Recommendation on interpretation of PAPR techniques in DVB-T2

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References

[1] ETSI TS 302 755 (V1.4.1): "Digital Video Broadcasting (DVB); Frame structure channel coding and modulation for a second generation digital terrestrial television broadcasting system (DVB-T2)"

[2] TM-T2-0587 (V1.1): “The DVB-T2 Reference Streams”

Background

In 2019, some questions to DVB highlighted that some aspects of the DVB-T2 specification may benefit from clarification: in particular, the two PAPR reduction techniques and especially the Active Constellation Extension (ACE) feature.

The PAPR clauses were added late in the drafting process and are written in such a way that they “stand alone”, not depending on symbols defined elsewhere in the specification. They also make use of symbols that are used with different meanings elsewhere. Internally to each clause, the symbols are used consistently, but there is a risk that implementers might confuse the symbols in those clauses with similar ones used elsewhere. Furthermore, both clauses also describe the techniques in the context of an intermediate signal that, whilst well known to implementers, does not appear explicitly in the rest of the standard. This document aims to provide additional guidance on the interpretation of the relevant parts of the DVB-T2 specification.

To DVB’s knowledge, the Active Constellation Extension (ACE) technique has not yet been deployed in real DVB-T2 networks, and it was not originally covered by the extensive Validation and Verification (V&V) work carried out by DVB. However, there is at least one commercially available implementation of the technique and it has also been independently implemented in the DVB Common Simulation Platform (CSP). Subsequent V&V comparisons have shown that these two implementations interpret the ACE algorithm in the same way. Nevertheless, implementing the algorithm based on the specification alone requires several steps of deduction and inference, and the present document aims to spell out those steps in detail in order to make implementation easier and avoid the risk of misinterpretation.

The use of ACE has been shown to allow potentially significant transmitter power savings (which increase with reducing order of modulation). Whilst network operators could regard this as a significant benefit, its use implies a small theoretical loss of link performance and, like any other previously unused feature, may give rise to compatibility issues in receiver populations deployed before ACE was brought into use. Accordingly, operators considering using ACE in a network should carry out appropriate receiver testing to ensure that receivers likely to be used in the network continue to work without problems and to determine the appropriate ACE parameters.

PAPR techniques

Order of processing and signal types

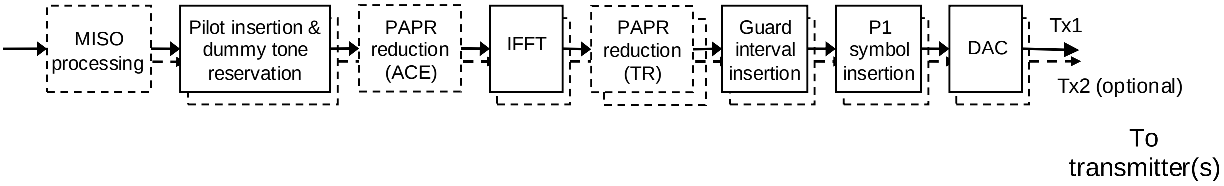
Before discussing the PAPR techniques in detail, some observations will be made on the order of the processing and the types of signal at each stage of the chain.

The expression for $s(t)$ in clause 9.5 of [1] corresponds to four blocks from Fig 2(f): IFFT, Guard Interval insertion, P1 symbol insertion and DAC, together with frequency up-conversion, not shown in fig 2(f). The expression transforms directly from the frequency-domain carrier modulation coefficients to the continuous-time and real-valued radio-frequency signal $s(t)$.

As a result, the PAPR techniques, which are shown as being applied after the IFFT and before the Guard Interval insertion, do not fit neatly into the structure of the specification. Firstly, they both deal with the discrete-time, complex baseband signal at the output of the IFFT, but this signal is not explicitly defined. Secondly, because the guard intervals are added automatically by the expression for $s(t)$, there is wording explaining that the guard intervals must be added specially if PAPR is used. (The D-to-A conversion and up-conversion are not mentioned).

As will be seen, these complexities could have been avoided by expressing the output of both PAPR techniques in terms of modified frequency-domain modulation values which can form the input to the expression of clause 9.5. In the case of ACE, this also corresponds the most likely position for the processing in a practical implementation, i.e. immediately before the IFFT. Conversely, Tone Reservation is essentially a time-domain technique that would be implemented immediately following the IFFT.

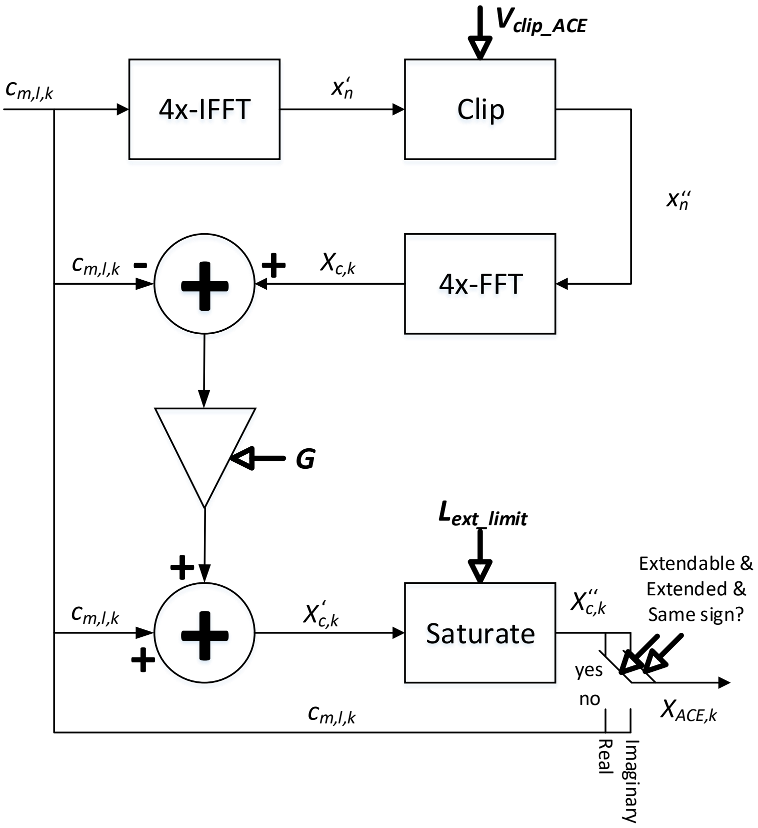
The figure below is a modified version of figure 2(f) that shows this likely order of implementation of the various processing stages in a real modulator. The PAPR reduction block has been separated into one block for each technique, and the ACE block has been moved before the IFFT.



ACE

ACE, as described in [1], effectively replaces the IFFT block, since it takes as its input the frequency-domain coefficients and produces as its output a modified time-domain signal that “replaces the original time-domain signal produced by the IFFT from a set of frequency domain values”. As was noted above and shown in the figures, in the present document the ACE block is considered to be applied before the IFFT, so here the output of the ACE block is modified frequency-domain coefficients.

From consideration of the OFDM expression for $s(t)$, the frequency-domain values that form the input to the ACE process, clearly consist of the coefficients $c_{m,l,k}$.



The diagram in the specification (figure 50) shows processes of IFFT, four-times oversampling and low-pass filtering, but the text explains that these three processes are done using a “four-times oversized IFFT operator”. The figure above is a modified version of figure 50 with this operator replacing the separate notional processes (and with the corresponding 4x-FFT – see below). The definition of this operator is as follows:

$$x'_n = \frac{5}{\sqrt{27K_{total}}} \sum_{k=K_{min}}^{K_{max}} c_{m,l,k} e^{\frac{j2\pi n(k-K_C)}{4N_{FFT}}} \qquad 0 \le n < 4N_{FFT}$$

Note the following points:

- The ACE description in the specification uses subscript k as a time-domain index, whereas it is used in the rest of the specification as a frequency-domain index. To avoid confusion, the time-domain index has been changed to n in the equation above (and the diagram).
- The overall gain factor $\frac{5}{\sqrt{27K_{total}}}$ is the same as that used in the OFDM expression, and ensures that the mean power $E\{|x_i'|^2\}$ of the output samples is (very close to) unity.

Aside from the scale factor, the expression shown is equivalent to a standard $4N_{FFT}$-point IDFT, provided that the modulation value $c_{m,l,k}$ is mapped to frequency bin $(k - K_C) mod\ 4N_{FFT}$ such that the centre carrier $k = K_C$ is mapped to the "DC" bin zero of the IDFT and the carriers below the centre are mapped to the higher-indexed bins, i.e. $c_{m,l,k}$ where $k < K_c$ should be mapped to bin $4N_{FFT} + k - K_C$.

$$x_n' = \sum_{k=0}^{N-1} C_k e^{\frac{j2\pi nk}{N}}$$

subject to $N = 4N_{FFT}$ and $C_{(k-K_C)\bmod N} = c_{m,l,k}$ for $K_{min} \le k \le K_{max}$.
The next stage, the clipping process, is set out precisely in the specification:

$$x_n'' = \begin{cases} x_n' & |x_n'| \le V_{clip\_ACE} \\ V_{clip\_ACE} \cdot \frac{x_n'}{|x_n'|} & |x_n'| > V_{clip\_ACE} \end{cases}$$

Note that the expression above differs from the one in the standard in four ways, none of which affects the meaning:

- The time-domain index k has been changed to n as discussed above.
- The clipping level V_{clip} has been renamed V_{clip_ACE} to distinguish it from the V_{clip} parameter of Tone Reservation. DVB-T2 allows both methods of PAPR reduction to be used together and in this case different values of V_{clip} may be used for each.
- The "complex magnitude" notation has been changed from $\|x\|$ to the more common $|x|$.
- The second condition has been changed to exclude the case of equality, so that there is no overlap between the two conditions. Both expressions give the same result when $|x_n'| = V_{clip}$, so there is no ambiguity in the specification.

The definition of the clipping threshold V_{clip_ACE} depends on the gain factor in the IFFT (see above). However, clause 9.6.1 of [1] states that the threshold should be specified relative to the "standard deviation of the original time-domain signal", rather than in absolute terms, so the gain factor is arbitrary provided V_{clip_ACE} is adjusted appropriately.

With the gain factor shown above, $V_{clip\_ACE} = 1$ will correspond to 0 dB.

The clipping process is followed by low-pass filtering, four-times downsampling and an FFT, but again the specification states that this is implemented using a four-times oversized FFT operator. As before, this operator is not explicitly defined but its form can be deduced:

$$X_{c,k} = \sqrt{\frac{27K_{total}}{20N_{FFT}}} \sum_{n=0}^{4N_{FFT}-1} x_n'' e^{-\frac{j2\pi n(k-K_C)}{4N_{FFT}}} \ , K_{min} \le k \le K_{max}$$

As before, this can be implemented using a standard $4N_{FFT}$-point FFT. Note that due to the periodic nature of the DFT, modulation values below the centre carrier will appear in the highest indexed bins of the FFT output, i.e. $X_{c,k}$ where $k < K_c$ should be taken from bin $4N_{FFT} + k - K_C$. Care must also be taken over the gain of the FFT implementation: the scale factor shown above ensures that the cascaded IFFT and FFT have an overall gain of unity as required.

Subsequent steps of the algorithm (extension gain, saturation, and selection) are implemented exactly as described in [1]; where the standard refers to the original modulation values X_k, these can simply be mapped to $X_k = c_{m,l,k}$.

Implementers should be aware that the symbol L is used with two different meanings in the ACE and L1-ACE clauses of [1] (9.6.1 and 7.3.3.3 respectively). In the present document, the parameter L in the saturation step in clause 9.6.1 of [1] is referred to as L_{ext_limit}. Hence the equation in clause 9.6.1 of [1] would be as follows (with the corresponding expression for the imaginary part):

$$Re\{X''_{c,k}\} = \begin{cases} Re\{X'_{c,k}\} & \text{if} \quad \left|Re\{X'_{c,k}\}\right| \leq L_{\text{ext\_limit}} \\ L_{ext\_limit} & \text{if} \quad Re\{X'_{c,k}\} > L_{\text{ext\_limit}} \\ -L_{ext\_limit} & \text{if} \quad Re\{X'_{c,k}\} < -L_{\text{ext\_limit}} \end{cases}$$

The inequality symbol for the middle case has been changed from "≥" to ">" to avoid overlapping conditions; the result in the case of equality is the same so this has no effect on the meaning.

Note that there is a potential source of confusion in the selection step that produces $X_{ACE,k}$. The text below the equations states that a component is extendable if (amongst other things) it is an unmodulated cell in the Frame Closing Symbol. However, such a cell would have both real and imaginary components equal to zero, and hence could never meet the condition that $Re\{X''_{c,k}\} \cdot Re\{X_k\} > 0$ or the equivalent condition for the imaginary part. The inclusion of the unmodulated cells in the set of "extendable" components, when they will never in practice be extended, might be misleading.

Note also that, for the same reason, the imaginary component of a cell whose original value is purely real can never be extended in the imaginary direction: this includes BPSK-modulated L1 cells, dummy cells and bias-balancing cells.

Implementers should take care to ensure that components whose values are theoretically equal to the maximum modulation value are correctly identified as extendable, noting the risk that notionally equal quantities may differ owing to finite precision arithmetic and differences in rounding.

Note that the condition for a component to be extendable includes the case where the magnitude is greater than the theoretical value: this is to deal with the case where an L1 signalling cell has already been extended by the L1-ACE algorithm.

The result of the selection stage is a set of frequency-domain coefficients $X_{ACE,k}$, and the specification states that the final output $\boldsymbol{x_{ACE}}$ is obtained from $\boldsymbol{X_{ACE}}$ by IFFT. This fits with the description in which the ACE processing replaces the IFFT. However, we can note that the same result could be achieved by feeding $X_{ACE,k}$ to the existing IFFT block, such that the ACE processing occurs entirely "upstream" of the IFFT as was shown in the modified figure 2(f) above.

An expression for the resulting continuous-time, real-valued, radio-frequency on-air signal can be obtained by using the expression for $s(t)$ given in the "IFFT-OFDM modulation" clause 9.5, but with $c_{m,l,k}$ replaced by $c'_{m,l,k} = X_{ACE,k}$. The waveform described by this modified equation includes the guard intervals and P1 preambles.

Tone reservation

Unlike ACE, the Tone Reservation (TR) algorithm has been implemented by several implementers, and was included in a phase of V&V activity [2]. This activity led to some clarifications, which were introduced in version 1.2.1 of the specification.

Having said this, the TR description in the standard shares one issue with the ACE description: it deals with a discrete-time, complex, baseband signal x_n that is not explicitly specified. There is no oversampling in this case and so the required operation is a standard N_{FFT}-point IDFT:

$$x_n = \frac{5}{\sqrt{27K_{total}}} \sum_{k=K_{min}}^{K_{max}} c'_{m,l,k} \times e^{\frac{j2\pi(k-K_C)n}{N_{FFT}}}$$

The overall gain factor is again chosen to make the mean power equal to unity. Again, note that the carriers below the centre carrier will modulate the highest indexed IFFT basis functions, as explained in the case of ACE.

Note that, if ACE is also being performed, Tone Reservation is applied after ACE. Consequently, the input signal x_n will already have had ACE applied, and the formula above will take the modified signal as its input. This is indicated in the formula by the use of $c'_{m,l,k}$, the frequency-domain output of the ACE process as defined in the previous section. If ACE is not used, then $c'_{m,l,k} = c_{m,l,k}$.

The rest of the TR description requires no further clarifications, except a reminder that the clipping level V_{clip} may be different to the corresponding V_{clip} that appears in the ACE clause, if both techniques are used; the latter was renamed to V_{clip_ACE} in the previous section but both have the same symbol in the specification itself.

Tone Reservation PAPR as described in the specification takes place entirely in the time domain, i.e. after the IFFT and before Guard Interval insertion, and, as noted above, this is probably the way it would be implemented in practice. However, the algorithm keeps track of the corresponding frequency-domain modulation values $r_k^{(i)}$, in order to ensure that the reserved tones do not exceed the maximum allowed amplitude. It may be helpful to note that the overall continuous-time, real-valued, radio-frequency signal $s(t)$ will be given by the equation of clause 9.5, with the $c_{m,l,k}$ values corresponding to the Reserved Tones replaced by new values $c''_{m,l,k}$ equal to the $r_k^{(i)}$ values from the last iteration i, scaled appropriately:

$$c''_{m,l,k} = \begin{cases} \dfrac{\sqrt{27K_{total}}}{5N_{TR}} r_k^{(i)} & k \in S_l \\ c'_{m,l,k} & otherwise \end{cases}$$

The resulting expression for $s(t)$ will include P1 preambles and guard intervals.

L1-ACE

The L1-ACE technique is clearly described and has undergone V&V testing. However, some of the text related to the symbols used is slightly inaccurate and this might be confusing:

- L is the maximum value of the real or imaginary part of the L1-post constellation *prior to* the L1-ACE process; this is clear from the list of values that follow.
- Note that this quantity has a different meaning to the L defined in the ACE clause of [1], which is the extension limit parameter. In the ACE section above, L has therefore been renamed L_{ext_limit}.
- $L_{\text{pre}}(m)$, $L_{\text{re\_post}}(m)$ and $L_{\text{im\_post}}(m)$ are the “correctable modulation values”, i.e. the initial values that can be extended; the phrase “correction levels” is unclear. Again, the following equations are explicit and unambiguous.
- $C_{L1\_ACE\_MAX}$ is the maximum *extension* that can be applied, not the maximum *extended value* as stated in the text; this is clear from the equations that follow.

Annex: Symbols and Definitions

The following symbols are not defined in the Symbols clause of [1].

$\|x\|$	Magnitude of x
x'_n	Complex baseband time domain signal at output of oversized IFFT in ACE algorithm
x''_n	Signal obtained from x'_n in ACE algorithm by applying clipping operator
C_k	Frequency-domain coefficient for k-th IFFT-bin
X_k	Alias for the cell value $c_{m,l,k}$ used in the ACE algorithm
$X_{c,k}$	Frequency domain representation of clipped signal x''_n in ACE algorithm
$X'_{c,k}$	Extended frequency-domain signal in ACE after application of gain G
$X''_{c,k}$	Signal obtained in ACE algorithm from $X'_{c,k}$ after saturation to $L_{\text{ext\_limit}}$
$X_{ACE,k}$	Signal obtained in ACE algorithm from $X''_{c,k}$ after application of extension criteria
$c_{m,l,k}$	Cell value for carrier k of symbol l of T2-frame m before PAPR reduction
$c'_{m,l,k}$	Cell value for carrier k of symbol l of T2-frame m, as modified, if applicable, by ACE algorithm

$c''_{m,l,k}$	Cell value for carrier *k* of symbol *l* of T2-frame m, as modified, if applicable, by ACE and TR
V_{clip_ACE}	Clipping threshold as parameter of the ACE algorithm
V_{clip}	Clipping threshold as parameter of the TR algorithm

NOTE: In [1] the same symbol, V_{clip}, is used for the corresponding parameters of both ACE and TR (see above)

K_C	Index of the central OFDM carrier
L_{ext_limit}	(L in ACE-PAPR of [1]): Extension limit of an OFDM cell as parameter of the optional ACE algorithm
L	(in L1-ACE): Maximum value – before extension – of real or imaginary part of an OFDM cell carrying L1-post signalling information.

The following symbols were defined in [1] but their definitions are clarified below:

$C_{\mathrm{L1\_ACE\_MAX}}$	Maximum correction applied by L1-ACE algorithm
G	Extension gain parameter as part of the optional ACE algorithm
$L_{\mathrm{im\_post}}(m)$	Extensible modulation value for the imaginary part of the L1-post used in the L1-ACE algorithm
$L_{\mathrm{re\_post}}(m)$	Extension modulation value for the real part of the L1-post used in the L1-ACE algorithm
$N_{\mathrm{pre}}(m)$	Number of L1-pre cells available for extension by the L1-ACE algorithm
$N_{\mathrm{re}}(m)$	Total number of L1 cells available for extension by the real part of the L1-ACE algorithm
$N_{\mathrm{re\_post}}(m)$	Number of L1-post cells available for extension by the real part of the L1-ACE algorithm

The following definition in the Definitions clause of [1] refers to “the active symbol period T_S”, but in fact the active symbol period is denoted by T_U, so the definition should read as follows:

FFT size: nominal FFT size used for a particular mode, equal to the active symbol period T_{u} expressed in cycles of the elementary period T