at certain frequencies has been demonstrated. Overall, a malicious source, working at these frequencies, could be injected, causing a severe Denial of Service. A proper metallic structure has been designed and fabricated, in order

to shield the electronic circuits driving the optical transmitter and receiver, without preventing the correct light path. Results show how the employment of the shield allows a significant improvement in terms of BER even at most critical frequencies, paving the way for designing robust VLC systems, also in high dynamic contexts. In a future extension of this work, we will test other TX-RX configuration, according to different components and PCB dimensions. We will further generalise the study to other interfering sources (like chirp signals used in commercial jammers). We will finally repeat the tests in a real scenario, adapting the shield to the use case.

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