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A DPI Test Bench that Relies on Time-Domain RF Measurements

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***Abstract*—The direct power injection method is a well established approach for evaluating the susceptibility of integrated circuits to radio frequency interference. It is widely used in the EMC qualification of ICs because, among the other, it provides the immunity level of each pin belonging to the device under test. This information is useful in module level EMC analysis as well as for the comparison with pin compatible ICs implementing the same functions.**
This work presents a critical assessment of the DPI test method prescribed in IEC 62132-4 and presents a novel approach based on radio frequency measurements carried out in the time domain. The test bench equipped to validate the effectiveness of the proposed test procedure is presented referring to the susceptibility tests carried out on a commercial operational amplifier.

***Index Terms*—Direct Power Injection, Integrated Circuits, Susceptibility, Radio frequency Interference, Immunity measurement.**

I. Introduction

The electromagnetic fields generated by radio transmitters can impair the operation of electronic systems nearby. This usually happens because such electromagnetic fields couple with the system interconnects so that nominal signals are corrupted by radio frequency disturbances. Depending on the level of such interference the signal processing carried out by the integrated circuits the electronic system is made of can fail [1]. Furthermore, radio frequency interference (RFI) may change the operation of integrated circuits in the sense that the functions they implement change in the presence of disturbances. For instance, it is known that base-band amplifiers demodulate out of band RFI [2]–[5].

The capability of electronic systems to work properly in environments featuring interference levels equal to or greater than those required by electromagnetic compatibility standards depends on multiple factors. Among them we can mention the design choices at the system level dealing with cabling, filtering, shielding and grounding as well as the design solutions implemented at the module level. All of these aim to improve the EMC performance including the immunity to EMI, meaning to reduce the magnitude of disturbances reaching the integrated circuits. Indeed, EMI induced failures experienced at the system level are always due to malfunctions at the integrated circuit level. Therefore, it can be said that the higher the EMI immunity of ICs, the less likely EMI-induced failures are experienced at the system level. Furthermore, the greater the immunity of the integrated circuits, the less the need of inserting EMI filters [1].

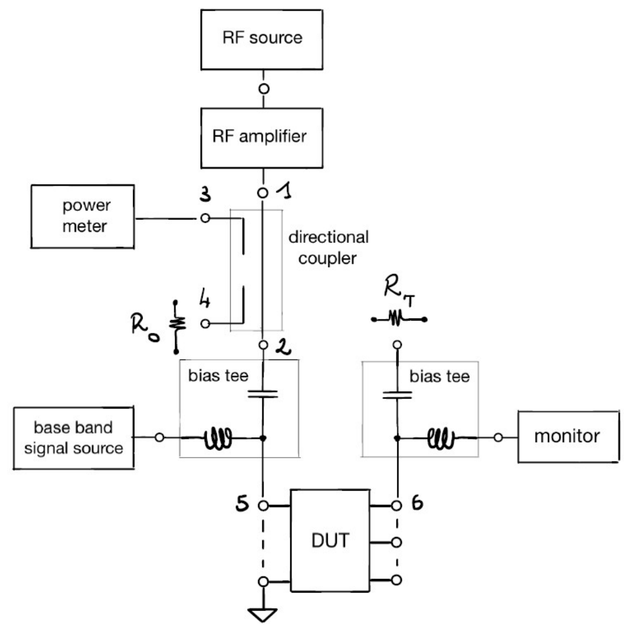

Fig. 1. Schematic view of the DPI test bench comprising the block diagram of the RF source chain and the monitoring instruments.

Based on that, in the last decades several measurement methods aimed to evaluate the electromagnetic immunity of integrated circuits have been developed [6], [7] and some of them were selected to be included in international standards like the IEC 62132 [11]. Usually, the immunity level of ICs is used to check the conformity to standard requirements [11] or customer design specifications. It is also common to compare such level with that of pin compatible components implementing the same functions [12]. Furthermore, the immunity level of ICs is useful to perform immunity analysis at module or system level.

Given the relevance of such measurement methods, over the years researchers and practitioners have improved some of them highlighting their pros and cons [13]–[15].

A common approach to evaluate the immunity to RFI of ICs is the Direct Power Injection (DPI) test. It consists in applying the RFI to one pin of the device under test (DUT) at time while monitoring at least one of its base-band output signals. The level of interference is increased step by step until the monitored signal exceeds a predefined mask. The level of RFI causing the failure is recorded. The measurement is repeated for a set of frequencies in the range of interest. For instance, wanting to evaluate the immunity to the RFI of a voltage regulator, the dc output voltage is monitored while injecting the RFI into the dc input. The RFI magnitude is increased until the dc output exceeds a maximum offset voltage or the maximum RF power level of the test setup is reached [16].

The DPI method is widely used in the EMC qualification of ICs because it provides the immunity level of each pin. This information is useful in module level EMC analysis as well as for the comparison of pin compatible ICs implementing the same functions. Given the wide use of the DPI method for the qualification of ICs for automotive applications, some European silicon makers and original equipment manufacturers (OEMs) collaborated to detail the measurement setup and the related test board to be used to qualify different types of ICs. The outcomes of that investigation are summarized in [17].

Despite this, DPI tests show low repeatability i.e., DPI tests carried out on the same device mounted on the same test board but inserted in different test benches compliant to IEC 62132-4, provide different results. Aiming to improve the performance of the DPI test bench, in [8] a proprietary injection probe comprising an RF voltmeter, and ammeter is proposed. The probe is costly and requires a specific ground plane adapter. Ayed et al. proposed a resistive RF injection probe (RFIP) [9]. Basically, a shunt resistor is added in the RF injection path for measuring the RF voltage and current. The test bench comprises two RF amplifiers to increase the measurement accuracy, but this introduces distortion issues when injecting high RFI level. The approach was validated up to 1 GHz but, due to the current measurement uncertainties, the impedance extraction degrades above 300 MHz. A test bench for measuring the RF voltage and current in DPI tests is also presented in [10]. The forward and reverse power resulting at the output of the directional coupler are processed by a circuit comprising a low cost RF detector. However, it should be noted that the measurement errors due to the directional couplers cannot be removed. This paper provides a critical assessment of the DPI test method as it is presented in [11]. The focus is on the limitations due to the components and instruments composing the RF injection chain and the related measurements. These limitations are at the basis of the investigations carried out in this work, which led to the development of a test bench that relies on RF measurements in the time domain rather than in the frequency domain.

The paper is organized as follows. Section II presents the DPI test method and highlights that the measurement of the RF source available power is affected by some errors. Section III shows the test setup developed within this work to overcome the limitations highlighted in Section II and some concluding remarks are drawn in Section IV.

II. DPI Test Setup and Method

As discussed in the introduction, the DPI test method, as shown in IEC62132-4, requires to monitor the base-band operation of the DUT while one of its pin (or a group of pins) is concerned by the RFI. More in detail, the DUT should be mounted on a dedicated test board comprising the ancillary components needed to make it work as prescribed by the manufacturer. Furthermore, the test board should comprise the bias-tees, i.e., the circuits needed for superimposing the interference onto the nominal signals and for monitoring the base-band output signals [11]. The test board is connected with coaxial cables to the source of RF interference, to the source of nominal signals, to the power supply and to the instruments needed for monitoring the operation of the DUT. A block diagram of the test bench is shown in Fig. 1. The standard IEC 62132-4 provides a limit of 3dB to the attenuation of the bias tee over the frequency range of interest and papers available in literature show insights on the solutions to put in place to minimize the impact on test board on the measurement results [13].

The RF interference is generated by a 50Ω RF source cascaded to an RF amplifier. The output (1) is applied to the DUT input pin through a directional coupler and a bias tee, which in turn allows for superimposing the RF interference onto the base-band signal. Port 4 of the directional coupler and the RF port of the bias tee used for monitoring the DUT output are loaded with $R_0 = 50\Omega$ and $R_\mathrm{T} = 150\Omega$, respectively. The available power (P_av) of the RF source is measured with a power meter or a spectrum analyzer connected to the coupled port of the directional coupler (3). The operation of the DUT is monitored looking at some of the DUT base-band output signals, which are sensed through a bias tee. The high frequency impedance loading the pins other than the one the interference is injected in is defined at the test board level (R_L).

The test consists in monitoring some base-band voltages or currents while the RFI is injected into one IC pin (or a group of). The interference level is increased step by step until one of the monitored signal exceeds its maximum allowable range, known as susceptibility criterion, or the maximum available RF power level is reached. The power level at which the failure occurs is recorded. The procedure is repeated for a set of frequencies in the range of interest. About the power level, it is given by

$$P_\mathrm{av} = C P_\mathrm{m} \tag{1}$$

where P_av is the RF source available power, C is the coupling factor of the directional coupler and P_m is the power measured by the power meter or the spectrum analyzer. Usually, the coupling factor is provided by the manufacturer of the directional coupler, and it is given by

$$C = \frac{1}{|S_{31}|^2}, \tag{2}$$

where S_{31} is the scattering parameter relating the incident power wave at port 1 (a_1) to the reflected power at port 3

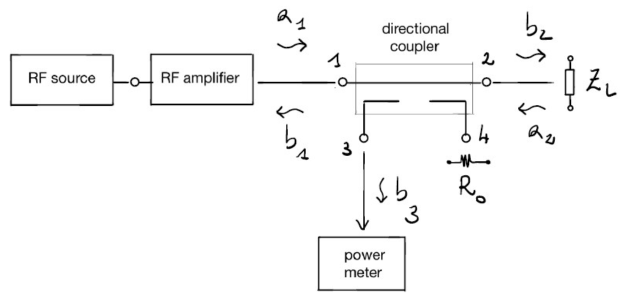

Fig. 2. Block diagram used to evaluate the coupling factor of the directional coupler ZFBDC20 [18].

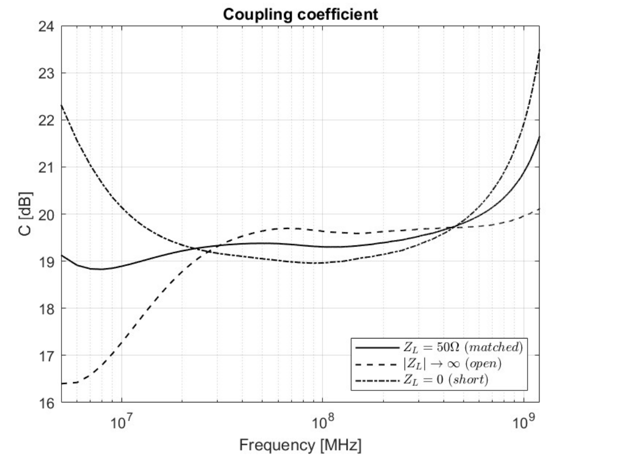

Fig. 3. Coupling factor of ZFBDC20 evaluated for for $Z_{\mathrm{L}} = 50\Omega$ (continuous line), $|Z_{\mathrm{L}}| \to \infty$ (dotted line) and $Z_{\mathrm{L}} = 0\Omega$ (dashed line).

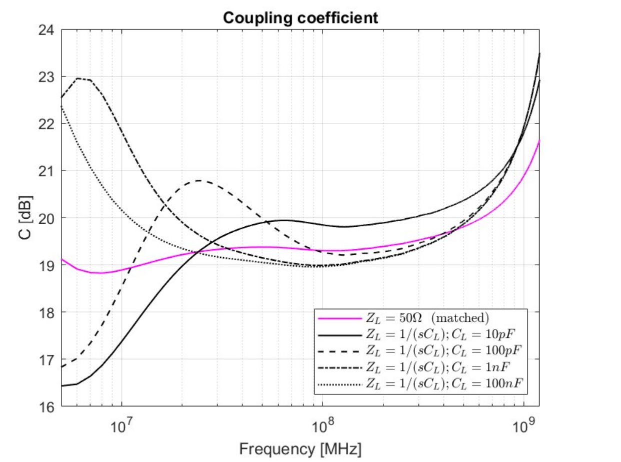

Fig. 4. Coupling factor of ZFBDC20 evaluated for for $Z_{\mathrm{L}} = 50\Omega$ (magenta-continuous) and capacitive load $C_{\mathrm{L}} = 10pF$ (black-continuous), $C_{\mathrm{L}} = 100pF$ (dashed), $C_{\mathrm{L}} = 1nF$ (dash-dot) and $C_{\mathrm{L}} = 100nF$ (dotted).

(b_3) with the other ports perfectly matched.

Actually, the power sensed by the power meter ($|b_3|^2$) depends on the impedance Z_{L} loading the DC at port 2, as shown in the block diagram in Fig. 2. Such an impedance represents that shown by the DUT at the injection pin in the DPI test. If port 2 is mismatched, the coupling factor is given by

$$C = \frac{1}{|S_{31} + S_{32}\Gamma_{\mathrm{L}}|^2}, \tag{3}$$

where S_{31} and S_{32} are the scattering parameters of the directional coupler between port 1 and port 3 and between port 2 and port 3, respectively. Γ_{L} is the reflection coefficient of the impedance Z_{L} loading port 2. It is defined as

$$\Gamma_{\mathrm{L}} = \frac{Z_{\mathrm{L}} - R_0}{Z_{\mathrm{L}} + R_0}. \tag{4}$$

To evaluate the impact of the mismatch at port 2 on the coupling factor, the directional coupler ZFBDC20 [18] was considered and the coupling factors evaluated for different load impedance using (3). Fig. 3 shows the coupling factor evaluated for $Z_{\mathrm{L}} = 50\Omega$ (continuous line), $|Z_{\mathrm{L}}| \to \infty$ (dotted line) and $Z_{\mathrm{L}} = 0\Omega$ (dashed line). The coupling factor differs markedly from the nominal one below $30\mathrm{MHz}$ and above $500\mathrm{MHz}$.

Considering that in DPI tests the load impedance, meaning the impedance shown by the DUT at the injection point is several cases is capacitive (e.g., analog or digital inputs, or decoupled power supply), the coupling factor of the directional coupler was also evaluated with port 2 loaded by capacitors of rising values. The results of this analysis are shown in Fig. 4. Also in this case, the coupling factor differs from the nominal one below $40\mathrm{MHz}$ and above $700\mathrm{MHz}$.

Furthermore, the coupling factor is affected by the RF source impedance, meaning the output impedance of the RF amplifier, which is supposed to be 50Ω. The output impedance of the RF amplifier we use in our laboratory to perform DPI tests was measured and used to calculate the coupling coefficient shown in Fig. 5.

To sum up, combining the error due to the load and to the source mismatch, it can be concluded that the measurement of the available power (P_{av}), i.e., the quantity used to quantify the susceptibility of integrated circuits, is affected by $\pm 6dB$ error. Next section shows a novel approach aimed to solve the issues discussed so far.

III. DPI Test Based on Time Domain RF Measurements

Aiming to overcome the limitations of the DPI test bench as described in IEC-62132-4, meaning the error affecting the measurement of the RF source available power and the frequency limitation due to the test board hosting the DUT, the test bench shown in Fig. 6 was set up. It comprises a small test board (3x3 cm) hosting the DUT and the ancillary components needed to make the DUT work properly. A commercial OpAmp was considered as DUT. The test board layout was designed to allow the user to land on the test board with the RF probes 40A-GS-300-DP [20], as close as possible to the DUT pins. A commercial bias tee [19] not mounted on the DUT test board was used to combine the base-band signal and the RF one. The overall signal was applied to one pin of

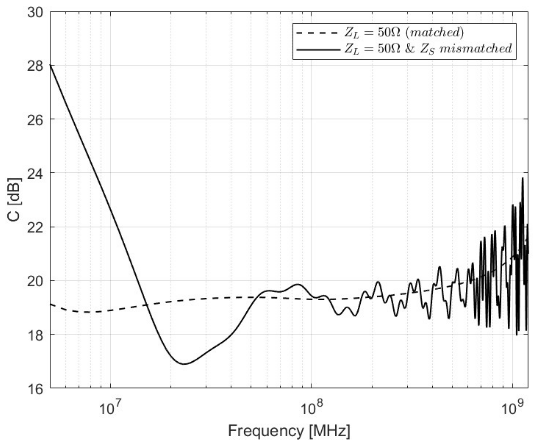

Fig. 5. Coupling factor evaluated with the RF source impedance mismatched. The source impedance of the RF amplifier available in the laboratory was considered.

the DUT at time (pin 5 in Fig. 6). Another RF probe (the one on the bottom in Fig. 6) was landed in the close proximity to that used to inject the RFI (the one on the top in Fig. 6). It was connected to the active probe D420-A-PB2 of the oscilloscope HDO9404-MS by a coaxial cable [21]. Finally, the effect of the RFI on the base-band operation of the DUT was monitored at pin 6 with a voltmeter, which was connected to the DUT pin through an off board bias tee, the same type used for the RFI injection. Furthermore, the available power of the RF source was measured with the traditional approach, meaning with a spectrum analyzer connected to a directional coupler, which in turn was inserted in the RF chain (not shown in Fig. 6).

The DPI test was carried out referring to the procedure presented in IEC62132-4, i.e., the interference frequency was set and the magnitude was increased step by step till the monitored signal exceeded the susceptibility criterion. As said, a feedback opamp was tested. The nominal signal was a dc voltage, the dc output voltage was monitored and the RF available power (P_{av}) needed to make the output exceeding $V_{\text{off}} = \pm 5mV$ was recorded. Actually, the power level was measured with the SA connected to the directional coupler and the peak-to-peak amplitude of the RF signal was measured with the oscilloscope.

$$v_{\text{RF,pin}}(P_{\text{av}}) = \left| \frac{Z_{\text{in,DUT}}}{Z_{\text{in,DUT}} + R_0} \right| \sqrt{8 R_0 P_{\text{av}}}. \quad (5)$$

The available power (P_{av}) measured with the SA was used to calculate the amplitude of the RF voltage at the DUT pin with (5). In this expression, $R_0 = 50\Omega$ is the source resistance and $Z_{\text{in,DUT}}$ is the DUT input impedance. Therefore, the impedance shown by the DUT (the opamp in our case) at the injection point was measured obtaining the plot shown in Fig. 7. Based on that, the amplitude of the RF voltage at the pin level (peak value) was calculated using (5). The results are shown by the dashed line in in Fig. 8. The amplitude of the RF voltage measured at the pin level with the active probe and the oscilloscope for a set of frequency is shown in the

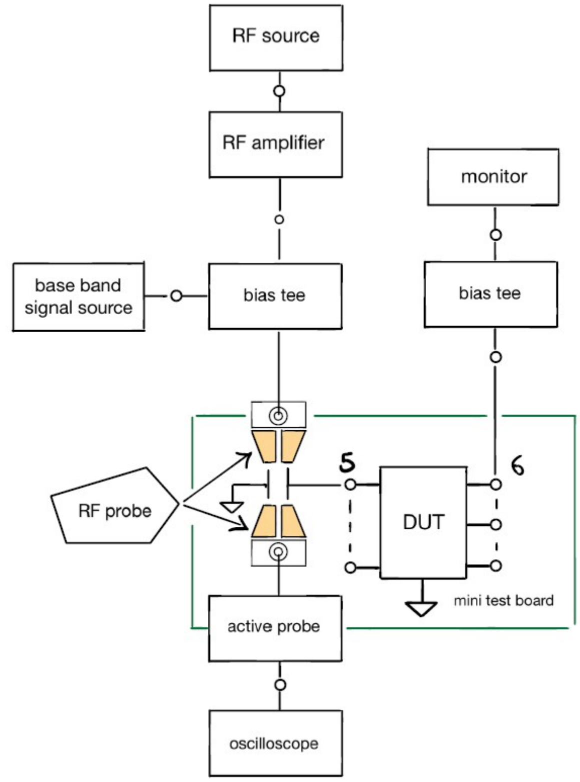

Fig. 6. Block diagram of the DPI test bench comprising the measurement of the interference magnitude with the oscilloscope.

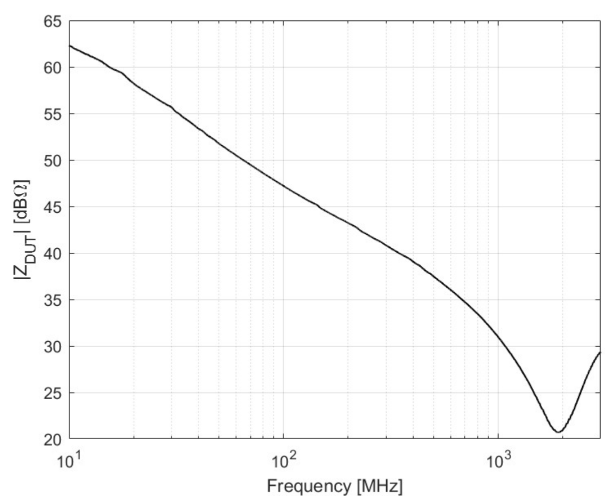

Fig. 7. DUT input impedance at pin 5.

same figure by the continuous line. The results are in good agreement from 40MHz to 1.5GHz but outside this range the difference between the curves is remarkable as highlighted by the plot shown in Fig. 9. Based on the above, it can be concluded that DPI susceptibility tests can be carried out measuring the amplitude of the RFI at the pin level, the DUT input impedance and calculating the available power of the RF source as if the RF source were ideal, meaning $R_0 = 50\Omega$.

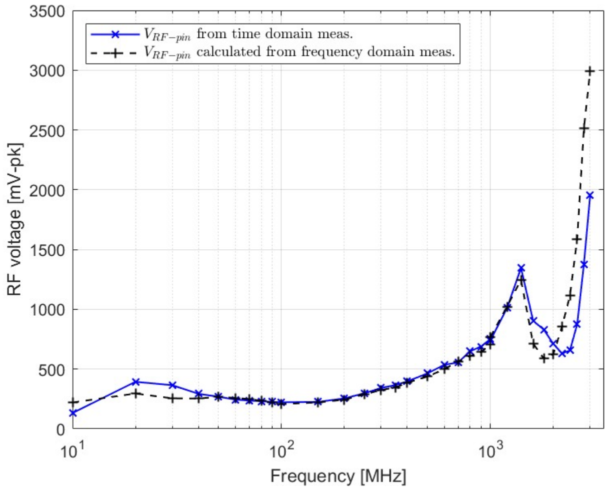

Fig. 8. DPI test results. Magnitude of the RF interference measured with the oscilloscope (continuous line) and calculated from the available power $P_{\rm av}$ (dashed line) vs. frequency.

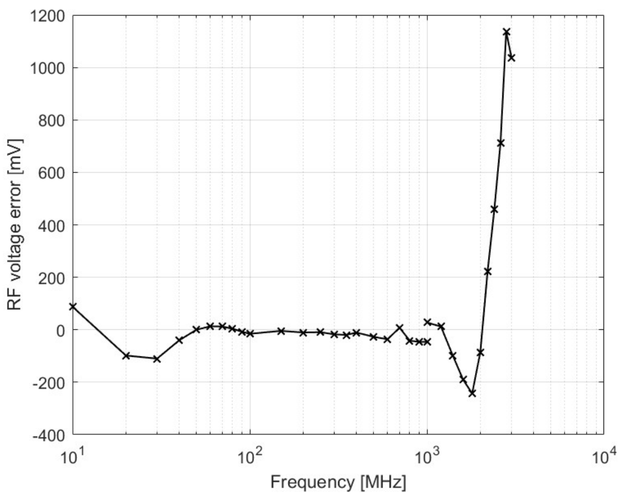

Fig. 9. Difference between the RFI magnitude measured in the frequency domain and in the time domain ($v_{\rm err} = v_{\rm RF,pin,meas} - v_{\rm RF,pin}(P_{\rm av})$) versus frequency.

Therefore $P_{\rm av}(v_{\rm RF,pin,meas})$ can be expressed as

$$P_{\rm av}(v_{\rm RF,pin,meas}) = \left| \left(1 + \frac{R_0}{Z_{\rm in,DUT}}\right) \right|^2 \frac{|v_{\rm RF,pin,meas}|^2}{8R_0}. \tag{6}$$

The comparison of the DPI test results obtained with the traditional approach (black dashed line and crosses) and that obtained from the RF voltage measured at the pin level (red continuous line and circles) is shown in Fig. 10. Based on the considerations reported in Section II, the differences below $40MHz$ and above $1.5GHz$ can be ascribed to the isolation of the directional coupler and to source impedance, which is not 50Ω.

Given the frequency range and the dynamic range of the interference in common DPI tests, the voltage measurement

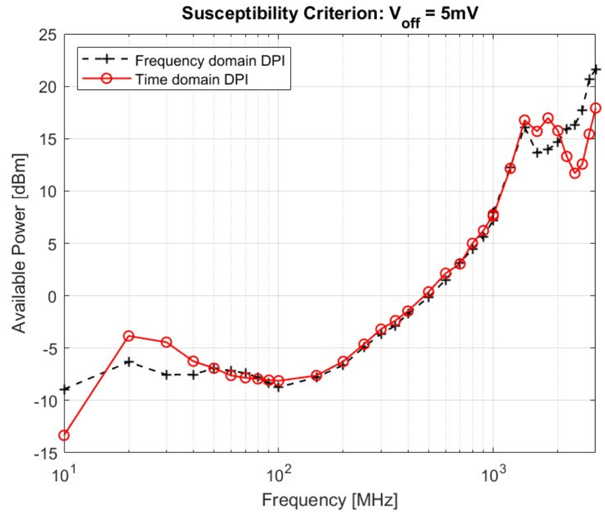

Fig. 10. DPI test results. RFI available power versus frequency obtained from the measurement of the RF amplitude in the time domain (red continuous line and circles) and in the frequency domain (black dashed line and crosses).

in the time domain with an oscilloscope is a valid alternative to those in the frequency domain that require a directional coupler and a spectrum analyzer or a power meter.

IV. Conclusions

This work highlighted that the results of measurements carried out using DPI test setup as in [11] are affected by errors due to the components used in the RF injection chain. The impedance of the equivalent RF source at the pin level usually is not 50Ω over the entire frequency range of interest. Furthermore, the coupling factor of the directional coupler is affected by the mismatch at the injection point. Wanting to overcome these limitations, a DPI test bench comprising a small test board, which hosts the pads needed for landing RF probes was designed and prototyped. The developed test bench is similar to that suggested in IEC-62132-4, but instead of the incident power, the RF voltage is measured at the IC pin using a wide band oscilloscope. The incident power of a 50Ω RF source generating the RF voltage measured measured with the oscilloscope is calculated using the impedance at the injection pin obtained with a VNA. This allows one to compare the susceptibility profile of the IC with the limits provided by the standard.

References

[1] H. W. Ott, Electromagnetic Compatibility Engineering. Hoboken, NJ, USA: Wiley, 2009.

[2] J. M. Redoute and M. Steyaert, EMC of Analog Integrated Circuits. New York, NY, USA: Springer, 2010.

[3] F. Fiori, "EMI-Induced Distortion of Baseband Signals in Current Feedback Instrumentation Amplifiers", IEEE Trans. on Electromagn. Compat. , vol. 60, no. 3, pp. 605-612, June 2018.

[4] F. Fiori, S. Benelli, G. Gaidano, V. Pozzolo, "Investigation on VLSIs' input ports susceptibility to conducted RF interference", IEEE Int. Symp. on Electromagnetic Compatibility, pp. 326-329, Aug. 1997, Austin, TX, USA.

[5] Y. Cui, Y. Jin, S. Wang, F. Dai, "A Unified Power-Based Model for RFI Demodulation in CMOS Operational Amplifiers", 2025 International Applied Computational Electromagnetics Society Symposium (ACES-China), pp.1-2, Aug. 2025, Huangshan, China.
[6] F. Fiori, F. Musolino, "Measurement of integrated circuit conducted emissions by using a transverse electromagnetic mode (TEM) cell, IEEE Trans. on Electromagn. Compat. , vol. 43, no. 4, pp. 622-628, Nov. 2001.
[7] T. Steinecke, M. Bischoff, F. Brandl, C. Hermann, F. Klotz, F. Mueller, W. Pfaff, M. Unger, "Generic IC EMC Test Specification", Asia-Pacific Symposium on Electromagnetic Compatibility, pp. 5-8, July. 2012, Singapore.
[8] G. Auderer. "High frequency conducted power injection, an alternative measurement methodology to IEC 62132-4 (DPI-method) to test robustness of VLSIs", Freescale Halbleiter GmbH, Bannewitz, Germany.
[9] A. Ayed, T. Dubois, J.-L. Levant, and G. Duchamp, "A new method for the characterization of electronic components immunity," IEEE Trans. Instrum. Meas., vol. 64, no. 9, pp. 2496–2503, Sep. 2015.
[10] A. Boyer, "A Low-Cost RF Detector to Enhance the Direct Power Injection Conducted Immunity Setup," in IEEE Letters on Electromagnetic Compatibility Practice and Applications, vol. 4, no. 4, pp. 108-113, Dec. 2022.
[11] Integrated Circuits—Measurement of Electromagnetic Immunity, 150 kHz–1 GHz, IEC Standard IEC-62132, 2006.
[12] M. V. Quitadamo, F. Fiori, "A SPICE Model of Operational Amplifiers for Electromagnetic Susceptibility Analysis", IEEE Trans. on Electromagn. Compat., vol. 64, no. 2, pp. 418-628, Apr. 2022.
[13] H. Pues, D. Pissoort, "Design of IEC 62132-4 compliant DPI test Boards that work up to 2 GHz", Int. Symposium on Electromagnetic Compatibility (EMC Europe), pp. 112-116, Sept. 2012, Rome, Italy.
[14] J. Catrysse, D. Pissoort, F. Vanhee, "Expanding the frequency range for DPI testing of IC's above 1 GHz: An alternative proposal", Int. Symposium on Electromagnetic Compatibility (EMC Europe), pp. 400-404, Sept. 2011, York, UK.
[15] A. Boyer, F. Caignet, "Analysis of Operational Amplifier Susceptibility to Multifrequency Disturbance", 2024 14th Int. Workshop on the Electromagnetic Compatibility of Integrated Circuits (EMC Compo), pp.5-10, Oct. 2024, Torino, Italy.
[16] P. S. Crovetti, F. Fiori, "A Linear Voltage Regulator Model for EMC Analysis", IEEE Trans. on Power Electronics, vol. 22, no. 6, pp. 2282-2292, Nov. 2007.
[17] Generic IC EMC Test Specification, Ed. l.2, 2007; [Online] Available: www.zvei.argllC_EMC_Test_Specificatian.
[18] Minicircuits: ZFBDC20-13HP-S+ datasheet, 2017. [Online]. Available: https://www.minicircuits.com/.
[19] Comba-Telecom: 8800NMF2 datasheet, 2020. [Online]. Available: https://www.comba-telecom.com/.
[20] Picoprobe: 40A-GS-300-DP datasheet, 2024, [Online]. Available: https://www.ggb.info/.
[21] Teledyne Lecroy: HDO9404-MS datasheet, 2018, [Online]. Available: https://www.teledynelecroy.com/