Development of an Affordable EMC Immunity Assessment Setup Using Direct Power Injection for Biosignals Instrumentation: Application to ECG Monitoring

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Abstract: The increasing number of connected electronic devices in our daily lives contributes to a more dense electromagnetic environment, increasing the challenge of resilience to electromagnetic interference. This is particularly concerning when the context is healthcare and the devices currently used to assess one's health condition. It is crucial that the development of new devices for biosignals acquisition takes into consideration the electromagnetic compatibility of the device from an early stage of the design. In this paper, a methodology to assess the immunity of a device based on direct power injection is proposed. We describe the setup used and the PCBs designed for the specific case of an ECG acquisition device. The validation of the setup is made with two scenarios previously evaluated in anechoic environment. We show that with the proposed setup we observe the same effects as in anechoic environment.

1 INTRODUCTION

The increasing number of electronic devices available to the masses, and especially those capable of wireless communication, is the source behind many electromagnetic disturbances (Alaeldine et al., 2008).

This trend tends to increase, as the number of connected devices is growing everyday. In fact, recent reports have shown that in the last five years the number of connected Internet of Things (IoT) devices has doubled. This number is expected to keep increasing yearly in the coming years (Sinha, 2023; Sujay Vailshery, 2023).

Many of these devices are wearables, i.e., devices that are designed to be worn embedded in clothing or used as accessories, such as smartwatches or wristbands, capable of acquiring different biosignals and used increasingly in medical applications. Be it in hospitals or at home, the environment in which a medical device is placed is no longer a controlled one, and it is becoming increasingly harsh from an Electromagnetic Interference (EMI) point of view.

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Their use is only expected to increase as we transition to an era of digital medicine. Therefore, it is crucial that good Electromagnetic Compatibility (EMC) design practices are put in place during the development of biomedical devices (Smuck et al., 2021; Lu et al., 2020).

Ensuring resilience to electromagnetic interference when designing a new device is key to make sure the system will be compliant with the standards, and immune to the noise in its intended use environment. In fact, one of the most common causes for Printed Circuit Board (PCB) redesign are EMC related issues.

While it is true that the smaller form factor of today's Integrated Circuits (IC) makes them intrinsically less prone to be disturbed by radiated and induced disturbances, their placement in a PCB can increase susceptibility as the traces leading to the IC can pick up noise and carry it to the pins of the component (Lavarda et al., 2017; Lavarda and Deutschmann, 2015; Jian-fei et al., 2011). Hence, good practices when designing a new PCB are essential to ensure a good performance from the device.

Typically, embedded applications, independently of the domain of application rely heavily on a microcontroller. This is arguably the most important ele-

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ment of the entire system since it makes the device achieve its main purpose. However, the microcontroller in itself is not able to fulfill the device purpose without a series of other modules such as power, communication and, in the specific case of a medical application, a biomedical sensor specifically designed for the physiological signal of interest in that particular equipment.

Traditionally, these systems have been using PCBs to assemble the components and interconnected these modules via traces.It is important to mention that all of the aforementioned elements, from the individual components to the PCB that brings them together, are susceptible to electromagnetic interference which can disturb the system.

Several studies have tried to demonstrate this fact by analyzing the various potential coupling victims using the Direct Power Injection (DPI) method.

Established by the standard IEC62132-4 (IEC, 2006), DPI is one of the most reproducible methods to evaluate a systems susceptibility to electromagnetic interference. It allows to characterize the immunity of a system in the presence of RF disturbances by injecting them capacitively in the circuit (Chang et al., 2013). It is widely adopted as it allows for rapid and easy assessment of a PCB. In fact, as soon as the first prototypes are ready, DPI can be immediately performed in a simple and intuitive way. This is possible as it doesn't require advanced knowledge on EMC (Pues and Pissoort, 2012; Miropolsky and Frei, 2011).

In a study carried out by (Dai et al., 2021), the conducted immunity of a microcontroller was investigated exposing the IC to a continuous-wave electromagnetic interference using DPI. They observed the conditions under which the IC failed and verified with an electron microscope the damage inflicted.

In (Jian-fei et al., 2011), the authors were interested in evaluating the susceptibility of a Low Dropout Voltage regulator (LDO) using direct power injection. They demonstrated via simulation and also experimentally how a Radio Frequency (RF) disturbance injected using DPI generates an offset in the output of the LDO.

In other works, the effects of electromagnetic interference in amplifiers were investigated using DPI to inject a disturbance through the ground plane and output pins of amplifiers in various topologies and configurations, such as the consequences of disturbances on precision voltage references (Lavarda et al., 2017; Deutschmann and Winkler, 2023; Richelli et al., 2020; Richelli et al., 2016; Richelli et al., 2017).

All of the modules mentioned above and previously investigated are key elements for a biomedical system to operate. It is of paramount importance that all these matters are taken into consideration during the design of a new device. While anechoic chambers are not easily accessible to everyone, and in particular to Small and Medium Enterprises (SME)s, DPI testing can be easily and affordable to conduct.

In this paper we present a system developed to evaluate the behavior of a device designed to acquire biosignals when in the presence of a disturbing signal. Our solution provides a simple approach to assess EMI immunity for SMEs and researchers who do not have the means or access to more complex and expensive solutions.

For this we use the DPI method as the noise injection method, and a simulated Electrocardiogram (ECG) as desired signal; in section 2 we present the equipment used for this setup; in section 3 we present two examples of application using this assessment method; and in section 4, we outline the main conclusions and future work prospects.

2 MATERIALS AND METHODS

The purpose of this setup is to input a simulated ECG signal for the Device Under Test (DUT) to acquire while a disturbance is injected in the system capacitively using DPI. To fulfill these requirements, two PCBs were designed: one with the purpose of simulating a differential ECG signal for the DUT to sample and another one to generate the interference to be injected in the system. The entire setup is placed inside a metallic enclosure to provide shielding against external electromagnetic noise. The 3D models of the two PCBs are presented in figures 1 & 2.

2.1 ECG Signal Simulator

To generate the ECG signal, an Analog Discovery 2 arbitrary waveform generator was used. This device featuring two Digital to Analog Converter (DAC) is able to generate common signals, such as sinusoidal waves, but also arbitrary signals with a 14-bit resolution and voltages up to 5 V. We make use of this feature to create the disturbing signal and the ECG signal: we use MATLAB 2023b to create the different signals that we want to test on the setup, and using a toolbox by Digilent we are able to send the signals directly to the signal generator where they are converted into analog single-ended signals.

Naturally, the ECG signal has a very low amplitude (+/- 1 mV) and for that reason, ECG sensors have a very high amplification gain (+/- 60 dB)(Singh et al., 2012). Therefore, we need to create a very low amplitude signal for both the ECG signal and the distur-

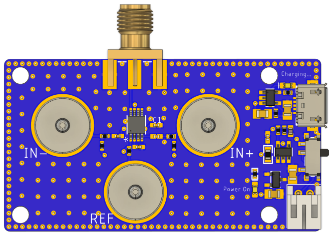

Figure 1: PCB designed to convert a simulated single ended ECG signal into a differential one.

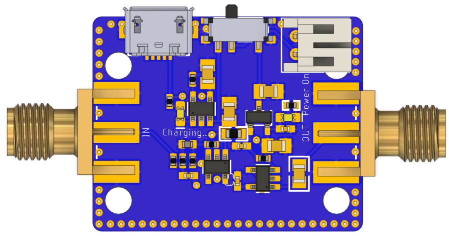

Figure 2: PCB for direct power injection.

bance. When generating low amplitude values with this generator, only the Least Significant Bits of the DAC are used, rendering a very low resolution signal. To overcome this, we use all the DAC's 14 bits to generate a high resolution signal and we decrease the amplitude using a voltage divider with the designed PCB's.

For the ECG signal, besides the need to reduce the amplitude, we also need to convert the single ended signal into a differential one for the sensor to acquire it. The IC used for this purpose is th LTC6363. The two outputs of this module will be centered over a reference voltage provided by the ECG sensor. The PCB presents snap connectors for the DUT to plug in by the means of electrode lead wires.

2.2 Direct Power Injection Board

For this specific application, a PCB was carefully designed with the purpose of delivering the disturbance to the DUT. This PCB, presented in Figure 2, is used to connect the signal generator to the DUT, in particular the ECG sensor. This kind of sensor presents a high gain on its amplification stage as biosignals have a very low amplitude. For that reason, when injecting a noise signal in this port, if the amplitude is too elevated, the amplifier will saturate and no particular conclusions can be deduced from the tests.

This particular setup is intended to be used with different types of disturbances while the effects are evaluated in the time domain by analyzing the influence they have on the ECG signals. To be able to see the effect of a small disturbance on the ECG signal, one needs to reduce the amplitude of the disturbance being generated by the signal generator. We use the same method as for the ECG signal generator, i.e., we make use of the full scale of the DAC to produce a high resolution signal and then decrease its amplitude with an voltage divider.

2.3 Considerations for PCB Design

During the design phase of any PCB in general, and PCBs for electromagnetic compliance assessment in particular, it is important to make sure that they operate with no major disturbances from the surroundings nor from the PCB itself. In the development of these PCBs, however simple they might be, several techniques were used in order to minimize interference.

4-layer PCB. In the earliest stage of the design of the PCB's, the decision was made to use a 4-layer PCB instead of a more common 2 layer one. While the complexity is slightly increased when the number of layers increase, the benefits extracted from it compensate the effort put into the design of the product. Opting for a 4-layer PCB not only provides more flexibility for routing traces but it also, and more importantly, allows for signal integrity optimization with the use of power and ground planes which effectively reduce crosstalk and electromagnetic interference. In the example of our application, layers were organized as follows:

- Layer 1 is where all the components are placed. Small traces connecting pins close to each other are routed directly on this layer. Pins spaced far from each other are routed through Layer 3.
- Layer 2 and Layer 4 are ground planes. Layer 2 creates a stable ground reference for all the elements of the PCB even in the higher frequencies, where a simple ground trace would not be sufficient (Armstrong, 1999). The two ground planes, top and bottom are connected though a dense network of vias. In combination with via fencing, this configuration turns the PCB into a Faraday cage, in which signals that can penetrate the structure are limited by the distance between vias.
- Layer 3 is used to route the traces connecting pins placed away from each other. Additionally this plane serves as a power plane providing power directly to the power pin of any component through a via. This plane is placed in the middle of two ground planes ensuring shielding of both the power connections and traces routed in it.

Via Spacing and Fencing. The downsize in the form factor of components has lead to increasingly

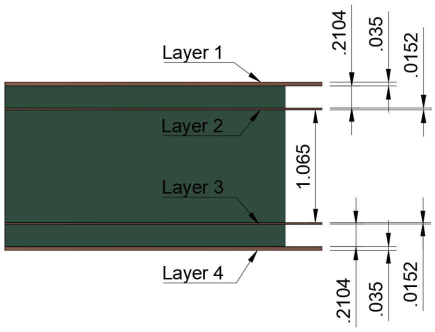

Figure 3: Cross section of the PCB showing the different layers that compose it. All units are in millimeters.

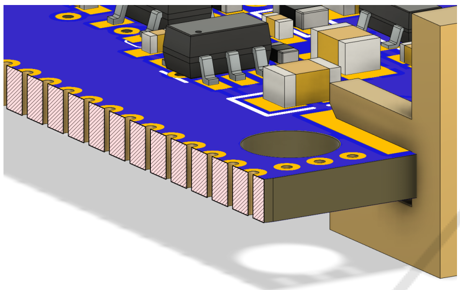

Figure 4: Fencing used around the PCB's to prevent radially propagated electromagnetic emissions.

complex and denser layouts in PCBs, which in turn leads to signal integrity problems such as crosstalk. To ensure a good connection between the top and bottom ground planes, as well as to prevent radially propagated electromagnetic emissions through the PCB's edges, a dense grid of vias is used. Additionally, it is also common practice to use via fencing as a measure of preventing radially propagated energy from the sides of a PCB. In fact, this constitutes one of the main sources of radiated emissions in a PCB. These propagate thanks to pseudo-waveguides formed by ground and/or power planes leading to emissions from the PCB's edge (Lindseth, 2016; Suntives et al.,).

Power Supply Decoupling. The power supply must be as stable as possible. As demonstrated by previous works mentioned in Section 1, voltage references and power/ground connections are susceptible to inducing disturbances on the device components. To be sure that the power lines are as stable as possible, decoupling capacitors are used to stabilize the supply and avoid high frequency noise. Their placement on the PCB is equally important. These must be placed as close as possible to the pins of the power supply of the components.

Coaxial Connections. The disturbance and simulated ECG signals created by the signal generator must arrive at the PCB undisturbed. The best way to do so is by using coaxial cables. Typically the signal generator's output is, by default, a coaxial connection BNC. Therefore, by applying a SMA connector to the PCB side, we can use a coaxial cable to connect the two devices. This is achieved by using a BNC to SMA cable ensuring that the signal produced by the signal generator arrives uncorrupted at the PCB.

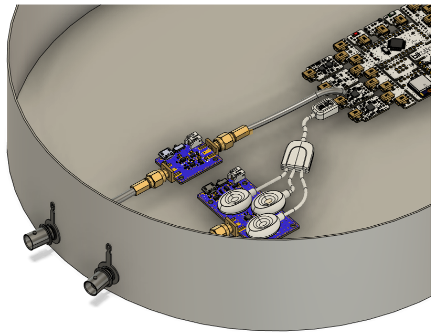

Figure 5: Enclosure used to protect the setup.

3 RESULTS

The validation of the setup was performed with time domain measurements using a BITalino (r)evolution (PLUX Wireless Biosignals, Lisbon, Portugal) as DUT. This device was designed to acquire multiple biomedical signals (in particular, the ECG) and transmit them via Bluetooth to a computer nearby.

A simulated ECG signal is generated with the setup previously presented and then sampled by the DUT. The latter, transmits the signal to a nearby computer where the signal can be visualized and stored for further post processing. The DPI board injects then a signal in one of the pins of the board while the acquisition is ongoing. The effects of the disturbance are evaluated on the signal acquired.

The system itself is quite sensitive to the inherent noise from the mains supply at 50 Hz. Such a signal can be of an order of magnitude big enough to completely mask all the other disturbances and even the ECG signal itself. In an attempt to contain such effects and focus on the disturbance being injected, we placed the setup inside a metallic box. Although the container is not completely sealed, the biggest apertures are small enough to prevent the 50 Hz noise from arriving at the DUT while allowing for Bluetooth communication to be established with the nearby computer.

This enclosure was fitted with BNC feedthroughs so that the signals from the waveform generator could be delivered to the PCBs using fully shielded cables

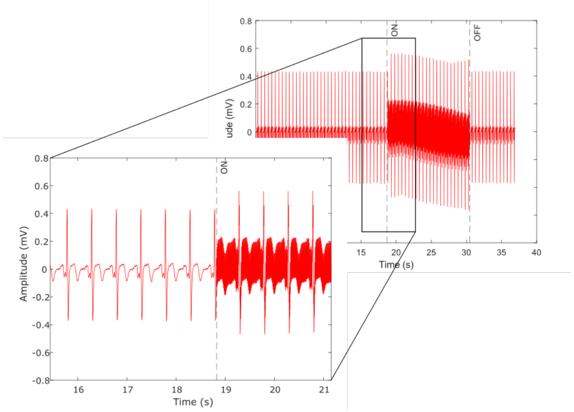

Figure 6: Acquired ECG in the presence of a disturbance modulated at 1.1 kHz.

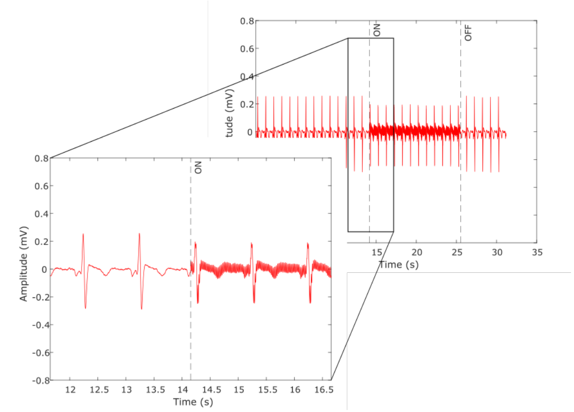

Figure 7: Acquired ECG in the presence of a disturbance modulated at 20 Hz.

thus preventing any interference from coupling to the signals. On the inside, an SMA cable carries the signal from the generator to each PCB as illustrated by Figure 5. Finally, the electrode lead wires connect to the PCB via the snap connectors and the disturbance is injected using an SMA probe.

3.1 Use Cases

Case 1. In standardized test procedures such as IEC61000-4-3, the disturbing signal modulates the carrier signal using a 1 kHz sine wave modulated at 80% depth (CENELEC, 2015). In previous works (Bastian et al., 2023), it has been demonstrated, by changing the modulating frequency with small increments, that when the modulating frequency matches the sampling rate some failure modes are missed.

Here, we attempt to reproduce the same phenomena by injecting a disturbance modulated in amplitude at 80% with a carrier of 1 kHz. This frequency is then incremented by 0.1 kHz and the effects are observed; in Figure 6 we can clearly see the moment in which the signal gets disturbed. At this point, the frequency of the carrier shifts from a multiple of the sampling rate to value slightly different.

Case 2. Another example used to validate the setup consisted in injecting a modulated signal with a low frequency AM modulation, in particular a 1 kHz sine wave modulated at 20 Hz with a 80% depth. The effects of such a signal on the same device for biomedical acquisition have previously been demonstrated in an anechoic chamber with radiated interference (Nunes et al., 2023).

We try to reproduce these effects by injecting a similar signal using DPI. In our setup, while the DUT was acquiring the ECG signal, the DPI board injected the disturbing signal in the input pin of the ECG amplifier. On the computer placed nearby, the signal being acquired was registered and is presented in Figure 7. It is possible to see the moment in which the disturbance is activated; the effects of a disturbance on the ground plane are immediately visible on signal being acquired.

4 CONCLUSIONS

Assessment of electromagnetic compatibility is a crucial step to guarantee a product behaves as expected, and to be able to certify the device before putting it in the market. Typical testing is performed in an anechoic environment, which is not always accessible small and medium enterprises and/or students and researchers. A more affordable method to assess electromagnetic immunity of devices is DPI.

We proposed a solution based on the DPI methodology, in which a device for biomedical acquisition can be tested against conducted immunity. Two PCBs were developed providing a simulated biosignal for the device to acquire and a disturbing signal to interfere with the first.

This approach provides students, researchers and SMEs with an affordable solution to verify and validate devices for biosignals acquisition against electromagnetic interference from an early stage of the design phase as it eliminates the need for expensive and specialized solutions such as anechoic environments.

Our system was validated reproducing tests previously conducted leading to the same conclusions.

In future works, it is foreseeable the addition of frequency analysis as a complement to better understand how the different disturbances affect the DUT while performing an acquisition.

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