On the Design of Branch Amplifiers in Outphasing Systems

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***Abstract*—The outphasing method is an efficiency enhancement technique used to improve the back-off efficiency of RF amplifiers transmitting variable envelope signals. This is achieved by translating the original amplitude modulation into the phase modulation of two constant envelope signals and reconstructing the original modulation at the output. Conventional design of outphasing amplifiers consists in optimising the output combining network, while identical saturated power amplifiers are employed for each branch. In this work different power amplifier modes of operation are being evaluated as upper and lower branch PAs for outphasing systems. Rather than designing a combiner to compensate for the reactive loading, by considering the intrinsic load modulation which each PA branch sees over the outphasing range, the phase shift introduced by the matching network of each PA branch can be tuned to obtain a significant performance improvement. Simulations and measurement confirm this, proving that PAs with a fundamental reactive loading and reactive second harmonic are more suitable for outphasing operation.**

***Index Terms*—Power amplifier, Outphasing**

I. INTRODUCTION

Wireless communications growth continues at an ever increasing rate. The number of mobile subscriptions worldwide will grow from 7.5 to 9.2 Billion in the next five years, with a total of 26 Billion wireless connected devices by 2020 [1]. Inefficiency of base-stations, mainly due to poor RF power amplifier performance, is reason for growing concerns, considering the predicted densification of the cells. As future communications standards will still feature signals with high peak-to-average-power-ratios, this will result in low single-ended amplifier efficiencies. Doherty and Envelope Tracking ystems, which rely on load modulation and dynamic supply modulation respectively, to increase efficiency over a larger Output Back-Off (OBO) [2], have now become industry standard. Outphasing systems however are now contending to become the new workhorse for future wireless transmitters. In the outphasing techinque, an amplitude modulated signal, is split into two constant envelope phase modulated signals, which are then amplified in two separate branches and combined at the output, where the original amplitude modulation is reconstructed. This represents an advantage over conventional techniques as PAs can be used in deep saturation without a degradation in the linearity of the transmitted signal. The reactive loading which each PA branch sees as a consequence of the outphasing operation is a significant shortcoming of the technique, as in conventional PAs, the reactive loading causes degradation in efficiency. Techniques to improve the back-off efficiency of the outphasing system have mainly consisted in modifications of the combining structure through the use of series transmission lines, or shunt reactances. Alternatively isolating combiners such as Wilkinson have been employed to eliminate the interaction between the two PA branches, improving the system linearity but also removing all the benefits of the load modulation. To achieve an efficiency improvement when Wilkinson combiners are used, the supply of the branch power amplifiers can be varied to create multiple levels for the constant vectors in what is known as Multi-Level LINC [3].

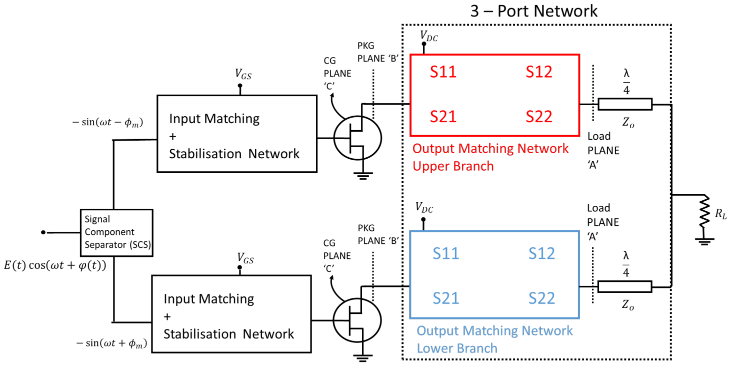

Fig. 1. Simplified block diagram of outphasing system. The upper and lower branch amplifiers Output Matching Networks (OMN) are generalised as 2-port networks and both OMN and combiner can be represented as a 3-port network.

This paper considers the case when the two branch PAs are let to interact with each other through a lossless combiner, and the active load-pull is exploited to achieve high back-off efficiency. It is shown how through the appropriate design of each outphasing branch PA, it is possible to improve on the efficiency of operation of an outphasing system.

II. THEORETICAL ANALYSIS

A. Outphasing Load Modulation

In outphasing systems, as previously explained, the original information bearing signal, is decomposed into two constant magnitude phase modulated signals. The two constant envelope signals are then amplified through two different paths and

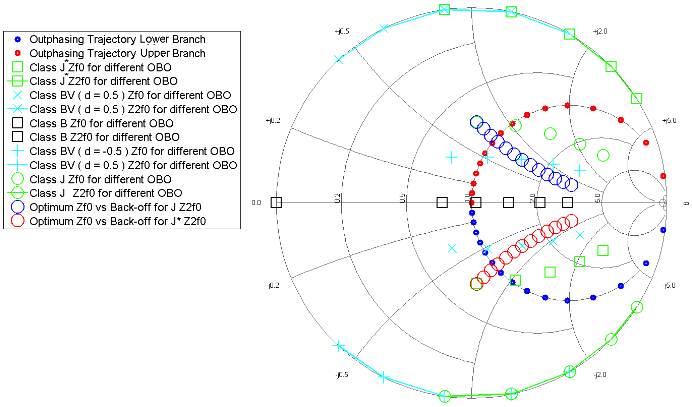

Fig. 2. Ideal outphasing and optimal load modulation trajectories for different values of design space d with fixed and variable second harmonic terminations.

then recombined at the output. This technique, known from the early stage of vacuum tubes amplifiers [4], theoretically allows PA to be operated constantly in saturation without affecting the linearity of the transmitted signals. In outphasing however the input drive of the PAs is constant as the amplitude modulation is only reconstructed via phase shift between the two branches at the output. Therefore when the PA operates heavily in saturation, the drain current is decreased by the action of the increasing load seen by each branch, or more precisely by the reduction in the voltage across the common load. In this case the drain current becomes a function of the outphasing angle and output power back-off. When non-isolating combiners are used in outphasing modulation, due to the phase shift between the signals combining at the output, the load seen by the two PA branches is subject to a highly reactive modulation, thus also affecting the efficiency of the system.

In an outphasing system with lossless combining, as shown in Fig. 1, the load modulation at Plane "A" derived in [5] can be written as:

$$Y_{1,2}(\phi) = R_{load}\frac{2\cos^2\phi}{Z_0^2} \pm jR_{load}\frac{\sin 2\phi}{Z_0^2} \tag{1}$$

where ϕ is the outphasing angle, used to control the output power level of the amplifier. Z_0 and R_L are the characteristic impedances of the $\frac{\lambda}{4}$ line and the load impedance annotated in Fig. 1. Fig. 2 shows the upper and lower load trajectories from Eq. 1 as ϕ is varied from 0 to 90 degrees. The load modulation seen at the current generator plane of the transistor can then be approximatively found by applying two linear transformations from Plane "A" to Plane "B" and from Plane "B" to Plane "C", approximating the devices's parasitics as a linear two port network. The intrinsic load modulation seen by each PA is what will affect the back-off efficiency of the system. The intrinsic load modulation depends on both the impedance presented to the package of each transistor by each branch OMN and by the combined phase shift introduced by the OMNs and combiner.

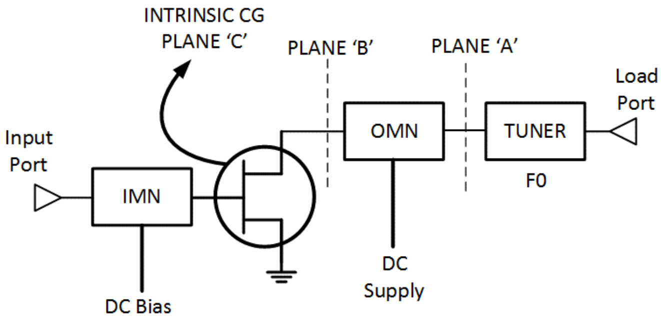

Fig. 3. Simplified block diagram of simulated and experimental set-up.

B. *Optimal Load Modulation of Branch Amplifiers*

Power amplifier modes of operation are defined by their intrinsic current and voltage waveforms. Continuous modes of operation expand the design space of the conventional modes by defining a continuous set of voltage and current waveforms, all presenting the same DC and fundamental Fourier components, thus resulting in the same efficiency and output power as their original mode [6]. The optimal fundamental and harmonic impedances for a given mode of operation can be defined as a function of back-off β and for different values of the continuous design space parameter d, as previously shown in [7] and [8].

For Class BV continuous mode PAs the fundamental and second harmonic impedances, shown in Fig. 2, are defined as:

$$Z_{f0} = R_{opt} + jdR_{opt} \tag{2}$$

$$Z_{2f0} = -j\frac{3\pi}{8}dR_{opt} \tag{3}$$

Where d $[-1, 1]$, R_{opt} is the optimal resistance defined as:

$$R_{opt} = 10^{\frac{|\beta|}{20}} R_L \tag{4}$$

And R_L is the Class B load-line:

$$R_L = \frac{2\left(V_{DC} - V_{knee}\right)}{I_{Max}} \tag{5}$$

Class B, Class J and Class J* PAs are all part of the continuous Class BV mode where the design space parameter d takes the value of 0, 1 and -1 respectively. From Eq. 3 it can be seen that for the same value of the design space d the reactance of the optimal second harmonic impedance termination varies with output power back-off. However, by fixing an optimal second harmonic impedance termination, it is possible to find a fundamental load termination which allows optimal operation over the output power back-off. The optimal fundamental load modulation for values of d = 1 and d = -1 follow the complex trajectories shown in Fig. 2. For Class B amplifiers with d = 0 the optimal fundamental load modulation remain on the real axis.

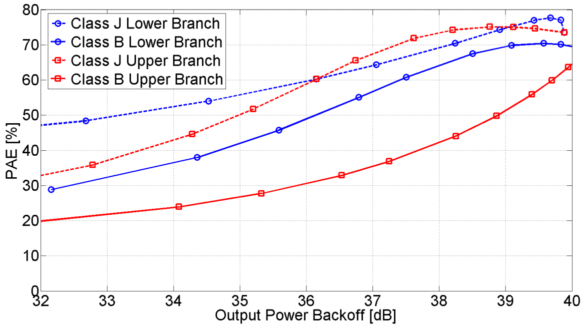

Fig. 4. Simulated efficiency of PAs subject to upper and lower outphasing trajectories.

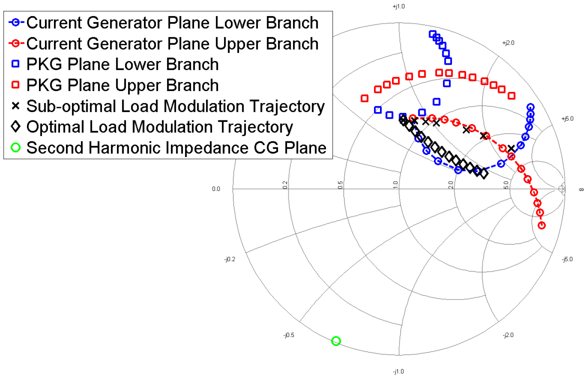

Fig. 5. Simulated package and intrinsic fundamental impedance terminations of best case upper and lower trajectories for Class J PA.

C. Branch Design for Outphasing

Conventional techniques for outphasing design have considered the reactive load modulation to always have a detrimental effect on the efficiency of the amplifiers, with the power factor of the combiner (scaled by a factor of $\frac{\pi}{4}$ for Class B PAs) as a metric used to determine the efficiency of outphasing system. This is only true for amplifiers where the optimal load modulation is purely real such as Class B PAs, where the load modulation is represented as a straight line on the real axis of the Smith chart. If amplifiers with reactive fundamental and harmonic impedance are considered, it is possible to design the OMN of the upper and lower branch amplifiers so that the intrinsic fundamental load modulation seen by the two transistors follows the wanted ideal profile. This can be achieved with an appropriate choice of phase shift and input impedance of the matching networks. The upper and lower branch outphasing trajectories present a concave and convex load modulation profiles which fit well with the optimal fundamental load trajectories shown in Fig. 2. The concave upper branch trajectory matches well the concave Class J* (d = -1) optimum fundamental load modulation, while the convex lower branch profile matches the convex optimal fundamental trajectory of Class J PAs (d = 1).

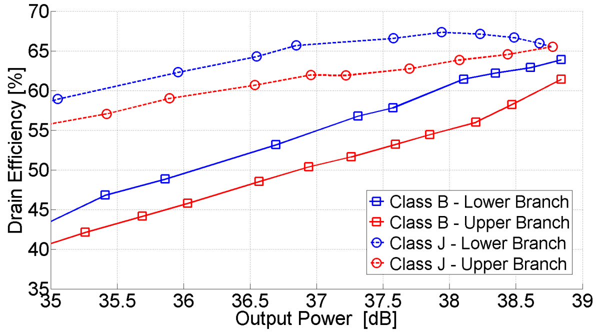

Fig. 6. Measured efficiency results of Class J and Class B PAs subject to upper and lower outphasing trajectories.

III. SIMULATED RESULTS

To validate the concept a comparison was made using a simulation test-bed set-up in NI AWR Microwave Office. The simplified block diagram of the simulation is shown in Fig. 3. The behaviour of Class J and Class B PAs was investigated when subject to the outphasing loading. The verified large signal model for the Cree CGH40010 GaN HEMT (6-port model, R6) was used to design both amplifiers. The device was biased in deep Class AB with a DC supply of 28 Volts and stabilised with a series resistor capacitor network. Two PAs were designed, one with the output matching network designed to present the appropriate fundamental and second harmonic impedance terminations for a Class B design, the other one for a Class J design. The frequency of operation was chosen to be 900MHz and a lumped low-pass π matching network topology was used for both OMNs. The value of R_L chosen was 36 Ω from IV curve analysis. In order to simulate the effect of the outphasing loading on the Class B and Class J PAs, ideal tuners were used to sweep both the upper and lower outphasing branch trajectories. The phase shift of the OMN of the amplifiers was optimised in each case by tuning the length of a series transmission line at the output of each amplifier. For both PAs the lengths of the lines achieving the highest back-off efficiency at 8dB back-off was chosen for the upper and lower outphasing trajectory sweep. For the Class J PA the package and current generator plane impedances resulting from the optimisation are shown in Fig. 5. The performance of both Class B and Class J PAs for both trajectories is shown in Fig. 4. As expected for the Class J PA which presents a complex optimal load modulation, the efficiency can be preserved by tuning the phase shift of the OMN, whereas for the Class B PA, the reactive loading inherently causes a degradation in performance. The trajectory which presents the highest efficiency in the back-off is the lower branch Class J trajectory where the fundamental load modulation follows closely its theoretical ideal trajectory.

IV. EXPERIMENT ON SINGLE-ENDED PA

A prototype branch amplifier was built and measured replicating the simulated experiment. The substrate which was used for the input and output matching networks was Duroid

5880. The relative permittivity of the material is $\epsilon_r = 2.2$ and thickness 1.57 mm. Using a Focus 1880 mechanical load-pull tuner calibrated with an Agilent PNA-X N5242A, the outphasing trajectories found from simulation were presented at the load plane of each amplifier, while keeping a constant input power level. A lumped π OMN was used for the design, to be able to present different fundamental and second harmonic impedance terminations for the Class B and Class J cases, by simply adjusting the component values. Measurements for the different load profile sweeps on the two PAs are shown in Fig. 6. Results show that the Class J PA performs better than the Class B PA over a 4dB output dynamic range. This dynamic range relates to a single branch back-off output dynamic range. This needs to be increased by 3dB when considering the system back-off as in outphasing system each PA delivers t the load half of the power. The reduced output power dynamic range compared to the simulation is due to the limitation in the tuning range of the tuner utilised at the frequency of test. The maximum magnitude of the reflection coefficient which could be achieved in the laboratory was 0.75. An improvement of more than 15% in drain efficiency was seen at 4dB back-off for both the upper and lower branch outphasing trajectories when using a Class J PA compared to the conventional Class B case.

V. CONCLUSION

PAs with an intrinsic reactive fundamental match (such as Class J) perform better than PAs with a resistive fundamental match (such as Class B). Simulations and measurements have evidenced a significant improvement in performance when the phase shift of an amplifier branch is optimised to follow the ideal current generator plane load modulation trajectory derived from the theory. This work represents a first step towards a holistic design approach in the design of outphasing amplifiers where the OMN of each PA branch and combiner are designed simultaneously and optimised through a known set of goals. The same principle presented in this paper could be applied in the design of Doherty or dynamic load modulated power amplifiers.

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