Abstract—There is a need to relate the peak-to-average power ratio (PAPR) of a single carrier QPSK modulated waveform to the amount of back-off needed in a power amplifier (PA) in relation to its 1-dB output compression point for the transmission of the waveform in the most efficient and cost effective way whilst meeting the out-of-band (OOB) spectral emission and bit error rate (BER) specifications. The concept of baseband and passband PAPR is defined and the complementary cumulative distribution function (CCDF) curve of the PAPR distribution is used in this paper to determine the back-off required for acceptable OOB and BER performance. The effect of root raised cosine filtering on the PAPR of QPSK waveform is also studied.

Keywords—PAPR, power amplifier efficiency, power amplifier back-off

I. INTRODUCTION

In industry, the 1dB output compression power is specified for power amplifiers and it is common practice to use the term back-off relative to this 1dB compression point. The term Peak-to-Average Power ratio (PAPR) of a modulated signal is often used in industry and academia. In industry, PAPR is often used to specify the amount of back-off needed to properly amplify the signal with minimal distortion. In practice, it is desirable to minimize the amount of power amplifier back-off as the efficiency of the PA gets progressively worse at higher back-off levels. There is often confusion and conflicting arguments regarding back-off requirements and PAPR between industry and academia. It has been heard in conversation with industry that the PAPR for QPSK is 0 dB and that no PA back-off is needed. Is this true? It is the objective of this paper to carefully consider the back-off and PAPR arguments by studying the complementary cumulative distribution function (CCDF) of the power generated by a QPSK/DQPSK modulated signal. The effects of various 1dB output compression powers on the PAPR, CCDF, in-band, out-of-band (OOB) spectral emissions and the BER performance will be investigated in this paper.

II. DEFINITION OF PAPR

There are many confusing definitions to the ratio of instantaneous power to the mean power in literature today [1] [2]. Many confuse baseband Peak-to-Mean Envelope Power Ratio (PMEPR) as the PAPR. PMEPR is the ratio between the maximum power and the average power for the envelope of a baseband complex signal \( \tilde{s}(t) \) that is,

\[
\text{PMEPR} \{ \tilde{s}(t) \} = \max |\tilde{s}(t)|^2 / E[|\tilde{s}(t)|^2] \tag{1}
\]

where

\[
\tilde{s}(t) = \tilde{s}_i(t) + j\tilde{s}_q(t) \tag{2}
\]

and PAPR on the other hand is the ratio between the maximum power and the average power of the complex passband signal \( \tilde{s}(t) \), that is,

\[
PAPR \{ \tilde{s}(t) \} = \max |\text{Re} (\tilde{s}(t)e^{j\pi/4})|^2 / E[|\text{Re}(\tilde{s}(t)e^{j\pi/4})|^2] \tag{3}
\]

\[
= \max |\tilde{s}(t)|^2 / E[|\tilde{s}(t)|^2]
\]

Note that the complex passband PAPR is 3 dB above the baseband Peak-to-Mean Envelope Power Ratio (PMEPR). It is important in simulation to know the difference as communication systems are simulated at baseband. To quote PAPR as PMEPR from baseband computations is wrong unless the 3 dB factor is considered. Nevertheless, relative changes in PAPR are equivalent to relative changes in PMEPR. As PAPR is the general accepted parlance in industry, this paper will use the term baseband PAPR to refer to PMEPR as defined in (1) and passband PAPR to PAPR as defined in (3). It is shown in [1] that the baseband signal for BPSK and QPSK has the same average and peak power, as such its baseband PAPR (PMEPR) is 0 dB. Meanwhile, the passband signal PAPR for BPSK and QPSK is 3.01 dB. For 16 QAM, the baseband PAPR is 2.55 dB and at the passband PAPR is 5.56 dB.

The question in everybody’s mind is what amount of back-off is needed in a practical transmitter power amplifier? It is a known phenomenon that a power amplifier driven beyond its linear operating range generates spurious signals (noise energy) which expands its occupied bandwidth and will cause interference with communications in the adjacent channels. The accepted practice is to ensure the average PA output power is sufficiently reduced or backed off from the power
amplifier’s 1 dB output compression power. The peak power should not exceed this 1 dB output compression power to ensure minimal spectral re-growth and good BER performance. The Error Vector Magnitude (EVM), a primary metric of modulation quality at the transmitter will be very small when sufficient back-off is used. The amount of back off to be chosen for a modulated signal depends not only on the PAPR of the waveform but for multi-carrier waveforms such as OFDM, also on the probability of the desired PAPR occurring. The complementary cumulative distribution function (CCDF) curve of the PAPR distribution of the waveform is used to determine or decide on an acceptable level of performance. This is typically a probability of $\leq 0.001\%$. At this chosen probability, one can pick off from the CCDF graph, the reading at which the power is $X$ dB above average power. The desired amplifier back-off can then be set to $X$ dB or slightly higher.

In practice, the available channel is band limited so it is necessary to filter the waveform before it is transmitted. Root raised cosine (RRC) filtering is normally used at the transmitter and the effect of RRC filtering increases the PAPR on the waveform.

III. SIMULATION RESULTS

The effect of baseband, passband, filtering and various 1dB PA output compression points on CCDF, OOB and BER is simulated on Matlab. BER was simulated in an additive white Gaussian noise (AWGN) channel and in a 2-path Rician channel model. The non-linearity in the PA is based on the Rapp model [3] [4] with smoothness parameter set to 1.6. The filtering at the transmitter and receiver is based on the square root-raised cosine (RRC) with the roll-off factor = 0.125. The baseband signal is up-converted to a carrier frequency of 4 MHz for passband measurements. The effect of RRC filtering on the CCDF is illustrated in Figure 1.

It can be seen in Figure 1 that the effect of filtering significantly increases the probability of large peak powers occurring above the average power. In the unfiltered baseband case, there are no occurrences of power increasing beyond 0.25 dB. In the filtered baseband case, the probability of peak powers above 3, 4 and 5 dB is about 3%, 0.5% and 0.0044% respectively. At passband, the filtered performance is about 3 dB worse than at baseband.

The effect of various back-offs on the PA in-band and out-of-band (OOB) spectrum can be seen in the following example. The modulation is DQPSK. In this example, the desired average output power is 0 dBW (1 Watt) and the 1 dB output compression point of the amplifier is set to 0.5, 1, 2, 4, 8 W and 1000W respectively.

It can be seen in Figure 2 that high levels of OOB emissions occur when the power amplifier is driven into compression, reducing significantly when the 1 dB compression point of the power amplifier is raised to 2 W (+3 dBm) and above. There is very little improvement when the 1 dB output compression point is 4 W (+6 dBm) and above. There is therefore a trade-off between spectral performance and amplifier 1dB output compression power point.

The CCDF of the signal measured at baseband and passband at the various compression points are shown in Figure 3.

![Figure 1 : CCDF measurement of baseband signal comparing unfiltered QPSK versus filtered QPSK](image1)

![Figure 2 : The in-band and out-of-band emissions of a PA at various 1dB output compression points](image2)
Looking at the baseband CCDF measurements (solid lines) in Figure 3, there is almost zero probability of the output power exceeding the average power beyond 0.6 dB and 2.2 dB for the case of 0.5 W and 1W 1-dB output compression powers respectively due to the high compression effects of the amplifier. At higher 1-dB compression powers of 4W (+6 dBW) and above, the baseband CCDF curves as expected approach the baseband filtered QPSK curve of Figure 1. The passband CCDF curves (dotted lines) are generally higher by 3 dB than their baseband counterpart except for the 1-dB compression case set at 0.5W (-3 dBW) where the highest degree of compression is encountered which severely limits the passband output power.

Looking at the curves, what actually is the PAPR of the waveform? Per the definition in (3), the passband CCDF curves is indicative of what the PAPR should be, that is 8.2 dB above average power for the QPSK RRC filtered (alpha=0.2) passband signal. Is this correct? Does it mean we design for 8.2 dB back-off for filtered QPSK? This seems too high and will not help PA efficiency operating at such high back-off. Or should we use the baseband CCDF for PAPR which is 3 dB lower at 5.2 dB. After all, studying the spurious OOB emissions in Figure 2 show that an amplifier with a 4 W (+6 dBW) 1-dB compression point is sufficient and is almost indistinguishable from an ‘ideal’ amplifier with a 1000W (+30 dBW) 1-dB compression point. At this stage of the investigation using DQPSK, choosing the back-off from filtered baseband CCDF curve is sufficient condition to ensure good in-band and OOB spurious performance.

The bit error rate (BER) performance of DQPSK at various 1-dB compression points is shown in Figure 4. The difference in performance of uncoded DQPSK in AWGN between the 1W (solid red) and the 2, 4 and 100 W (solid black) 1dB compression powers is less than 0.5 dB over SNR. It shows that BER performance is robust for DQPSK in AWGN primarily because it is phase modulated and therefore tolerant of amplifier saturation effects. With a Reed-Solomon and 1/2 rate Convolutional coding (RSCC) scheme, the system shows no errors above 6 dB SNR in the AWGN channel.

The performance degrades significantly in a 2-path Rician channel with maximum Doppler Shift specified at 550 Hz, gain Vector : [0 -12] and delay Vector: [0 2.7000e-07]. Here the BER for uncoded DQPSK floors around 2x10^-2 at high SNR (red and black dashed lines) regardless of their 1dB compression power values. With RSCC coded DQPSK, the performance at high SNR improves (solid blue with markers) significantly with higher 1dB compression power settings giving better BER performance. There is no BER performance difference between the 4W (+6 dBW) and the 100W (+20 dBW) 1dB compression power settings.

IV. CONCLUSION
This paper has studied the effects of various 1dB output compression powers on the PAPR, in-band, out-of-band (OOB) spectral emissions and the BER performance for QPSK/DQPSK signal.
The CCDF computation of a signal is a useful measurement to determine the PAPR of a signal and to determine the appropriate back-off that is needed for the PA to amplify a QPSK/DQPSK signal.

The argument that PAPR for QPSK is 0 dB and no back-off is needed is true only for the unfiltered baseband PAPR case. However, in any practical band limited system where filtering must be used to meet strict regulatory requirements for in-band and adjacent channel power specifications, a 0 dB back-off will result in severe OOB spurious emissions and will fail regulatory specifications although it is possible to pass BER as the degradation of BER performance in the AWGN channel is only slight (0.5 dB) for QPSK.

For lowest OOB spurious emissions and best BER performance, this paper recommends the use of baseband PAPR at 5.2 dB as PA back-off for RRC filtered QPSK. This is based on probability that the chance of the peak power exceeding 5.2 dB above the average power is less than 0.001 %. The graphs in Figure 2 and Figure 4 show that an amplifier with 4W 1dB compression point, that is a 6dB back-off, is sufficient to meet the spurious and BER performance requirements.

This paper finds that the use of passband PAPR, which is 3 dB higher than baseband PAPR, is unnecessary for QPSK/DQPSK signals. This condition may however be necessary for multi-level higher order QAM modulations or multi-channel modulations such as OFDM.

REFERENCES