IEEE EMC SOCIETY | Letters on Electromagnetic Practice and Applications

Improving the Performance of Direct-Conversion SDRs for Radiated Pre-Compliance Measurements

C. Spindelberger and H. Arthaber, *Senior Member, IEEE*

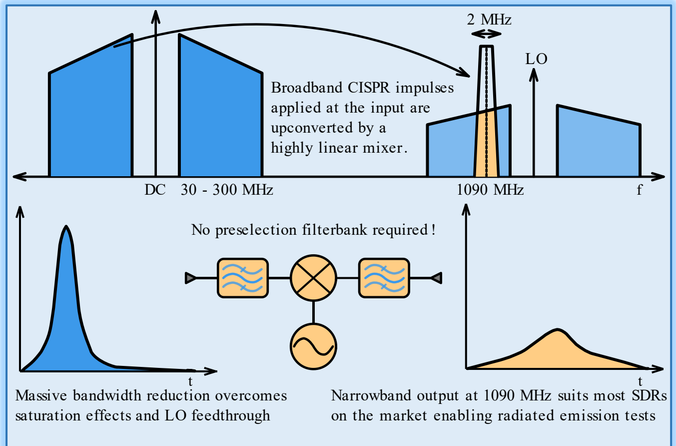
***Abstract*—In this paper, a highly linear frontend to improve the performance of (software-defined radios) SDRs for radiated pre-compliance measurements is presented. In *CISPR* band C/D, the test receiver needs to fulfill stringent requirements for using the quasi-peak detector. Usually, an expensive preselection filter bank is necessary to make fully compliant measurements of broadband transients. Direct-conversion based SDRs show a limited out-of-the-box performance for pre-compliance measurements caused by, e.g., harmonic mixing and saturation effects. With the use of a triple-balanced mixer, a highly linear up-conversion stage is built, eliminating the need for a filter bank. The dynamic range requirements for the SDR are strongly reduced by a narrowband intermediate frequency filter, making *CISPR 16-1-1* compliant measurements possible. The sensitivity of the frontend is comparable to professional receivers on the market, although no low-noise amplifier is implemented. The performance is verified by continuous wave and transient signals according to *CISPR* norms. The broadband measurement results are compared with traditional characterizations of the dynamic range using the compression level and the noise figure. It shows that assumptions on the RF-link budget for a compliant design can be made with continuous wave measurements. Based on our results, the requirements for the SDR frontend are derived.**

Index Terms*—software-defined radio (SDR), electromagnetic compatibility (EMC), electromagnetic interference (EMI), *CISPR

I. INTRODUCTION

The direct-conversion receiver (DCR) enables frequency down-conversion without the necessity of preselection filtering. The basic topology consists of a single mixer stage and anti-aliasing filters. Due to its simple structure, it is often utilized for low-cost applications, e.g., software-defined radios (SDRs). Typically, such receivers are highly configurable and applicable to many different use-cases. In this paper, the focus is put on the performance improvement of SDRs for radiated pre-compliance measurements in *CISPR* band C/D.

In *CISPR 16-1-1*, highly demanding requirements for electromagnetic interference (EMI) receivers are specified [1]. Broadband impulses, being flat up to 1 GHz, must be measured and weighted in terms of repetition rates using different detectors. Below 1 GHz, the quasi-peak detector (QPD) represents the largest challenge for analog receiver frontends. To achieve the required dynamic range



Highly linear up-conversion stage designed for compliant radiated emission tests using homodyne software-defined radios.

(DR), professional equipment makes use of expensive preselection filter banks. Thus, low-cost receivers suffer from a degraded indication range, saturation effects, and accuracy.

In the past, digital sampling oscilloscopes (DSOs) have been used successfully for conducted emission tests below 30 MHz [2–3]. A fully compliant broadband time-domain measurement system, usable up to 1 GHz, with a nonlinear ADC structure is presented in [4]. The downside of these techniques is that DSOs are limited in bandwidth (BW) vs. acquisition time and giga-sample ADCs need expensive signal processing units to cover the large amount of data. Occasionally, recordings up to 15 s must be made for EMI measurements. SDRs can be tuned arbitrarily up to a few gigahertz, performing narrowband signal analysis. In contrast to DSOs, continuous data streaming allows

Take-Home Messages:

- Characterization of a highly linear up-conversion stage by *CISRP 16-1-1* measurement procedures.
- Massive bandwidth reduction prevents from saturation and feedthrough effects.
- With the designed board, fully compliant radiated emission measurements in *CISPR* band C/D can be made.
- The high DR of triple-balanced mixers eliminates the need for an expensive preselection filter bank.

Manuscript received June 15, 2022; revised 2 September 2022 and 31 October 2022; accepted 29 November 2022. Date of publication xx December 2022; date of current version 5 December 2022.

C. Spindelberger and H. Arthaber are with the department of Electrodynamics Microwave and Circuit Engineering (EMCE) at the Technical University of Vienna, TU Wien, 1040, Austria. (e-mail: christian.spindelberger@tuwien.ac.at)

This article has been accepted for publication in IEEE Letters on Electromagnetic Compatibility Practice and Applications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/LEMCPA.2022.3227409

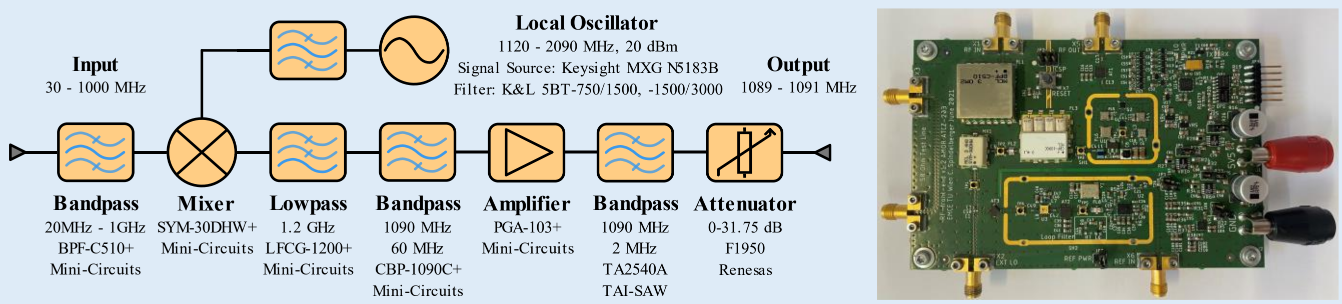


Fig. 1. Block diagram of the implemented IF stage (left) and a picture of the realization (right).

to make recordings for several seconds which are limited by the hosts memory. Furthermore, configurable onboard resources can be utilized to control the amount of data preprocessing by implementing, e.g., a QPD algorithm. Hence, they offer a low-cost solution for radiated pre-compliance measurements. In [5], popular SDRs have been investigated in conjunction with TEM cell requirements. Besides saturation effects of the frontends, it was shown that DCRs suffer significantly from out-of-band interference down-converted by local oscillator (LO) harmonics. In SDRs, rectangularly driven doubled-balanced mixers are widely used [6]. While this improves the linearity, DCR-based SDRs are prone to harmonic mixing. This problem can be solved by implementing a polyphase harmonic-rejection mixer [7]. Up to now, this method is only available for very few SDRs on the market and filtering the LO is often not accessible. Because of the large BW and relatively low frequencies of *CISPR* band C/D, it is therefore not possible to make accurate pre-compliance measurements using DCRs. Consequently, this type of SDR would benefit from a frontend extension with a narrowband output suppressing frequencies at LO harmonics. To achieve this, the design of a highly linear up-conversion stage, eliminating the need for a preselection filter bank, is targeted.

The structure of this letter is as follows. In Sec. II, the design criteria for the frontend are explained. In Sec. III, the derived requirements are verified by measurements using continuous wave (CW) signals. Then, broadband performance characteristics are given in Sec. IV. Lastly, the letter concludes resultant requirements for possible SDRs in Sec. V.

II. DESIGN CRITERIA

Triple-balanced frequency converters outperform older topologies in terms of linearity and DR [8]. This complex structure has a set of two diode quads implemented with the benefit of a higher suppression of intermodulation products. The inputs are decoupled and allow to perform broadband frequency conversion regardless of overlapping RF, LO, or intermediate frequency (IF) bands. Due to the large bandwidth of *CISPR* band C/D and the stringent linearity requirements, this kind of mixer is used for the IF stage, depicted in Fig. 1. According to *CISPR 16-1-1*, no LNA is implemented at the input to maintain the maximum DR of the mixer. Furthermore, nonlinear distortions added by the amplifier are minimized by reducing the input BW to 60 MHz. The circuit was realized on a 4-layer FR4 material with coplanar-ground transmission lines. In the following, the design criteria for this board are explained.

A. Frequency Conversion

Choosing an appropriate IF depends on several factors. *CISPR* requires a minimum suppression of 40 dBc for detuned CW interferers. State-of-the-art mixers provide an isolation and intermodulation distortion (IMD) above this range allowing an overlap of the RF and IF frequency bands. Typically, LOs produce harmonics causing interference due to feedthrough. To omit this problem, the lower sideband is mixed up. Additionally, highly linear mixers have a large LO power level, i.e., 20 dBm and the LO carrier may be located only 30 MHz apart from the IF. This can cause aliasing or a decreased sensitivity of the SDR. Hence, the IF should be kept as low as possible for LO carrier suppression promoted by the relative BW of the bandpass filter. Due to the high availability of filters centered at 1.09 GHz, the IF was chosen accordingly. It must be mentioned that the implemented mixer has a limited bandwidth up to 3 GHz. As the LO frequency range is 1.12–2.09 GHz, odd-order harmonics cannot be covered. Consequently, a rectangular LO does not lead to an increased linearity, as suggested in Sec. I. Therefore, a CW source was utilized in the setup.

B. RF-Link Budget

In *CISPR 16-1-1*, it is mentioned that the noise figure (NF) of compliant receivers with a preselection filter bank and an internal LNA are sufficient for most radiated emission measurements, e.g., *CISPR 11, 22,* and *32*. Investigating the noise floor of professional EMI receivers, i.e., *Keysight MXE N9038B* and *R&S* ESW26, a total NF of 10–15 dB is set as design goal. The NF of the up-conversion stage is mainly dominated by the conversion loss of the mixer. Typical triple-balanced converters have a loss of approx. 7 dB in the investigated frequency range [9]. Utilizing filters with low insertion loss and an LNA after the mixer keeps the frontends NF in the desired range.

Next, the expected peak power level at the mixer input is calculated. The filter in front of the detector is defined by *CISPR* having a 6 dB BW of 120 kHz. Usually, a Gaussian shape is utilized to fulfill the required selectivity. The noise and impulse BWs are $B_N^{CISPR} = 90.3$ kHz and $B_I^{CISPR} = 127.7$ kHz. The resulting impulse envelope is weighted by the QPD in terms of repetition rates. The overload factor (OVF) describes the difference between the 1 dB compression level of the frontend preceding the detector and the maximum indication level. In band C/D, an OVF of 43.5 dB is mandatory. As the QPD enhances the noise power by 5 dB and a maximum uncertainty of ±2 dB is allowed, the required DR at the *CISPR* filter output is approx. 50 dB [10]. Based on this value, with (1), it is possible to assess the minimum DR at the first mixer using the targeted NF and the BW parameters of the preselection and *CISPR*

$$\mathrm{DR} = 50\mathrm{dB} + 20\log_{10}\left(\sqrt{\frac{B_N^{CISPR}}{B_N^{pre}}\frac{B_I^{pre}}{B_I^{CISPR}}}\right) + \mathrm{NF} \qquad (1)$$

This article has been accepted for publication in IEEE Letters on Electromagnetic Compatibility Practice and Applications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/LEMCPA.2022.3227409

filters. Assuming an ideal rectangular preselection filter with an equal impulse and noise BW of 300 MHz and a NF of 10 dB, the DR must be at least 92 dB. The peak power level at the mixer input can now be derived by the thermal noise power and the DR resulting in a minimum power handling of 3 dBm. To minimize the DR requirements for the SDR connected to the extensions output, a narrowband IF filter with 2 MHz of BW was chosen.

III. PERFORMANCE VERIFICATION

The performance of the IF stage, depicted in Fig. 1, was verified with CW stimuli. The LO signal is provided by a CW source fulfilling the required tuning accuracy of ±2 %. Tunable filters are applied to neglect influences on the NF due to phase noise. The LO power level is set to 20 dBm. With the results, an insight for the achievable DR in terms of broadband signals is derived.

A. Linear Measurements

Firstly, linear measurements, i.e., conversion gain, matching, and NF were performed. Fig. 2 illustrates the corresponding results of the IF stage. As assumed, the NF mainly depends on the conversion gain having a maximum of 13 dB and fulfilling the targeted sensitivity. The rather high $|S_{11}|$ could be traced to a layout design error caused by the parasitic capacitance of large SMD pads of the frontend mixer. This problem can be solved with an adjustment of the layer stack-up. On a redesigned mixer test-PCB, it was verified that the requirement $|S_{11}| \leq -10$ dB can be achieved.

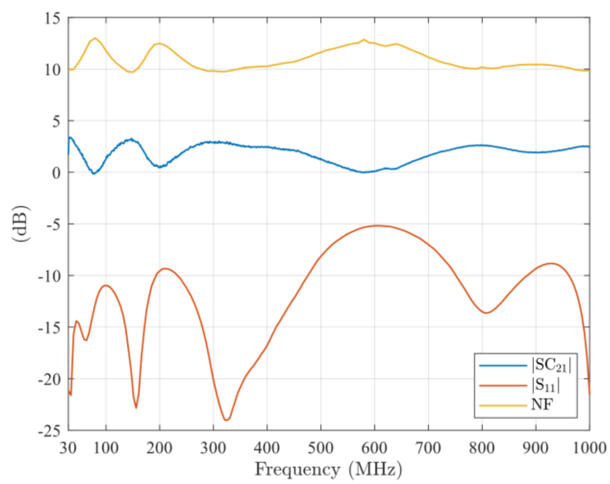


Fig. 2. Linear measurements: conversion gain $|SC_{21}|$, matching $|S_{11}|$, and NF.

B. Dynamic Range

With the measured NF (see Fig. 2) it is possible to calculate the minimum DR at the input of the up-conversion stage using (1). The broadband impulses, seen by the mixer, are limited in frequency domain to band C and D. A low and high pass filter were added to the preselection filter showing the following overall BW parameters: $B_N^{LPF} = 307$ MHz, $B_I^{LPF} = 270$ MHz, $B_N^{HPF} = 730$ MHz, and $B_I^{HPF} = 630$ MHz. In Fig. 3, this theoretical limit is compared to the achieved DR considering the 1 dB compression level of the mixer and the noise power. As band D is analyzed separately, the OVF can be reduced to 26 dB. The provided DR is high enough over the whole frequency range with a minimum margin of 10 dB. Moreover, it is assumed that the required CW measurement accuracy of ±2 dB can be calibrated. In Sec. IV, it will be proven how well this approach fits the

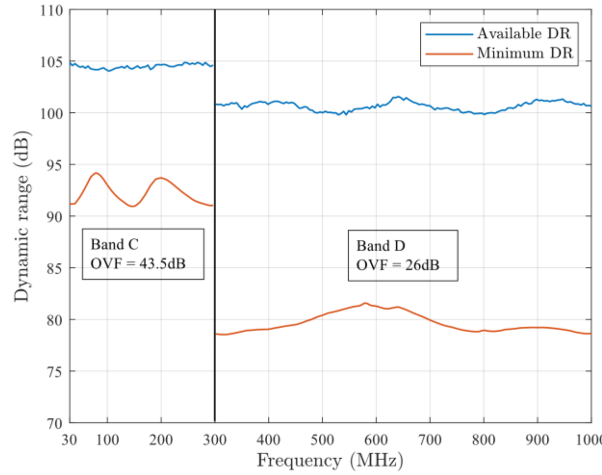


Fig. 3. Dynamic ranges of the IF stage at the input for CW signals.

characterization with impulses.

C. Isolation and Intermodulation Distortion

CISPR compliant receivers must suppress any kind of CW interference with at least 40 dBc. The RF-IF isolation was failing this requirement up to 3 dB for tuning ranges between 0.9–1 GHz. As the preselection roll-off is not sharp enough at 1.09 GHz, this problem could be solved by shifting the IF to frequencies above 1.1 GHz. Due to the small BW of the IF filter, image frequency isolation is a minor problem. As the LO-IF suppression over frequency is larger than 100 dB, a maximum LO feedthrough of −80 dBm must be considered at the IF output. Lastly, the IMD of nonlinear products was verified to be compliant for power levels up to 0 dBm.

IV. QUASI-PEAK DETECTOR LIMIT

In the following, the broadband capabilities of the IF stage in terms of *CISPR 16-1-1* are analyzed for the QPD. The test setup is depicted in Fig. 4. The impulse source generates transients which can be assumed being flat up to 1 GHz in frequency domain. Therefore, the spectrum is limited by the specified filters (Sec. III-B) to the dedicated bands. It is recommended to introduce an attenuator to improve the matching of the source. The IF output was analyzed with a fully compliant EMI receiver tuned to 1.09 GHz in zero IF configuration.

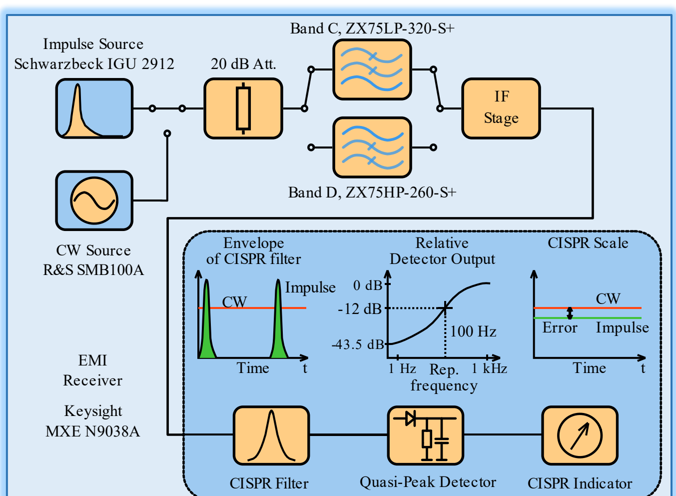


Fig. 4. Measurement setup for *CISPR 16-1-1* characterization.

This article has been accepted for publication in IEEE Letters on Electromagnetic Compatibility Practice and Applications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/LEMCPA.2022.3227409

A. Absolute Calibration

Firstly, the absolute calibration procedure according to *CISPR 16-1-1* is performed. The impulse source is calibrated to indicate the same *CISPR* power level as the CW source at a repetition rate of 100 Hz. The IF stage is tuned through band C/D and the error between the two signals is evaluated with the EMI receiver. For this test, the output of the impulse source has a peak voltage of 73.3 V for 300 ps. As the frontend has no input attenuators available, the maximum input power must be reduced to prevent from destruction and saturation. The OVF refers to the 1 dB compression level and corresponds to a minimum IMD of 20 dBc. With a noise power ratio measurement, using compliant notch filters at 60 and 500 MHz, the IMD was determined. As the minimum DR (see Fig. 3) varies up to 3 dB, a maximum IMD of 23 dBc was targeted. The indicated power level was set to −65 dBm in band C and to −75 dBm in band D. The error between the impulse and CW power level is depicted in Fig. 5. For the described configuration, the error stays well in the allowed ±1.5 dB error bound.

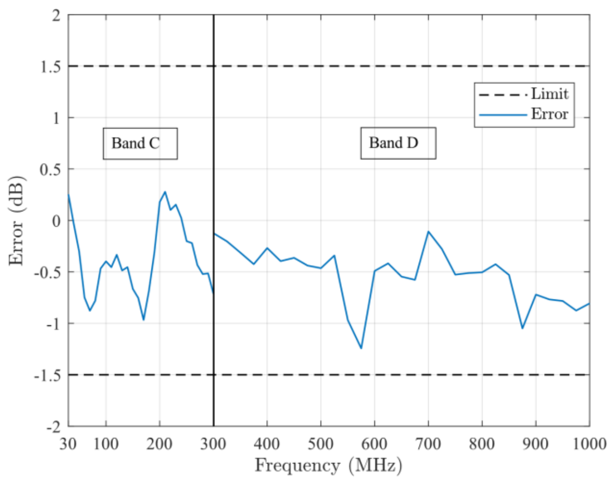


Fig. 5. Absolute calibration error: −65 dBm in band C, −75 dBm in band D.

B. Relative Impulse Weighting

With the adjusted power levels from the absolute calibration, the relative detector weighting range is derived. For this measurement, the indicated power level at 100 Hz is taken as reference. By reducing the repetition rate, the relative detector output is evaluated in Fig. 6. Due to the reduced OVF in band D, the QPD is already compliant for repetition rates of 10 Hz. Obviously, the IF stage complies with *CISPR*

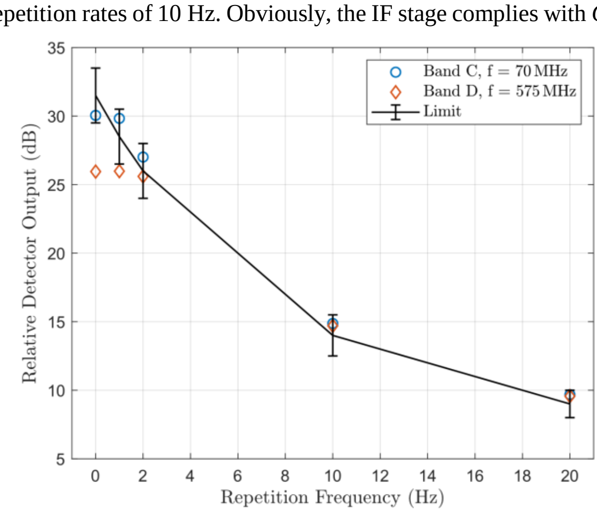


Fig. 6. Relative calibration error.

keeping the IMD larger than 20 dBc. It must be mentioned that in the calculations from Sec. II-B, IMDs or detector deviations have not been considered. The measurements were made with a peak input power close to the available DR, depicted in Fig. 3. Operating the IF stage at the theoretically derived minimum DR caused an inaccurate weighting of isolated transients in band C. To improve the accuracy of the QPD, the 10 dB margin was necessary and confirms the CW based RF-link budget to estimate compliance of a receiver design.

V. SDR REQUIREMENTS

In the following, the measurement results are put into context with DCR requirements, i.e., the *Nuand bladeRF 2.0 Micro* [11]. It was shown in Sec. IV that the IF stage can provide a DR at the QPD up to 60 dB. According to [5], the effective number of bits (ENOB) of the ADC to resolve this DR can be estimated by (2). The maximum

$$\mathrm{ENOB} = \log_2\left(\sqrt{\frac{2\,\mathrm{DR}\,\mathrm{B}_\mathrm{N}^{CISPR}}{3\,f_s}}\,\frac{\mathrm{B}_\mathrm{I}^\mathrm{IF}}{\mathrm{B}_\mathrm{I}^{CISPR}}\right) \tag{2}$$

sampling rate f_s of the SDR is 61.44 MSa/s with an ADC resolution of 12 bits. The impulse BW $\mathrm{B}_\mathrm{I}^\mathrm{IF}$ is estimated by the 6 dB BW of the filter which is approx. 12 MHz requiring a theoretical ENOB of 11.5 bits. With the specified IIP_3 level vs. NF of the analog path, the achievable DR can be estimated [12]. To keep the overall distortion below 20 dB an IMD of 31 dBc is targeted. At maximum gain, the NF is below 3 dB and the IIP_3 level is −18 dBm. Hence, the maximum input power results in −34 dBm. The calculus DR=-34 dBm+20 log ($\mathrm{B}_\mathrm{I}^{CISPR}/\mathrm{B}_\mathrm{I}^\mathrm{IF}$)-(-174 dBm/Hz+10 log $\mathrm{B}_\mathrm{N}^{CISPR}$ +NF) shows that the SDR is limited to 48 dB by its frontend. To conclude, the *bladeRF 2.0* is presumably capable enough to make compliant measurements in band D. As the SDRs receive path cannot provide full scale resolution of the ADC in band C, a degraded QPD performance must be expected.

VI. CONCLUSION

Throughout this paper, the design and characterization of an IF stage for radiated pre-compliance measurements using low-cost SDRs was presented. It could be shown that with the use of a highly linear mixer, compliant QPD measurements in *CISPR* band C/D can be made without the necessity of a preselection filter bank. It was possible to measure even isolated transients and keeping the IMD larger than 20 dBc. As the NF of the system is in a range between 10–13 dB, the IF stage has a comparable sensitivity to professional EMI receivers. It was shown analytically that the IF output suits typical low-cost SDRs. In conjunction with, e.g., the *bladeRF 2.0*, compliant measurements are theoretically possible. Moreover, due to the narrowband output, the SDRs frontend requirements are lowered, and harmonic mixing became a minor problem.

ACKNOWLEDGEMENT

This work has been funded by Interreg EFRE foundation through the project AMOR ATCZ-203.

REFERENCES

[1] CISPR 16-1-1 Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-1: Radio disturbance and immunity measuring apparatus - Measuring apparatus, Std. CISPR 16-1-1:2019.

[2] M. Parvis, G. Perrone, A. Vallan, “A precompliance EMC test-set based on a sampling oscilloscope,” IMTC/2002. Proceedings of the 19th IEEE Instrumentation and Measurement Technology Conf., vol.2., pp. 1197-1201, 2002.

[3] C. De Capua, C. Landi, “A digital measurement station for RF-conducted emissions monitoring,” in IEEE Trans. on Instrumentation and Measurement, vol. 51, no. 6, pp. 1363-1366, Dec. 2002

[4] S. Braun, M. Aidam, P. Russer, “Development of a multiresolution time domain EMI measurement system that fulfills CISPR 16-1,” Int. Symp. on Electromagnetic Compatibility, pp. 388–393, Vol. 2, August 2005.

[5] C. Spindelberger and H. Arthaber, “Out-of-the-Box Performance of popular SDRs for EMC pre-compliance measurements.”, IEEE Int. Symp. On Electromagnetic Compatibility - EMC Europe, pp. 677-682, October 2022

[6] Z. Ru, N. A. Moseley, E. A. M. Klumpernik, and B. Nauta, “Interference robust, flexible radio receivers in CMOS,” IEEE RFIC Virtual J., no. 6, Oct. 2014.

[7] B. Razavi, “The harmonic-rejection mixer [a circuit for all seasons],” IEEE Solid-State Circuits Mag., vol. 10, no. 4, pp. 10–14, Nov. 2018.

[8] F.Marki and C.Marki, “A tutorial on high linearity high IP3 RF and microwave mixers,” Marki Microwave, 215 Vineyard Ct. Morgan Hill, CA, Tech. Rep.

[9] F. Marki and C. Marki, “Mixer basics primer - a tutorial for RF and microwave mixers,” Marki Microwave, 215 Vineyard Ct. Morgan Hill, CA, Tech. Rep.

[10] D. B. Geselowitz, “Response of ideal radio noise meter to continuous sinewave, recurrent impulses, and random noise,” IEEE Trans. Radio Freq. Interference, vol. RFI-3, no. 1, pp. 2–11, May 1961.

[11] Nuand, “bladeRF 2.0 Micro”, [Online], Available: https://www.nuand.com/bladerf-2-0-micro/, Datasheet, Accessed: 1.9.2022.

[12] Analog Devices, “RF Agile Transceiver AD9361”, [Online], Available: https://www.analog.com/media/en/technical-documentation/datasheets/AD9361.pdf, Datasheet, Accessed: 1.9.2022.