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An RF-input Outphasing Power Amplifier with RF Signal Decomposition Network

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Abstract—This work presents an outphasing power amplifier that directly amplifies a modulated RF input. The approach eliminates the need for multiple costly IQ modulators and baseband signal component separation found in conventional outphasing power amplifier systems, which have previously required both an RF carrier input and a separate baseband input to synthesize a modulated RF output. A novel RF signal decomposition network enables direct RF-input / RF-output outphasing by directly synthesizing the phase- and amplitude-modulated RF signals that drive the branch PAs from the modulated RF input waveform. The technique is demonstrated at 2.14 GHz in a four-way lossless outphasing amplifier system with transmission-line-based power combiner. The resulting proof-of-concept outphasing power amplifier has a peak CW output power of 95 W, and peak drain efficiency of 72%.

Index Terms—base stations, outphasing, power amplifier (PA), Chireix, LINC, load modulation, signal component separator, transmission-line resistance compression network.

I. INTRODUCTION

From its first implementation by Chireix in 1935, a limitation in outphasing architectures has been the need for multiple (two or more) modulators operating from a baseband input to produce the multiple phase-modulated RF inputs to the branch power amplifiers. For example, an early commercial outphasing amplifier, Ampliphase, used two sets of dynamic phase-modulating amplifiers to modulate the carrier signal by the (baseband) audio signal and drive the branch PAs [1]. In modern outphasing amplifiers, phase-shift modulation is typically realized using digital-to-RF IQ modulators operating on data from a baseband signal component separator. This use of multiple upconverting modulators incurs excessive cost and complexity as compared to a system with a single input, and can complicate any digital correction scheme. In many applications, a preferred solution would be an RF-input / RF-output power amplifier with high efficiency over a wide dynamic range that can serve as a drop-in replacement for amplifiers using less efficient techniques.

In this work, we present for the first time an RF-input / RF-output outphasing power amplifier, eliminating the need for multiple costly IQ modulators. An RF signal decomposition network directly synthesizes the multiple branch PA drive signals from a modulated RF input signal, performing both the phase and amplitude modulation utilized in outphasing systems to control the output power over a wide range [2], [3]. This signal decomposition network (or RF signal component separator) is based on use of a resistance compression

network (RCN) [4]–[6] terminated with nonlinear elements. The resulting system is a true RF amplifier in that its input is a modulated RF signal, and its output is an amplified version of that signal.

The approach is demonstrated in a proof-of-concept four-way lossless outphasing system with a transmission-line combiner, as in [7]. The system operates at 2.14 GHz with a peak output power of 95 W. The RF signal decomposition network is likewise implemented using transmission-line techniques. Although the system is not optimized for overall efficiency performance, the drain efficiency of the final RF stage has a peak of 72%, indicating that this system performance is similar to that of the related baseband-input outphasing system in [7].

II. RF SIGNAL DECOMPOSITION NETWORK

Fig. 1 shows the prototype RF-input / RF-output system, consisting of a decomposition network, driver and branch PAs, and a lossless multi-way power combiner. The RF signal decomposition network is based on a four-way RCN terminated with nonlinear components (whose effective resistance varies as a function of input power) and performs both outphasing of the four branch PAs over a specified range and amplitude modulation for operation below the nominal outphasing range. Driving the PAs through an appropriately-terminated RCN network in this way can yield the desired signal decomposition for the outphasing system.

Outphasing combiner analysis typically assumes that the branch PAs operate with constant output envelopes, i.e. driven in saturated or switched mode, with output power control achieved only through modulation of the effective load impedance seen by each PA [4], [8]. In principle, then, the output power of an outphasing system can be modulated by phase-only control of the multiple signals driving the branch PAs. Practical implementations, however, often include amplitude modulation of the signals driving the branch PAs in order to extend the system's output power range below a specified outphasing operating regime to include zero crossings [2], [3]. This mixed-mode operation avoids the situation of requiring the multiple power branch PAs to exactly cancel to produce zero output power. The nonlinear terminations on the RCN network in this work are designed to perform these dual functions in two operating modes.

In the outphasing regime, the function of the RF signal decomposition network is to convert amplitude modulation at the system RF input into relative phase modulation among

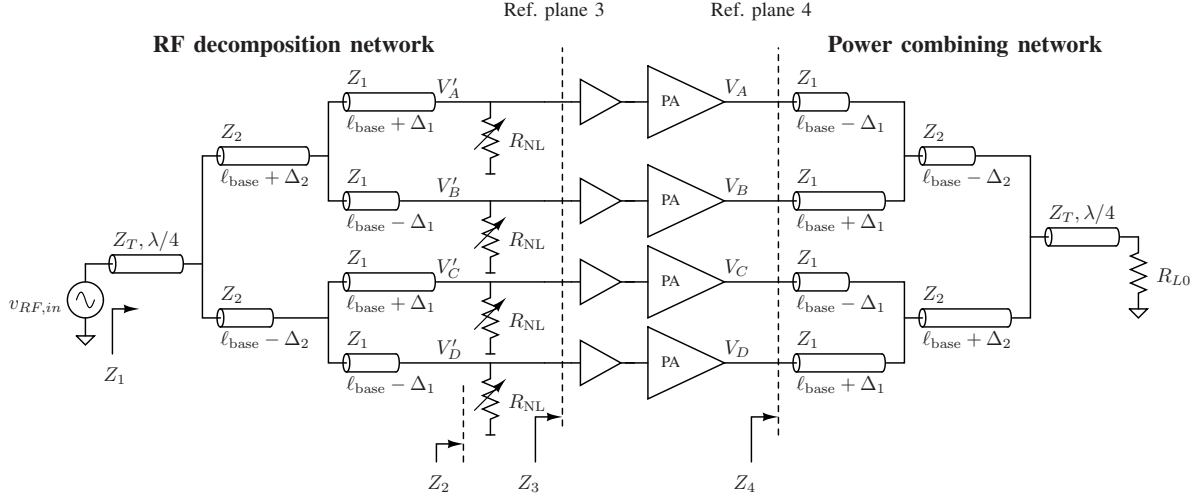


Fig. 1. The new RF-input / RF-output outphasing system simplified schematic showing the four-way transmission-line implementation of the RF decomposition and combining networks used in the experimental prototype in this work.

the inputs to the four branch PAs. Conceptually, the phase relationship between the four combiner inputs that results in nearly-resistive load modulation (over e.g. a 10:1 range) can be synthesized by varying the RCN terminating resistances over the same resistive range. In practice, the varying RCN terminating resistances are synthesized with nonlinear networks (as described in Section II-A below). This approach exploits the approximate time-reverse duality of the RCN and multi-way power combiner networks; similar RF decomposition networks can likewise be synthesized for other outphasing power combining networks. As shown in Fig. 2, when this outphasing control scheme is used the expected branch PA loading impedances remain closely matched and nearly resistive over the operating range.

The inverse RCN (IRCIN) outphasing control strategy forms the basis of the RF signal decomposition in the outphasing regime. Net phase modulation of the input signal appears directly as a common phase shift of all four branch PA inputs. Note that because the RCN and combiner networks are not exact (double) time-reverse duals, the actual combiner output power will not precisely track the input power [4]. This and other nonlinearities in the implemented system can be addressed through pre-distortion of the input signal (or through improved selection of the termination nonlinearity in the RF decomposition system).

Below the desired outphasing power range, the resistive terminations to the RCN are held fixed and the four signals V'_A - V'_D are amplitude-modulated with the input signal, producing the mixed outphasing and amplitude modulation control that allows practical outphasing transmitters to accurately produce zero-crossings [2], [3].

A. Implementation of Nonlinear Terminations

In this proof-of-concept prototype, the nonlinear loads are implemented using anti-parallel diodes and parallel resistance R_p as shown in Fig. 3. When the input drive to this network is sufficiently large, the output voltage waveform will be a

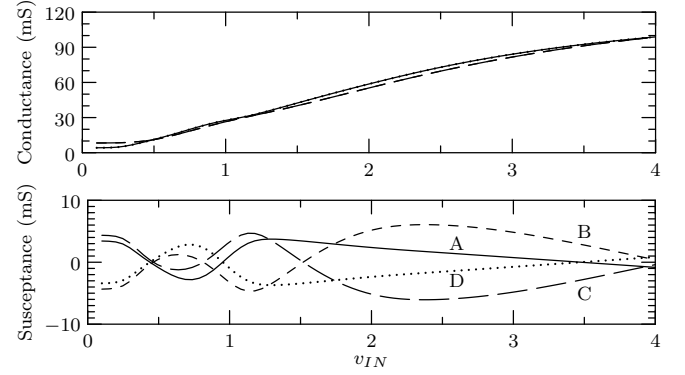


Fig. 2. Effective loading impedances seen by the four branch PAs in the RF-input / RF-output system (Z_4 , Fig. 1) as a function of the system RF input voltage $v_{RF,in}$, when the outphasing angles resulting from the decomposition network are applied to the power combiner (simulated). Note the order of magnitude difference in the scales for the two plots.

clipped version of the input current. As the power and current into a nonlinear termination is increased, the voltage across it will remain at the clipped amplitude set by the forward voltage of the diodes. As a result (and neglecting the effect of R_p and any parasitic resistance), the effective input impedance R_{NL} of this network will be an inverse function of input power. This relationship produces the appropriate phase relationship for the outphasing system: increased input power leads to a smaller resistive termination on the decomposition network, thereby producing the relative phases of the branch PAs that results in higher system output power (through load modulation of the branch PAs from outphasing). When the parallel resistance R_p is included, the nonlinear network's resistance is limited at low drive levels. The relative phases of V'_A - V'_D are therefore fixed for low drive amplitude (below that at which the diodes become forward biased), producing amplitude modulation of the branch PAs at a fixed phase for the lower-power operating regime.

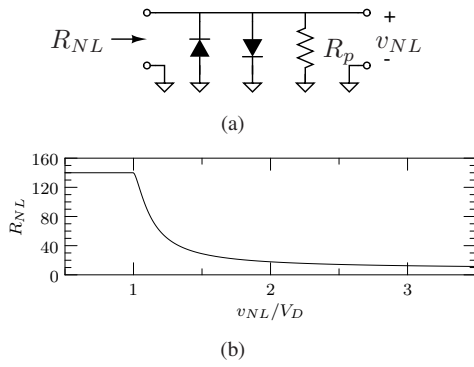


Fig. 3. Nonlinear load element used to terminate the RCN: (a) – equivalent schematic, and (b) – effective input resistance at the fundamental (ideal diode with turn-on voltage V_D and on-resistance $r_d = 8 \Omega$, $R_p = 140 \Omega$ assumed).

III. IMPLEMENTATION AND MEASUREMENT

The experimental system is designed to operate at 2.14 GHz, with both the decomposition and combining network implemented with microstrip lines in 60-mil-thick Rogers 4350 substrate.

The signal decomposition network is implemented with an all-transmission-line RCN [5], although many alternative implementations are possible. The network and loads are designed such that the nonlinear loads vary over an approximately 10–85 Ω range, corresponding to the range that the combining network is designed to present to the branch power amplifiers. The low-impedance end of this range corresponds to that of the HSMS-286C diodes driven into hard clipping, while the upper end is limited by the parallel resistance formed by input impedances Z_3 (see Fig. 1). Parasitic reactance of the diode pair is compensated for using a transmission-line matching network (not shown).

The decomposition and power combining networks are designed using the same parameters as the power combining network in [7], with characteristic impedances $Z_1 = Z_2 = 100 \Omega$, and delta electrical lengths $\Delta_1 = 0.049\lambda$ and $\Delta_2 = 0.054\lambda$ following the design methodology in [7].¹ An impedance-transforming quarter-wave transmission line is included in both the combiner and decomposition networks, with $Z_T = 40.8 \Omega$. Combined with the resistance compression behavior of the TLRCN, this impedance transformation establishes a 50- Ω input impedance to the power amplifier system. The TLRCN provides a narrow-range resistive input impedance even when its terminating impedances vary, so that the reflection coefficient at the input port has $|S_{11}| < -30$ dB (simulated) over the entire range of operation.

The network is characterized by measuring the phase relationship at the four output ports of the splitter when the input power is varied. Fig. 4 shows the measured phase relationships at reference plane 3 (see Fig. 1) with 50- Ω loads representing the input impedances to the PA drivers, and at reference plane

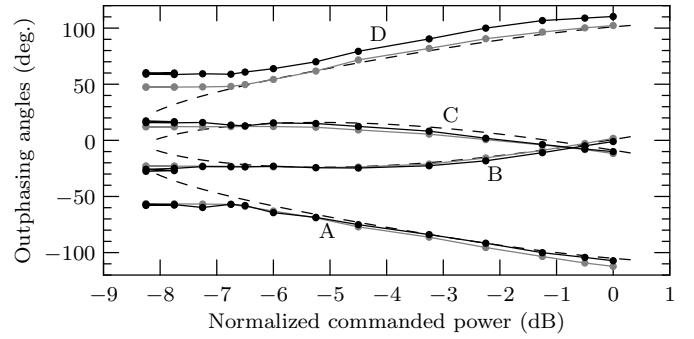


Fig. 4. Comparison of measured phases at the outputs of the decomposition network (grey), the full PA paths (black), and the ideal optimal-susceptance (OS) phase relationship (dashed). The mixed-mode behavior can be seen below -6.5 dB normalized commanded power, where the measured outphasing angles are held constant.

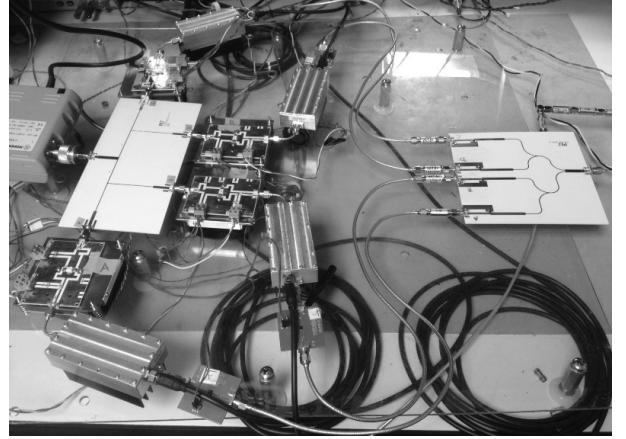


Fig. 5. System photograph (RF input and decomposition network at right).

4, with the branch PAs terminated in 50 Ω . A close match can be observed between the measured and desired control angles at the output of the signal decomposition network, while a phase offset is observed in path D due to delay in that RF path. This delay was not compensated for in the system characterization, nor were other forms of mismatch in the four branch PAs. The transition between outphasing control and drive amplitude modulation can be seen near -6.5 dB normalized commanded power. Note that for the plot in Fig. 4, the x -axis corresponds to the normalized commanded power used to calculate the optimal-susceptance (OS) control law phases (dashed lines), while the points of the measured curves are aligned to best correspond to that control law. (The OS phase control law provides superior performance to the IRCN control law, and would be the preferred control for outphasing of this 4-way system [7].) Each marker of the measured curves corresponds to a step of 2 dB in input power.

The complete system is shown in Fig. 5, including (right to left) the decomposition network, two predriver stages, inverse class F branch PAs, [3], [9] and the power combining network [7]. As can be seen, the system components are not optimized for size. The decomposition network is designed for input powers up to 23 dBm, while a 100 W system output power is desired. Pre-driver stages are therefore required to produce the

¹The original paper [7] indicated values $\Delta_1 = 0.201\lambda$ and $\Delta_2 = 0.196\lambda$ in error; the lengths $\Delta_1 = 0.049\lambda$ and $\Delta_2 = 0.054\lambda$ were used in both the transmission-line combiner and TLRCN.

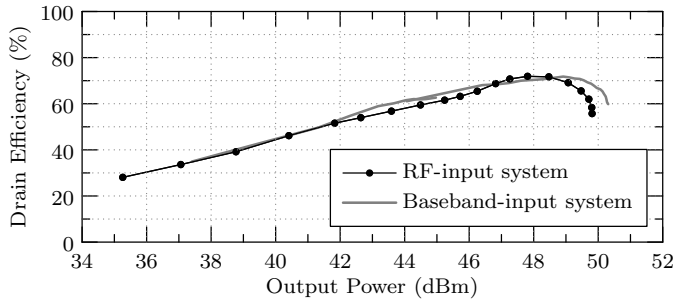


Fig. 6. Measured system performance comparing the RF-input system showing 95 W peak output power and a peak drain efficiency of 72%, and a baseband-input 4-way outphasing system [7].

necessary gain. For this proof-of-concept prototype, the driver stages are not optimized, and so are neglected in the efficiency characterization.

The CW measurement of drain efficiency of the final RF power stage vs. output power is shown in Fig. 6. The power amplifier has a peak output power of 49.8 dBm and a peak drain efficiency of 72%. Also shown (grey curve) is a system characterization in which the branch PA drive signals are generated based on the OS outphasing control law using four separate *IQ* modulators [7]. The close match in final-stage efficiency performance of these systems demonstrates the effectiveness of the RF decomposition network. Compared to the system using multiple *IQ* modulators, furthermore, this proof-of-concept RF-input / RF-output implementation has significant advantages in system complexity.

IV. CONCLUSION

The RF signal decomposition network presented in this work exploits the relationship between resistance compression networks and lossless outphasing power combiners, producing the first-ever RF-input / RF-output outphasing power amplifier.

The approach eliminates the baseband signal component separator and multiple *IQ* modulators required for prior outphasing system implementations. Advantages of the approach include reduced system cost and baseband signal processing complexity, and the ability to work with many existing calibration and digital pre-distortion schemes.

The proof-of-concept prototype in this work is implemented using transmission-line techniques and demonstrates the feasibility of this approach through CW measurements at 2.14 GHz in a 4-way lossless outphasing power amplifier system.

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