Power Amplifier Efficiency for Telecom Signals: ● Physics ● Problems ● Solutions

ABSTRACT: Power amplification efficiency is often held prisoner by nonlinear behaviors. Wide band signals with wide dynamic ranges, common in systems like 4G and 5G, pose *dramatic* obstacles to signal amplification efficiency, when using the prevailing techniques of signal amplification. Quantized Digital Amplification (QDA) provides order of magnitude increases in efficiency bypassing limitations of prevailing improvement techniques. This paper outlines the physics of the problem and explains how QDA overcomes the efficiency obstacles.

The Nonlinearity Efficiency Problem; the Back-off Alleviation – and its Cost

The most cost-impacting factor in mobile networks base stations, like 4G and 5G, is the Power Amplifier (PA). Notably, PAs are also the most power consuming components in communication systems and account for up to 59% of the total RAN (Radio Access Network) budget.[i] The cause of this huge power appetite: the inherent nonlinearity of PAs. This nonlinear operation negatively impacts performance in two critical ways:

1. It generates spectral regrowth. This leads to unwanted radiation and adjacent-channel interference.
2. It causes in-band distortion, which degrades its error vector magnitude (EVM) performance.

To avoid these effects, a PA's operating point needs to be backed-off far from its saturation point (see Fig. 1). This leads to very low power efficiency, typically less than 10%, meaning that more than 90% of the DC power gets wasted by turning into heat.

For example: suppose we need to transmit 50 W of power, on average, to provide RF coverage to a cell. If the transmit signal has a constant envelope, i.e., a PAPR (Peak to Average Power Ratio) of 0 dB, we simply need an amplifier with a power rating of 50 W; more specifically, an amplifier able to output 50 W during linear operation. However, when the dynamic range of the signal grows, the signal envelope then varies, and the PAPR then rises above zero - reducing the PA efficiency. For instance, if the signal has PAPR of 6 dB, it will need an amplifier capable of 200 W to linearly amplify peaks of the signal. Correspondingly, for a PAPR of 10 dB, the amplifier maximum output power should be 500 W to linearly amplify the peaks of the signal, which corresponds to a back-off of 10 dB. Thus, the PAPR and dynamic range dramatically affects PA efficiency

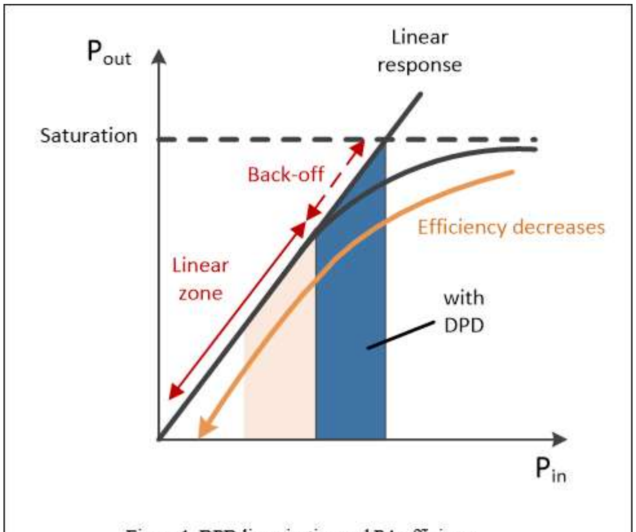

Figure 1. DPD linearization and PA efficiency.

Decreasing the Back-off Cost

To reduce wasted power caused by back-off, linearization techniques such as Digital Pre-Distortion (DPD) can be employed improving the efficiency of the amplifier over at least part of the dynamic range (see Fig. 1). In these practices existing techniques such as Envelope Tracking or Doherty use DPD for a back-off equal to the PAPR (or crest factor). Even though they yield some improvement, they still suffer high inefficiency in the remaining range of the signal dynamic range (to the left of the blue area in Figure 1 above). As a measure of this, it is typical to see Doherty and Envelope Tracking amplifiers with an efficiency optimized for a back-off of 8 dB, but the inefficiency remains for the remaining 15.9 dB where the envelope has most occurrences.

To effectively remove the distortion, DPD usually needs to generate a pre-distorted signal with 5× bandwidth of the original transmit signal. As the bandwidth of wireless communication systems continues to increase, the sampling rate of DPD becomes a significant issue. For example, to process a 200-MHz signal, a 1-GHz clock is required in the DPD implementation. Not only is this power hungry, but it is also challenging to implement. This explains why wideband 4G/5G applications DPD power consumption estimates are around 3 W.

Efficiency Measurement Challenges: Point of Reference, Rate of Change

The definition of efficiency is given by the ratio of the output RF power divided by the DC input power. However, the ubiquitous presence of high dynamic ranges and PAPR tend to decrease efficiency[ii], as follows:

1. PA power consumption is roughly proportional to the peak RF output power capacity.
2. This means that high RF power output requires a high level of bias current **at all times.**
3. This bias is reflected in the DC power consumption, even when the PA is not outputting high levels of output power.
4. Thus, PA efficiency decreases when Pin decreases as shown in figure 1.

Often described as the key drawback the PAPR the limitation can be limited between 7 and 13 dB. Despite the limitation of the PAPR, the dynamic range of the signal is still much higher than PAPR. For instance, the OFDM signal in 5G nr may have a dynamic range between 13.5 and 23.9 dB, which has significant negative impact on the overall efficiency of the amplifier.

Reducing the above analysis, PAs' efficiency presents several challenges, which include:

- Wide bandwidth. For DPD, the challenge of increased signal bandwidth is two-fold.
  - Firstly, PA's exhibit increased memory effects with wideband signals and require more complex modelling techniques to characterize and compensate.
  - Secondly, DPD adaption requires that the feedback path sampling rate be high enough to capture five times the signal bandwidth – meaning increased cost and implementation complexity as bandwidth increases.
- Consumption with the Back-off and over the dynamic range of the signal.

QDA Overall Operation

QDA (Quantized Digital Amplification) operates by building a process, out of a system of complex parts, which essentially behaves like a linear amplifier. While from a global system perspective it operates as a linear amplifier, it also has stages that behave as non-linear amplifiers which are then compensated, within the system, to maintain efficiency. The process works as follows.

It starts with a signal processing portion using a quantizer combined with a decomposition of the quantized symbols into Nm polar components that are amplified individually by a nonlinear amplifier. The inputs for the quantizer are the time domain samples of the complex envelope that can be obtained from a multi-carrier or single-carrier signal. The values of the samples of variable envelope signals are quantized by N, quantization bits that are converted into polar components in which the quantization symbol is decomposed as the sum of several polar components. Each one is modulated as a serial Offset Quadrature Phase Shift Keying signal with reduced

envelope fluctuations or as a constant envelope signal before being amplified by a separate amplifier. The modulation format is selected to achieve good tradeoffs between reduced envelope fluctuations and compact spectrum (e .g ., a Gaussian minimum shift keying signal). Note that the pulse shape employed in the N modulators can be selected to achieve high spectral efficiency and constant envelope

Next, in each branch, the resulting signals are submitted to a mixer for up-conversion before being amplified by the switching-based amplifier, which can operate in saturated mode or near to it. The amplification stage is composed of N amplifiers in parallel whose outputs are the inputs of a smart combiner controlled by the signal processing portion that performs the quantization and decomposition.

The smart combiner is followed by a transducer connected to an antenna or equivalent.

How QDA manages the Back-off over the dynamic range

Consider the configuration of Table I, with 4 power amplifiers PA1, PA2, PA3 and PA4 with power outputs of 1W, 2W, 4W and 8W, respectively. When each component is present, the corresponding DAC injects a sinusoidal signal at the PA input. Accordingly, each PA will be activated or deactivated by the presence or absence of the corresponding constant envelope component. Table I shows how the back-off is managed by activating or deactivating PAs. With all PAs turned on the output power is 41.7 dBm. By turning off all the PAs except the strongest PA (PA4) a back-off of 2.73 dB is achieved. With only the second strongest PA (PA3) turned on the back-off is 5.74 dB, and with only PA2 on the back-off is 8.75 dB. Despite, the several back-off levels all the active PAs are working always near the compression point, i. e. at the maximum efficiency. Thus, by activation and deactivation of PAs we can achieve maximum efficiency over the dynamic range as opposed to substantially using the back-off. In this example, the dynamic range is 11.76 dB. However, we note that the QDA manages dynamic ranges up to 24 dB and the number of components can be reduced to 3 without impact on the dynamic range.

Additionally, compared to existing techniques, DC consumption is reduced at least a third - or more. This accrues from the total maximum output power divided across several power amplifiers, and in particular, for most of the time only the PAs with lower output power need to be turned on.

	PA1	PA2	PA3	PA4			
P=1W	1P	2P	4P	8P	Pout (W)	dB	dBm
	on	on	on	on	15	11.76	41.7 dBm
	off	off	off	on	8	9.03	39 dBm
	off	off	on	off	4	6.02	36 dBm
	off	on	off	off	2	3.01	33 dBm
	on	off	off	off	1	0	30 dBm

Table I – PAs Activation / deactivation and back-off levels.

QDA Wide Bandwidth Advantages

The QDA decomposition of the envelope signal samples into a set of constant envelope components with different amplitudes allows the amplification of each one by a power amplifier operating near the saturation without introducing nonlinear effects. Avoiding nonlinear effects also means that linearization techniques such as DPD are no longer needed. This avoids the complexity that a wider band brings to the overall processing associated to DPD. Bandwidth limitations in QDA are only related with the frequency band limitations of the PAs employed in the parallelized structure and the overall frequency response of the smart combiner. Smart combiner bandwidth limitations are mostly due to the speed of the switches employed at chip design, which allow bandwidths up to several hundred MHz without any impact on the processing complexity.

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[i] https://networkbuilders.intel.com/docs/networkbuilders/a-holistic-study-of-power-consumption-and-energy-savings-strategies-for-open-vran-systems-1676628842.pdf

[ii] https://spectrum.ieee.org/5gs-waveform-is-a-battery-vampire