Linearization and Efficient 5G Radio Front-Ends

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***Abstract*—Evolution of the Transmit Radio Front-End from 2G to 4G for mobile devices and infrastructure, with cost and energy efficiency driving demand, has resulted in the widespread adoption of envelope tracking and Doherty techniques for efficiency enhancement, augmented by digital predistortion.**

The step-change in 5G requirements, especially bandwidth, operating frequency and beamforming, presents an opportunity for more significant technical and commercial differentiation.

This paper reviews the subject matter of Linearization, proposing a classification method. Within that classification, the incumbents are shown to be just two pieces in a much broader, efficient and intrinsically linear, radio front-end solution jigsaw.

Considering the bigger picture of practical 5G frontend implementation challenges, their cohorts offer potentially advantageous side-effects that transcend mere energy efficiency and linearity concerns.

Keywords*—*efficiency enhancement, linearization, envelope restoration, Outphasing, Doherty amplifier, beamforming, radio frontend, 5G, energy efficiency.

I. LINEARIZATION CLASSIFICATION

Linearization is the process of sufficiently "cleaning up" an efficiently generated signal. Complete elimination of unwanted components in the signal is not possible, nor cost- or energy-efficient.

Despite the domination of digital predistortion (DPD) in recent years, there are a plurality of linearization schemes in the literature. To help make sense of their salient features, the classification of (Table I) is proposed and populated with a few well-known schemes.

TABLE I. PROPOSED CLASSIFICATION OF LINEARIZATION METHODS

Correction Location	**Correction Signal Source**	
	Predicted	***Extracted***
Pre-	DPD	Cartesian feedback [9] Polar feedback [8]
Post-		Feedforward [11]

DPD is an example of a predictive, pre-correction scheme. Key features of predictive schemes is that they must both generate the correction signal but have potentially unlimited correction capability.

The proposed classification, highlights the existence of a *prima facie* less exploited category, predictive post-correction.

II. PREDICTIVE POST-CORRECTION

A predictive post-correction scheme comprises at least a second signal path in the transmitter, carrying a signal intended for compensating unwanted content carried in the first path.

As it happens, this branch of linearization is widely documented, but generally marketed under the heading of efficiency enhancement techniques.

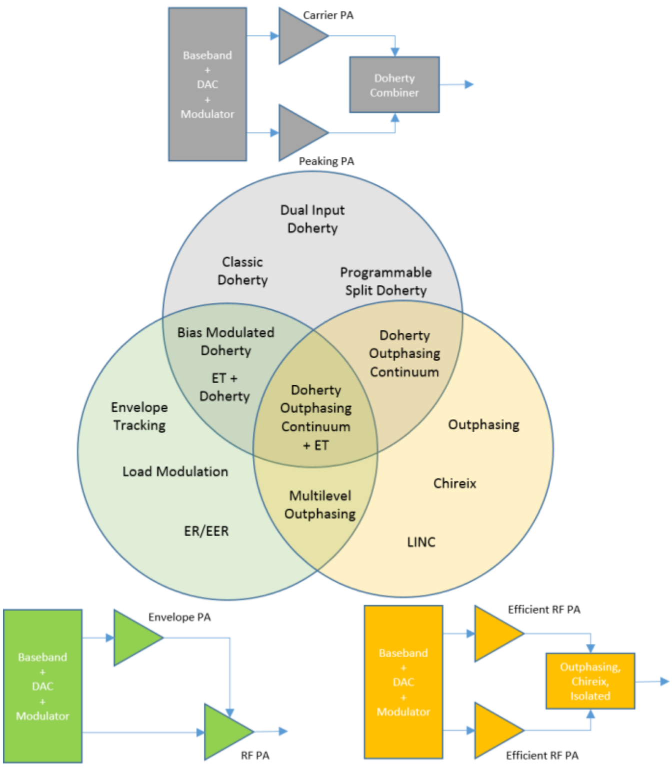

Fig. 1. Predictive, post-correction architectures, based on Outphasing [4], Doherty [1] and Envelope Restoration (ER) [2], adapted from [10].

In [10], it was proposed that there are three types of transmitter architecture that combine two signal paths, Outphasing [4], Doherty [1] and Envelope [2].

Reviewing the literature with this perspective, a much wider set of dual-path transmitters hybridizing the three basic techniques [3], [5], [6] are identified. The ensemble is described in (Fig 1).

Using a reference 64-QAM signal (z=x+iy), these techniques can be appraised in the context of a 5G Front-end realization. Constellation and spectrum plots of the signal are shown in (Fig 2). It has a peak-to-average-ratio of 6.1dB.

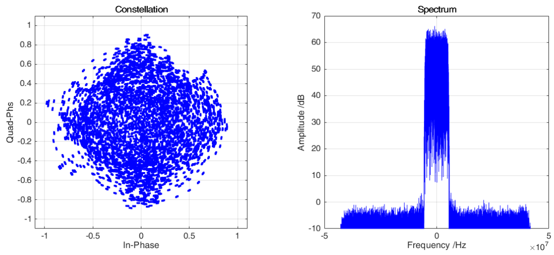

Fig. 2. Reference signal (64-QAM) constellation and spectrum, as used in this paper, shown after transmit filtering.

A. *Outphasing*

The fundamental form of outphasing constructs the wanted output signal by the summation of two vectors that are both constant envelope and equal-in-magnitude.

For illustration, this paper uses "Linear Amplification with Non-linear Components" [7], commonly known as LINC, using off-the-shelf amplifiers and power combiner (Mini-Circuits® ZHL-42 and ZN2PD-9G-S+).

Instantaneous envelope amplitude is created by the differential-mode phasing between the two vectors. Envelope phase is created by the common-mode phasing between them.

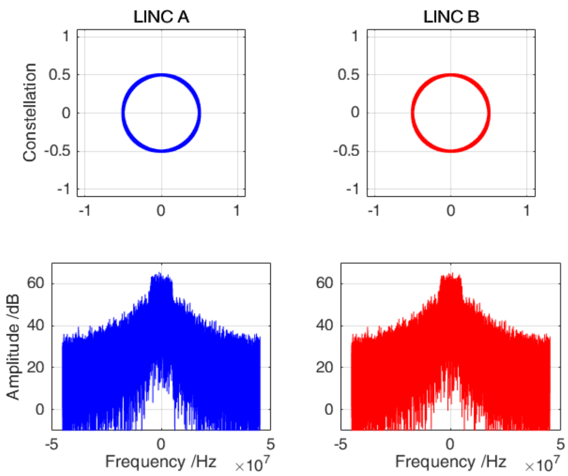

Fig. 3. The two decomposed Outphasing-LINC signals, shown in constellation and magnitude spectrum form.

The requisite outphasing decomposition calculation, applied to the signal z, is given in (1) and (2):

$$\Theta = \tan^{-1}(z) \qquad (1)$$

$$\varphi = \cos^{-1}(\mathrm{abs}(z)) \qquad (2)$$

where Θ represents the common mode angle of, and φ the differential mode between, the outphasing vectors.

The outphasing vectors are used to modulate two RF carriers with phase offsets of (Θ+φ) and (Θ-φ). The constellation and spectra of the two paths, are shown in (Fig 3).

An exemplary demodulated measurement of the signal output from the combiner, is shown in (Fig 4).

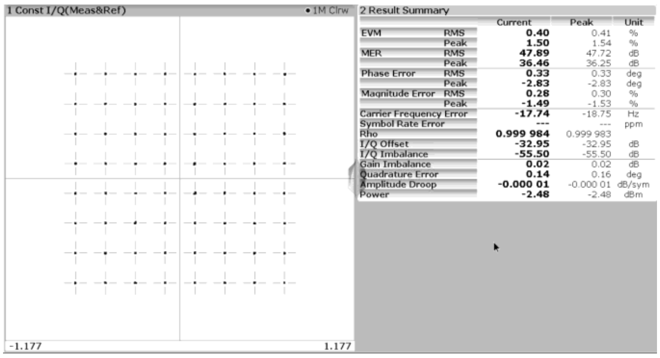

Fig. 4. The measured and demodulated, outphased 64-QAM signal.

Thus, the Outphasing concept in its fundamental form, is capable of generating an arbitrary signal (i.e. even containing AM components), synthesized from two constant-envelope, phase modulated vectors.

Within the scope of 5G hardware, this technique is interesting because it offers the designer degrees of freedom in both generation (phase modulated, only) and amplification (efficient, constant envelope).

B. *Envelope Restoration (ER)*

The basic form of the envelope transmitter constructs the wanted output signal by multiplication of two components, one representing amplitude (AM), the other phase (PM). This is equivalent to ER operation.

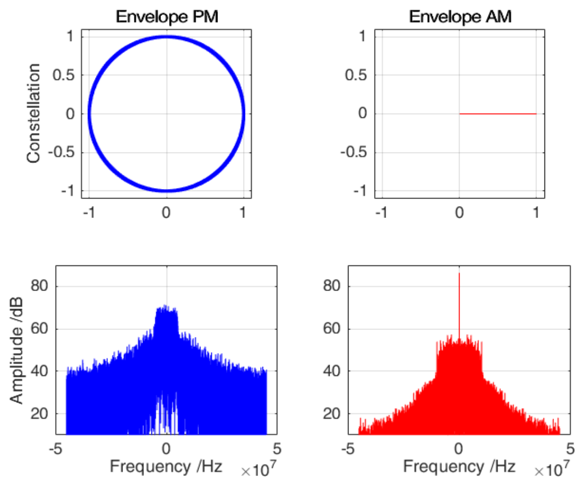

Fig. 5. The two decomposed ER signals, shown in constellation and magnitude spectrum form.

Decomposition of the reference signal (z) into AM and PM components is achieved using (3) and (4):

$$AM = z / abs(z) \quad (3)$$

$$PM = angle(z) \quad (4)$$

The decomposed signals are shown in (Fig 5).

The envelope concept is demonstrated using a mixer (Mini-Circuits® ZX05-C60MH-S+), feeding the AM signal to the IF-port and PM signal to the LO-port.

Measurement of the resultant signal, output from an off-the-shelf-mixer, when driven with the decomposed AM and PM is shown in (Fig 6). This measurement is shown superimposed with the mixer operated using a conventional intermediate (IF) up-conversion step.

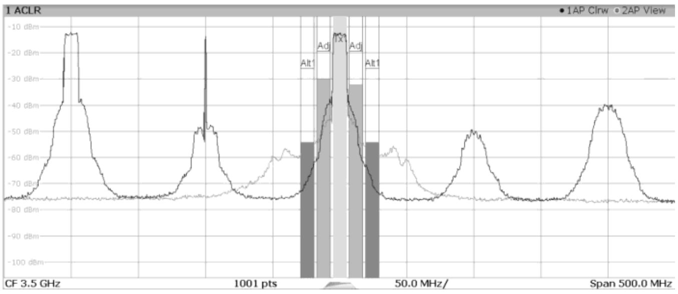

Fig. 6. Output spectrum of the ER generated signal (LO = PM, IF = AM), superimposed with the conventional IF (LO = CW, IF = QAM).

Advantageously, the output spectrum of the ER generated signal, unlike the IF scheme, is free from any image, LO-leakage and higher order mixing products.

This can reduce the front-end filtering requirements, especially when covering multiple frequency bands. Furthermore, as that unwanted energy is reduced, the useful power delivered from the mixer is increased. These side-effects can heavily impact size, component count, efficiency and cost.

Additionally, the synthesized AM and PM signals may have offsets directly applied, in order to create weighting functions for beamforming arrays.

Finally, as the PM signal is constant envelope, it may be more robustly and efficiently handled in the frontend.

C. Doherty

The Doherty is already widely documented in the literature. Treatment here is limited to a simple illustration, for comparison of the decomposition signals, shown in (Fig 7).

Note that the output of the Doherty ideally replicates that of the “Main” signal path (i.e. linearity), whilst “Auxiliary” ideally provides only the efficiency enhancement.

III. Conclusions

A classification for linearization schemes has been presented. Within that classification, a family of predictive, post-corrective architectures, previously marketed as efficiency enhancement schemes, have been demonstrated.

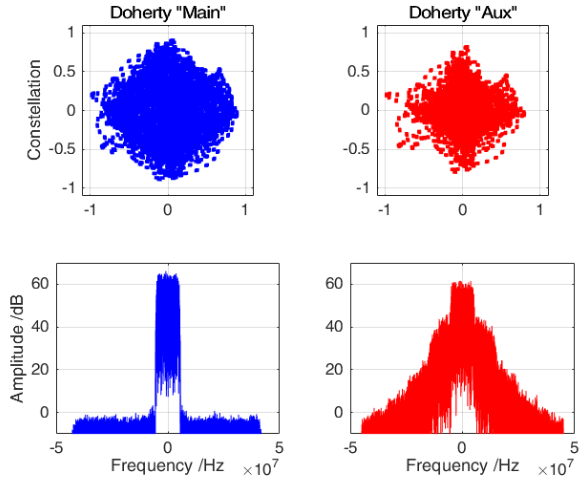

Fig. 7. The decomposed Doherty “Main” and “Auxiliary” signals.

These multipath transmitters, and their hybrids, offer an interesting mix of intended and unintended features. In the context of functional requirements presented by 5G, one or other may be worthy of further consideration, ahead of the commodity, quasi-linear solution.

IV. References

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