

Low Distortion Amplification of Multisine Signals Using a Time-Frequency Technique

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Abstract—A novel time-frequency technique is presented for reducing intermodulation distortion when a multisine signal is applied to a nonlinear radio-frequency amplifier. A fast periodic switch is used to apply only one spectral tone at a time to the nonlinear amplifier. A bandpass filter following the amplifier removes switching spurious signals, leaving only the linearly amplified multisine signal at the output. The technique is used to linearize the response of a broadband amplifier with a four-tone uniform phase input signal centered at 465 MHz. The technique yields a 14 dB improvement in intermodulation distortion in comparison to the response of the original four-tone signal at the same output power.

Index Terms—Time division multiplexing, time division switching, time-frequency analysis, bandpass filters, passive filters, distortion, amplifier distortion, intermodulation distortion, nonlinear distortion, amplitude modulation.

I. INTRODUCTION

Multisine signals are commonly used for laboratory characterization of nonlinear amplifiers because of their well understood amplitude modulation characteristics [1], but generating a linear high power multisine signal is challenging due to the wide amplitude variation of the signal. Application of linearization techniques such as predistortion correction, feedforward cancellation, or Cartesian feedback [2] provide 10 dB–40 dB improvement in intermodulation performance; however, these techniques respectively require iterative signal processing, feedforward circuits, or stable feedback networks to provide input signal correction. Therefore, it is desirable to develop noniterative open loop techniques with straightforward implementation requirements for generating linear high power signals.

The amplitude modulation of a multisine signal arises from the instantaneous sum of amplitudes at any given moment in time. Intermodulation distortion results when an amplifier clips or limits the high value peaks that occur at moments in time where the sinusoidal signals add constructively. A new time-frequency technique is presented that prevents the generation of intermodulation distortion by presenting only a single tone of the multisine signal to the nonlinear amplifier at a time, thereby effectively eliminating the interaction between tones which creates amplitude modulation. The tones are switched at a much faster rate than the period of the modulation, such that the desired amplitude modulation information is not altered, lost, or distorted. However, the fast switching process

consequentially creates a wideband signal containing many spectral images of the original signal at offsets related to the switching period. Therefore, a bandpass filter is required after the amplifier to select the original signal and reject the undesired images. The technique is applied to a four-tone, zero initial phase, multisine signal with 100 kHz tone spacing centered at 465 MHz and a solid-state broadband amplifier. The time-frequency technique yields a 14 dB reduction in intermodulation distortion when compared to the original signal at the same output power.

II. TIME MULTIPLEXED MULTISINE THEORY

The time multiplexed multisine architecture used to minimize intermodulation distortion is shown in Fig. 1. It consists of a switch that selects between four different inputs with four different frequencies, the RF amplifier, and a bandpass filter (BPF). The switch may be either a solid-state multipole switch or implemented in DSP if a high sample rate arbitrary waveform generator is available.

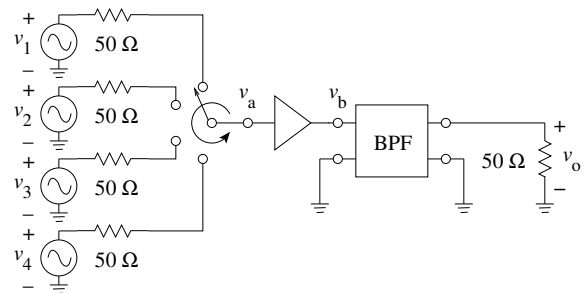


Fig. 1. Time multiplexed multisine circuit architecture: switch-amplifier-filter circuit.

Let the input signal $v_m(t)$ be a four-tone multisine signal given by

$$v_m(t) = \sum_{m=1}^4 A_m \cos(\omega_m t + \phi_m). \quad (1)$$

For this work, the four-tone multisine has a uniform amplitude of A_0 and zero initial phase $\phi_m = 0$ with a resulting peak-to-average envelope variation of 6 dB, which is 3 dB higher than a two-tone signal.

The switching frequency is ω_s with 25% of the switching period allotted to each tone. The frequency spectrum of v_a , the time multiplexed multisine signal [3], is given by

$$V_a(\omega) = A_0 \sum_{m=1}^4 \sum_{k=-\infty}^{+\infty} \left\{ \frac{\sin(k\pi/4) e^{-j\omega T[m-1]/4}}{\left[\begin{array}{c} \delta(\omega - k\omega_s - \omega_m) + \\ \delta(\omega - k\omega_s + \omega_m) \end{array} \right]} \times \right\} \quad (2)$$

The unfiltered, amplified spectrum is shown in Fig. 2. Overlaid is the amplitude response of the bandpass filter.

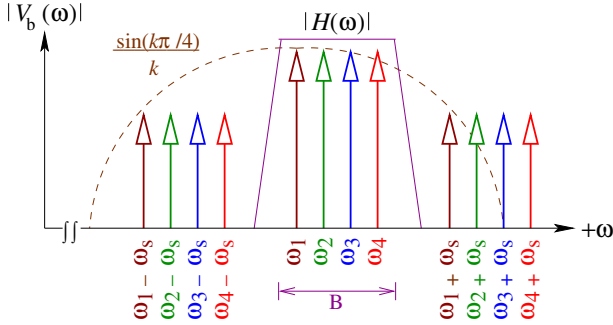


Fig. 2. Spectrum of switched-tone signal, before amplifier and filter.

If the switching frequency is chosen to be greater than the bandwidth of the filter, $\omega_s \gg B$, the filter removes all spectral components above and below the original tones. If the amplifier gain is assumed to be a constant G_0 over a narrow frequency band of interest, then the resulting filtered spectrum is given by

$$V_o(\omega) = \frac{G_0 A_0}{4} \sum_{m=1}^4 \left\{ \frac{H(\omega_m) e^{-j\omega T[m-1]/4}}{\left[\begin{array}{c} \delta(\omega - \omega_m) + \\ \delta(\omega + \omega_m) \end{array} \right]} \times \right\}. \quad (3)$$

If the filter transfer function is given by

$$H(\omega) = |H(\omega)| \exp\{j\theta(\omega)\}, \quad (4)$$

then the time-domain equivalent of $V_o(\omega)$ is

$$v_o(t) = \frac{G_0 A_0}{4} \sum_{m=1}^4 |H(\omega_m)| \cos \left[\begin{array}{c} \omega_m t + \theta(\omega_m) \\ -\omega_m \frac{T}{4} [m-1] \end{array} \right]. \quad (5)$$

The output of the circuit of Fig. 1 is thus a superposition of the original four sinusoids without time-multiplexing. The amplitudes of the tones have been reduced by the switch duty cycle and the filter response, and increased by the amplifier gain. The phases of the tones depend upon the filter phase response and the time delay for each tone to be applied to the amplifier in the switching sequence. The circuit achieves minimum nonlinear distortion because the signal applied to the amplifier is constant in amplitude and because only one tone is applied to it at any one time.

III. MEASUREMENTS

A measurement system which demonstrates the minimal-distortion concept is shown in Fig. 3. The Agilent E8267C functions as the tone generator and switch; it outputs four tones, spaced 100 kHz apart, centered on $f_0 = 465$ MHz, and time-multiplexed with a switching frequency of $f_s = 10$ MHz. This waveform is a digitized version of the ideal switching waveform v_a with a bandwidth of 80 MHz; this bandwidth contains at least the first lobe of the sinc function given by (2). The RFMD RF2320 is a broadband amplifier with a gain of $G_0 = 16.6$ dB in the neighborhood of 465 MHz. The filter is a low-ripple Chebyshev design, 5th order, with an insertion loss of 6.0 dB. A 10-dB attenuator is used to lower the signal power to a level that may be captured without damaging the oscilloscope's input port. The Tektronix TDS684B oscilloscope records the time-domain waveforms, while the Agilent E4445A spectrum analyzer records the frequency-domain data.

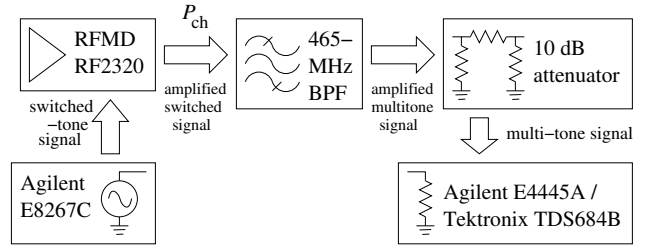


Fig. 3. Test setup block diagram.

The switched-tone to multi-tone conversion shown mathematically in Section II is illustrated by measured data in Figs. 4 and 5. The switched-tone input to the amplifier v_a is shown in Fig. 4(a); its spectrum is displayed in Fig. 5(a). This time-domain waveform has a nearly-constant RF envelope and its spectrum is wideband. The multi-tone output from the amplifier v_o is shown in Fig. 4(b); its spectrum is displayed in Fig. 5(b). This time-domain waveform resembles a steady-state four-tone interference pattern and its spectrum is narrowband. The result given by (5) is confirmed.

A significant reduction in intermodulation distortion is demonstrated across comparisons of measured power. Third-order intermodulation (IM3) power levels recorded when the filter is absent are given in Table I. Here, the switched-tone output is compared against its multi-tone counterpart, where each of the sources $v_1 \dots v_4$ are connected in series without switching, and each sinusoid has an initial phase of $\phi_m = 0$.

Both switched-tone and multi-tone measurements have the same total amplified channel power P_{ch} ; although, it should be noted that the total average power for the wideband switched signal is higher than the desired channel power. For the four data points listed, the IM3 levels are consistently lower in the switched-tone case than in the multi-tone case. For output channel powers between 10 and 19 dB, time-multiplexing

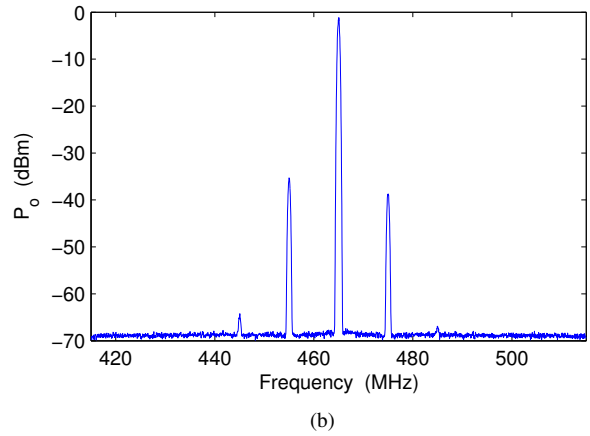
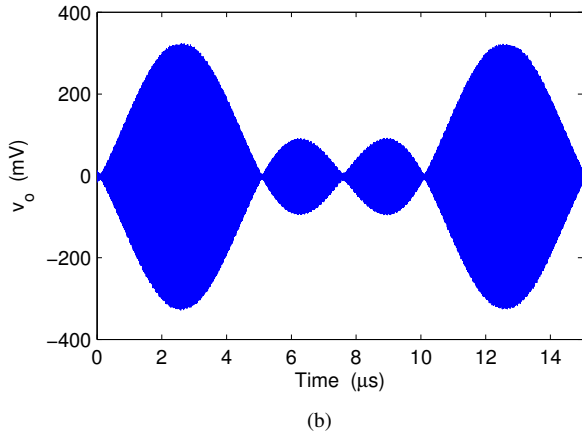
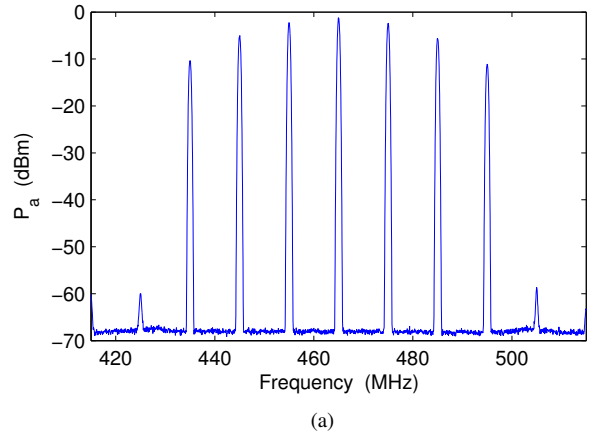
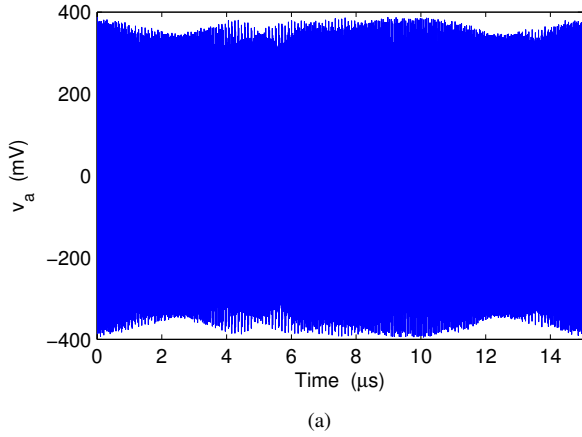


Fig. 4. Measured time-domain comparison of switched-tone to multi-tone conversion, $P_{ch} = 16.0$ dBm: (a) input to amplifier, (b) output from filter, after 10-dB attenuation.

Fig. 5. Measured frequency-domain comparison of switched-tone to multi-tone conversion, $P_{ch} = 16.0$ dBm: (a) input to amplifier, wideband, (b) output from filter, narrowband. There are four tones embedded in each visible peak.

the four-tone signal provides an improvement in distortion between 14.4 and 16.0 dB.

The two spectral plots of Fig. 6 display the distortion reduction when the filter is present. The amplified, filtered steady-state multi-tone signal is given in Fig. 6(a), while the switched-tone output is given in Fig. 6(b). A distortion level of 31.3 dBc is seen in the multi-tone case, whereas a distortion level of 45.2 dBc is seen in the switched-tone scenario. By time-multiplexing the four-tone signal and filtering after the RF amplifier, a 13.9 dB improvement in nonlinear distortion is achieved.

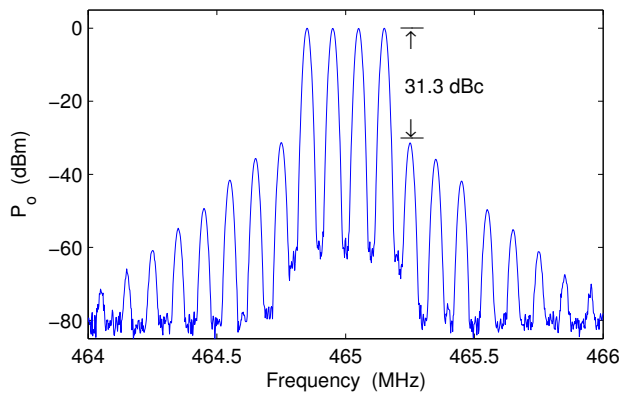
TABLE I
EFFECT OF SWITCHING ON AMPLIFIED 4-TONE SIGNAL

| Channel Power (dBm) | Multi-Tone IM3 (dBc) | Switched-Tone IM3 (dBc) | Delta (dB) |
|---------------------|----------------------|-------------------------|------------|
| 19 | -23.6 | -39.6 | 16.0 |
| 16 | -32.1 | -46.5 | 14.4 |
| 13 | -42.1 | -56.5 | 14.4 |
| 10 | -50.2 | -65.0 | 14.8 |

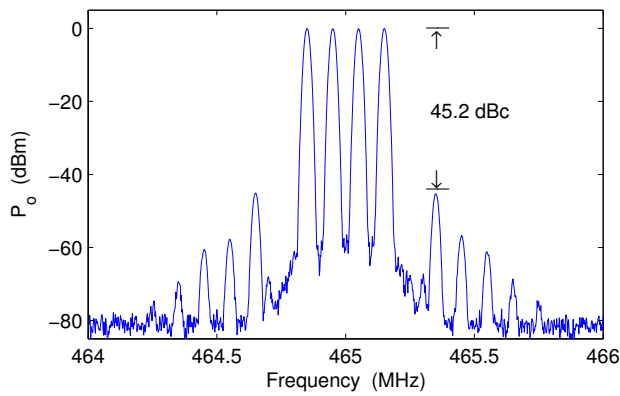
IV. DISCUSSION

The reduction of distortion in the switched-tone scenario is understood by comparing the signals applied to the amplifier in each case. Under steady-state multi-tone conditions, the RF envelope of the input to the amplifier varies periodically. For four tones, the peak-to-average ratio (PAR) of this variation is 6 dB. When the RF envelope is relatively small, the amplifier achieves the expected small-signal gain of 16.6 dB. When the RF envelope applied to the amplifier is larger, however, the amplifier output is slightly compressed, achieving a gain of slightly less than the ideal small-signal value. This mismatch in gain over the full period of the four-tone signal is the primary source of the intermodulation distortion of Table I and Fig. 6.

In the switched-tone case, however, the envelope is (ideally) constant, with a PAR of 0 dB. Since the RF envelope variation is considerably less than the steady-state case, the intermodulation produced by variations in gain over the period of the switched-tone signal is significantly reduced. This accounts for the 14.4 to 16.0 dB difference in distortion between the reduced-system outputs of the second and third columns of



(a)



(b)

Fig. 6. Switching and filtering the 4-tone signal, $P_{ch} = 16.0$ dBm: (a) steady-state multi-tone, amplified, (b) time-multiplexed, amplified.

Table I and the 13.9 dB difference in distortion between the full-system outputs of Fig. 6(a) and Fig. 6(b). Filtering is a purely linear process across the signal levels used in these experiments; thus, no distortion is added to the system by the BPF.

V. CONCLUSION

A novel time-frequency method for minimizing amplitude modulation distortion from a radio-frequency front-end has been presented. Amplitude modulation was produced by applying a switched-tone signal to a narrowband filter. Distortion caused by amplifying this amplitude modulated signal is minimized by applying the constant-amplitude switched-tone signal before the amplifier, and filtering out the switching harmonics after the amplifier. A switched four-tone test shows an improvement in distortion of 14 dB in comparison to testing with the original four-tone test signal of equivalent channel power.

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