Experimental Validation of a Four-Way Outphasing Combiner for Microwave Power Amplification

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Abstract—**This paper presents a 2.14-GHz, four-way power combining and outphasing system for high-power amplifiers such as those in radio basestations (RBS). The combiner is ideally lossless, and enables power control through load modulation of the power amplifiers (PAs). A discrete-component power combiner is designed and characterized, and combined with inverse Class-F PAs using GaN HEMT devices to develop a complete PA system. We demonstrate the effectiveness of the system over a range of outphasing control angles. This first-ever microwave implementation of the outphasing system has a peak CW drain efficiency of 68.9%, with efficiency greater than 55% over a 5.5-dB power range. It provides an average modulated efficiency of 57% for a W-CDMA signal with 3.47-dB peak to average power ratio (PAPR) at 42-dBm output power.**

Index Terms—**base stations, outphasing, power amplifier (PA)**

I. Introduction

WIRELESS communications standards are evolving towards higher data rates, with systems employing aggressive modulation schemes having high peak-to-average power ratios (PAPR) to effectively use the allowed spectrum. In order to reproduce a signal varying over a wide output power range, the PA has the competing requirements of simultaneous linearity and efficiency. A wide variety of techniques have been explored in an effort to develop power amplifier systems providing both high linearity and high average efficiency.

The inherent efficiency advantage of switching PAs over linear ones leads naturally to a strategy of combining multiple switching PAs in an overall-linear architecture. One example of this approach is Chireix outphasing, e.g., lossless power combining and phase-shift control of a pair of switching PAs [1]. For high-power PA designs in particular, it is often preferable to combine the outputs of multiple, relatively low-power PAs, so that multiple active devices are used. Once power combining is necessary, an outphasing architecture becomes particularly appealing because it can provide the most effective use of the multiple PAs.

The four-way power combining and outphasing system demonstrated in this work was recently proposed as a way to overcome the limitations of conventional outphasing techniques such as Chireix outphasing [2]. A design procedure and development of outphasing control laws have been described in [3]. This paper presents the first experimental

results demonstrating that this approach can be extended to microwave frequencies, and presents the first application towards communications. The technique, which realizes load modulation of the PAs through outphasing, is demonstrated to be more efficient than PA drive amplitude back-off over a 5.5-dB range of output power.
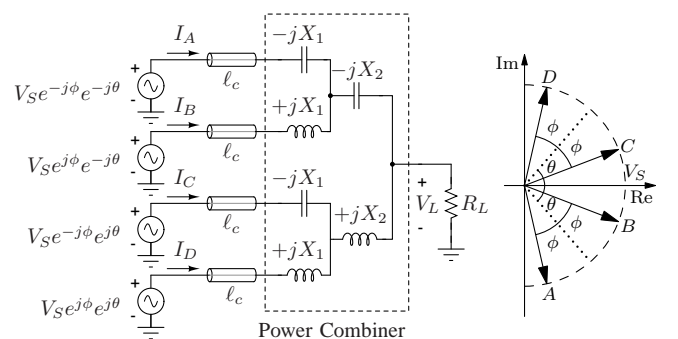

Fig. 1. The four-way outphasing and power combining system. The PAs are represented as ideal, constant-amplitude voltage sources with the phasor relationship shown [2]. The transmission lines represent interconnects from the PA reference planes to the combiner input reference planes.

II. Architecture

The selected implementation of the new four-way outphasing power combiner system is shown in Fig. 1. For analysis purposes, the four PAs driving the combiner are treated as ideal, constant-amplitude voltage sources with magnitude V_S and with the phasor relationship shown. At microwave frequencies, the connector length between the reference plane at the input of the combiner and the output plane of the PA must be considered. The total electrical length of the connections between the combiner and PAs, treated here as transmission lines with length ℓ_c, is chosen so that a real impedance at the combiner reference plane appears as a real impedance to the amplifiers. Thus there are two options for connector length: it can provide a net half-wavelength (no net rotation) or a quarter-wavelength (impedance inversion).

For the configuration in Fig. 1 with connector length $\ell_c = \lambda/2$ and with the system driving a resistive load R_L, the output power is given by [2]:

$$P_{\text{out}} = \frac{8R_L V_S^2}{X_1^2} \sin^2(\phi) \cos^2(\theta) \qquad (1)$$

The optimal susceptance (OS) control law developed in [3] can be rewritten in terms of normalized commanded output

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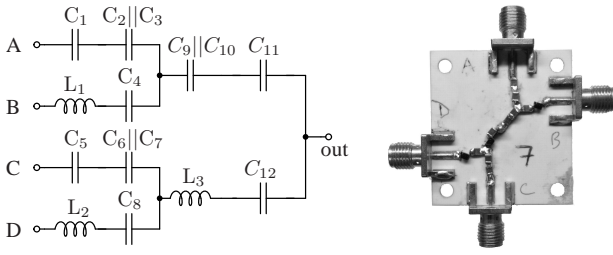
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Fig. 2. Discrete-component combiner implementation and photograph. The output (center) connector is mounted on the reverse side.

TABLE I
COMPONENT VALUES FOR THE IMPLEMENTED COMBINER.

Component	Value	Part #	Manufacturer
C_{10}	1pF	MC08CA010D-F	Cornell
C_1-C_8, C_{11}, C_{12}	2pF	MC08CA020D-F	Dubilier
C_9	3pF	MC08CD030D-F	(ML series)
L_1, L_2, L_3	3.85 nH	0906-4GLB	CoilCraft

power $P_n = P_{\text{out}}/P_{50}$, where $P_{50} = (2V_s^2)/(50)$ is the total output power of the four PAs driving 50-Ohm loads.

If an $\ell_c = \lambda/4$ connector length is chosen, the input impedance to the combiner is transformed so that the load impedance seen by the PAs *increases* with increasing commanded power P_n. The OS control law can be adapted for this inversion by replacing P_n in the control law with $1/P_n$:

$$\theta = \cos^{-1}\left(\sqrt{\frac{P_n}{4} + \frac{1}{4P_n}\left(\frac{X_1}{R_L}\right)^2}\right), \ \phi = \tan^{-1}\left(\frac{X_1}{R_L P_n}\right)$$
(2)

Following the design method in [2], X_1 and X_2 are uniquely determined by design parameter k. This parameter controls the tradeoff between output power dynamic range for optimum load modulation and the maximum variation in the phase of the load admittance seen by the four PAs. For this work, a value of $k = 1.05$ is chosen, corresponding to an output power ratio of approximately 10 dB for which an admittance phase of less than $2°$ is realized (assuming ideal-source PAs). For this value of k and load resistance $R_L = 50 \ \Omega$, the calculated combiner reactances are $X_1 = 35.60 \ \Omega$ and $X_2 = 48.78 \ \Omega$. This control method provides nearly resistive loading for the power amplifiers over the entire operating range, with power controlled via load modulation.

III. IMPLEMENTATION

A. Combiner

A discrete-component combiner is constructed with Coil-Craft Micro-Spring inductors and silver mica capacitors on

TABLE II
MEASURED AND SIMULATED ($k = 1.05$) PORT AMPLITUDES AND PHASES
WHEN OUTPUT IS DRIVEN AND INPUT PORTS ARE TERMINATED IN 50 Ω.

Port	Measured Ampl.	Measured Phase	Simulated Phase
A	1.02	$+86°$	$+88°$
B	0.97	$+16°$	$+17°$
C	1.01	$-16°$	$-17°$
D	1.01	$-87°$	$-88°$

a Rogers 4350 substrate. Inductive branch impedances are synthesized from series LC combinations in order to provide DC blocking, and capacitive branch impedances use both series and parallel capacitor combinations to facilitate tuning and so that all branches have the same total physical length.

The combiner is characterized by driving the center (output) terminal and measuring the amplitude and phase of the signals at the 50-Ohm terminated input terminals. An accurate match to the theoretical phase relationship between the four input terminals can be achieved by an iterative component selection process. Initially, the $+jX_2$ and then $-jX_2$ branches are shorted across in turn, and the phase and amplitude relationship between terminals A and B and between terminals C and D are trimmed by selecting the branch capacitor values with nominal inductor values. Capacitors are stacked in parallel where necessary. Then, the phase relationship between ports A and C is set by choosing the component values that set $\pm jX_2$. This methodology directly addresses phase shifts and shunt capacitances occurring due to the physical size of the combiner components in order to synthesize reactances matching the theoretical values found through the combiner design method.

The combiner implemented with the values in Table I (see Fig. 2) has amplitudes that match within $\pm 3\%$ and phases that are within 2 degrees of the theoretical values for a combiner with $X_1 = 35.60$ and $X_2 = 48.78$ as for the proposed combiner with design variable $k = 1.05$ above. The measured combiner performance is summarized in Table II.

The combiner efficiency is measured for 50-Ω terminations by driving the output port and measuring the power transmission to each input port. The total insertion loss of the combiner and the connectors is measured to be 0.29 dB when the center terminal is driven with 20 dBm.

B. Inverse Class F Power Amplifier

The prototype outphasing system includes four Inverse Class F PAs using the design in [4]. The PAs were fabricated on a 30-mil Rogers 4350 substrate and operated at a supply voltage of 20V and gate bias -3.4V. The output power and drain efficiency of each PA is characterized by loading with a range of real impedances similar to those in the combiner system. The output powers are then summed, assuming zero combining loss, and the drain efficiencies averaged, to produce the upper curve in Fig. 3. This curve represents the idealized performance using these PAs. When the 0.29-dB combiner loss, measured when the combiner is terminated with 50-Ω loads, is applied to the measurement of the PA performance into 50-Ω loads, the expected system output power and efficiency can be predicted. This value, indicated by the single dot in Fig. 3, predicts the measured performance of the outphasing system within 3 percentage points. It is important to note that the power combiner loss is not expected to be constant with outphasing angles (that is, effective port impedances) or power levels.

C. Connectors Between PAs and Combiner

For prototyping purposes, the combiner is built on a separate PCB from the power amplifiers. The connectors are realized

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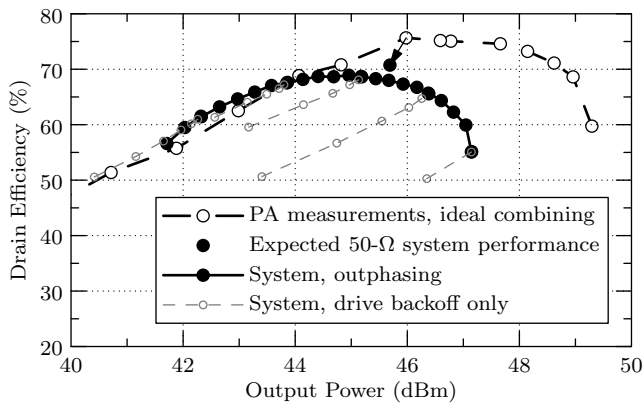
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Fig. 3. Measured drain efficiency and output power: (dashed) - calculated from individual PA measurements and assuming ideal, lossless power combining; (single dot) - expected performance for 50-Ω PA loading based on individual PA and combiner efficiency measurements; (solid) - system performance using outphasing for output power control; (dashed, grey) - system performance using drive back-off at various outphasing angles.

with PCBs with 434-mil long 50-Ω traces on RO4350 substrate, as can be seen in Fig. 4. This length, plus the output matching network of the PA and SMA connector electrical length, provides a net quarter-wave inversion at 2.14 GHz.

IV. EXPERIMENTAL RESULTS

A photograph of the power stage of the RF amplifier system is shown in Fig. 4. Phase modulators for the 60-W, 2.14-GHz outphasing system are implemented using Analog Devices AD9779A 16-bit DAC evaluation boards with upconverting mixers. An FPGA provides digital phase commands to the phase modulators. Power splitters distribute both the carrier signal and the data clock to each phase modulator PCB. The phase modulators drive the switching PA inputs via a preamplifier chain.

The measurements shown in Fig. 3 are performed by varying the relative phase relationships of the four CW input signals according to the control law for $\lambda/4$ interconnects (2). The drive amplitude is simultaneously scaled corresponding to the output power level to keep the PAs saturated. The output power is measured using an HP 8482B power sensor with an HP436A power meter using a pulsed CW measurement.

Also shown in Fig. 3 are efficiency curves for drive backoff, where for various fixed outphasing angles amplitude control is demonstrated using input drive scaling only. The system drain efficiency is greater than 55% over the entire 5.5-dB power range and has a peak value of 68.9%. The practical range for outphasing is limited by the PA efficiency performance over load modulation as well as the operating range of the combiner and outphasing control law. Below the 5.5-dB outphasing range it becomes beneficial to use input drive back-off to modulate the output power.

Table III contains a summary of the system performance demonstrating modulated W-CDMA performance and comparison to other works. For these modulated tests, a combination of outphasing and drive amplitude scaling was used to produce a W-CDMA signal with 3.84-MHz signal bandwidth and 3.47-dBm peak to average power ratio (PAPR) with an
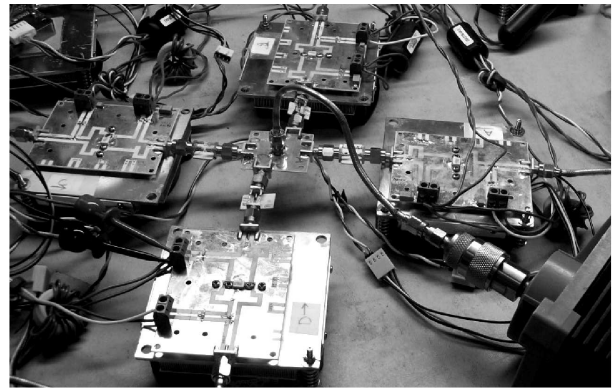

Fig. 4. Power stage of the experimental RF power amplifier system.

TABLE III
COMPARISON TO OTHER WORKS: WCDMA PERFORMANCE

System Arch.	Arch	Carrier (MHz)	PAPR (dB)	P_{out} (dBm)	$ACLR_1$ (dBc)	Drain Eff.
[6]	Chireix	2140	9.6	39.5	-47 dBc	50.5%
[4]	Doherty	2140	6.5	43	-31 dBc*	61%
[7]	Doherty	2600	7	57.3	-50.6 dBc	48%
This Work	4-way	2140	3.47	42	-36.6	57%

* - without linearization

average output power of 42 dBm. This average efficiency result closely matches the performance expected based on the static measurements in Fig. 3. A static lookup-table and sequence-based linearization method were used for linearization [5].

V. CONCLUSION

This work is the first-ever demonstration of a new four-way outphasing and combining system at microwave frequencies. This new system provides a considerable efficiency advantage over conventional amplitude modulation due to the wide output power range over which the four PAs operate in switched mode with load modulation. With the wide dynamic range over which power is efficiently modulated through outphasing-based load modulation, it is anticipated that this power amplifier architecture will be an effective approach for achieving high power, high efficiency and high linearity in wireless communications.

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