Active Cancellation of Switching Noise for DC-DC Converter-Driven RF Power Amplifiers

Hidenori Kobayashi*, Peter M Asbeck

University of California, San Diego, La Jolla, CA 92093-0407
*Fuji Electric Co., Ltd. 4-18-1, Tsukama, Matsumoto, Nagano, 390-0821 Japan

Abstract — **The use of DC-DC converters to dynamically vary the supply voltage for RF power amplifiers in accordance with the transmitted power is an increasingly popular technique that can significantly improve the efficiency. However the DC-DC converter ripple noise may degrade the power amplifier output signals. In this paper, we demonstrate an active cancellation technique that can dramatically reduce the noise. The technique can be easily integrated into present systems employing DSP and DC-DC converters.**

I. INTRODUCTION

Linearity and efficiency are key concerns for next-generation power amplifiers. A promising technique to improve RF power amplifier efficiency while maintaining linearity is to dynamically vary the power supply voltage in accordance with the power level to be transmitted [1-3]. The power supply variation can be done on a relatively slow scale, corresponding to changing fading and shadowing conditions, or on a time-scale of the RF signal envelope (as in the "envelope tracking" or "dynamic supply voltage" architecture). Supply voltage variation is particularly beneficial for CDMA and W-CDMA transmitters. Because of the power control imposed by the system, for the CDMA wireless handset the most probable value of output power is of the order of 20dB lower than the maximum output power. In conventional CDMA power amplifiers, the efficiency at this output power level is low, usually several percent. The dynamic voltage supply technique can greatly improve efficiency at this output level. Recently over 40% power-added efficiency at 10dB back-off point was reported [4].

A significant problem in power amplifiers employing high efficiency switching DC-DC converters is the high value of converter output noise. The most prominent noise contribution is ripple noise (or switching noise), which is periodic noise at the switching frequency. Fig. 1(a) shows a schematic output power spectrum of a DC-DC converter. The spectrum exhibits not only a DC component but also spurious outputs at the switching frequency (f_{sw}) of the DC-DC converter and its harmonics. When the converter is used as the amplifier power supply, there is generally mixing action of the power amplifier which generates unwanted side bands and degrades the output spectrum (Fig. 1.b). For CDMA power amplifiers, the resulting linearity degradation is unacceptable and these side bands must be suppressed. This ripple noise can be suppressed by increasing the switching frequency and/or using a large and low equivalent series resistance (ESR) capacitor at the output. However, a higher switching frequency tends to degrade the efficiency of the converter. The large capacitor approach increases cost and physical size, and it lowers the output response speed of the converter.

In this paper we propose another method to suppress the unwanted side bands. Rather than suppressing the DC-DC converter output noise level, the unwanted RF side bands are suppressed with an appropriate cancellation signal. With this technique, the required side-band suppression without any degradation of DC-DC converter performance can be achieved.

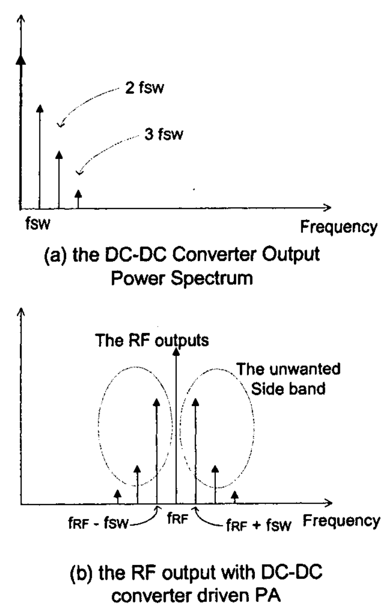


Fig. 1 Output power spectrum

0-7803-7239-5/02/$10.00 © 2002 IEEE

II. ACTIVE CANCELLATION CONCEPT

Fig. 2 shows the basic configuration used in the technique. This configuration is almost identical to what is employed in the digital pre-distortion technique [5] except for the presence of the DC-DC converter. A digital signal processor (DSP) is used, which may be the same DSP employed for CDMA signal generation. The switching frequency of the converter is synchronized by the DSP. The DSP generates an input base-band signal which includes the cancellation signal to eliminate the unwanted side bands due to the DC-DC converter ripple noise. The DSP algorithm takes account of the relationship between the RF amplifier supply voltage, and its gain and phase. The system includes appropriate phase delays in the pre-distortion signal to account for differences in delay between the DC-DC converter and its output filter, and the RF signal up-conversion path. The technique can be easily integrated with conventional digital signal generation or pre-distortion system without any additional components.

III. PERFORMANCE ANALYSIS

Fig. 3 shows AM-AM and AM-PM characteristics of a commercial IS-95 CDMA amplifier which were measured for single tone inputs at a number of different supply voltages. The gain and phase depend significantly on the supply voltage, and as a result, the supply voltage changes associated with the converter noise cause unwanted amplitude (gain) and phase modulation. We can calculate the output side bands due to this modulation by MATLAB using this AM-AM and AM-PM conversion data [6]. In this calculation we assume the supply voltage is of the form:

$$VDD = V_{dc} + m_{sw} \cos(\omega_{sw} t) \qquad (1)$$

where, V_{dc} is the DC voltage and m_{sw} is the amplitude of voltage variation (set to 3v and 0.1v, respectively). We calculated the side bands power under different PA configurations as described in the following:

a) PA with only gain variation with VDD (the phase is fixed: no phase modulation)
b) PA with only the phase variation with VDD (the gain is fixed: no amplitude modulation)
c) PA with the gain and phase variation with VDD

Table 1 shows the results of this calculation. The side bands caused by the gain variation (AM-AM conversion effect) are for the most part larger than the side bands due to phase variation (AM-PM conversion). However, the side bands due to phase variation are not negligible. For example, at Pin = -20dBm, the side-band power levels for both cases are almost equal. This implies that cancellation

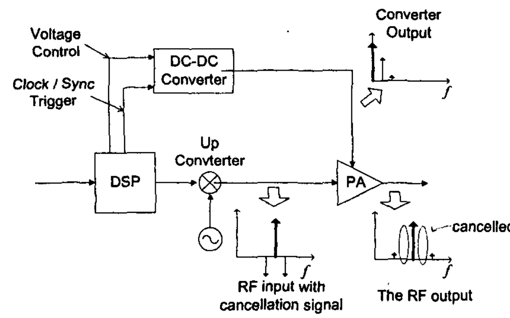


Fig. 2 side bands due to the ripple noise

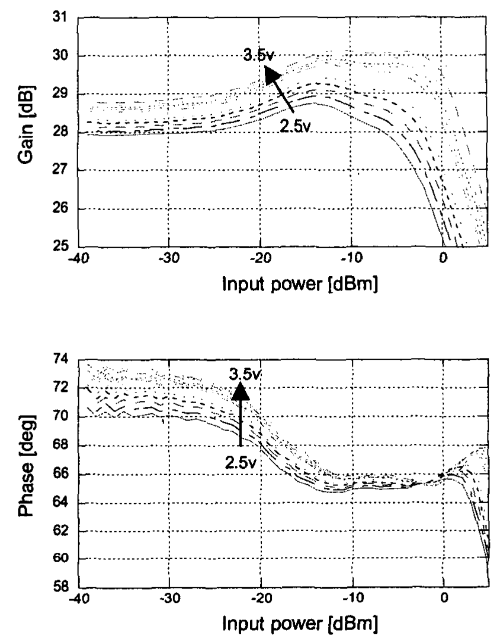


Fig. 3 AM-AM and AM-PM characteristics of IS-95 CDMA power amplifier

Table 1 The predicted sideband

input power [dBm]	The sideband power [dBc]		
	Gain only	Phase only	Gain and Phase
-40	-50.76	-60.44	-50.31
-30	-50.78	-62.28	-50.49
-20	-49.65	-51.39	-49.32
-10	-45.21	-63.08	-45.14
0	-35.95	-59.91	-35.93

of the gain-induced sidebands is not sufficient, and would result in only a very small improvement (0.7dB in this case). Thus both gain and phase variations must be considered in the cancellation signals.

The ripple noise cancellation signals can be derived from the previous simulation results. We can cancel out the side band due to gain variations using an appropriate (inverse) AM modulation of the input signal, and the sideband due to phase variation using anti-phased PM modulation. This is easily implemented in conjunction with the I and Q base band signal generation. For a single tone RF input case, we use the following I and Q signals to cancel out 1st order ripple noise side bands:

$$I = 1 + m_I \cos(\omega_{sw} t + \theta) \quad (2)$$

$$Q = m_Q \cos(\omega_{sw} t + \theta) \quad (3)$$

where m_I and m_Q are the pre-distortion signal strengths, which can be calculated from the previous simulation results. θ is the phase of both cancellation signals, selected to be ideally 180-degrees out of phase with the VDD variation in this case.

With the MATLAB calculation employing cancellation signals, the unwanted side bands are always below –80dBc from the center carrier power with appropriate values of m_I and m_Q.

Similar cancellation signals can be computed for arbitrary narrowband input sigals (such as CDMA modulation).

IV. Experimental Techniques and Results

We demonstrated the cancellation technique using a commercial CDMA power amplifier with a simple buck-type switching converter. Fig 4 shows the experimental setup. A simplified converter (corresponding to only the output stage) was made with a discrete power pMOS FET and a diode. The switching frequency was set to 500Khz by the arbitrary waveform generator and the duty cycle was controlled manually to set the output voltage to 3V. The output inductance was 1uH and output capacitance was 1uF. These inductance and capacitance values are usually not enough for a 500kHz switching frequency; we intentionally chose the values to demonstrate the technique. The arbitrary waveform generator also generated I and Q base band signals and the RF Signal Generator (Agilent ESG-D) was used to up-convert the I and Q signals, thus generating the RF input signal for the power amplifier. The output spectrum was observed by a spectrum analyzer.

Fig. 5 illustrates the results when the input power was –10dBm. Fig. 5(a) is the measured converter output voltage waveform. The voltage changes by around 0.2Vp-p in this case. Fig. 5(b) shows the output spectrum with and without cancellation when input signal is a single tone. Without cancellation signal, the ripple noise generated sidebands at –53dBc from the RF carrier tone. However, with cancellation signal, the side bands decreased to -75dBc and more than –20dB suppression could be achieved.

Table 2 shows the results of output sideband power levels without and with cancellation when the input power varied between –40dBm and 0dBm. For the low power case, we can suppress the output sidebands by approximately 10dB. Over 20dB or 30dB suppression can be achieved in the high power case. With the cancellation technique, the side-band power level is always –70dBc or more below the RF carrier. This side-band power level is

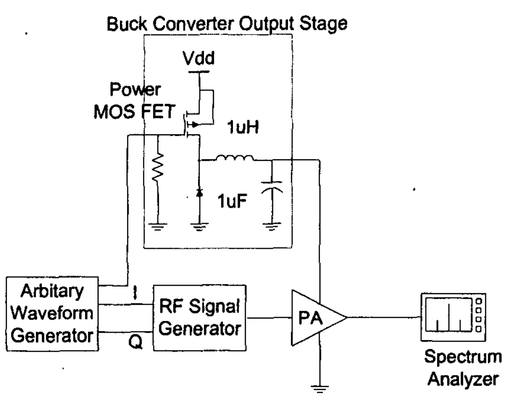
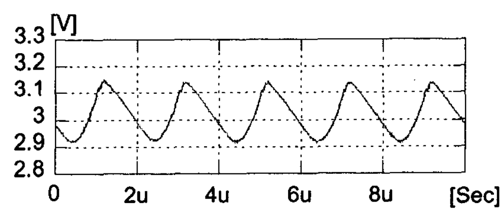
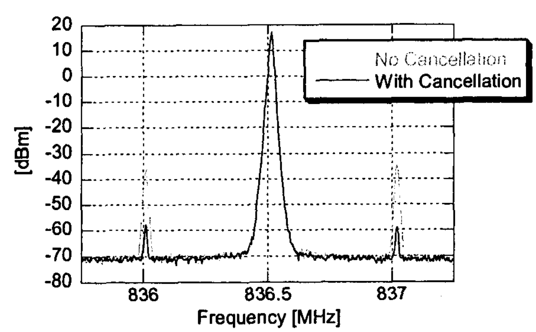


Fig. 4 The experimental setup



(a) Tthe converter output voltage waveform



(b) Output spectrum

Fig. 5 The output spectrum (Pin = -10dBm)

Table 2. Experimental results

Input Pow. [dBm]	Out. Pow. [dBm]	Without Cancellation [dBc]		With Cancellation [dBc]		Suppression [dBc]		Pre-distortion Coefficients	
		LSB	HSB	LSB	HSB	LSB	HSB	m_{AM}	m_{PM}
-40dBm	-13.9	-65.57	-61.07	-73.4	-73.23	7.83	12.17	0.24%	0.15%
-30dBm	-3.23	-64.73	-59.73	-70.4	-72.73	5.67	13	0.32%	0.16%
-20dBm	7.27	-62.23	-58.23	-71.4	-69.07	9.17	10.83	0.34%	0.24%
-10dBm	17.93	-52.9	-51.57	-74.4	-75.73	21.5	24.17	1.06%	0.30%
0dBm	28.43	-36.23	-35.57	-71.9	-73.9	35.67	38.33	7.10%	0.32%

low enough for most applications such as CDMA handsets.

The cancellation coefficients, which are described in equations (2) and (3), show that the side-band contributions due to gain variation are dominant for high output power, but side-band contributions from gain and phase are comparable at Pin ~ –20dBm. This is in reasonable agreement with simulation results of table 1.

Fig. 6 illustrates the results obtained with an IS-95 CDMA signal. In this case, we used an output capacitance of 0.47uF, and the switching frequency was adjusted to exactly half the CDMA modulation chip-rate (624.4 KHz) to facilitate generation of the pre-distorted signal. With the cancellation technique, the distortion due to the ripple noise is effectively suppressed, and the ACPR is the same as for the situation with no ripple noise.

V. Conclusion

We proposed a pre-distortion technique to remove unwanted side-bands due to DC-DC converter ripple noise. Simulation and experimental results show the unwanted side bands can be suppressed effectively. This technique can alleviate the DC-DC converter requirements and make designing dynamic supply voltage power amplifier system easier. The technique can be easily implemented using

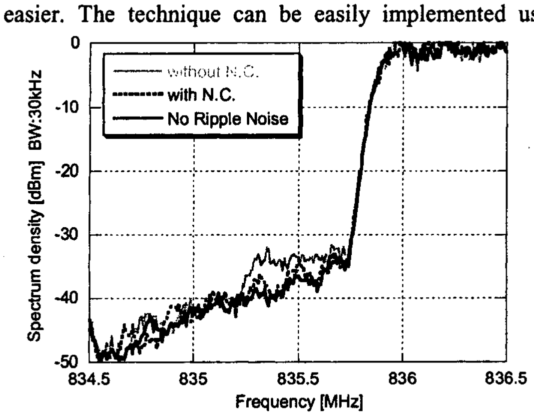


Fig. 6 Noise Cancellation with CDMA (IS-95)

existing DSP and power amplifier hardware, and is a promising technique for next generation CDMA power amplifiers.

Acknowledgement

Funding for this work was provided by the UCSD Center for Wireless Communications and by the ARO.

References

[1] G. Hanington, P. F. Chen, P. M. Asbeck, and L. E. Larson, "High-efficiency power amplifier using dynamic power-supply voltage for CDMA applications", *IEEE Trans. Microwave Theory and Technique*, vol. 47, pp. 1471-1476, Aug. 1999

[2] T. B. Nishimura, N. Iwata, and G. Hau, "Wide-band CDMA highly-efficient heterojunction FET over wide range output power with DC-DC converter", *Microwave Symposium Digest, 1999 IEEE MTT-S International*, Vol. 3, pp. 1091 –1094 (1999)

[3] M. Ranjan, K. H. Koo, G. Hanington, C. Fallesen, and Asbeck, P. "Microwave power amplifiers with digitally-controlled power supply voltage for high efficiency and high linearity", *Microwave Symposium Digest. 2000 IEEE MTT-S International*, Vol. 1 , pp. 493-496 (2000)

[4] G. Hau, T. B. Nishimura, and N. Iwata, "A highly efficient linearized wide-band CDMA handset power amplifier based on predistortion under various bias conditions", *IEEE Trans. Microwave Theory and Techniques*, Vol. 49, pp.1194-1201, Jun. 2001

[5] F. Zavosh, M. Thomas, C. Thron, T. Hall, D. Artusi, D. Anderson, D. Ngo and D. Runton, "Digital Predistortion Techniques for RF Power Amplifier with CDMA Applications", *Microwave J.*, Oct. 1999.

[6] P. M. Asbeck, H. Kobayashi, M. Iwamoto, G. Hanington, and S. Nam, "Augmented band-Pass Nonlinearity Model for Power Amplifier Characterization", *2001 IEEE Topical Workshop on Power Amplifiers for Wireless Communications.*