A Novel Mixed-Mode LINC Architecture For Efficiency Enhancement

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***Abstract*—This paper proposes a new architecture for linear amplification with nonlinear components (LINC) to achieve high efficiency enhancement. The proposed scheme, mixed-mode LINC, operates with two modes depending on an input signal level. It operates as a conventional LINC for a low input level and performs as the mixed-mode LINC, consisting of the conventional LINC system and an auxiliary amplifier, for a high input level. The system is verified with a WCDMA signal at 830 MHz. Using the mixed-mode LINC architecture, we achieved drain efficiency of 68% with a CW signal and 41% with the modulated signal, including −37 dBc and −47 dBc adjacent channel power ratio at 5 MHz and 10 MHz frequency offsets, respectively.**

I. INTRODUCTION

Recently power-efficient transmitter architecture has been inevitable choice because power consumption has become a hot issue in the field of mobile communication systems. Linear amplification with nonlinear components (LINC), consisting of two very highly efficient nonlinear amplifiers, is one of the strongest candidates for a highly efficient power amplifier (PA) [1], [2]. However, the LINC architecture has a challenging issue about steep efficiency degradation for modulated signals with high peak-to-average power ratio (PAPR). Because high PAPR signal degrades the efficiency of LINC transmitter, many studies have been conducted to solve the problem of performance degeneration [2]-[4]. Chireix combiner is introduced for high efficiency, but this combiner suffers from a degraded linearity problem from non-ideal voltage source [2]. Although [3] showed a possibility of a hybrid-type LINC, the original LINC mode and a balanced mode using class-B PAs share linear mixers and amplifiers. Therefore, the efficiency enhancement is achieved by sacrificing signal's linearity.

This paper proposes a new LINC architecture, called mixed-mode LINC, to enhance power efficiency and simultaneously minimize linearity deterioration. The architecture can increase the total efficiency by separating LINC operation for a high PAPR signal, then the linearity can be restored at the final output with an auxiliary amplifier.

II. PROPOSED MIXED-MODE LINC ARCHITECTURE

A. Operating Principle

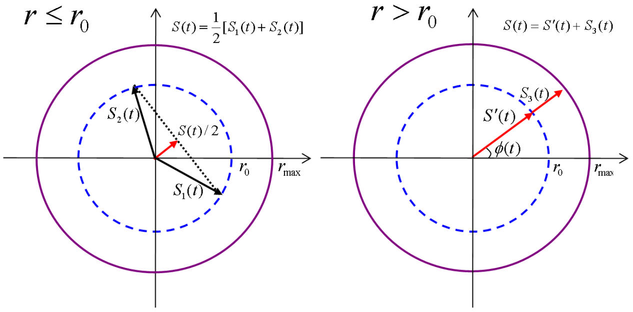


Fig. 1. Signal decomposition of mixed-mode LINC.

The mixed-mode LINC system consists of a conventional LINC system and an auxiliary amplifier. Mixed-mode LINC operation is divided by an input signal level. For low level signals, LINC operates alone, and for high level signals, the auxiliary amplifier operates with the conventional LINC system.

With this divided operational mode, the mixed-mode LINC system achieved efficiency enhancement compared to a conventional LINC system. Equations (1)-(6) describe the creation of each signal. The exceeded boundary level signal $S(t)$ is decomposed into three components - $S_1(t)$, $S_2(t)$ and $S_3(t)$. $S_1(t)$ and $S_2(t)$ go towards LINC and $S_3(t)$ heads to the auxiliary amplifier.

$$S(t) = A(t)\angle\phi(t) \tag{1}$$

$$S_{1,2} = \begin{cases} \frac{1}{2}S(t)[1 \pm je'(t)], & r \le r_0 \\ \frac{1}{2}S'(t), & r > r_0 \end{cases} \tag{2}$$

$$e'(t) = \sqrt{\frac{r_0^2}{r(t)^2} - 1} \tag{3}$$

$$S'(t) = r_0\angle\phi(t) \tag{4}$$

$$S_3 = \begin{cases} 0, & r \le r_0 \\ S(t) - S'(t), & r > r_0 \end{cases} \tag{5}$$

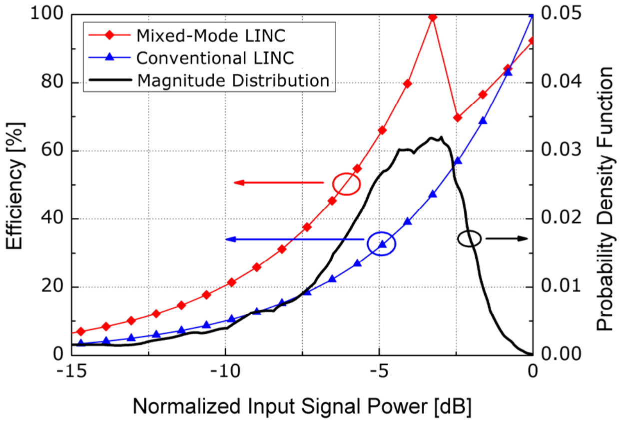


Fig. 2. Simulated efficiency comparison and WCDMA signal distribution.

$$S(t) = S_1(t) + S_2(t) + S_3(t)\,. \qquad (6)$$

In the equations shown above, $A(t)$ and $\phi(t)$ represent the amplitude and phase of $S(t)$, respectively. In (5), $S_3(t)$ = 0 means that the auxiliary amplifier is off. Each signal is plotted in Fig. 1. On the left-hand side of Fig. 1, the signals below the boundary level are described, where the proposed system performs the same as a conventional LINC system. On the right-hand side of Fig. 1, the operation of the mixed-mode LINC and its signal decomposition are drawn.

The mixed-mode LINC system is very efficient in the vicinity of the r_0 signal level. Fig. 2 shows the efficiency curves of the conventional and mixed-mode LINC systems according to the magnitude of the input signal, assuming the switching amplifiers have 100% efficiency, and the auxiliary amplifier has 50% efficiency, which means that the auxiliary amplifier is assumed to be a linear amplifier. A WCDMA signal with 5.3 dB PAPR is used as a test signal. When the signal level increases, efficiency increases rapidly and reaches a peak value at r_0. However, at the auxiliary amplifier's operating point – which is slightly higher than r_0 – total efficiency drops slightly because of the linear amplifier's inefficiency as the auxiliary amplifier. However, the overall efficiency is greatly improved, considering the modulated signal's distribution. Also, the maximum efficiency can be controlled by adjusting r_0, according to the applied signal distribution. This scheme maximizes LINC's efficiency, and focuses on the highest probability density function region of the magnitude distribution.

B. Implementation of Mixed-Mode LINC

Fig. 3 shows a system block diagram to verify the mixed-mode LINC. To operate a conventional LINC at a signal range smaller than r_0, two high efficiency class-E PAs were configured to make LINC system using a Wilkinson combiner.

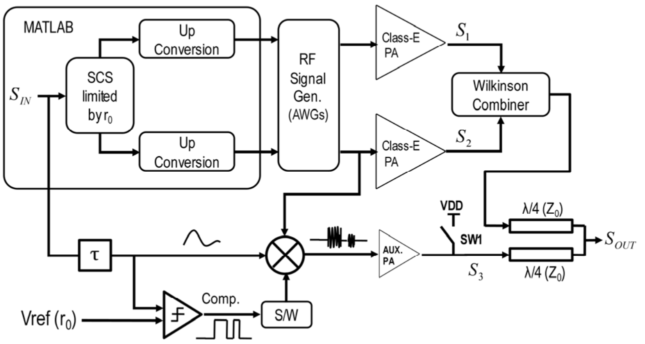


Fig. 3. Verification set-up of the mixed-mode LINC system.

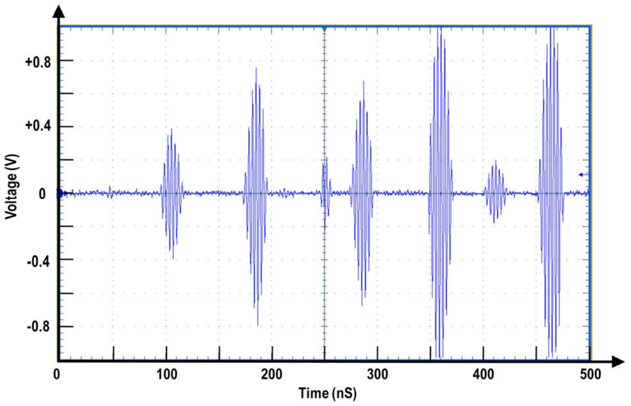
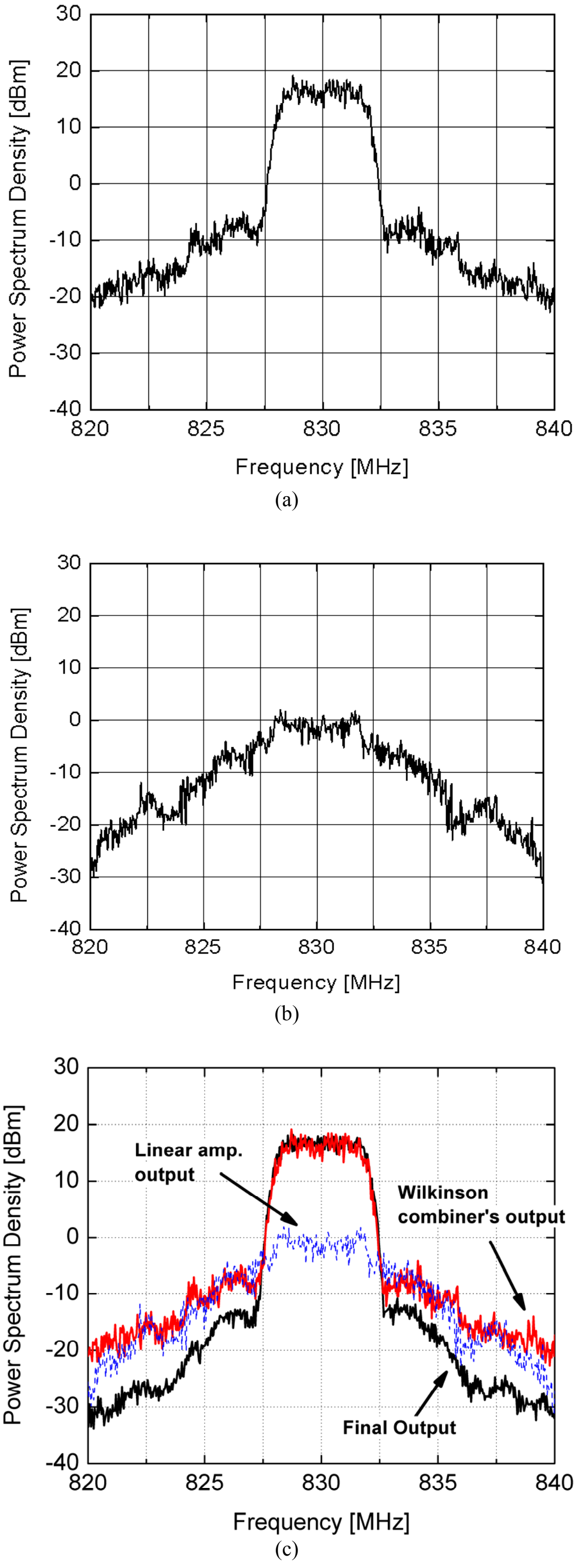


Fig. 4. Measured input signal of the auxiliary amplifier in time domain.

For the auxiliary signal path, a class-AB linear PA, closely biased to the threshold voltage of the input transistor, is utilized. Thus, even when input signal is not exist, this linear amplifier dissipates the power under 10% of maximum power consumption. The linear amplifier's input is fed from a mixer's output and the mixer operates for amplitude modulation. Although this configuration seems to be complicated, recent digital-assisted circuit integration will reduce this burden in near future. For input levels larger than r_0, the phase information in the class-E amplifier's input signal is the same as that of the original signal, $S(t)$, except for the amplitude, because the two separated signals are in-phase at maximum radius in LINC. Therefore, an upconverted original signal can be generated by mixing the switching amplifier's input signal and the original baseband signal's envelope signal. The auxiliary signal, $S_3(t)$, can be made by controlling the enabling of the mixer. Fig. 4 shows the mixer's output signal where the switching operation using an FET switch at the supply port is used to turn the mixer off and on, and the maximum switching bandwidth achieved was 50 MHz. The faster operation is not necessary, because the signal distribution shows there is little signal operating in that frequency



(a)

(b)

(c)

Fig. 5. Measured power spectrums: at: (a) output of Wilkinson combiner, (b) output of auxiliary amplifier, and (c) final output with (a) and (b).

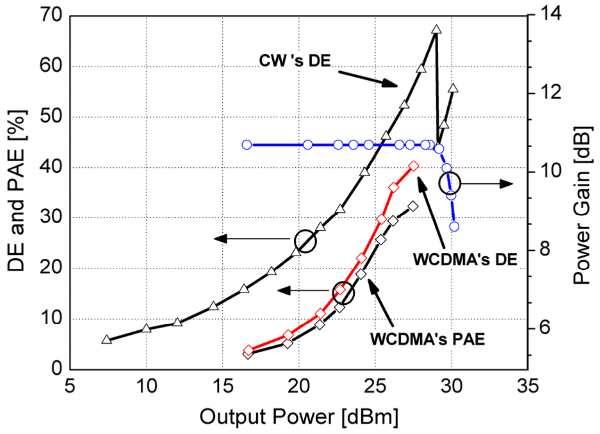


Fig. 6. Measured drain efficiency according to the output power.

To combine the output power signals from the auxiliary amplifier and the Wilkinson combiner, λ/4 lines are utilized. The Wilkinson combiner's output power is much larger than the auxiliary amplifier's, because the auxiliary amplifier turns on for only a small portion of the entire signal. The threshold radius, r_0, is set at around 0.7, which depends on the modulated signal's distribution. To combine the two signals of different signal path, λ/4 lines with same characteristic impedances are used. The value and the ratio of the characteristic impedances were set for maximized overall efficiency. To minimize the power loss of main signal, the 50 Ω characteristic impedance of λ/4 line was selected at the path of the original LINC. Therefore, when the auxiliary amplifier is active, power combining is conducted as a normal transmission line combiner. However, when the auxiliary amplifier is inactive, SW1 in the Fig. 3 is also closed, which means the impedance seen from the final output became large. This operation makes the signal power from Wilkinson combiner passes to the final output with very small power loss (0.3 dB). The switch is also operated by the comparator output signal limited 50 MHz frequency. However, the signal efficiency from the auxiliary amplifier is degraded when the amplifier is inactive because of non-ideal switching operation of SW1 and input biasing. However, the signal power is much smaller compared to the output power of Wilkinson combiner and the operation is active during limited time. In addition, the signal from the auxiliary amplifier is not for the large output power, but for linearity restoration. Therefore, the efficiency degradation from the linear amplifier is not dominant at the overall efficiency. In measurement results, maximum DE is reduced by 8% due to the idle power of linear amplifier. The output powers of Wilkinson combiner and auxiliary amplifier were 27.8 dBm, $S_1(t)+S_2(t)$, and 9.5 dBm, $S_3(t)$, respectively. And, the final output power was 27.5 dBm. Therefore, only 0.3 dB of additional power loss occurred in the combiner using λ/4 lines, which means that the power loss of this combiner do not seriously deteriorate overall efficiency.

III. MEASUREMENT RESULTS

For the measurement, we utilized a WCDMA signal of 830MHz band. The WCDMA signal is generated for LINC operation by the HP Advanced Desing System (ADS). The original signal is separated into two constant envelope signals for LINC operation using MATLAB program. The two signal were uploaded into two Agilent 4438C signal generators for RF up-conversion signals. For amplifiers, we used two GaAs class-E switching PAs which show 72% drain efficiency (DE) and 63.5% PAE at 29.3 dBm output power and a GaAs PA as an auxiliary PA which has 35% DE and 31% PAE at 23 dBm output power. And, the mixer, comparator and switches are used with commercial products. Fig. 5 shows the spectrum waveforms at the outputs of the Wilkinson combiner, auxiliary amplifier and final λ/4 combiner. Although the output power from the auxiliary amplifier (9.5 dBm) is much smaller than the output power of Wilikinson combiner (27.8 dBm), the overall signal's linearity is considerably improved by adding the signal. Moreover, the overall efficiency followed the high efficiency of switching amplifiers used for LINC. The ACPR values achieved were −37 dBc at 5 MHz offset and −47 dBc at 10 MHz offset, which satisfies the spectrum mask of WCDMA specifications. The ACPR characteristics can be further enhanced by adjusting the radius (r_0). The DE curves at CW signal and WCDMA modulated signal are shown in Fig. 6, according to the output power. To aid mixed-mode operation, high efficiency can be obtained over a wide power range. The maximum achieved DE was 68% at the CW signal and 41% at the WCDMA modulated signal. Also, the maximum 32% PAE is achieved. The DE is derived from the final output power and the overall dissipated power consumption in two switching PAs and one linear PA. Power-added efficiency (PAE) is also derived from the DE and input power to the three PAs. The PAE of the proposed LINC structure was improved using the auxiliary linear path, minimizing sacrificing signal linearity.

IV. CONCLUSIONS

This paper proposes a new mixed-mode architecture to enhance the efficiency of LINC transmitter. Using an auxiliary amplifier in the LINC system can increase overall efficiency performance with increased complexity. The optimized radius, depending on the signal magnitude distribution, of mixed-mode LINC improves the system's efficiency enhancement minimizing linearity deterioration. At these conditions, maximum 32% PAE and the satisfied ACPR characteristics for WCDMA is achieved.

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