A Precision Millimeter-Wave Modulated-Signal Source

Kate A. Remley, Paul D. Hale, Dylan F. Williams, and Chih-Ming Wang

NIST Electromagnetics Division, Boulder, CO, 80305, USA

Abstract — We develop and characterize a modulated-signal source for use at millimeter-wave frequencies. Components within the source are phase-locked by a 10 GHz reference source to minimize drift and improve synchronization. The complex frequency response of the source is characterized with a calibrated sampling oscilloscope. We illustrate use of the source by determining the phase error of a vector signal analyzer. [1]

Index Terms — Microwave measurement, millimeter-wave source, modulated signal, sampling oscilloscope, wireless system.

I. Introduction

The large increase of wireless data transmission brought about by the use of smart phones and other mobile devices has led to a shortage of radio spectrum. As an example, Cisco's 2011 mobile forecast predicts global data transfer on the order of 6 million terabytes per month worldwide by 2015, up from 0.24 million terabytes in 2010 and 0.6 million terabytes in 2011 [1]. The resulting "spectrum crunch," is a key driver for investigating the use of higher-frequency spectrum for wireless telecommunications.

Utilization of millimeter-wave frequencies for mobile applications may soon become a reality, enabled, in part, by new silicon-based devices that now have adequate power and speed for wireless applications at millimeter-wave frequencies. Silicon technology allows high levels of integration for components such as antennas, transmitters, and receivers, at relatively low cost. As such, the U.S. military, notably through the Defense Advanced Research Projects Agency's (DARPA) Efficient Linearized All-Silicon Transmitter ICs (ELASTx) program [2-4] and various commercial entities [5] have started to investigate the development of millimeter-wave wireless technology.

Important in the development of any new electronic technology is the ability to measure and quantify its performance. However, hardware verification at millimeter-wave frequencies is challenging. The precision of modulated-signal test methods necessarily increases linearly with frequency in order to maintain the same level of accuracy, while accounting for increased electrical parasitics, more precise circuit timing, and model complexity, among others.

To address these issues and facilitate the development of wireless systems at higher frequencies, we have developed a precision millimeter-wave modulated-signal source for use as a transfer standard in calibrating vector receivers. Vector receivers, such as vector signal analyzers, real-time spectrum analyzers, and real-time oscilloscopes, are often used to verify wireless device and system performance.

The source, currently operating with a center frequency of 45 GHz, may be tuned to other millimeter-wave bands by selection of different hardware components, as discussed below. It has a usable modulation bandwidth of approximately 2 GHz, and generates various digitally modulated waveforms and multisine [6] calibration signals. Traceability to the volt, meter, and second is provided by a calibrated sampling oscilloscope through a photodiode transfer standard characterized with an electro-optic sampling system [7].

II. Modulated-Signal Source

A. Source hardware

The source is based on a fast (up to 22 GS/s) commercially available arbitrary waveform generator (AWG), as shown in the block diagram of Fig. 1. The modulation bandwidth of the AWG is nominally 5 GHz when operating with a center frequency of 5 GHz. We upconvert the 5 GHz intermediate frequency supplied by the AWG to a center frequency of 45 GHz by use of a harmonic mixer. Not shown in the block diagram are filters, isolators, and attenuators that filter the upconverted image, eliminate harmonics of the local oscillator (LO), and reduce reflections, spurs and distortion.

As shown in Fig. 1, the 10 GHz continuous-wave source serves as the local oscillator for the frequency converter. Through power splitters, it is also the clock for the AWG and is used for time-base correction of the sampling oscilloscope measurements. This distribution of the 10 GHz reference is a key feature of the source, enabling more precise synchronization of the various signals within the source than could be obtained through the use of a standard 10 MHz reference. The distributed 10 GHz reference also allows us to characterize the source with the sampling oscilloscope, overcoming limitations of the oscilloscope and time base.

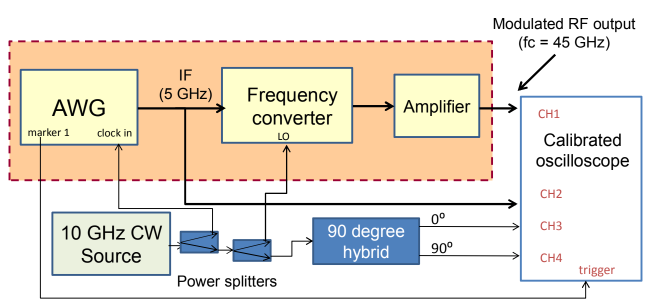

Fig. 1: Block diagram of the precision millimeter-wave modulated-signal source (shaded) and equivalent-time sampling oscilloscope.

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B. Characterization of the source

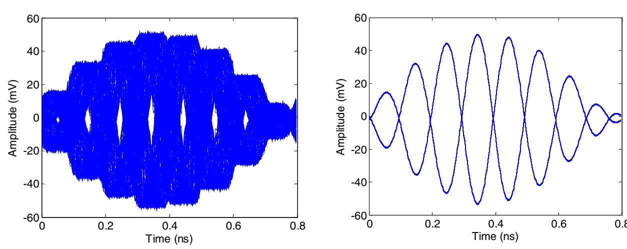
We have characterized the magnitude and phase response of the millimeter-wave modulated-signal source using a calibrated sampling oscilloscope [8-10]. The sampling oscilloscope restricts our measurements to repetitive waveforms, including multisines and digitally-modulated signals such as pseudo-random bit sequences (PRBS), which are commonly used in wireless tests.

Several corrections to the oscilloscope measurements are necessary to accurately characterize the signal emanating from the modulated-signal source. These include: (1) correction of jitter, drift, and systematic errors in the oscilloscope's time base [8, 11] (see Figure 2); (2) correction for the oscilloscope's internal response [7] (see Figure 3); and (3) impedance mismatch correction of the oscilloscope's sampling head and the modulated-signal source. Also, time-domain averaging is carried out to improve the dynamic range of the measurement to approximately 60 dB at 45 GHz.

Denoting the oscilloscope's complex frequency response as $H(f)$, and the frequency-dependent impedance mismatch of the source and oscilloscope as $\Gamma(f)_{\text{source}}$ and $\Gamma(f)_{\text{scope}}$, respectively, the corrected measurement of the voltage $v(f)_{\text{source}}$ at the output of the modulated-signal source may be given by [12]

$$v_{\text{source}} = v_{\text{source,raw}}\left(\frac{1-\Gamma_{\text{source}}\Gamma_{\text{scope}}}{H}\right), \qquad (1)$$

where the frequency dependence of all quantities has been suppressed.



(a) (b)

Fig. 2: Equivalent-time oscilloscope measurement of several envelope cycles of a periodic modulated signal overlaid (a) before and (b) after time-base distortion correction. Jitter and time-base discontinuities are corrected in (b) by use of the method in [8].

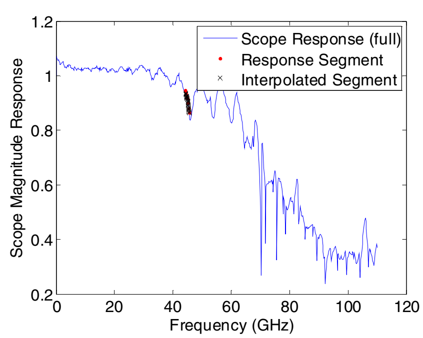
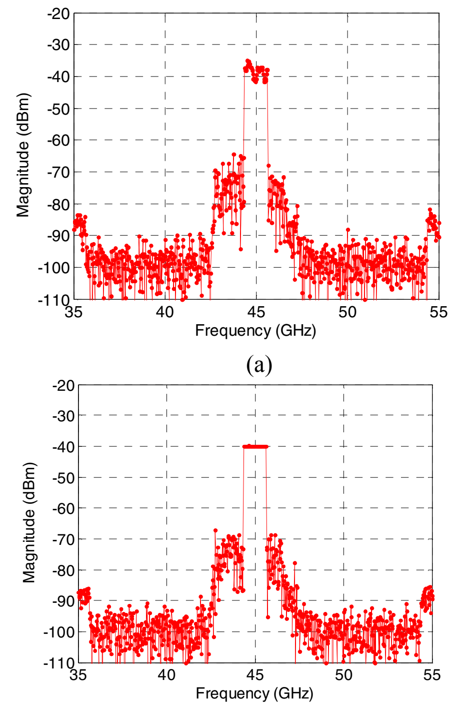


Fig. 3: Measured magnitude response of a 50 GHz sampling oscilloscope head. The symbols illustrate the frequency range over which measurements of the modulated-signal source must be corrected, both in magnitude and phase.



(a)

(b)

Fig. 4: Measured magnitude response of millimeter-wave modulated signal source (a) before and (b) after predistortion.

Figure 4 shows the magnitude response of the modulated-signal source when generating a 1.25 GHz bandwidth, 51-tone Schroeder multisine [6]. In order to capture several samples per cycle at the 45 GHz center frequency, the oscilloscope time step was set to 2.5 ps. With a time record corresponding to the multisine envelope period of 40 ns, 16,000 points were captured and corrected. When recording digitally modulated PRBS signals, much longer time records may be required, so that the techniques in [11] are employed.

Nonidealities in the AWG, frequency upconverter and other components in the source introduce both magnitude and phase distortion into the signals that it generates. In Fig. 4(a), AWG quantization noise is also evident in the frequency bands adjacent to the modulated signal. Not shown is an RMS phase error of approximately 10 degrees across the band.

Because the modulated-signal source is based on an AWG, we may also predistort the waveform that we upload into the generator to correct for the source's nonideal hardware. In Figure 4(b), we have iteratively predistorted the measured complex frequency coefficients from the source, correcting for both linear and nonlinear distortion. This allows us to create a waveform with desired characteristics at the 45 GHz output reference plane of the signal generator. This "reference" waveform may then be used to calibrate other vector receivers.

III. Phase Error of a Vector Signal Analyzer

To illustrate use of the characterized source, we measured various multisine signals with the calibrated sampling oscilloscope and with a commercially available vector signal analyzer having a 160 MHz analysis bandwidth. In Fig. 5, we plot the phase error, defined as the difference between the detrended [13] VSA-measured phases and the reference sampling-oscilloscope-measured phases. We see that the phase error introduced by the VSA is less than 2° over the 120 MHz modulation bandwidth of the measured signal.

In Figure 5, the constant magnitude, constant phase multisine has a higher peak-to-average-power ratio than the constant magnitude, Schroeder phase multisine [6]. The curve labeled “comb” denotes the measurement of a comb generator, having a high peak-to-average-power ratio as well.

By use of a paired *t*-test [14], we compared the mean multisine phase with the comb generator phase at each frequency. The difference, averaged over the 13 frequencies, was 3×10^{-5} and its standard deviation was 0.042. Their ratio of 7.5×10^{-4} led to a *p*-value of 0.999. Therefore, based on the data, we do not find a significant difference between the multisine- and comb-based phase errors. A similar result was seen for the magnitude error.

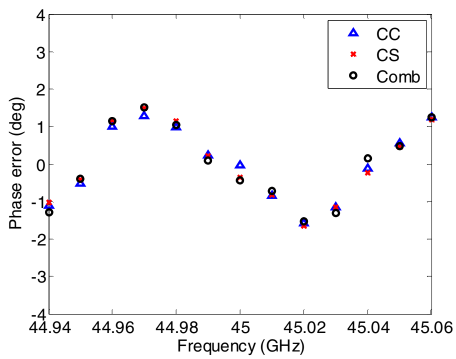


Fig. 5: Measured phase error of a vector signal analyzer. The constant magnitude, Schroeder phase (CS) and constant magnitude, constant phase (CC) multisines were generated by the millimeter-wave modulated-signal source.

This result demonstrates that we are able to measure the linear frequency response of the vector signal analyzer repeatably using the millimeter-wave source described here. Unlike the work of [15], our vector receiver characterization was conducted at millimeter-wave frequencies, on unaliased waveforms with wide modulation bandwidths, and was fully mismatch and response corrected.

IV. Conclusion

We described a precision modulated-signal source capable of generating repetitive wideband digitally modulated signals. The complex frequency response of the source was quantified by a calibrated receiver, enabling traceability in the measurement of modulated signals at millimeter-wave frequencies. We demonstrated the utility of the source in the characterization of a vector receiver.

V. Acknowledgments

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