Conducted Emissions Verification Setup Improvement for Space Applications

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***Abstract*—Just-before-test verification is needed to ensure that electromagnetic interference measurements are correctly performed. Some standards cover such specific requirements regarding test verification, this is the case of the ECSS-E-ST-20-07c for space applications. However, some drawbacks in the standard procedure have been identified, and in this work, we provide advice for improving the conducted emissions verification. For instance, we argue that the complete frequency range of the test should be evaluated during the verification of the test equipment, not just two single frequencies. Likewise, it is demonstrated how the standard verification setup introduces a significant mismatch that can compromise the accuracy of the result. Moreover, this work highlights the capabilities of novel instrumentation like high-end oscilloscopes that effectively provide convenient alternatives to improve further and simplify the measurement methodology while achieving even more accurate results if applied correctly.**

***Index Terms*—conducted emissions, verification, electromagnetic interference, measurements**

I. Introduction

Just-before-test verifications are essential to prevent, detect and correct errors or faults during electromagnetic compatibility (EMC) testing. Ensuring that the instrumentation, signal paths, and transducers (current probes, LISN, etc.) are correctly performing and mounted is critical to provide accurate measurements when testing the Equipment Under Test (EUT). Some EMC standards, like ECSS-E-ST-20-07C [1] or MIL-STD-461G [2], introduce test equipment verification procedures to be conducted just-before-tests. From a practical point of view, the verification shall be quick and "easy" meaning that it is not desirable to spend a long time on the verification procedure or to obtain very refined results. Hence, the ECSS standard [1], in its clauses for conducted emissions (CE) at power and signal leads between 50 kHz and 100 MHz, the test verification only considers two frequency points, and with a tolerance of $\pm 3\,\mathrm{dB}$ when measuring the radio frequency (RF) current. Even though the CE verification procedure for the test equipment is simple and fast to implement, it might not be fully effective and reliable.

Former research projects have addressed this necessity through novel setups and techniques for emissions and immunity tests. For instance, during the IND60 (2013 - 2016) and RFMicrowave (2016 - 2019) projects, a just-before-test verification approach was defined for conducted emissions [3], [4]. In [3], a multitone signal was used to verify the entire frequency range quickly and to identify failures due to grounding or the measuring receiver. The methodology enabled the authors to identify faulty ground connections at the Line Impedance Stabilisation Network (LISN). Moreover, using arbitrary waveform generators (AWG) for injecting the excitation signal and oscilloscopes for measuring the whole spectrum at once was crucial for accelerating the verification and validating the test setup more completely.

In this work, we followed a similar approach but aimed at the conducted emissions verification procedure defined by the ECSS standard. The standard CE verification method is analyzed by injecting a known signal either in Common Mode (CM) or in Differential Mode (DM). As detailed in the following sections, several improvements are proposed to obtain more accurate and reliable verification results. Among the proposed improvements, one is to evaluate the entire frequency range instead of two unique single frequencies while keeping the method as fast and agile as initially intended for an efficient measuring system performance check.

The rest of the work is organised as follows; section II describes the verification procedure's main concerns for the CE test; section III proposes significant improvements that allowed us to identify the critical performance of the test setup; section IV presents and discusses the results that support the recommended improvements. Finally, a conclusion is drawn in Section 5.

II. Verification setup concerns

The verification procedure defined in the ECSS standard is described in its Section 5.4.3 [1], where the setup shown in Fig. 1 is presented.

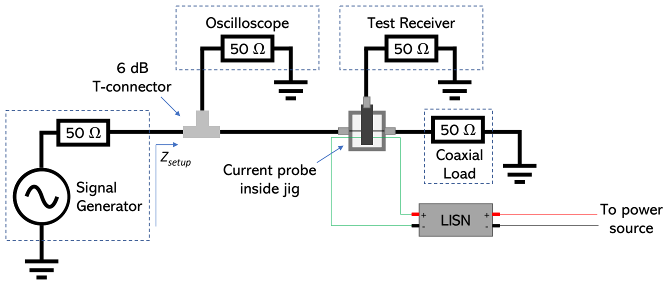

Fig. 1. Verification setup defined at the ECSS standard for CE [1].

According to this standard, an RF signal generator shall be connected through a $6\,\mathrm{dB}$ "T-type" splitter to an oscilloscope and to the coaxial line, including the $50\,\Omega$ terminated jig, where the current probe (CP) is placed. The oscilloscope branch is used to derive the RF current level injected into the jig, assuming the attenuation and impedance of both branches are equal. The calibrated signal level should be at least $6\,\mathrm{dB}$ below the applicable limit at two discrete frequencies, 1 MHz and 10 MHz, or at a level allowing out of the noise reading on the oscilloscope, whatever is greater, to the current probe in the jig. The measuring receiver should scan in the same manner as during the standard test and record the data within $\pm 3\,\mathrm{dB}$ of the injected level. Additionally, a DC current equivalent to the EUT nominal supply current should be applied through the current probe to check that the current probe is not saturated. Finally, the standard indicates that "*if readings are obtained which deviate by more than* $\pm 3\,\mathrm{dB}$*, locate the source of the error and correct the deficiency before proceeding with the testing*".

When the diagram shown in Fig. 1 is analyzed in conjunction with the description found in the standard, the following concerns emerge:

Generator mismatch. Assuming that a $50\,\Omega$ generator is employed, it is connected to two nearly $50\,\Omega$ impedances in parallel, that is, $Z_{setup} \approx 25\,\Omega$. This topology contributes to a significantly mismatched network, which means the reflection coefficient at the signal generator output is expected to be higher than the generally recommended value of $-13\,\mathrm{dB}$.

Unbalanced branches. The input impedance of the oscilloscope and jig+load branches could be different, especially in high frequency. Therefore, the current derived from the oscilloscope can differ from the one flowing through the jig.

Reduced number of frequencies evaluated. Only two frequency points are evaluated ($1\,\mathrm{MHz}$ and $10\,\mathrm{MHz}$). Hence, most of the spectrum is not covered during the verification, which can easily cause undetected failures. Commonly, damaged RF cables can present resonance frequencies around 50 MHz, without noticing any malfunction in frequencies up to 10 MHz.

Sensitivity of the measurement system. In combination with the previous point, it can occur that current probes or other critical instrumentation cannot be sensitive enough to measure accurately low-current values, especially at the higher frequency range (above $30\,\mathrm{MHz}$), where the resolution bandwidth (RBW) is increased, and the measurement accuracy can be compromised.

III. Proposed improvements

A. Improvements description

To improve on the main limitations of the standard verification method and develop a more efficient methodology, several improvements are proposed in what follows. These modifications are divided into two different categories, the ones that are considered *essential* because they provide fixes to the most concerning aspects of the current verification procedure and the *advanced improvements*, which can benefit the verification stage by exploiting other features of the instrumentation available. The *essential improvements* are:

Remove the oscilloscope branch. To eliminate the different impedance branches, it is necessary to remove the oscilloscope branch as defined in the standard. An alternative to obtain the current that is flowing through the jig is proposed in the next point.

Replace the termination. The termination should be replaced by a measuring device to determine the RF current circulating through the jig. The measuring device can be an oscilloscope, a spectrum analyzer or an EMI receiver. In all cases, the rated input impedance of the measuring instrument should be $50\,\Omega$, and the voltage standing wave ratio must be kept low (VSWR$<$1.2).

Measure the entire frequency range. It is important to measure the entire frequency range with enough frequency resolution to identify setup failures. Although for a just-before-test verification, it might not be necessary to scan the whole spectrum using a small frequency step (i.e. RBW/4), we need sufficient resolution to detect failures observable in broadband, like cable resonances or a damaged receiver input. Therefore it is necessary to cover up to $100\,\mathrm{MHz}$ either through a single-frequency sweep or using broadband excitation.

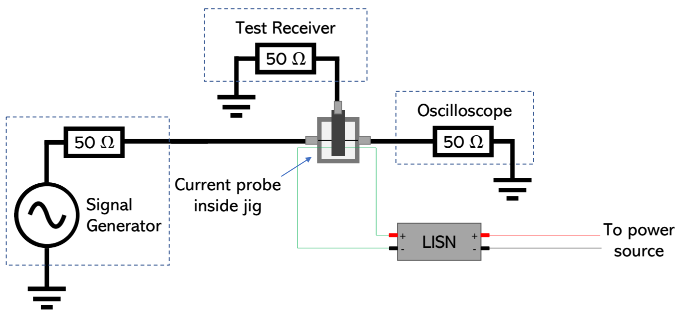

Fig. 2. Diagram with essential recommendations.

As mentioned, additional changes can be made to further optimize the performance of the verification setup in terms of speed and simplicity. They are:

Employ a multitone signal to excite the verification setup. The use of a multitone signal should be considered as it has been proven an accurate and convenient way to excite a wide frequency range. The multitone has the advantage of using a low crest factor when the phases of the tones are properly selected. If an AWG generates full periods of the signal, no leakage is produced, and a very high dynamic range can be achieved [5].

A single instrument for the complete verification. Nowadays, state-of-the-art oscilloscopes combine different features that can be advantageous for this application. For instance, some high-end oscilloscopes include AWG. Moreover, the low-noise and high-speed ADC used in such state-of-the-art oscilloscope have enough dynamic range for most EMI measurements, and when processed accordingly, it can deliver results equivalent to EMI receivers according to CISPR 16-1-1 [6]–[9].

Multichannel measurements. Finally, if an oscilloscope is used according to the previous point, it allows conducting several synchronized measurements using multiple channels. Hence, using the different input channels simultaneously, it is possible to run the CE test with several current probes, covering different frequency ranges and/or measuring the common mode and differential mode simultaneously [10], [11].

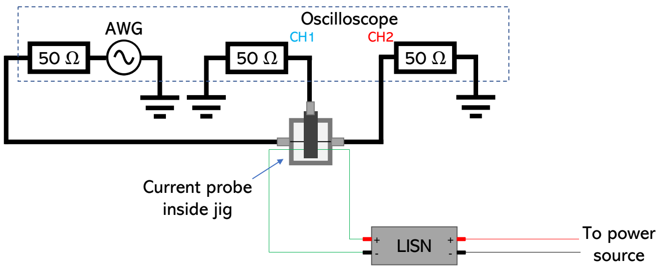

Fig. 3. Diagram with further step recommendations.

B. Validation measurements of the proposed improvements

The measurement campaign was carried out in the EMC laboratory of ESA-ESTEC.

1) Scattering parameters measurements: To assess the standard setup mismatch, we measured the reflection coefficient (S_{11}) with a Keysight E5061B Vector Network Analyzer (VNA), connecting its Port 1 instead of the RF signal generator. The measurement was performed with the standard configuration and the proposed new setup.

Complementary, the transfer function (S_{21}) is measured in three different configurations. Port 1 is always connected instead of the RF signal generator while Port 2 is connected at different points. When the setup is according to the standard verification setup, we measure the S_{21} between the signal generator plane and the oscilloscope branch and between the RF signal generator plane and the load end after the jig. Otherwise, with the new verification approach, we connect Port 2 always to the jig's load.

The results are captured with the two current probes used during the CE verification measurements, with the CP models 6741-1 and 9145-1 from Solar Electronics Company.

2) CE verification: Regarding the CE verification, we employ the AWG available at an R&S RTO6 oscilloscope to generate the multitone excitation. As detailed in past studies, reducing the crest factor of the excitation signal is crucial to obtain a high dynamic range [5], [12]. Hence, the Schroeder [13] approach has been applied to compute the tone phases to minimize the crest factor. Additionally, two multitones have been created to cover the entire frequency range. The first signal, applied to the low-frequency range, generates a multitone following the limit line $-6\,\mathrm{dB}$ between $50\,\mathrm{kHz}$ and $10\,\mathrm{MHz}$, with a frequency step of $50\,\mathrm{kHz}$. For the frequency range between $10\,\mathrm{MHz}$ and $100\,\mathrm{MHz}$, the frequency separation between tones is $1\,\mathrm{MHz}$.

Regarding the measuring device to conduct the verification, two different instruments have been used. On the one hand, the R&S EMI test receiver model ESW44 has been used as a reference to validate the novel verification approach. Alternatively, the full-time-domain measurement and processing system using digital oscilloscopes have been used. The oscilloscope employed to carry out these measurements has been the R&S RTO6, also used to generate the RF signal for verification. Therefore, we can generate the RF current with a single instrument and entirely validate the test setup.

IV. Validation-Results

In this section, several results are presented. Firstly, the measurements obtained employing the VNA to characterize the reflection coefficient (S_{11}) and the transfer response (S_{21}) for the different setup options are described in subsection IV-A. In subsection IV-B, the verification results employing the R&S ESW44 EMI test receiver are presented, and finally, in subsection IV-C, the oscilloscope results are compared to the conventional EMI test receiver to assess the possibility of employing it instead of the conventional EMI receivers.

A. VNA measurements

In Fig. 4, the reflection coefficient measured at the generator's end is presented for different configurations. In red, the measurement was conducted when the verification setup was according to the ECSS standard with the two current probes. In blue, we show the results when the T and the oscilloscope branch are removed, and in green, when we replace the termination of the jig with the oscilloscope using $50\,\Omega$ as input impedance.

As expected, in the standard case, the return losses are about $9.54\,\mathrm{dB}$, which is the theoretical value when we have a $25\,\Omega$ load. The reason is that the equivalent circuit with the two branches of the system has two parallel $50\,\Omega$ loads which result in an equivalent $25\,\Omega$ termination poorly adapted to the generator impedance. Additionally, at frequencies above $10\,\mathrm{MHz}$, a noticeable ripple is observed at the reflection coefficient. Then, when the oscilloscope branch is removed, and we have either the termination after the jig or the oscilloscope, the system's

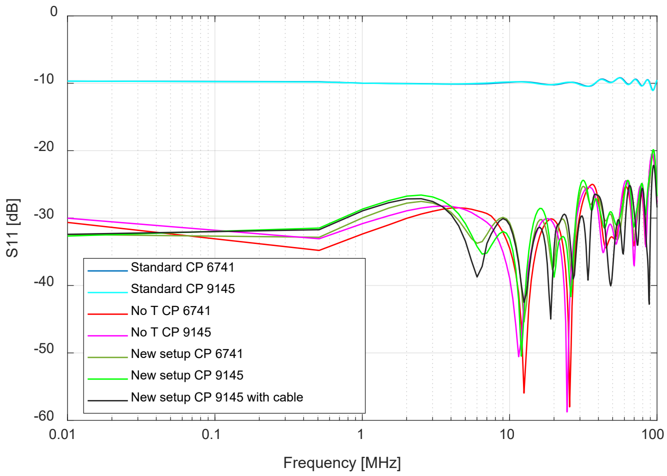

Fig. 4. Reflection coefficient results. In red, standard setup, in blue removing the oscilloscope branch and in green substituting the termination by a measuring device.

matching is improved significantly, more than 10 dB at all frequencies. In summary, employing the new configuration makes the reflection coefficient always lower than -20 dB.

In Fig. 5, the results of the transfer function of the different test setups and branches are shown. The novel setup is measured in blue. On the other hand, in green, we have the transfer function for the two current probes for the standard setup in the jig branch and the transfer function for the oscilloscope branch in red. The results show that with the standard setup, we have quite different attenuation for each branch, especially at frequencies above 10 MHz. This deviation impacts the current sensing as it is done on the oscilloscope branch. At 100 MHz, a difference close to 3 dB between the jig and the oscilloscope branches is identified. On the other hand, with the novel setup proposed, we see a better matching, and the introduction of the cable implies a difference lower than 0.5 dB. Therefore, employing the new setup can be suitable for more precisely obtaining the RF current flowing within the jig.

B. CE Verification

In Fig. 6 and Fig. 7, the results of the CE verification for the standard setup with the two current probes are shown. Regarding the low-frequency range, up to 10 MHz, the results with the two current probes are similar and follow the limit line -6 dB as it is described in the standard. Nevertheless, when the high-frequency-range is evaluated in Fig. 7, the measurements employing the 9174 CP are at the limit line, meaning that we are measuring 6 dB more than the expected value. On the other hand, with the 9145 CP, the results are close to the expected value. The accuracy of the measurement is compromised by the increase of the RBW and the probe factor value. Above 10 MHz, when the RBW is set to 100 kHz, the noise floor is close to the measurement, as shown in Fig. 6.

In Fig. 8, and Fig. 9, we can see the results when the new verification setup is measured. As before, the results for the low-frequency range are accurate. Regarding the high-

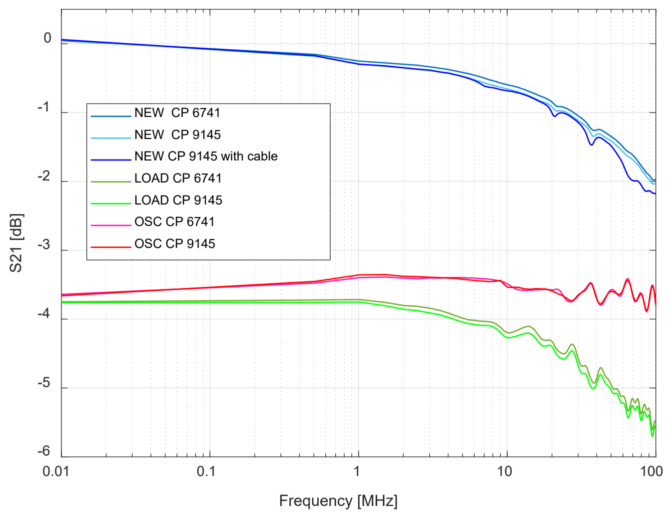

Fig. 5. Transfer function results. In blue, employing the new setup, in red measuring the oscilloscope branch and in green the results at the termination point.

frequency range, the results are similar to the standard setup, but the accuracy of the 6174 current probe has improved. In this occasion, the results are within the ± 3 dB margin, being more accurate as the system matching is better. Otherwise, the results are excellent when the 9145 CP is used, as the sensitivity is 15 dB better in this frequency range than the 6174 CP.

Finally, it is essential to highlight that for the verification measurements, all the results were excellent for the two unique frequency points that should be evaluated according to the ECSS standard procedure. Nevertheless, we have seen that significant deviations can be identified at higher frequencies.

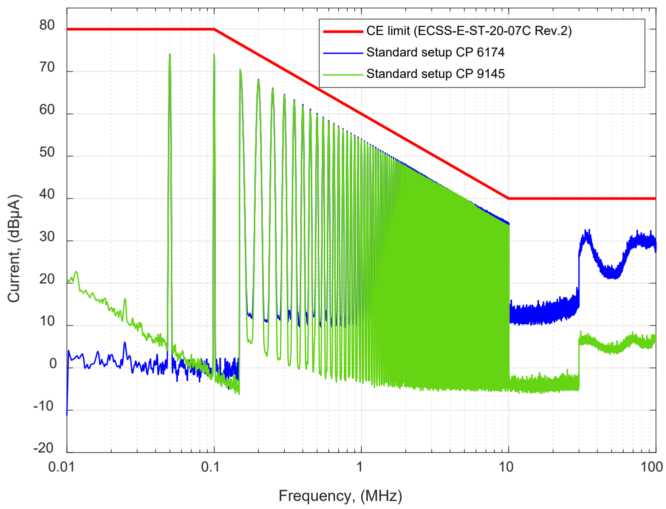

Fig. 6. Low-frequency verification results using the standard verification setup.

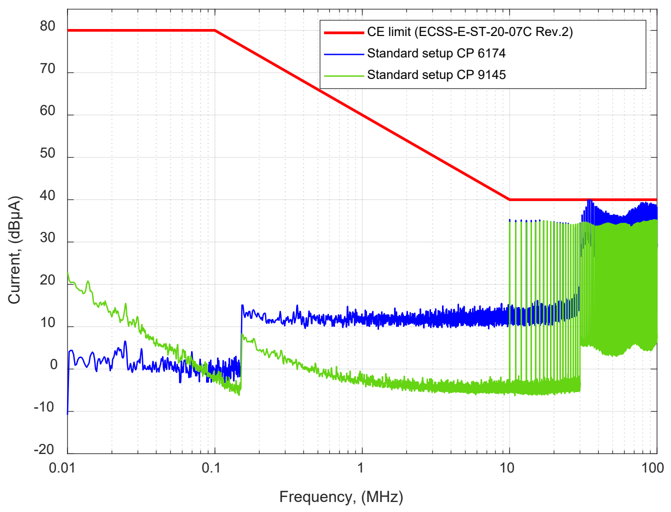

Fig. 7. High-frequency verification results using the standard verification setup.

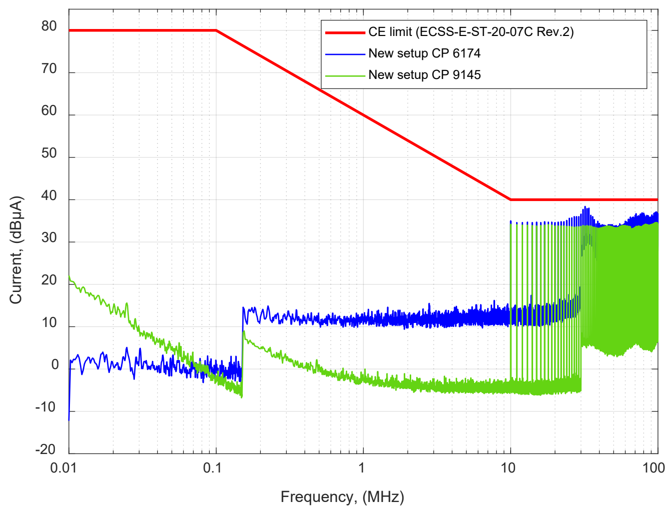

Fig. 9. High-frequency verification results using the novel proposed verification setup.

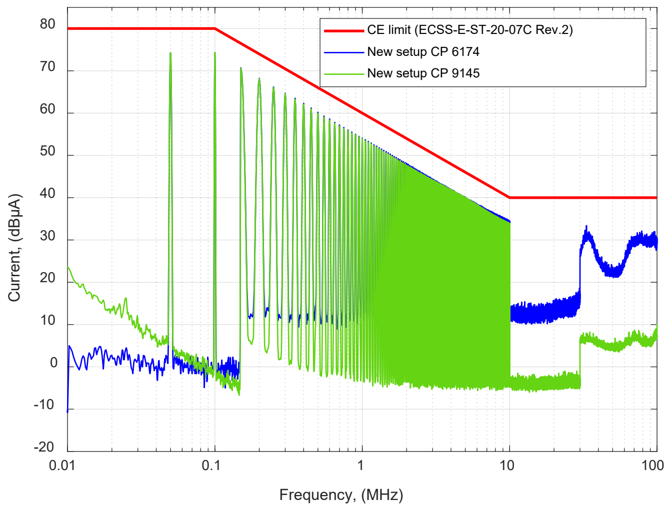

Fig. 8. Low-frequency verification results using the novel proposed verification setup.

C. Full oscilloscope approach

In this subsection, we substitute the EMI receiver for the scope to measure the current. All the frequency range has been successfully evaluated, but in this work, we want to focus on the high-frequency, where higher sensitivity is required. Figure 10 and Fig. 11 compare the receiver and oscilloscope results when the new setup is employed in combination with the 9145 CP. The R&S oscilloscope, combined with adequate post-processing, can obtain excellent results. An excellent dynamic range of up to $60\,\mathrm{dB}$ from the limit line is achieved using the oscilloscope. If we compare the uncorrected value of the excitation signal with the theoretical transfer function, in Fig. 11 we observe that the result obtained with the oscilloscope is closer than $0.5\,\mathrm{dB}$. Therefore, the advanced setup can be employed to perform conducted measurements as it is more accurate than the $\pm 3\,\mathrm{dB}$ needed according to the standard. Moreover, we have several advantages, like just using one instrumentation to generate and measure the current.

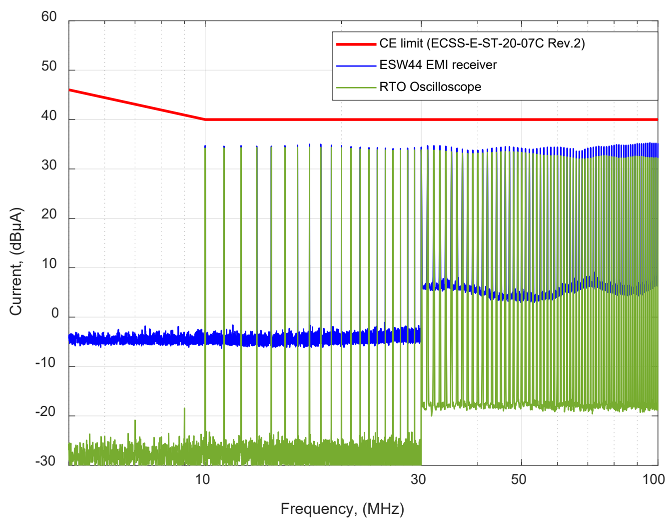

Fig. 10. Measurements comparison between the results obtained with the R&S ESW EMI receiver and the R&S RTO oscilloscope.

V. Conclusions

For the standard CE verification setup, the results obtained using the VNA reveal the significant impedance mismatch and different path losses found between the oscilloscope branch and the jig branch. The reflection coefficient can be improved from values higher than $-10\,\mathrm{dB}$ to $-20\,\mathrm{dB}$ when the oscilloscope measuring parallel branch is removed. Moreover, with the transfer function measurements, we have seen differences in the branches close to $3\,\mathrm{dB}$ at $100\,\mathrm{MHz}$, which can induce verification errors as it is close to the $\pm 3\,\mathrm{dB}$ criteria.

Thanks to the multitone approach using the AWG of the oscilloscope, we have developed a method to evaluate accu-

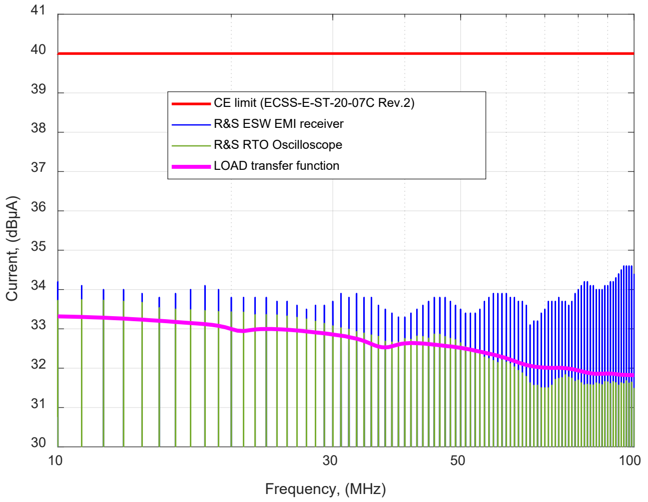

Fig. 11. Zoom on the measurements comparison shown in Fig. 10, including the transfer function found in Fig. 4.

rately and fast the entire frequency band of interest, observing significant differences in the measured current. Although at the two standard verification frequencies, the two probes were within requirements, when the multitone was applied, differences between them arose above 10 MHz, where the RBW was increased to 100 kHz. Using the new methodology, the importance of sensitivity was highlighted.

Finally, the multichannel approach allows us to generate and verify directly and indirectly the current flowing through the jig. This allows to simplify the setup and obtain accurate results comparable to the ones obtained with high-end receivers. Complementary multichannel capability can be used to employ different current probes for better sensitivity in different frequency ranges or to perform CM DM measurements simultaneously.

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