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Determination of Multisine Coefficients for Power Amplifier Testing

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Abstract

This paper proposes a setup for a best multisine design method that uses a time-domain optimization. The method is based on minimization of the time-domain error, so its resulting multisine has a very accurate ACLR estimation. This is because its probability distribution and sample-to-sample correlation are close to those of the original signal, which are crucial for the testing of nonlinear power amplifiers. In addition, a hyperbolic-tangent function is introduced to control the ripple of tone magnitudes within signal bandwidth. For the verification, multisines were generated and compared for many aspects such as normalized error, in-band ripple, and ACLR estimation. Test results with different numbers of tones provide supporting evidence that the suggested multisine design has better ripple suppression, by up to 7 dB, and better accuracy, by up to 0.2 dB, when compared to the conventional method. The accuracy of the ACLR was improved by about 5 dB when the number of tones was 4. The suggested method improves the ACLR estimation performance of multisine testing due to its closer resemblance to the target modulation signal.

Key words: Least Squares, Multisine, Power Amplifier.

Ⅰ. Introduction

The methods used to generate the testing signal for linearity testing of power amplifiers (PAs) are receiving increasing attention as they represent one way to reduce testing time and costs [1]. In particular, the multisine stimulus is being studied as a replacement for the original modulated signal because of its analytic clarity and the relatively low cost of signal generation [1]～[3]. In most of the multisine design methods suggested so far, the coefficients of each tone are set either by the Discrete Fourier Transform (DFT) of the target signal or by the probability distribution of the sample magnitudes [2], [3]. However, these approaches do not guarantee the best resemblance of the multisine to the target signal, which causes a discrepancy in test results between the adjacent channel leakage ratio (ACLR) and the original signal. Therefore, a multisine design approach is suggested to minimize the time-domain error for an accurate estimation of the ACLR test. Section 2 describes the process of optimizing complex coefficients of multisine tones. A hyperbolic-tangent function is then introduced in the following section to increase the in-band spectral accuracy of the suggested multisine. Finally, the performance of the suggested multisine is compared to that of the conventional DFT-based multisine by simulation and experiment.

Ⅱ. Time-Domain Optimization and the Suppression of In-Band Ripple of Multisine Signals

The multisine signal $x_{tone}(t)$ is defined by the sum of sinusoids with complex coefficients:

$$x_{tone}(t) = \sum_{k=0}^{N-1} C_k e^{j\omega_k t} \tag{1}$$

where C_k, ω_k, N are the complex coefficient, frequency of k^{th} tone, and number of tones, respectively.

When the communication signal $x_c(t)$ of the modulation bandwidth BW is given, the goal of the multisine design is to find the best set of C_k coefficients, so that the synthesized multisine will show an optimal waveform from the viewpoints of the time domain and probability distribution function (*pdf*). Therefore, rather than finding C_k from the Fourier series expansion, we suggest a time domain process, in which the instantaneous error, $e_t(t)$, is defined as the difference between the multisine, $x_{tone}(t)$, and the target signal, $x_c(t)$ [4]:

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Meanwhile, tone frequency is defined by $\omega_k = kBW/(N-1)$. Since the synthesized multisine should resemble the given communication signal, which is statistically random in most cases, the cost function for the optimization is defined as an expectation of the instantaneous error function in the time domain.

$$J_t = E\left[\left|x_c(t) - x_{tone}(t)\right|^2\right] = E[e_t(t)\, e_t^*(t)] \tag{2}$$

Based on the Wiener-Hopf method, the optimal C_k is found from the gradient of J_t in the N-dimensional C_k space. Therefore, the optimal coefficient of the k^{th}-tone is found when the following condition is met [3]:

$$\nabla_k J_t = \frac{\partial J_t}{\partial C_k} = E\left[\left(\frac{\partial e_t(t)}{\partial C_k} e_t^*(t) + e_t(t)\frac{\partial e_t^*(t)}{\partial C_k}\right)\right] = 0\,. \tag{3}$$

This optimization guarantees the best emulation of the original signal in terms of the statistical and sample-to-sample correlation aspects. The optimized coefficient vector is therefore found by statistical processes of the target and the multisine signals [4].

As a figure-of-merit to evaluate the design of multisines, a normalized error is defined as follows:

$$err_{norm} = \frac{1}{L}\sum_{k=0}^{L-1}\left|\varepsilon_t(kT_s)\right|^2 / P_{avg} \tag{4}$$

where T_s, L, and P_{avg} are the sampling period, sample length, and average power of the target signal, respectively.

The time-domain optimization can provide the best sample-to-sample correlation to the original signal, but some undesired in-band ripple is still observed in the frequency domain, as is also the case with conventional multisines. This issue is addressed by introducing a hyperbolic-tangent function to mitigate ripples within the bandwidth, by modifying the magnitude of the multisine tones using two control parameters. The modified tone magnitude is defined as follows:

$$\left|C_k'\right| = \left|C_{k,avg}\right|\left\{1 + \alpha \cdot \tanh\left[\beta\left(\left|C_k\right| - \left|\overline{C_{k,avg}}\right|\right)\right]\right\} \tag{5}$$

where $\left|\overline{C_{k,avg}}\right|$ is the desired average magnitude of C_k within the bandwidth BW, α is to set the upper limit of the ripple, and β sets the ripple sensitivity.

Among these parameters, $\left|\overline{C_{k,avg}}\right|$ is mathematically determined so that the total power equals the equivalent channel power of the target signal. On the other hand, α is mainly affected by the average spectral response of the target signal, which generally is between 2 to 6 dB. Finally, β controls the sensitivity of $|C_k'|$ to $|C_k|$, and it is tuned to make the slope as linear as possible.

Therefore, with these control parameters, the in-band ripple of the multisine can be controlled within proper bounds and better spectral resemblance to the target signal is obtained.

Ⅲ. Simulation and Experimental Validation

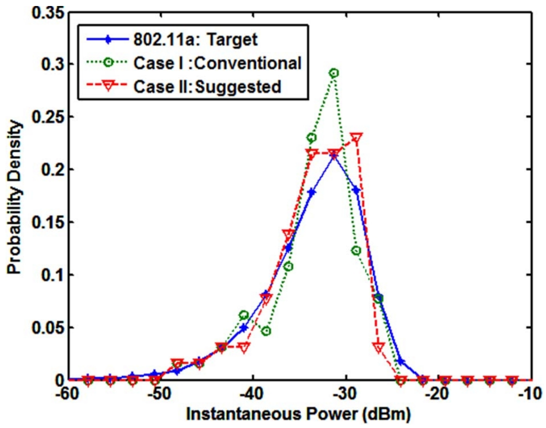
The suggested approach is verified by synthesizing two multisine signals. The first multisine (Case I) is made from the conventional DFT method and the other (Case II) is from the suggested time-domain optimization followed by the hyperbolic-tangent process of α=3 and β=4.5. In both cases, the target signal is 802.11a OFDM, with PAPR of 9.5 dB, BW of 16 MHz, and a sample length of 65536. The accuracy of the generated multisines is compared in Table 1, in which the in-band ripple and normalized average error are compared with different numbers of tones. The table shows that the suggested Case II method has superior in-band ripple suppression, by up to 7 dB, and better normalized error, by up to 0.2 dB.

In addition, Fig. 1 (a) shows *pdf* distributions of the original signal and the multisines when N=14. The suggested Case II shows a closer *pdf* to that of the target signal because of the optimization. In Fig. 1(b), in-band ripples are compared, and again the suggested Case II shows reduced ripple of at least 15 dB.

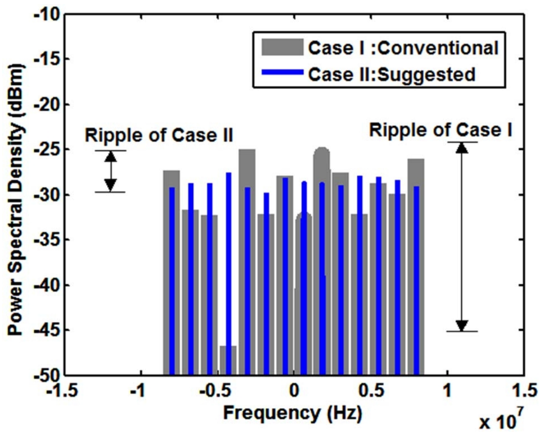
The synthesized multisines were used to evaluate the linearity of a commercial PA (MMPA-572) by the ACLR, at 16 MHz offset from the center frequency of 2.4 GHz. The measured ACLR results with N=4 are shown in Fig. 2, which indicates that the optimization method shows a closer accuracy, by about 5 dB, compared to the conventional method. As the number of tones increases, the ACLR estimations of both cases converge on that of the original signal because the degrees of freedom of the two cases are sufficient to emulate the nonlinear interaction of the target signal. However, the

Table 1. Comparison between multisine synthesis methods.

Item	Synthesis method	N=4	N=10	N=14
Normalized error (dB)	Case I: Conventional	0.01	−0.02	0.03
	Case II: Suggested	−0.05	−0.19	−0.20
In-band ripple (2σ, dB)	Case I: Conventional	3.75	9.13	11.23
	Case II: Suggested	3.72	4.11	3.67



(a)



(b)

Fig. 1. (a) Comparison of *pdf* between multisines (Case I and Case II) and the original signal, (b) In-band ripple comparison between Case I and Case II.

suggested multisine still maintains an advantage in its spectral stability and the time-domain accuracy, as shown in Table 1.

Ⅳ. Conclusion

This paper introduces a time-domain optimization for the multisine design for the testing of nonlinear PAs. The conventional multisine design has a limited performance in linearity testing, which requires similar statistical distribution or the sample-to-sample correlation to the target signal. Therefore, the multisine should be optimized in the time domain and processed by a hyperbolic-tangent function so that the synthesized multisine follows the statistical distribution of the original signal while controlling the in-band ripple. For the verification, two cases of multisine signals were synthesized to emulate the 802.11a signal, and applied to a PA at 2.4 GHz. The comparison shows that the suggested optimization method has superior results in terms of the normalized error (by up to 0.2 dB) and average in-band ripple (by up to 7 dB) for all test cases. The measured ACLR of the suggested method also shows better accuracy by about 5 dB, especially when the number of tones is relatively small. With a higher number of tones, although ACLR estimations of both methods converge, the suggested method maintains its advantage in terms of the time-domain error and statistical and spectral accuracies. Therefore, among the many multisine design methods currently available, the proposed method shows accurate ACLR estimation performance owing to its accurate time-domain and in-band responses.

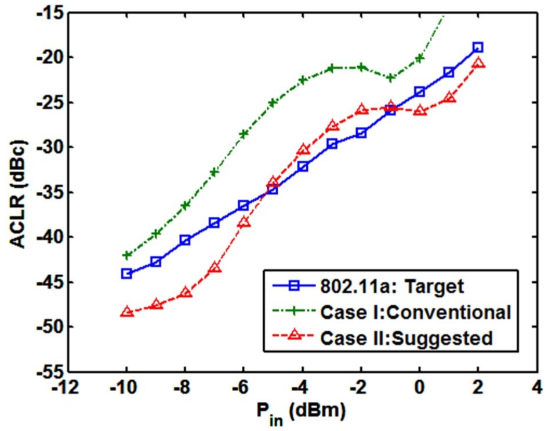


Fig. 2. ACLR estimations over the input power when N =4: The suggested method (Case II) shows closer results than Case I does.

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