Efficiency and Linearity of LINC Amplifiers: Recent Trends

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Abstract: The efficiency and linearity of power amplifiers based on the LINC technique are discussed. The use of resistive combiners as well as lossless Chireix combiners are detailed and their impact on amplifier linearity and efficiency are highlighted. The tradeoffs between linearity and efficiency in Chireix combiners are investigated experimentally and optimal choice of Chireix combiners is demonstrated. The use of LINC-based power amplifiers for SDR-enabled platforms is discussed.

Key words: RF Power Amplifiers, Linearity, Power Efficiency, LINC, Chireix combiners.

INTRODUCTION

The need for linear and power efficient wireless transmitters continues to be a major driving force in the development of linearization and power efficiency enhancement techniques. Transmitter linearity is key to the overall system performance in terms of quality of service (QoS) and the underlining Bit Error Rate (BER) performance. Transmitter power efficiency on the other hand is critical for operational cost and battery life, which determines the talk time of wireless hand held terminals. To meet both objectives simultaneously, the LINC (Linear amplification with Non-linear Components) technique offers a power amplifier architecture that is inherently linear while using two power amplifiers operated at their peak power efficiency. As such, it is one of the few techniques that continues to solicit considerable interest in the scientific community [MYO 08, HEG 07].

1. The LINC Technique

1.1. LINC principle

The LINC technique is based on the principle of converting the amplitude modulation of the input signal, S(t), into two phase-modulated constant envelope signals, $S_1(t)$ and $S_2(t)$. The resulting two signals can be amplified by nonlinear and highly efficient amplifiers. The resulting amplified signals are then summed to produce an amplified version of the original signal. Figure 1 illustrates the main building blocks of a LINC amplifier while the following equations give the various relationships between the signals [BIR 04, RAA 85]:

$$S(t) = r(t).e^{j.\varphi(t)} = S_1(t) + S_2(t) \quad (1)$$

$$r(t) = r_{\max}.\cos(\theta(t)) \quad (2)$$

$$S_1(t) = \frac{r_{\max}}{2}.e^{(\varphi(t)+\theta(t))} \quad (3)$$

$$S_2(t) = \frac{r_{\max}}{2}.e^{j(\varphi(t)-\theta(t))} \quad (4)$$

where $r_{\max}$ is the maximum of $r(t)$, φ(t) is the phase of the base band signal and *θ(t)* is the additional phase modulation angle the bottom of the page. In order to do so, use the following setting:

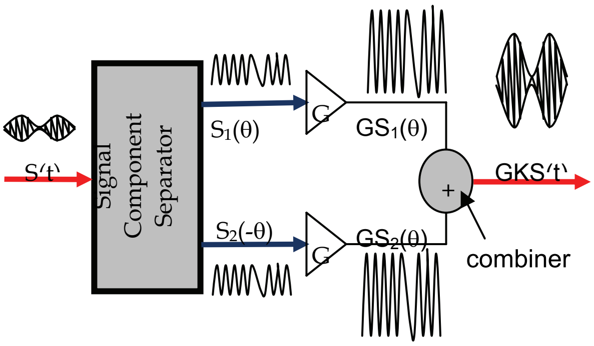
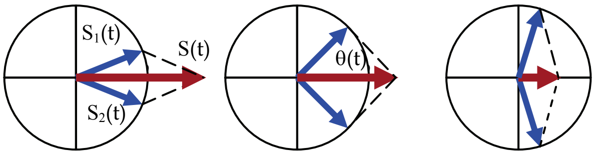


Fig. 1. LINC amplifier structure.

1.2. LINC performance limitations

While the power amplifiers in the LINC technique are highly efficiency, it is at the combining stage that efficiency is degraded. Indeed this is clearly demonstrated by Fig. 2 where it is seen that during the transmission of low power symbols, the LINC amplifier becomes highly inefficient. This vector representation shows that the original envelope variation is restored at the output of combiner and that only the in-phase components of $S_1(t)$ and $S_2(t)$ contribute to the output signal S(t) while the out-of-phase components are lost.



(a) (b) (c)

Fig. 2. Vector representation of signal variation for a LINC amplifier: (a) high envelope level, (b) medium power level and (c) low envelope level.

This degradation in efficiency is obtained at the output of the combiner. For resistive combiners, such as Wilkinson combiners and 3dB hybrid couplers, the combining efficiency, i.e., the instantaneous ratio of the output power over the sum of the two input powers, can easily be shown to vary as $\cos^2(\theta)$ reaching the maximum when $S_1(t)$ and $S_2(t)$ are in phase, i.e., $\theta=0^o$, and equal to 0 when they are out-of-phase, i.e., $\theta=90^o$ [BIR 04]. For envelope varying signals with increasing peak to average ratio, the combining efficiency limits the performance of LINC amplifier. Indeed, the average combining efficiency, η_{avg}, for an envelope varying signal is obtained by [BIR 04]:

$$\eta_{avg} = \sum_{i=1}^{N} P(\theta_i).\cos^2\theta_i \qquad (5)$$

where $P(\theta_i)$ represents the probability density function (PDF) of the input signal and N the number of sampled points. Using various digitally modulated, RRCF-filtered signals (roll-off=0.35), Table I shows the impact of the combining efficiency on the overall efficiency of the LINC amplifier as the peak-to-average ratio (PATR) of the signal increases. This behavior can be well understood by considering Fig. 3 where the PDF of the signal is plotted with the combined efficiency. Here, the peak signal corresponds to 0^o phase and occurs very rarely. Similarly, the minimum of the signal is at or near 90^o and occurs equally rarely, i.e. zero or near-zero crossing. The maximum of the PDF corresponds to the statistical average of the signal. Clearly, when the PATR is high, the PDF curve shifts towards higher values of θ. When this happens, the instantaneous combining efficiency seen by the signal is low for most of the time. Since the average combining efficiency is the integral of the instantaneous efficiency multiplied by the PDF, a shift towards higher θ values of the PDF will lead to a lower average combining efficiency.

Table I. AVERAGE EFFICIENCY VS. SIGNAL DYNAMICS.

Modulation	QPSK	16QAM	64QAM	OFDM/16 QAM
PTAR/dB	3.75	6.43	6.82	11.75
η_{avg}	45%	25%	24%	8.4%

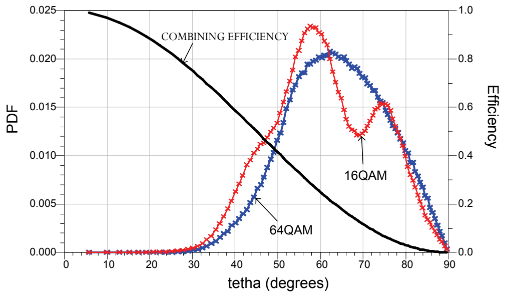


Fig. 3. PDF for 16/64QAM signals and corresponding combining efficiency for resistive combiners.

2. Chireix Combining

To overcome the efficiency limitations of resistive combiners, lossless combiners were proposed [RAA 85] consisting of quarter-wavelength transmission lines with optional stubs of opposite susceptance values, as shown in Fig. 4. A rigorous analysis of this combiner was presented in [KOU 04] where it was demonstrated that the average combining efficiency can be significantly improved by use of this loss structure but at the cost of linearity. Unlike the resistive combiners, Chireix combiners do not present any isolation between the two input ports. Consequently, each amplifier sees a time-varying impedance, i.e., a varying reflection coefficient. While this behavior can be exploited to reduce DC power consumption by the amplifiers [GRU 04] thus improving overall efficiency, it does lead to nonlinearities, particularly for non-zero stubs. Consequently, a tradeoff between combining efficiency and linearity must be sought.

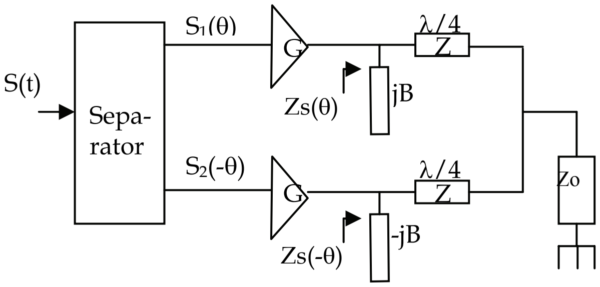


Fig. 4. LINC amplifier topology with a Chireix combiner.

To establish the desired tradeoff between efficiency and linearity, we propose to carry out an experimental investigation as described in the following section.

3. Efficiency vs. Linearity Tradeoffs

Fig. 5 shows the experimental setup used to investigate the tradeoff that can be achieved between efficiency and linearity when using Chireix combiners with varying stub length. Here, the stub length is represented by γ, which represents its electric length. The test bench consists of two programmable signal generators (Agilent ESG4438C) equipped with synchronization options, the Chireix combiner under test and vector signal analyzer (Agilent VSA 89600). Two digitally modulated signals, 16QAM and 64QAM, having the same symbol rate of 150KHz and filtered with a RRCF having a roll-off factor of 0.35 were generated and separated according to equations (1-4) using Agilent's ADS software. The resulting decomposed signals were then loaded into the memories of the respective signal generators and tests were carried out at 2GHz.

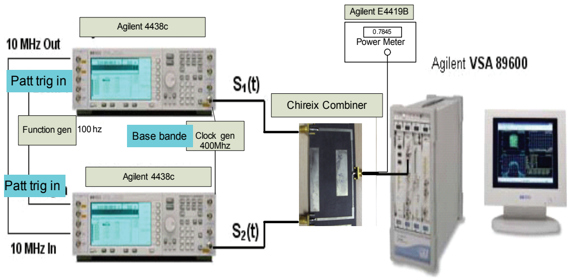


Fig. 5. Experimental setup for efficiency/linearity measurement.

Table II presents the measured results of average efficiency and Adjacent Channel Interference (ACI) for the various combiners tested. All combiners were made on a Duroid substrate (ε_r=2.33, h=31 mils). This substrate was chosen since it is readily available and leads to easily realizable microstrip lines. These results clearly illustrate how linearity is degraded as the efficiency is increased through the use of stubs. Since most wireless systems allow for a certain level of nonlinearity, i.e., a certain level of ACI, a stub of the appropriate length can then be found to increase efficiency while meeting the linearity specification of the system. For example, if a 45dBc is used as a cutoff for a 16QAM system, then a stub having an electrical length of 8° can be used and would increase efficiency from 30%, which would correspond to the resistive combining case, to 41%. Similarly for a 64QAM signal, even a short 4° stub would lead to an increase in efficiency from 23% to 28% while the ACI remains at 47dBc. It is to be expected that higher order constellation would be more sensitive to nonlinearities.

To further illustrate the impact on linearity of the choice of a Chireix combiner, Fig. 6 shows the resulting 16QAM constellation at the output of a Chireix combiner of variable stub length. As the stub length is increased, the constellation is further deformed leading as expected following the results of Table II.

Table II. TRADEOFF BETWEEN EFFICIENCY AND LINEARITY.

	16 QAM		**64 QAM**	
Stub length (γ)	η_{avg}	*ACI (dBc)*	η_{avg}	*ACI (dBc)*
0^o	0.3	-74	0.23	-70
4^o	0.35	-56	0.28	-47
8^o	0.41	-45	0.34	-38
12^o	0.47	-42	0.4	-34
16^o	0.54	-38	0.47	-30
20^o	0.60	-32	0.53	-24
24^o	0.66	-28	0.6	-22

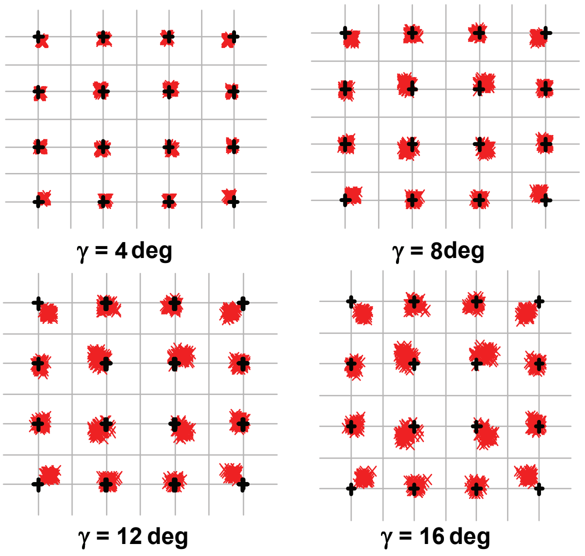

γ = 4 deg
γ = 8deg
γ = 12 deg
γ = 16 deg

Fig. 6. 16QAM constellation at the output of a Chireix combiner of electric length γ.

4. Adaptive Wireless Transmitters

As illustrated in the previous section, a tradeoff between efficiency and linearity can be found by the proper choice of the stub length for a given modulation. This principle can be very useful in adaptive wireless communication where digital modulation can be adaptively changed to respond to network needs or to accommodate changing propagation channel conditions. Today, Software Defined Radio platforms exist that can offer such capability. Therefore, to take full advantage of the increase in efficiency that can be achieved with a short stub for various modulations, the stub length must be reconfigurable as a function of the modulation used. One possible solution for this is to use in line diode-based, low impedance switches to electronically adjust the length of the stub being used. Simulations of this type of combiner have been completed and demonstrate the feasibility of the proposed approach. Currently fabrication and testing of a switchable stub are underway. MEMS-based switches are also being investigated due to their low loss and low power consumption characteristics.

In addition, this proposed switched stubs technique can be combined with the MILC (Modified Implementation of the LINC Concept) technique [POI 06], which is based on a judicious baseband signal decomposition algorithm, as well as digital predistortion to achieve even further efficiency and linearity gains. This combination can make LINC-based power amplifier architectures viable options for commercial deployment.

5. Conclusion

The LINC technique offers excellent potential for achieving both increased power efficiency and linearity, two objectives which have proven illusive over the past several years. It is through the judicious choice of combiners, baseband signal decomposition and digital predistortion that this potential will be reached in future years.

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