

# Effect of efficiency optimization on linearity of LINC amplifiers with CDMA signal

Jaehyok Yi, Youngoo Yang, and Bumman Kim

Department of Electronic and Electrical Engineering and Microwave Application Research Center,  
Pohang University of Science and Technology, Pohang, Kyungpook, 790-784, South Korea

**Abstract** — The linear and efficient power amplification can be achieved with LINC (linear amplification with nonlinear components) amplifiers because RF power amplifiers deal with constant envelope signals in LINC systems. To increase the average efficiency in some modulation schemes with high peak to average ratio, reactance termination in combining circuit is used. However, the shunt reactance termination degrades the linearity performance of LINC. This work shows the effect of efficiency optimization with reactance termination on ACLR(Adjacent Channel Leakage Ratio) of LINC amplifiers with WCDMA modulation systems using envelope simulation.

## I. INTRODUCTION

The efficiency and linearity are key factors in performances of power amplifiers for wireless communication systems. In general, there is trade-off between two properties and it is difficult to make those two performances good at the same time. The LINC amplifier is a promising solution with high efficiency (theoretically 100%) and good linearity. However, the average efficiency in the recent modulation systems, such as CDMA, decreases due to signal nature of varying envelopes. The method of reactive termination in signal combining part increases efficiency in average and there are optimum values for the given signal distribution profiles. References [2] and [3] analyzed the average efficiency enhancement by this combining method for various modulation signals. However, the reactive termination introduces the gain and phase imbalances at signal combiner and it degrades the linearity of the amplifier [4], [5], [6], [7].

This work presents the trade-offs between efficiency and linearity of LINC amplifier with reactive terminated signal combiner. The simulation results on the average efficiency and linearity with WCDMA modulation signal are shown for the signals with different peak-to-average ratios.

## II. LINC AMPLIFIER OPERATION

Fig. 1 shows the structure of LINC amplifier. The signal component separator converts input envelope signal  $a(t)$  to phase modulated constant envelope signals,  $S_1(t)$  and  $S_2(t)$ , with in-phase  $I_1(t)$ ,  $I_2(t)$  and quadrature  $Q_1(t)$ ,  $Q_2(t)$  components [8].

$$S(t) = G[a(t)\cos(\omega_o t)] = G[S_1(t) + S_2(t)] \quad (1)$$

$$a(t) = \sqrt{x^2(t) + y^2(t)} \quad (2)$$

$$I_1(t) = 1/2[x(t) - C(t)y(t)] \quad (3)$$

$$Q_1(t) = 1/2[C(t)x(t) + y(t)] \quad (4)$$

$$I_2(t) = 1/2[x(t) + C(t)y(t)] \quad (5)$$

$$Q_2(t) = 1/2[-C(t)x(t) + y(t)] \quad (6)$$

$$C(t) = \sqrt{\frac{V - (x^2(t) + y^2(t))}{x^2(t) + y^2(t)}} \quad (7)$$

where  $\max[a(t)] \leq V$ . The  $S_1(t)$  and  $S_2(t)$  components are efficiently amplified by RF amplifiers since they have constant envelopes. The outputs are combined by signal combiner and the original signal envelope is restored.

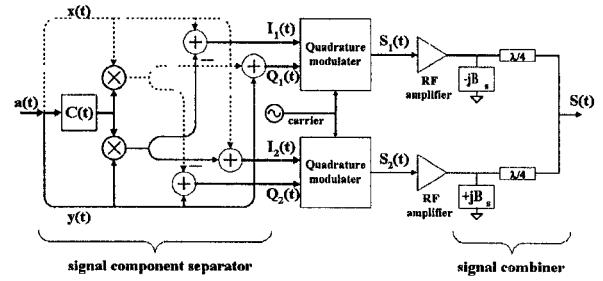


Fig. 1. Structure of LINC amplifier with reactive termination in signal combiner.

The RF amplifiers are terminated with shunt susceptances  $B_s$  and  $B_s'$  (see Fig. 1). With a proper choice of these reactive elements values, the imaginary parts of the loads are canceled out and the maximum instantaneous efficiency can be achieved at a broad power level. Assuming an ideal class B RF power amplifier the instantaneous efficiency is given [2]

$$\eta = \frac{\pi}{4} \frac{V_o^2}{\sqrt{V_o^2 - 2B_s' V_o \sqrt{1 - V_o^2} + (B_s')^2}} \quad (8)$$

where  $V_o$  is the normalized amplitude of output signal,  $R_o$  is the output termination load resistance,  $R_L$  is the characteristic impedance of quaterwave transformer and  $B_s$  is normalized shunt susceptance.

$$B_s' = B_s (R_L^2 / 2R_o) \quad (9)$$

The average efficiency of the LINC amplifier for the CDMA signal is statistical mean of equation (8) and it varies with the distribution of signal amplitude. There are corresponding optimum values maximizing average efficiencies for each signal modulations with various peak-to-average ratios [2],[3].

### III. LINEARITY OF LINC AMPLIFIER WITH EFFICIENCY OPTIMIZATION

The input signals to RF amplifier,  $S_1(t)$  and  $S_2(t)$ , generated by signal separation part have constant envelopes but they are highly nonlinear. The power spectra of  $S_1(t)$  and  $S_2(t)$  in frequency domain are the sum of source signal  $S(f)$  and error component  $E(f)$  [5],

$$S_1(f) = S(f) + E(f) \quad (10)$$

$$S_2(f) = S(f) - E(f) \quad (11)$$

where  $E(f)$  is frequency spectrum of  $e(t)$ ,

$$e(t) = jS(t) \sqrt{a_{\max}^2 / a^2(t) - 1} \quad (12)$$

To suppress the error signal at the output, the gain and phase between the two paths in signal combiner must be exactly balanced. The tolerance of error cancellation varies with modulation schemes and peak-to-average ratios of signals because  $e(t)$  depends on the input signal and its peak envelope value as shown in equation (12).

Fig. 2 illustrates that the error signal level is varied with input signal peak-to-average ratio. We have simulated the power spectra of  $S_1(t)$ 's using CAD tool of Agilent Advanced Design Systems with the WCDMA Design Library. The chip rate of WCDMA signal is 4.096Mcps and the signal peak-to-average ratio is 5.9dB for 1 user channel and 11.2dB for 5 users channels. The results are shown in Fig. 2. The error spectrum level is raised about 5dB with signal of higher peak-to-average ratio and this

means that more stringent requirements are needed for gain and phase balances to achieve the same level of error suppression.

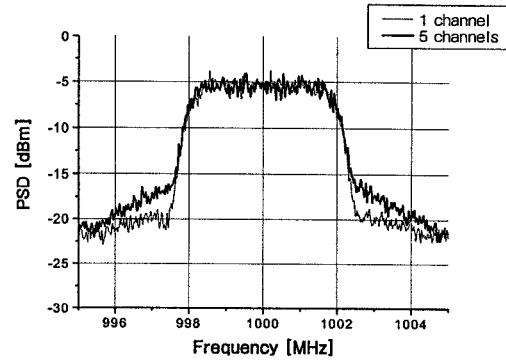


Fig. 2. Power spectra of  $S_1(t)$  with WCDMA input signal (1 traffic channel and 5 traffic channels with signal peak-to-average ratio of 5.9dB and 11.2dB, respectively).

The reactive terminations at the RF amplifiers maximize the average efficiency but they introduce the phase imbalance between two signal paths at the output combiner. The phase difference by shunt susceptances value  $B_s$  is shown in Fig. 3.

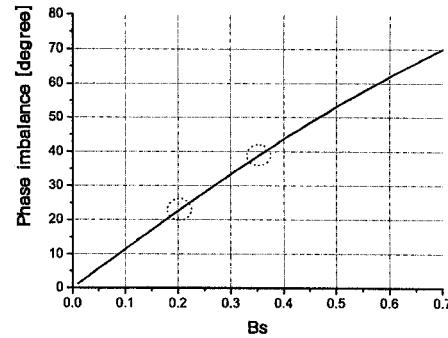


Fig. 3. Phase difference as shunt susceptances  $B_s$  is varied.

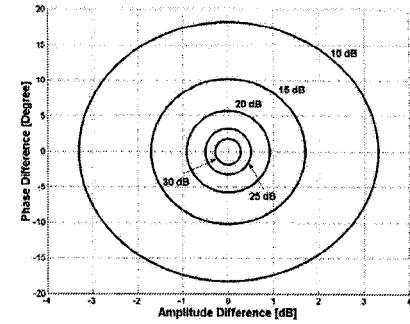


Fig. 4. The amount of cancellations for the gain and phase imbalances.

The requirements of gain and phase balances for signal cancellations are shown in Fig. 4. The phase imbalance must be within  $\pm 2^\circ$  for 30dB error cancellation when gain is perfectly balanced. The error level is about 10~15dB as shown in Fig. 2, and more than 45dB error cancellation is needed to satisfy the linearity requirement of 55~60dBc in power amplifiers for CDMA base stations, for example. Hence a very tight phase balance is required to achieve the linearity performance of LINC amplifiers.

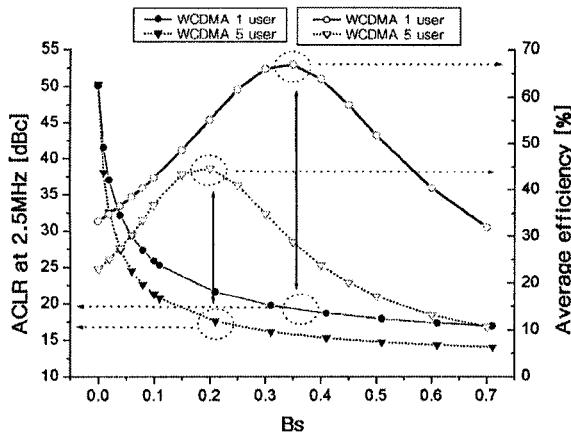


Fig. 5. Average efficiency and ACLR (from the center frequency to 2.5MHz offset) as shunt susceptances  $B_s$  is varied.

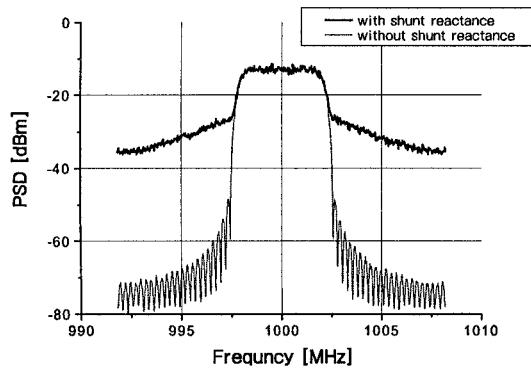


Fig. 6. Comparison of output power spectra with shunt susceptances,  $B_s=0.35$  (maximum average efficiency condition) and without shunt susceptances,  $B_s=0$ .

Fig. 5 shows the simulation results of the average efficiency and ACLR vs. shunt susceptance  $B_s$  assuming ideal class B RF amplifiers. WCDMA signals of 1 user and 5 user channels with peak-to-average ratio of 5.9dB and 11.2dB, respectively are used for the simulation. ACLR is the value of spectrum delta at the center frequency and 2.5MHz offset. As  $B_s$  increases, the phase

imbalance increases as shown in Fig. 3, resulting in rapid decrease of ACLR. In case of 1 user WCDMA signal, the ACLR decreases to 20dB at maximum average efficiency point. The spectral regrowth level of  $S_1(t)$  signal is about 15dB as shown in Fig. 2, and error is cancelled by only 5dB because the phase imbalance is  $34^\circ$  at the value of  $B_s=0.35$  for the maximum average efficiency. Similarly, the susceptance of  $B_s=0.2$  for maximizing average efficiency introduces  $23^\circ$  phase imbalance and degrades ACLR to about 17dB in the case of 5 user WCDMA signal. Fig. 6 shows the simulation results of the output power spectra with efficiency optimization by adjusting  $B_s$  and without it. The error is suppressed to the source error level without the reactive termination.

#### IV. CONCLUSION

The linearity performance of LINC amplifier with the shunt susceptance for average efficiency enhancement has been studied with WCDMA modulation signal by simulation. As the average efficiency is maximized, LINC amplifier becomes more nonlinear because the shunt susceptance increases the amount of phase imbalance in output signal combiner. For the WCDMA modulation schemes, ACLR is about 20dB at the maximum average efficiency condition. Hence a careful choice of shunt susceptance value is need to trade-off the efficiency and linearity, especially for the modulation schemes with high signals peak-to-average ratio such as CDMA modulation.

#### REFERENCES

- [1] H. Chireix, "High power outphasing modulation," *Proc. IRE*, vol. 23, no. 2, pp. 1370-1392, Nov. 1935.
- [2] F. H. Raab, "Efficiency of outphasing RF power-amplifier systems," *IEEE Trans. Commun.*, vol. 33, pp. 1094-1099, Oct. 1985.
- [3] B. Stengel and W. R. Eisenstadt, "LINC power amplifier combiner method efficiency optimization," *IEEE Trans. on Vehicular Technology*, vol. 49, no. 1, pp. 229-234, Jan. 2000.
- [4] F. Casadevall and J. J. Olmos, "On the behavior of the LINC transmitter," *IEEE 40<sup>th</sup> Vehicular Technology Conference*, pp. 29-34, 1990.
- [5] L. Sundström, "Automatic adjustment of gain and phase imbalances in LINC transmitters," *Electron. Lett.*, vol. 31, no. 3, pp. 155-156, Feb. 1995.
- [6] S. Ampem-Darko and H. S. Al-Raweshidy, "Gain/phase imbalance cancellation technique in LINC transmitters," *Electronics Letters*, vol. 34, no. 22, pp. 2093-2094, Oct. 1998.
- [7] S. A. Olson and R. E. Stengel, "LINC imbalance correction using baseband preconditioning," *Radio and Wireless Conference*, pp. 179-182, 1999.
- [8] F. J. Casadevall and A. Valdovinos, "Performance analysis

of QAM modulations applied to the LINC transmitter," *IEEE Trans. on Vehicular Technology*, vol. 42, no. 4, pp. 399-406, Nov. 1993.