A Compact Millimeter-wave Comb Generator for Calibrating Broadband Vector Receivers

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Abstract—We propose a compact and low-cost waveform source that can be used to calibrate the magnitude and phase response of vector receivers over a bandwidth as large as a few gigahertz. The generator consists of a broadband comb generator followed by a filter and amplifier. As a demonstration, we constructed and calibrated a source suitable for calibrating vector signal analyzers operating between 43 GHz and 46.5 GHz. We then used the source to characterize the response of a commercially available vector signal analyzer. We compared the result with calibrations performed with a general-purpose source.

Index Terms—Calibration, comb generator, oscilloscope, vector signal analyzer, vector signal generator.

I. INTRODUCTION

BROADBAND vector receivers are used to characterize signals that are modulated in phase as well as amplitude such as quadrature amplitude modulation (QAM). A simplified schematic of a vector signal analyzer (VSA, a type of vector receiver) is shown in Fig. 1. The VSA consists of an optional bandpass filter, a downconverter and an analog-to-digital converter. These components cause linear and nonlinear distortion in the signal measurement as demonstrated in, *e.g.*, [1] and [2]. Assuming the instrument is operated in a linear voltage regime, linear distortion dominates the measurement and can be quite significant [1], [2]. If the distortion can be characterized, then digital processing can be used in the VSA to compensate/calibrate the measurement system.

VSA calibration at microwave frequencies is often accomplished by internal calibration routines, however at millimeter-wave frequencies, calibration can be more of an issue. In this work we propose and demonstrate a compact, low-cost waveform generator that can be used to calibrate the response of vector receivers operating in the millimeter-wave frequency regime.

A modulated signal source can be used to calibrate a VSA by assuming that the response of the source is ideal. However, modulated sources can exhibit significant phase errors that increase with modulation bandwidth, as in *eg.*, [3]–[6]. Alternatively the source can be calibrated by use of a sampling oscilloscope and then used to calibrate the vector receiver [5]. However, most currently available general-purpose modulated sources are based on arbitrary waveform generators

Fig. 1. Simplified schematic of a typical vector signal analyzer consisting of an optional bandpass filter (BF), a downconverter (mixer) and an analog-to-digital converter (ADC). The output of the ADC is digitally processed to form, for example, a constellation diagram or a plot of magnitude and phase versus frequency.

and frequency converters. These are typically large, expensive, and susceptible to temperature changes and mechanical shock, making them impractical for field applications such as self-calibration of a VSA.

Comb generators are often used for calibrating large-signal network analyzers (LSNAs). Since they can be based on a variety of nonlinear circuits, they are relatively simple, compact, and inexpensive, but are not as versatile as arbitrary waveform generator-based multisine sources. Some comb generators are based on step-recovery diodes and are sensitive to changes in drive power [7], [8] and temperature [9]. Recently, more stable comb generators have been demonstrated, *e.g.* [8], [10]. These generators produce impulse-like periodic pulses with a broad spectrum.

Because the energy in a train of impulse-like pulses is localized in a very short time interval, the power P_k in the k th tone of the comb is quite low for a given peak voltage V_p . For example, if the pulse repetition frequency is f_0 and the pulse is approximated as rectangular with duration Δ , P_k is given by

$$\begin{aligned} P_k &= \frac{V_p^2 f_0^2}{50 \Omega} \left(\int_{-\Delta/2}^{\Delta/2} \cos(2\pi k f_0 t) dt \right)^2 \\ &\leq \frac{(V_p f_0 \Delta)^2}{50 \Omega} \end{aligned}$$

so that $P_k \leq -81$ dBm for typical parameters $V_p = 0.1$ V, $f_0 = 10$ MHz, and $\Delta = 20$ ps. The noise background of a typical VSA is on the order of -100 dBm or more, giving only a 20 dB dynamic range without averaging. (A dynamic range on the order of 40 dB is required to obtain

cause errors if energy is present away from the main pulse, as is the case in our comb generator system (as shown in Fig. 3). In our case, this extra pulse causes ripple in the spectrum with period of 20 MHz and approximately 0.4 dB peak-to-peak magnitude variation (not resolved in Fig. 4) and 0.3 degree peak-to-peak phase variation.

A typical single waveform measurement is timebase corrected by use of the sequential timebase correction algorithm described in [13]. To facilitate further processing steps that use discrete Fourier transforms, the timebase corrected waveform is interpolated onto an evenly spaced temporal grid over an epoch equal to the period of the comb, that is, $1/f_0$. Measurements of the comb are time consuming and subject to temperature drift. The drift error is efficiently corrected by first Fourier transforming the data and then using the phase-alignment algorithm of [15]. After drift correction, the waveforms are transformed back to the time domain and averaged. In our measurements the rms noise of a single waveform is approximately 1 mV and is reduced to 0.1 mV by averaging 100 measurements. Finally, the averaged measurements are corrected for the response of the oscilloscope and impedance mismatch, as described in [16], to obtain the response of the comb generator. Note that, while the samplers are calibrated by electro-optic sampling techniques through a National Metrology Institute, all other steps described above may be implemented by users.

IV. CALIBRATION OF A VSA AND COMPARISON WITH RESULTS OBTAINED WITH OTHER SOURCES

We used our comb generator system to calibrate the response of a commercially available VSA over a bandwidth of 120 MHz centered at 45 GHz. For comparison, we also synthesized two different multisines with 10 MHz tone spacing centered at 45 GHz [4]. These multisines were calibrated with the oscilloscope in the same way as with the comb generator system and had peak voltages that were comparable to that of the comb generator system. The first multisine had a (nominally) constant phase with respect to frequency and the second had Schroeder phase [17] characteristic.

The VSA was configured to acquire an integer number of cycles of the comb [18]. The input range was set about 4 dB below saturation. Multiple measurements of all signals were acquired, aligned using the technique of [15] and then averaged. Measurements of the comb generator system were aligned to a constant phase of zero.

Results of the measurements are shown in Fig. 5. The phase of the VSA measurements were compared to those measured by the calibrated oscilloscope. Agreement in the characterization of the VSA's phase error indicates that the portable comb system is performing on par with the rack of equipment that constitutes the AWG-based source. To quantify this, we used a paired t -test [19] to compare the mean measured phase $\bar{\phi}_{MS}(f_j) = (\phi_C(f_j) + \phi_S(f_j))/2$ of the two multisine signals with the comb phase $\phi_{comb}(f_j)$. The difference $d_j = \bar{\phi}_{MS}(f_j) - \phi_{comb}(f_j)$ averaged over the 13 frequencies is $\bar{d} = 3 \times 10^{-5}$ and its standard deviation is $s_{\bar{d}} = 0.042$. The test statistic $\bar{d}/s_{\bar{d}} = 7.5 \times 10^{-4}$ produces

Fig. 5. Difference between phase measured with oscilloscope and phase measured with VSA based on measurements with the comb (o) and multisines with fixed phase (Δ) and Schroeder phase ($\times$).

a p -value of 0.999. Therefore, based on the data, we find no significant difference between the multisine- and comb generator-based calibrations.

V. CONCLUSION

We presented a straightforward measurement technique for calibrating vector signal analyzers at millimeter-wave frequencies by use of a calibrated comb generator. The method uses off-the-shelf parts and is portable, allowing users to conduct these calibrations in their own labs, without use of cumbersome, expensive AWG-based sources. The results presented here demonstrate that our prototype millimeter-wave comb generator can be used for calibrating VSAs without a significant degradation in the calibration of the phase response.

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