Chireix Power Combining with Saturated Class-B Power Amplifiers

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***Abstract* — This paper describes the realization of a Chireix power combining part of an outphasing system for 2.14 GHz consisting of two saturated class-B power amplifiers and a Chireix power combiner circuit. The Chireix power combining scheme can be used in Chireix outphasing architecture, which is currently together with EER and the Doherty amplifier one of the most prominent research topics in power amplifier linearization / efficiency enhancement area.**

In an outphasing system, also known as LINC (Linear Amplification of Nonlinear Components), an amplitude and phase modulated signal is separated into two constant envelope signals containing only phase modulation. The original signal waveform can subsequently be reconstructed by varying the phases of the two constant envelope signal branches, thus enabling, ideally, linear amplification of the original signal with system efficiency comparable to the efficiency of the used PAs.

In this paper, the design and implementation as well as the measurement results of a microstrip-line Chireix-combiner together with saturated class-B pHEMT power amplifiers for WCDMA downlink band 2.11-2.17 GHz are reported. The measurement results verify that the concept is indeed functional, and significant efficiency improvement over traditional power combining can be attained. At peak envelope power 37.4 dBm system efficiency of 77 % was measured, and at –8 dB back-off, representing the computational average point for WCDMA signal, system efficiency of 43 % was measured.

I. INTRODUCTION

Outphasing power amplifier (PA) system was first introduced by Henri Chireix in 1930s [1] to improve the efficiency and linearity of tube-era transmitter systems. The considerable development in solid-state devices during last decades has brought up the possibility of realization with modern electronic hardware. Recent papers on LINC have mostly concentrated on the linearization side of the outphasing system, although some theoretical publications have addressed the power combining efficiency also [2], [3].

One of the major drivers behind the rekindled interest in the outphasing system is the growing need for high-capacity data transfer in third and subsequent generation cellular telephone systems. Intricate modulation schemes needed to increase the data-transfer rates have hardened the linearity requirements of transmitter system considerably. This has lead to the inability of conventional power amplifier solutions to meet the stringent linearity requirements without dramatic efficiency loss.

Efficiency is one of the most important parameters in a transmitter system, as it determines the amount of wasted power. In portable devices the effect of efficiency on the battery lifetime is obvious, whereas in base station applications the heat dissipation, dictated by the efficiency, is the major quandary. The heat has to be transferred out of the system in order to ensure reliable operation, which necessitates the implementation of expensive cooling mechanisms like fans and heatsinks. These factors have compelled the industry to search for means to improve the efficiency of the PAs while maintaining the required linearity and for this purpose the outphasing system is one strong candidate.

The basic idea of the outphasing system lies in the use of RF synthesis. In RF synthesis the original signal containing both amplitude and phase modulation is divided into two constant envelope signals by a signal separator block. Ideally, no amplitude variation is present, and it is therefore possible to use highly efficient nonlinear PAs to amplify the constant envelope signals without any AM-AM or AM-PM distortion taking place in the individual branches. The original signal waveform can then be reconstructed by varying the phases of the two branches. In essence, the maximum envelope condition is obtained when the branches are in-phase and low envelope condition when the branches are almost anti-phase. This operational principle is illustrated in Figure 1.

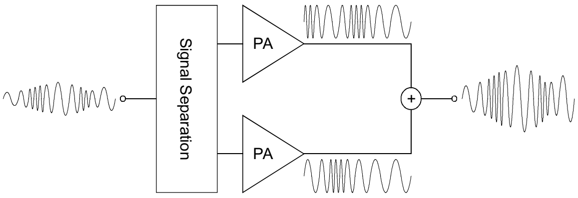

Fig. 1. RF synthesis principle

However, the efficiency of the outphasing system is comparable to that of the used PAs only during high-envelope condition, as conventional power combining results in severe losses when the phases of the combined branches vary. If no isolation between the branches is provided, the load impedance seen by the PAs increases as the phase difference grows. This phenomena can be exploited if the used PAs behave as ideal voltage sources, since the efficiency of such PA is theoretically independent of the load impedance. Realistic PAs do not behave as ideal voltage sources, but the output characteristics of switching PAs, and to some extent saturated class B/C PAs, are such that the approximation can be made.

The realization of switching PAs at gigaherz frequencies, especially at higher power levels, is extremely hard, and therefore the saturated class B/C amplifiers appear to offer an easier approach. The difficulty with the use of saturated class B/C amplifiers is the fact that even though they do exhibit a certain level of independence of the load impedance, they do not generally respond well to reactive load impedances. To address this problem the original paper by Chireix introduced a special power combining structure, known as the Chireix power combiner, in order to extend the high efficiency power combining region. However, actual implementation of this circuitry together with class-B PAs has to this Author's knowledge not been reported. The purpose of this paper is to shed light on the practical possibilities of such system.

II. CHIREIX COMBINER OPERATION

In order to analyse the operation of the Chireix combiner, the outputs of the two PAs can be written in form of two voltages

$$\begin{aligned} V_1 &= V(\cos\phi + j\sin\phi) \\ V_2 &= V(\cos\phi - j\sin\phi) \end{aligned} \qquad (1)$$

connected differentially to a common load R, where ϕ is the phase offset from the absolute output phase. The voltage generator formulation is based on the assumption that the PAs exhibit rail-to-rail voltage swing [4]. The current flowing through the load can then be written as

$$I = \frac{V_1 - V_2}{R}. \qquad (2)$$

Now the effective RF load seen by the V_1 generator is

$$Z_1 = \frac{V_1}{V_1 + V_2} R = \frac{R}{2}(1 - j\cot\phi)\cdot \qquad (3)$$

It can be seen that the resistive component of the impedance is equal to half of the original differentially connected resistor. There is also an additional series capacitive reactance, which is a function of the phase offset angle ϕ, meaning that the phase difference between the two generators is causing a reactive component to be seen by an individual voltage source. As ϕ decreases towards zero, the outphasing action reduces the composite output envelope value, and the reactive component starts to have a bigger impact on the load impedance, in effect reducing the efficiency.

The main idea of a Chireix combiner is to add a parallel compensating inductance to shunt the V_1 generator (or capacitive compensation for V_2 generator), which cancels out the reactive part of the load impedance. Therefore, at two predefined phase offset values, the load impedance seen by the generator is purely resistive enabling the maximum power combining efficiency to be reached. Thus, the power combining efficiency will not gradually decay as the phase offset increases, but will instead peak again at the angle value for which the reactive compensation is perfect. The optimum values for the compensating elements vary with the phase offset angle, and need to be selected carefully in order to provide efficiency improvement at desired offset angle value corresponding to a certain signal envelope level. Relation between a certain offset angle value ϕ and the corresponding signal back-off level is given by

$$backoff = 20\log(\cos\phi) \qquad (4)$$

A simplified circuit diagram of the Chireix combiner is shown in Figure 2. An idealized plot of the Chireix combiner's effect on the power combining efficiency for three different compensating reactance values is given in Figure 3. For a reference a curve depicting a situation without reactive compensation is also presented as "Plain outphasing".

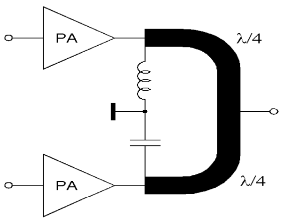

Fig. 2. The Chireix power combiner circuit

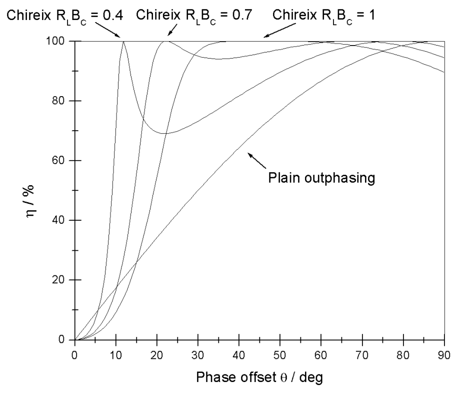

Fig. 3 The Chireix combiner's effect on the power combining efficiency vs. regular power combining

III. DESIGN OF CHIREIX POWER COMBINING SYSTEM

In order to test the functionality of the Chireix power combining system a test set-up constituting of two saturated class B push-pull PAs and a microstrip Chireix combiner was built. Both PAs utilized two discrete unpackaged pHEMT power transistors bonded directly to microstrip matching circuitry. The realized PAs exhibited drain efficiency of 75% to a 50 Ω load at P_{out} = 34.5 dBm, which corresponded to class- B biased deep saturation operation. The output power level of the PA was rather low which was due to weak breakdown characteristics and low DC-currents of the used pHEMT process. A photograph of the designed pHEMT power amplifier is given in Figure 4.

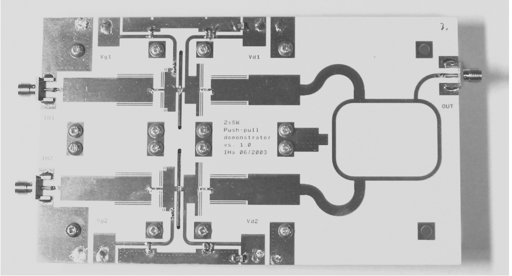

Fig. 4. The pHEMT push-pull PA

A realization of the Chireix combiner with lumped elements was not practical, which lead to an implementation with microstrip lines and a movable short circuit. The short was realized by a shunt capacitor having a self-resonant frequency at the system operating frequency 2.14 GHz. The shunt capacitor was soldered between the resonating line and ground, and by changing the placement of the capacitor-short the generated effective capacitance and inductance could be modified, i.e. the location of the combining efficiency maxima in the phase-offset plane could be tuned. Three versions of the combiner with capacitor placement offset of 2.1 mm (Combiner1), 3.6 mm (Combiner2) and 5.6 mm (Combiner3) were assembled, which corresponded to efficiency peaks at back-off values of 13dB, 9dB and 7dB, respectively. A photograph of the combiner circuits is given in Figure 5.

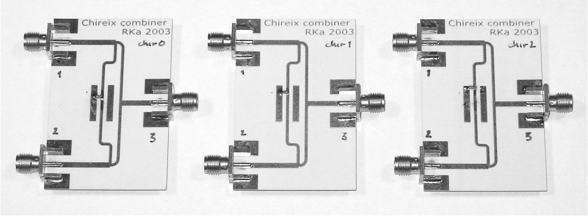

Fig. 5. The Chireix combiner circuits

Two signal generators were used in order to provide separate inputs for the PAs, so that the phase difference between PAs could be adjusted. This allowed also the fine-tuning of the input power levels of the branches in order to counter the slight imbalance of the used PAs, which was introduced by pHEMT process variation. The input signals were fed through preamplifiers to reach the necessary input power level of 29 dBm.

It is also essential for the operation that the PAs see complex conjugate load impedances, in order for the reactive part cancellation to take place. For this reason the length of the transmission lines connecting the PAs to the combiner had to be selected carefully to correspond to a certain phase shift value. A simplified diagram of the measurement setup is shown in Figure 6. The transmission lines used to set the correct phase shift are marked with $\Delta\phi$ in the figure.

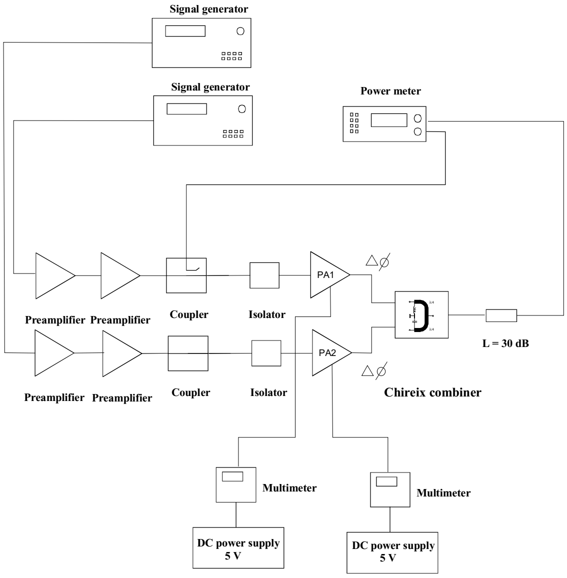

Fig. 6. The measurement setup

IV. MEASURED RESULTS

The system efficiency was determined by sweeping the phase difference of the two sinusoidal input signals and simultaneously monitoring the output power and DC power consumption. System efficiency versus output power level was calculated from the measured data, and the results are shown in Figure 7. It is important to notice that the system efficiency is the sum of the PA efficiencies and the power combining efficiency. The efficiency of the used PAs decrease gradually as the phase difference grows, which has a dominating effect on the total sum efficiency. Thus, the shape of the curve is rather smooth, and no actual efficiency peaks predicted by theory are visible. A curve representing the Chireix Combiner3 together with a reference curve measured with a Wilkinson combiner is given in the below figure.

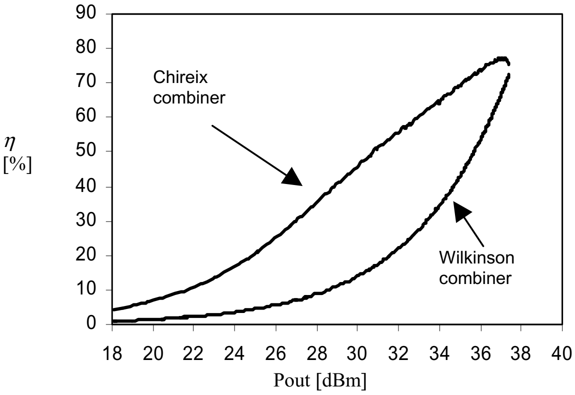

Fig. 7. The system efficiency vs. output power

The Chireix combiner shows a clear efficiency improvement over the Wilkinson combiner. With the Chireix Combiner3 a peak system efficiency of 77% is reached, compared to 73% of the Wilkinson combiner system. It can be seen that the peak efficiency is actually higher than that exhibited by the PAs for 50Ω load. This is explained by the fact that the used PAs' efficiency reaches its maximum for a slightly higher load impedance value. At –8 dB back-off from the peak output power of 37.4 dBm, a system efficiency of 43% is achieved with the Combiner3, and at –10 dB back-off the efficiency is still 32%. With the two other realized Chireix combiners the results are slightly worse, as their efficiency peaks were designed for larger back-off values. The system efficiencies with these combiners were not higher at larger back-offs, though, which was due to the inability of the used PAs to remain efficient at higher phase offset values, i.e. at higher load impedances.

Figure 8 shows the system output powers versus phase offset for a Wilkinson combiner system and a system employing the Chireix Combiner3. Ideally, the output power scales linearly with respect to the phase difference between the amplifier branches. Thus the output power curve will be sinusoidal, and the reconstitution of the original signal waveform can be obtained simply by varying the phases of the branches. The power curve for the Chireix Combiner3, however, shows a somewhat distorted sinusoidal shape.

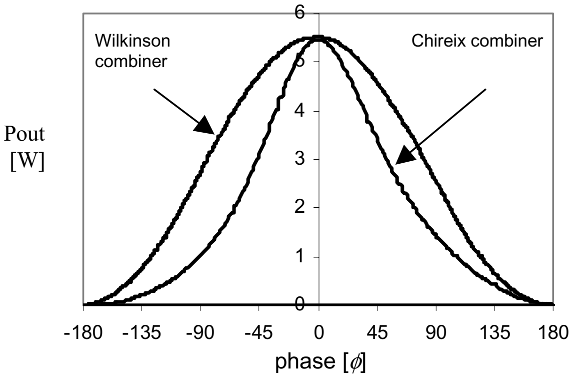

Fig. 8. The output power vs. phase offset

A more informative way to represent this phenomenon is to plot the output power with respect to the computational back-off level, which can be obtained from equation (4). From this kind of presentation it is immediately visible if the output of the system exhibits nonlinear behavior. This is illustrated in Figure 9.

It can be observed that the curve representing the Wilkinson system is highly linear, as can be expected, but the curve depicting the Chireix combiner system shows a certain level of expansive nonlinearity. This nonlinearity is partly due to imperfect phase tuning of the branches, and partly to the interaction between the power amplifiers and the time-varying impedance presented by the Chireix combiner. In a transmitter system this nonlinearity needs to be compensated, for example, with a predistortion of the input signal in order to achieve linear output.

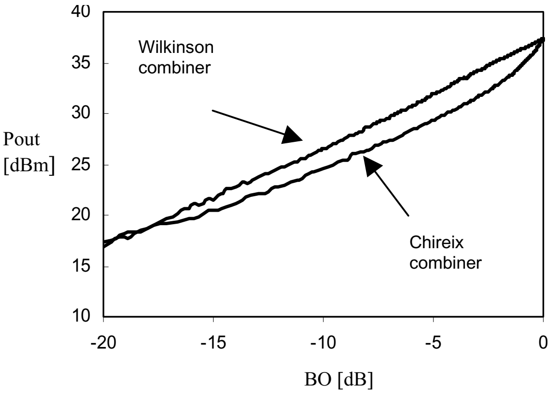

Fig. 9. Output power vs. computational back-off

Bandwidth of the Chireix system is largely determined by the quarterwave transformers in the combiner. As no special attention was paid to the bandwidth of the microstrip combiner circuit at the design stage, the system efficiency dropped clearly when the frequency of the input signals was altered. The measured efficiency with the Chireix combiner system was, however, over 28% at –8 dB back-off for the measured frequency band of 2.12 GHz-2.16 GHz.

V. CONCLUSION

An experimental Chireix outphasing power combining system has been developed. The efficiency performance of the system has been investigated with three different Chireix combiner circuits, and the results have been compared to those achievable with regular Wilkinson power combiner. The bandwidth and linearity of the system have been considered.

Results verify the functionality of the Chireix power combiner with saturated class-B power amplifiers. A clear improvement in the system efficiency over traditional power combining was achieved. The achieved efficiency improvement suggests that if the signal separation at the input can be successfully implemented, the outphasing system with class-B PAs can offer a significant efficiency advantage over existing transmitter techniques, including the Doherty amplifier.

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