Precisely Synchronized NVNA Setup for Digital Modulation Signal Measurements at Millimeter-wave Test Bands

Yichi Zhang#, Xiaotao Guo#, Zilong Zhang#, Zhao He#, Aining Yang#
#National Institute of Metrology, China
1zhangyichi@nim.ac.cn

Abstract—In this paper, we present a novel Nonlinear Vector Network Analyzer (NVNA) setup for generating and measuring digital modulation signal at millimeter-wave test bands. The first difference between this setup and commercial VNAs is the use of a user-defined multisine signal as the phase reference, in order to enable more precise synchronization and denser spectral grid. To achieve this, a single 12.5-GHz microwave source is used for generating both the 64-QAM test signal and the phase reference, which not only triggers the arbitrary waveform generator for user-defined intermediate frequency (IF) waveform generation at 3 GHz, but also provides the 25-GHz local oscillator drive after frequency doubling. The second novelty of this work is the use of pulsed-RF signals for NVNA phase calibration. By replacing the 64-QAM IF waveform with a pulsed-RF, tone-by-tone phase calibration on a dense spectral grid of 500 kHz can be easily achieved without any modification of the precisely-synchronized NVNA setup. According to the experimental verification at 28 GHz, the errors of NVNA phase calibration are less than ±2 deg. within the 125-MHz measurement bandwidth, and the measured EVM of 100-MSymbol/s 64-QAM test signal is 2.2% after waveform reconstruction and demodulation.

Index Terms—Digital modulation signal, Error Vector Magnitude (EVM), millimeter-wave, Nonlinear Vector Network Analyzer (NVNA), phase calibration, pulsed-RF

I. INTRODUCTION

Digital modulation signals have been widely used in the modern communication systems, and play a very important role for high-speed transmission [1]. Along with the worldwide promotion of 5G networks, millimeter-wave frequency bands get more and more attention due to the increasing demand of wider bandwidth. As a result, the task of millimeter-wave modulated-signal measurements has become the key for future device characterization and system design, where the main challenge arises from phase spectrum measurements.

Commercial Nonlinear Vector Network Analyzers (NVNA) have been widely used and investigated in recent years due to the capability of complete magnitude and phase measurements of complex radio frequency (RF) signals [2]-[5], however, they are not well suited to the characterization of digital modulation signals at this time because of the degraded performance on dense spectral grids. In this paper, we present a novel NVNA setup for generating and measuring digital modulation signal at millimeter-wave test bands. The novelties of this work include:

(i) In order to enable more precise synchronization and denser spectral grid, a user-defined multisine signal is used as the phase reference, replacing the commercial one based on equally-spaced ultra-fast impulse trains.

(ii) To achieve phase calibration on desired spectral grids, pulsed-RF signals are used as phase standards, which can be easily generated with high accuracy under proposed NVNA setup.

II. NVNA SETUP

As shown in Fig. 1, the proposed NVNA setup for millimeter-wave digital modulation signal generation and measurement comprises a four-port Vector Network Analyzer (VNA), a two-port Arbitrary Waveform Generator (AWG), a continuous-wave (CW) source, and several functional components (power dividers, frequency doublers, mixers, filters, etc.). In practice, the internal sources of VNA can be taken full advantage of to replace the CW signal generator. In this work, however, an external CW source is used to achieve high-power output over 22 dBm, so that desired local oscillator (LO) powers can be obtained to drive the mixers.

A. Test Signal

Following the method of millimeter-wave signal generation described in [6], the desired digital modulation signal under test is obtained through up-conversion based on a non-quadrature mixer. As shown in Figs. 1 and 2, a 64-state quadrature-amplitude-modulated (64-QAM) signal is originally generated at 3 GHz by an AWG. Afterwards, it is up-converted to the 28-GHz millimeter-wave band by mixing a 25-GHz LO signal. To achieve precise synchronization of the various signals, the CW source is used to provide a 12.5-GHz signal, which not only serves as the clock for the AWG (working with an effective sampling rate of 25 GSample/s), but also offers the 25-GHz LO drive after frequency doubling.
The 64-QAM test signal is designed to have a symbol rate of 100 MSymbol/s, and a bandwidth of 125 MHz (root-raised-cosine roll-off factor of 0.22). To make sure that at least three symbols can be measured at each constellation point, the length of this 64-QAM signal is 200 symbols (a period of 2 μs). In this way, the frequency-domain measurement target has at least 251 tones on a spectral grid of 500 kHz.

In this paper, pulsed-RF signals with a duty cycle of 50% have been found valid serving as phase standards. As shown in Fig. 3, we only use the sideband components to perform phase calibration, where the spectral grid is twice of the repetition frequency. To perform the phase calibration at measurement tones (i.e., 28 GHz ± 0 MHz, ±0.5 MHz, ±1 MHz ...), the carrier and repetition frequencies of pulsed-RF generated by the AWG have to be 3.00025 GHz and 250 kHz.

B. Phase Reference Signal

As shown in Fig. 2, the phase reference signal is obtained in a similar way as the 64-QAM test signal. The main difference between the phase reference signal and the test signal is the design of spectrum. Without loss of generality, Schroeder phase relation [7] and constant magnitude are used in this paper to generate a 361-tone multisine at 3-GHz (180-MHz bandwidth on a spectral grid of 500 kHz), which is later up-converted to the 28-GHz millimeter-wave test band. One of the key points of our NVNA setup is the use of coherent RF drives for the up-conversion of both the test signal and the phase reference signal. Only in this way, precise synchronization can be achieved.

As shown in Fig. 1, the test signal and the phase reference signal are simultaneously measured with Port 1 and 3 of the VNA. According to the measurement principle of NVNA [8], the raw measurement $X_{\text{Raw}}$ is derived by (1).

$$X_{\text{Raw}} = b_i \frac{|b_j|}{b_j} \angle(b_i/b_j)$$

(1)

C. Phase Calibration Signal

To perform the phase calibration of our NVNA setup, a novel methodology is developed in this work. In the stage of phase calibration, the 64-QAM test signal is replaced with a pulsed-RF signal. There is no hardware or parameter setting modification but only the operation to upload the pre-edited pulsed-RF waveform (working with the same sampling rate of 25 GSample/s) to the AWG. In this way, a standard signal is up-converted to the millimeter-wave test band as shown in Fig. 2, whose ideal phases are used for phase calibration.

III. Experiments

A. Experimental Setup

Using the equipments and devices listed in Table 1, we establish an experimental setup as shown in Fig. 4. To inspect the performance of our NVNA setup for measurement and demodulation of digitally modulated signals, an additional Vector Signal Analyzer (VSA) is particularly used for comparison. It is worth mentioning that the symbol rate of 64-QAM test signal is restricted to 100 MSymbol/s in this work only because of the 140-MHz demodulation bandwidth limitation of the VSA. As a matter of fact, the proposed NVNA setup is capable of GSymbol/s demodulation in practice.
B. Frequency-domain Measurements

Frequency-domain magnitude measurements of the test signal, the phase reference, and the phase calibration standard are shown in Fig. 5. Although only the 28-GHz test band is of interest in this work, full-band measurements are displayed to confirm the illustration of signal generation in Fig. 2.

![Fig. 5. Magnitude measurements of the 64-QAM test signal, the multisine phase reference signal, and the pulsed-RF phase calibration signal.](image)

Fig. 5. Magnitude measurements of the 64-QAM test signal, the multisine phase reference signal, and the pulsed-RF phase calibration signal

The comparison between NVNA measurements and the ideal spectrum of designed 64-QAM test signal is shown in Figs. 6 and 7. It is obvious that the magnitude and phase errors arising from AWG, NVNA and mixer distortions are less than ±0.5 dB and ±2 deg. respectively. This result also gives us the confidence to use the pulsed-RF for phase calibration.

![Fig. 6. Magnitude comparison between NVNA measurements and the ideal spectrum of designed 64-QAM signal. (a) Magnitude. (b) Deviation.](image)

Fig. 6. Magnitude comparison between NVNA measurements and the ideal spectrum of designed 64-QAM signal. (a) Magnitude. (b) Deviation.

![Fig. 7. Phase comparison between NVNA measurements and the ideal spectrum of designed 64-QAM signal. (a) Phase. (b) Deviation.](image)

Fig. 7. Phase comparison between NVNA measurements and the ideal spectrum of designed 64-QAM signal. (a) Phase. (b) Deviation.

C. Time-domain Comparison

In the time domain, the reconstructed waveform based on NVNA measurements is also compared with the designed 64-QAM waveform uploaded to the AWG. To achieve that, the waveform is reconstructed after moving the spectrum from 28 GHz to 3 GHz. As shown in Fig. 8, the two waveforms fully agree with each other, where a small delay of the carrier phase is added to facilitate the observation.

![Fig. 8. Comparison between the reconstructed waveform based on NVNA measurements and the designed 64-QAM signal uploaded to the AWG.](image)

Fig. 8. Comparison between the reconstructed waveform based on NVNA measurements and the designed 64-QAM signal uploaded to the AWG.

![Fig. 9. Comparison of the EVM results between NVNA and VSA.](image)

Fig. 9. Comparison of the EVM results between NVNA and VSA.

D. Demodulation

To confirm the validity of proposed NVNA setup for characterizing digital modulation signals, we further demodulate the reconstructed waveform based on spectral measurements. Fig. 9 shows the comparison between constellation diagrams derived by NVNA and VSA. The consistency of error vector magnitude (EVM) results proves that the proposed phase calibration method is valid and applicable. From our perspective,
it is reasonable to expect that the NVNA setup should have lower EVM measurement than the VSA, because the synchronization of signals is more precise than using a 10-MHz reference [6]. From the application perspective, pre-distortion techniques can also be used to obtain more accurate digital modulation signals at millimeter-wave bands, by predistorting the signal uploaded to the AWG [6].

![Graphs showing phase deviations for different bandwidths.](image)

**Fig. 10.** Deviation between phase calibration results using pulsed-RF signals with different carrier frequencies. (a) Magnitude spectra. (b) When 200-MHz bandwidth is used by each pulsed-RF. (c) When 80-MHz bandwidth is used. (d) When 40-MHz bandwidth is used.

IV. PHASE CALIBRATION ERROR

Thanks to the high-speed AWG used in this work, the distortions of pulsed-RF signals mainly exist near the rising and falling edges with a short duration. When the repetition rate is high (e.g., 1 MHz or above), the phase and magnitude errors of pulsed-RF signals are remarkable, and the ideal values cannot be used as calibration standards. Fortunately, the magnitude of "error vector" drops by 6 dB in theory for each time the repetition rate reduces by half. In this way, when the repetition rate of pulsed-RF is low (e.g., 250 kHz or less), the phase errors become negligible, and the ideal phase spectrum can be used for calibration purpose. This situation can be easily proven by oscilloscope-based measurements at sub-6GHz microwave band.

To confirm the validity and accuracy of proposed phase calibration method based on pulsed-RF signals, we also generate seven pulsed-RF signals with different carrier frequencies (i.e., 27.94025, 27.96025, 27.98025, 28.00025, 28.02025, 28.04025, and 28.06025 GHz, see Fig. 10 a), and investigate the deviation between phase calibration results. As shown in Fig. 10 b, when a bandwidth of 200 MHz is used by each pulsed-RF, the deviation is up to ±2 deg. This is reasonable because the phase error increases when the power drops (the contribution of "error vector" becomes noticeable). If the available bandwidth is limited to 80 MHz, the deviation can be decreased to ±1 deg (see Fig. 10 c). Furthermore, a calibration error less than ±0.5 deg. can be anticipated when only the center 40-MHz bandwidth is utilized (see Fig. 10 d). This result also reveals the possibility of using proposed NVNA setup for GSymbol/s demodulation, where tens of pulsed-RF signals can be used for wideband calibration based on spectral stitching [9] (alignment is even unnecessary due to the precise synchronization of various signals [10]).

V. CONCLUSION

This paper presents a novel NVNA setup for generating and measuring digital modulation signal at millimeter-wave test bands. Precise synchronization of the various signals is the key for achieving stable phase measurements on dense spectral grids. Moreover, a novel phase calibration method, which is based on pulsed-RF signals and specially applied to the proposed NVNA setup, is also developed to meet the requirement of dense-spectral-grid application conditions.

ACKNOWLEDGMENT

Project funded by National Key R&D Program of China under Grant 2017YFF0206202 and National Natural Science Foundation of China under Grant 61701469.

REFERENCES