Research White Paper

WHP 156

October 2007

DVB-T and Voltage Ratings of Transmission Equipment

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Abstract

BBC Strategy and Distribution have asked Kingswood Warren staff to look into a question that has existed since the advent of digital broadcast services in the 1990s: Given the nature of COFDM signals, what voltage rating is required for transmitter antenna feeders — or, for that matter, the associated antennas and combiner/splitter units? The conventional wisdom is that, statistically, a COFDM signal is similar to Gaussian noise; hence there is a possibility of very large voltage peaks that could initiate flashovers. Until now, the problem has been contained by the relatively low power levels of the COFDM signals. However, the situation will change as the television 'digital switchover' takes place over the coming few years.

Not surprisingly, the BBC needs some reassurance that terrestrial television will continue to work after switchover. There is also the related question of how to carry out realistic acceptance testing. A transmitter might work perfectly overnight, for instance, but does that mean a flashover is unlikely over the subsequent year?

This Technical Note looks at the questions of feeder ratings and acceptance testing. The conclusion is that the current philosophy regarding feeder ratings is adequate, and that an overnight acceptance test at slightly enhanced power should be sufficient to highlight any potential flashover problems.

DVB-T and Voltage Ratings of Transmission Equipment

Ranulph Poole

1 Introduction

For broadcasters, an important question arose with the advent of digital transmissions in the 1990s: Given the nature of COFDM signals, what voltage rating is required for transmitter antenna feeders — or, for that matter, the associated antennas and combiner/splitter units? The received wisdom is that, statistically, a COFDM signal is similar to Gaussian noise; hence there is a possibility of very large voltage peaks that could initiate flashovers. Until now, the problem has been contained by the relatively low power levels of the COFDM signals. However, the situation will change as the television 'digital switchover' takes place over the coming few years.

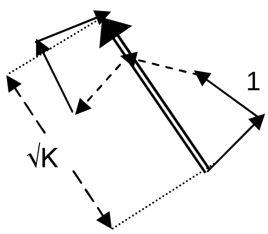
It is tempting to leave such concerns to the transmission providers along with their equipment suppliers. Even so, the BBC needs some reassurance that terrestrial television will continue to work after the switchover. There is also the related question of how to carry out realistic acceptance testing. A transmitter might work perfectly overnight, for instance, but does that mean a flashover is unlikely over the subsequent year?

This Technical Note looks at the questions of feeder ratings and acceptance testing. The hope is to provide confirmation that transmission equipment is being adequately specified.

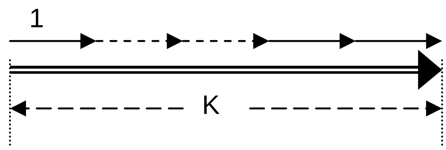
2 COFDM Signals and Peak-to-Mean Ratios

The television (DVB-T) COFDM signal comprises a large number of equally-spaced carriers, each amplitude and phase modulated by the data to be transmitted.[1] Depending on the DVB-T variant chosen, there could be 1,705 carriers ('2K') or 6,817 ('8K'). The modulation schemes available are QPSK, 16-QAM and 64-QAM, both uniform and non-uniform. **[1]** Data interleaving and scrambling are used so that, within certain constraints, the amplitudes and phases of the carriers are essentially random.

When the carriers are combined, the mean power of the signal equals the sum of the mean powers of the individual carriers, and the corresponding RMS voltage is easy to calculate. However, at any one time, there is a theoretical chance of all carriers adding constructively, in which case the instantaneous voltage — and power — is considerably greater. The diagram below illustrates an ensemble where the carriers have equal amplitude but random phases:[2]



Carriers of equal amplitudes but random phases. If there are K carriers, each of unity power, the total power is K. The corresponding RMS voltage is √K if the power is being delivered to a 1 Ω load.



Carriers of equal amplitudes and co-phased. If there are K carriers, each of unity power, the overall voltage is K. Again, this assumes that the power is being delivered to a 1 Ω load.

Caution: For simplicity, 1 V of carrier is taken to deliver a power of 1 W into a 1 Ω load. Remember that this 1 V is an RMS value: as the carrier is a sinusoid, the actual amplitude is √2 greater.

Figure 1: Phasor Representations of the COFDM Signal

The theoretical power ratio, or 'peak-to-mean ratio', for the two cases shown above is K^2/K, or K. For K = 1,704, this is equivalent to a very large 32 dB. It would be larger still if each COFDM carrier possessed the maximum possible amplitude allowed by the modulation scheme.

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[1] For the sake of argument, complications such as the pilot carriers are being ignored.

[2] Note that, because the carriers possess different frequencies, the phase relationships are changing continuously.

Fortunately, as will be seen, the chances of all the carriers aligning in this way are vanishingly small. Indeed, the COFDM signal can be clipped ruthlessly with very little practical degradation. A simple simulation with an *Excel* spreadsheet illustrates this well:

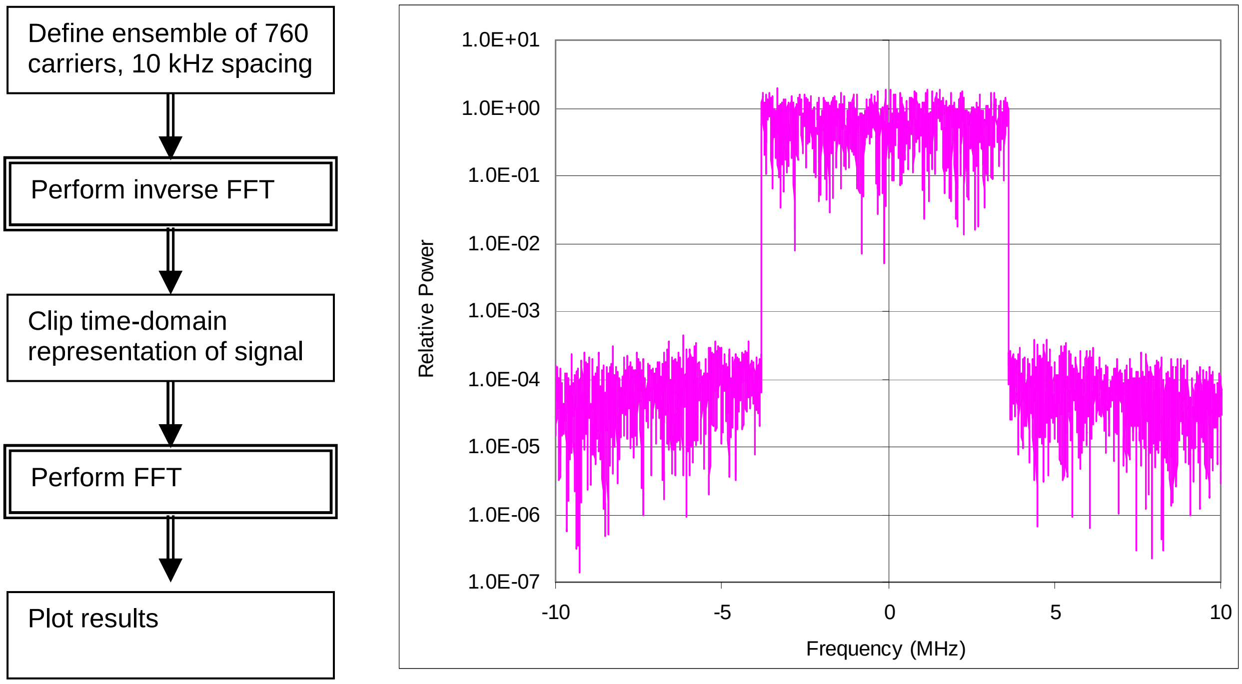

Figure 2: Illustration of Clipped COFDM Signal

In this example, the COFDM signal has been clipped to give a peak-to-mean power ratio of 8 dB. The price paid is a noise floor of intermodulation products (IPs) with approximate relative power 10^{-4}, or –40 dB.[3] A more realistic simulation, carried out by a colleague with appropriate software, yields a figure of –37 dB for a 7 dB peak-to-mean ratio.

Transmission providers typically take the peak-to-mean ratio (PMR) at the transmitter output as 10 dB. High-power amplifiers do not clip cleanly, with the result that IP levels are often worse than the above treatment suggests.[4] A good installation can achieve an IP floor of about –35 dB when the power amplifiers are backed off to give 10 dB PMR.[5]

At first sight it would seem that feeders should be voltage-rated so as to be safe with a 10 dB PMR. In other words, the maximum expected voltage is 3.16 times that corresponding to the mean power. Unfortunately, life is not that simple: a real system may well transmit several COFDM signals simultaneously, and there may also be filters to remove out-of-channel IPs.[6] The effects of both these complications will be considered in more detail later. For the moment, it is sufficient to say that the PMR of a clipped signal will increase slightly on passing through a filter — so-called PMR regeneration. The statistics of several clipped signals after being combined are not yet known, but the overall voltage can never be greater than the sum of the individual peak voltages, and for most of the time will be considerably less.

After this discussion, it is a relief to learn that the BBC's transmission providers calculate feeder voltage ratings on the following assumptions: a 10 dB PMR for the individual signals, peak voltage addition, and a further 50% for good measure. This would seem to be foolproof.

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3 The peak-to-mean ratio has been defined here as peak power *after* clipping divided by mean power *before* clipping. Clipping reduces the mean power very slightly.
To be strictly correct, we should talk about relative powers *in a given bandwidth*.

4 With high-power amplifiers, AM to PM conversion significantly degrades performance.

5 This means that the saturated output power of the amplifier is 10 dB greater than the mean power of the COFDM signal. Determining the amount of back-off is a compromise between signal quality and power efficiency.

6 Often the filtering and signal combining are carried out within the same item of equipment.

3 COFDM Signals, Probabilities and Peak-to-Mean Values

The previous discussion has hinted at some of the complications associated with a real COFDM transmission system. However, assume for the moment that the signal being transmitted is a single, ideal COFDM ensemble comprising a large number of equally-spaced carriers. There is good reason to believe that such a system is the most 'difficult' that could be encountered: with no mechanism in place to clip the peaks, the theoretical peak-to-mean ratio (PMR) equals the number of carriers. How often are the peaks likely to exceed a dangerous level?

Statistics come to the rescue here: they can tell us the relative chance of the signal possessing a given overall amplitude at any instant. The Central Limit Theorem states that 'if the sum of the variables has a finite variance, then it will be approximately normally distributed (i.e. it will follow a normal or Gaussian distribution).' **[2]** In other words, a Gaussian distribution is appropriate to a system where the variables (individual carrier amplitudes) are largely independent of each other, and where no variable exerts an excessive influence (no COFDM carrier amplitudes are much larger than the average). As the carriers are equally as likely to have negative and positive values, the Gaussian distribution is centred about zero. It falls rapidly beyond the *scaling factor* σ. σ^2 is known as the *variance*, and in the present context can be thought of as the mean signal power.

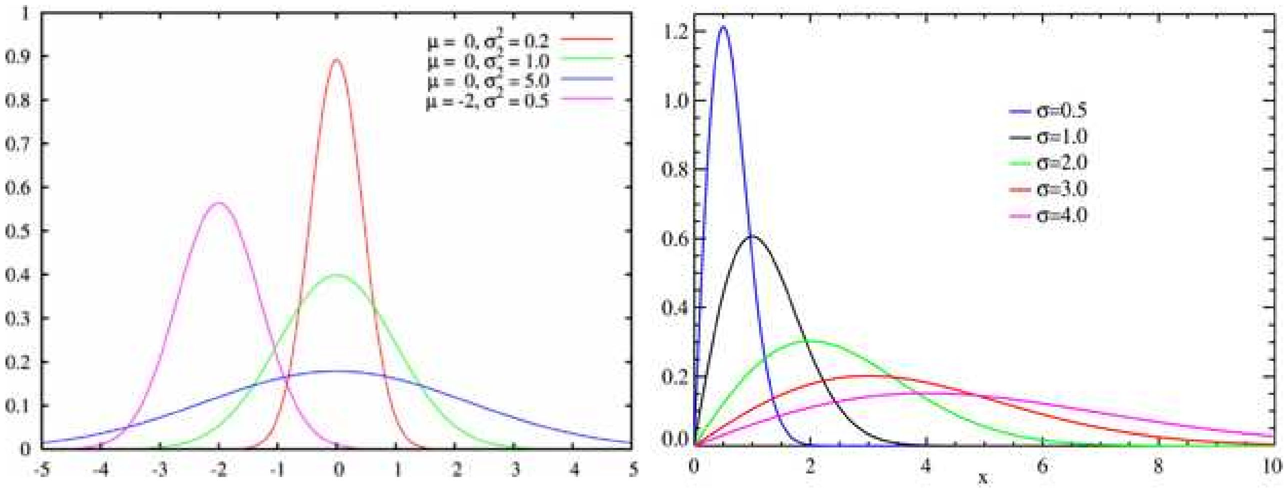

Figure 3: Gaussian *(Left)* and Rayleigh *(Right)* Distribution Functions

A slight complication is caused by the COFDM carriers being two-dimensional: they possess random phases, as shown in Figure 1, and hence are evenly spread between the two axes. The appropriate distribution is the Rayleigh:[7] **[3]**

$$\frac{x \exp\left(\frac{-x^2}{2\sigma^2}\right)}{\sigma^2}$$

Unlike the Gaussian distribution, this is zero for zero amplitude, and possesses a peak at x = σ. Of particular interest to us is the *cumulative distribution function* (CDF), which gives the fraction of the total distribution that falls below a given value of x:

$$1 - \exp\left(\frac{-x^2}{2\sigma^2}\right)$$

The complement (1 – CDF) — the *exceedance probability* — represents the fraction exceeding that same value of x. By great good fortune, this is a remarkably simple formula: x^2 represents the instantaneous power, and $2\sigma^2$ the mean power; hence (1 – CDF) equals exp (–PMR).[8]

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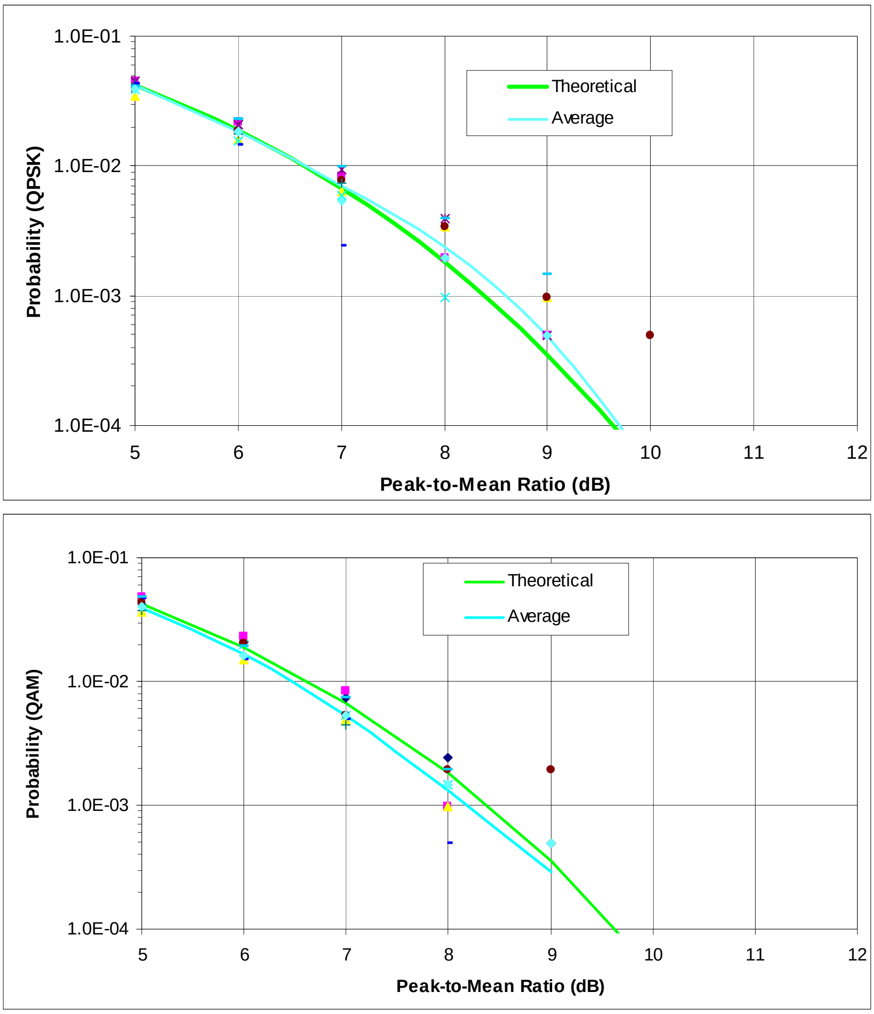
[7] The terminology is a little misleading. In the expression, x refers to the signal amplitude — not the component of it that lies along the x-axis. The term 'exp' means 'e to the power of', where e is 2.718 (to 4 figures).

[8] Once again, the terminology is slightly misleading. The literal PMR would be determined by recording the peak signal power over an infinite period. As stated in the first paragraph, this would approach the number of carriers for an 'ideal' COFDM signal. The exceedance formula embraces all peaks greater than a given PMR value.

This result might seem too good to be true. As a check, the author simulated two COFDM ensembles, in the manner used to obtain Figure 1. The first was generated from individual 'carriers' whose x and y components were random numbers falling between –1 and +1. This signal would correspond approximately to a high-order modulation scheme such as 64 QAM. The second allowed the two components to be –1 and +1 only — an approximation to QPSK. If the Central Limit Theorem is true, the distributions of the two ensembles should match, and (1 – CDF) should follow the simple exp(–PMR) law.



For the plots alongside, the data was generated with the help of a 2k FFT. As 2,000 points are inadequate for calculating probabilities of 10^{-3} and below, 10 measurement runs were made and the results averaged. The individual runs are shown as dots, while the averages are given as continuous lines.

In both cases, agreement between the simulations and theory is good, hence giving confidence in the exp(–PMR) formula.

A colleague, Jonathan Stott, has carried out a much more sophisticated simulation of 100,000 DAB symbols. A plot of his results is given in Appendix 1. There is near perfect agreement with the simple formula.

Figure 4: Exceedance Probability for Simulated QPSK and QAM

The plot overleaf extends the theoretical exceedance probability (EP) curves shown above. To put the tiny numbers into context, the EP has been scaled to seconds per year. The extreme dependence of EP on peak-to-mean ratio (PMR) is obvious: a PMR of 15 dB will only be exceeded for 1 μs in a year — probably an acceptable risk.

Without some rather complicated calculations, it cannot be said precisely how many exceedance events will take place in a period of 1 μs. However, the duration of each event will approximate to the reciprocal of the channel bandwidth: an 8 MHz channel corresponds to 125 ns, and so about 8 events could be expected. There is no need for greater accuracy, as a further dB reduces the EP by 4 orders of magnitude — truly negligible by any standards. A PMR of 17 dB would only be exceeded for a little over a microsecond in the present age of the universe!

The provisional conclusion seems to be that transmitter installations are adequately rated. The '10 dB peak-to-mean ratio + 50%' rule corresponds to a PMR of 13.5 dB, and the cable manufacturers cautiously allow a 6 dB safety margin. **[4]** A further consequence of the steep dependence of EP on PMR is that endurance could be checked by running the system at slightly enhanced power for only a short period.

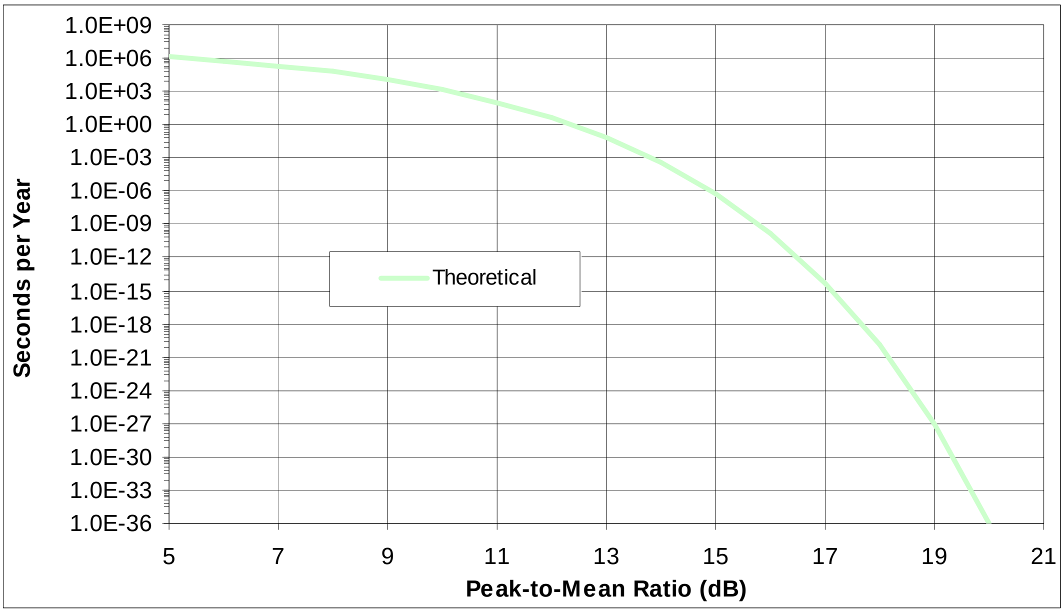


Figure 5: Exceedance Probability for Rayleigh Distribution

4 Peak-to-Mean Regrowth in Filters

It was mentioned in Section 2 that the presence of filtering within the COFDM system introduces a 'complication'. A bandpass filter is always needed at the output of a high power transmitter to remove intermodulation products (IPs) in the adjacent channels and beyond. The filter may be an integral part of a multi-channel combiner.

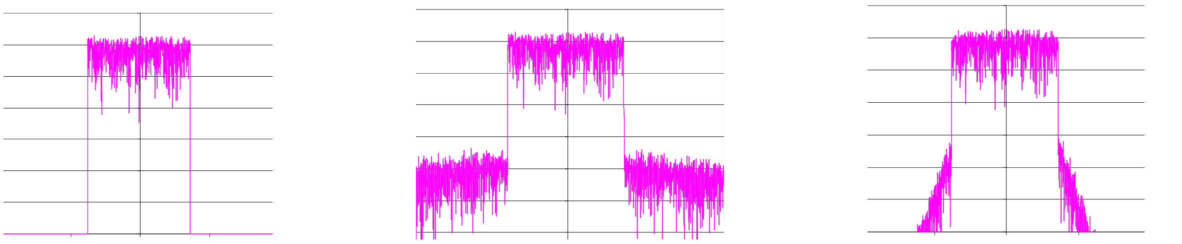
An ideal COFDM signal possesses a large number of independent carriers, each with low bandwidth modulation. No realistic bandpass filter can appreciably damage the signal, since the filter's bandwidth is necessarily very much larger than that required by the individual carriers. The statistics of the overall signal are also preserved, as the carriers retain their random relationships with each other.

The complication arises if the signal is clipped, either intentionally or unintentionally, before reaching the bandpass filter. As demonstrated in Section 2, PMRs can be limited to modest values without seriously compromising the IP performance. Clipping constrains the carriers by changing their instantaneous amplitudes and phases, and hence removes the random relationships between them. If the amplitude and (particularly) the phase relationships are subsequently disturbed by a filter, some of the clipping is likely to be undone.

This 'regrowth' of PMR is difficult to treat analytically, and the author is grateful to his colleague Peter Moss for carrying out some simulations using *Matlab*. Only a summary of the method is presented here; full details are given in Appendix 2. For each trial:

- A random complex vector is generated to provide a Rayleigh envelope for a given time.
- The vector is interpolated by a factor of 4, giving the necessary Nyquist range to accommodate distortion products and filtering.
- The peak value is found, and added to the running total of an 'initial_peak' register.
- The Rayleigh envelope is clipped to the specified threshold.
- The resulting signal is filtered to its original bandwidth.
- The peak value is found, and added to the running total of a 'restored_peak' register.
- The contents of the 'initial_peak' and 'restored_peak' registers are divided by the number of trials (100 in this case), hence providing average values.

The results are best presented in the form of a diagram, as shown overleaf. Note that two different clipping levels — 7 dB and 10 dB — were simulated.



PMR is **12 dB**.	PMR is **10 dB** *(Level 1)*.	PMR is **11.25** dB.
PMR is **12 dB**.	PMR is **7 dB** *(Level 2)*.	PMR is **9.50** dB.

Figure 6: Peak-to-Mean Regeneration in Bandpass Filter

There are no great surprises here: the bandpass filter does give PMR regeneration. In this example, the regenerated PMR is about halfway between that of the unclipped and clipped signals. Without carrying out much more simulation work, it is difficult to say whether the result is typical. One would expect that regeneration would be greater for higher orders of filter.

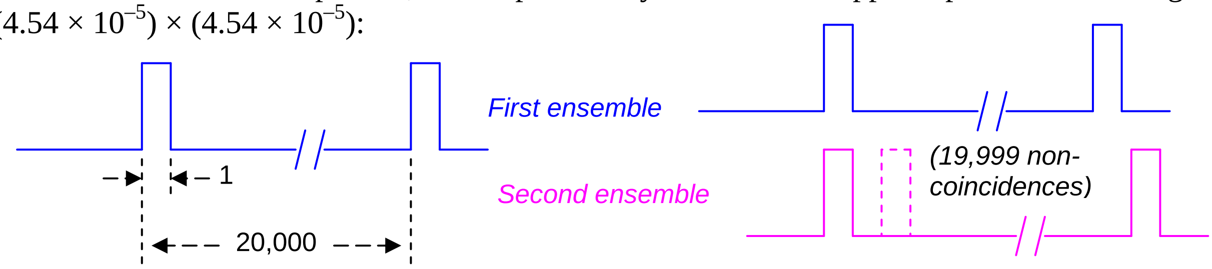
Another question is what effect the bandpass filter has on the statistics of the clipped signal; in particular, are there now more large amplitude peaks? The author is indebted to Chris Nokes for providing plots of the EP before and after bandpass filtering. These are reproduced at the end of Appendix 2. There is no suggestion that the EP has any untoward characteristics: it falls away gracefully to near zero at a PMR consistent with Peter Moss's calculations.

5 Multiple Services

The other 'complication' mentioned in Section 2 is that several COFDM ensembles are likely to be present on the same antenna feeder. What can one say about the peak voltages that could be present, and how often are they likely to occur? For the sake of argument, we assume that six ensembles of equal power are to be transmitted.

The worst possible case occurs where the individual ensembles have not been clipped or processed in any way. They then combine to form a 'super ensemble' possessing the same Rayleigh distribution as its constituent parts. Indeed, even if the individual ensembles are not ideally Rayleigh, the Central Limit Theorem implies that the super ensemble would be a closer approximation. The work of Section 3 shows that taking the PMR as 15 dB should be safe.

A kinder and more likely situation occurs when the individual ensembles are clipped to 10 dB PMR before being combined. According to the exceedance ratio formula, the probability of clipping taking place is 4.54×10^{-5}, or 1,400 seconds per year, for the single ensemble. Where a second ensemble is present, the probability of two clipped peaks coinciding is $(4.54 \times 10^{-5}) \times (4.54 \times 10^{-5})$:



Single ensemble: There is a 1 in 20,000 chance of a peak being present at any one time.

Two ensembles: There is a 1 in 20,000 chance of the first generating a peak at any instant, and a further 1 in 20,000 chance that a peak from the second will coincide. The net chance is 1 in $20{,}000^2$.

Figure 7: Illustration of Peaks from Two Ensembles Coinciding

In general, the probability of all peaks coinciding is $(4.54 \times 10^{-5})^n$, where n is the number of ensembles. It is easy to demonstrate that this is just the value yielded by the formula EP = exp (–PMR): The PMR equals the peak-to-mean ratio for a single ensemble (10 dB, or a factor of 10) times the number of ensembles.[9] Hence, in this case,

$$EP = \exp(-10\,n) = \{\exp(-10)\}^n, \text{ or } (4.54 \times 10^{-5})^n$$

— as before. The table below gives some feel for the numbers involved.

No. of Ensembles	PMR (dB)	Seconds per Year
1	10.00	1.43E+03
2	13.01	6.50E-02
3	14.77	2.95E-06
4	16.02	1.34E-10
5	16.99	6.09E-15
6	17.78	2.76E-19

Figure 8: PMRs and Exceedance Values for Multiple Ensembles

Note that, if the individual ensembles are clipped to 10 dB PMR, the PMR values in the table are hard limits that cannot be exceeded. On the other hand, if the ensembles are unclipped, the Rayleigh distribution continues beyond those values.

The results given in Figure 8 can be summarised as follows:

- Perhaps contrary to intuition, the philosophy '10 dB PMR for the individual signals, peak voltage addition' is safest where large numbers of ensembles are present. The PMR values shown in the table correspond to this dictum, and three or more ensembles are 'safe' whether or nor clipping has taken place: the EP, as quantified in seconds per year, is always negligible.
- Two ensembles are safe if they are individually clipped to 10 dB, but not if the clipping is 'undone' by subsequent filtering. Fortunately, the transmission providers allow 50% peak voltage safety margin (3.5 dB) when calculating feeder ratings. The system is therefore safe for a PMR of 16.5 dB — which would never be exceeded in practice.
- The single ensemble is the most critical case. Of course, the system is safe provided that the ensemble is clipped, and remains clipped. The simulation work carried out suggests that the safety margin of 3.5 dB is more than adequate to allow for peak-to-mean regeneration in the transmitter output filtering.

6 Conclusion

This report has looked at what was feared to be an intractable problem — how much allowance to make for the peak levels of multiple COFDM signals when designing high power feeder systems. The conclusions are as follows:

- For a single, unclipped COFDM signal, a Rayleigh distribution is appropriate for calculating the likelihood of exceeding a given peak power.
- Where three or more ensembles are present, each clipped to 10 dB peak-to-mean ratio (PMR), the same distribution is appropriate. It is safe to assume that PMRs will never exceed 16 dB.
- The transmission providers' philosophy of '10 dB PMR for the individual signals, peak voltage addition plus 50% safety margin' is safe — increasingly so for larger numbers of ensembles.

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9 This was demonstrated in Figure 1: the mean power and the peak voltage both double, but the peak power quadruples, since it is proportional to the square of the peak voltage.

- PMR regeneration will occur in bandpass filters designed to limit spurious signals in the adjacent channels. The amount is difficult to calculate, but need not cause concern: the transmission providers' philosophy always provides adequate margin.
- As the safety margin is generous, no special provision needs to be made when carrying out acceptance tests. However, a possibility would be to increase the transmitted power by a modest 1 dB (say) over an 8 hour period. If there are no problems in that time, there are unlikely to be any 'events' over the next year at the normal power.

7 Acknowledgements

The author would like to thank the following colleagues:

- Jonathan Stott, for providing the simulation of the 'real' DAB signal in Appendix 1.
- Peter Moss, for looking into the problem of peak-to-mean regrowth in bandpass filters.
- Chris Nokes, for checking the statistics of the above 'regrown' signal.
- John Salter, for checking through the report and making useful suggestions.
- Dave Darlington, of BBC Strategy and Distribution, for commissioning this work.

8 References

1. ETSI, 1996. 'Digital broadcasting systems for television, sound and data services: Framing structure, channel coding and modulation for digital terrestrial television.' ETS 300 744.
2. The Central Limit Theorem is explained and discussed in Wikipedia: http://en.wikipedia.org/wiki/Central_limit_theorem
3. The Rayleigh distribution is explained in Wikipedia: http://en.wikipedia.org/wiki/Rayleigh_distribution
4. An interesting discussion of cable properties and ratings is provided by Radio Frequency Systems (RFS): http://www.rfsworld.com/userfiles/pdf/technical-description-rfcables.pdf

Be careful! RFS define the peak power handling of their cables in terms of the peak voltage present. In other words, this is the instantaneous peak power and not the peak envelope power. It is the peak envelope power that is relevant when talking about COFDM peak-to-mean ratios.

The BBC's transmission providers have made it clear that they correctly convert peak envelope power into instantaneous peak power when specifying cables.

Appendix 1: A DAB Simulation

Jonathan Stott has carried out a statistical analysis of a 'true' DAB signal — 'true' in the sense that factors such as the symbol duration, number of carriers, pilot carriers and the QPSK modulation scheme are included. The computation involved is considerable, and Jonathan's 'Mac' was left running for hours in order to generate the necessary number of samples. The results are given below:

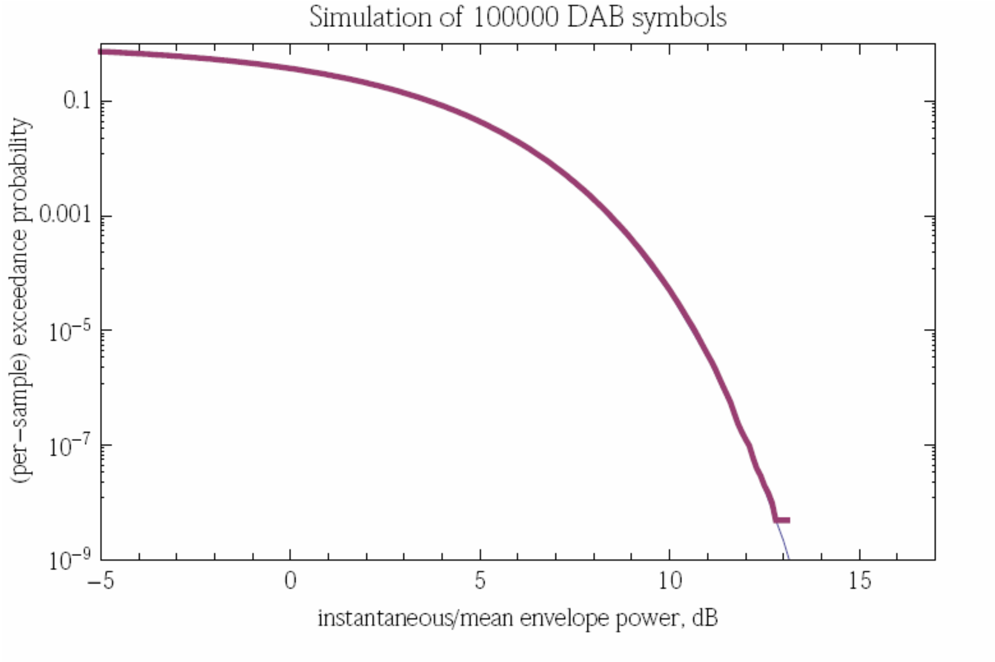

Figure 9: Exceedance Probability Plot for a 'True' DAB Signal

Figure 9 shows exceedence probability (EP) plotted with respect to the ratio of instantaneous (or peak)-to-mean power (PMR). For example, the chances are approximately 1 in 10^5 that the instantaneous power will exceed the mean power by 11 dB. Even with a large amount of computing power, chances below 1 in 10^8 are intractable, and so the final section of the curve, shown in grey, is theoretical.

A plot of the expression EP = exp (–PMR), as described in Section 3, is shown below. Agreement with the simulation is excellent, giving confidence that the simple approach adopted elsewhere is valid.

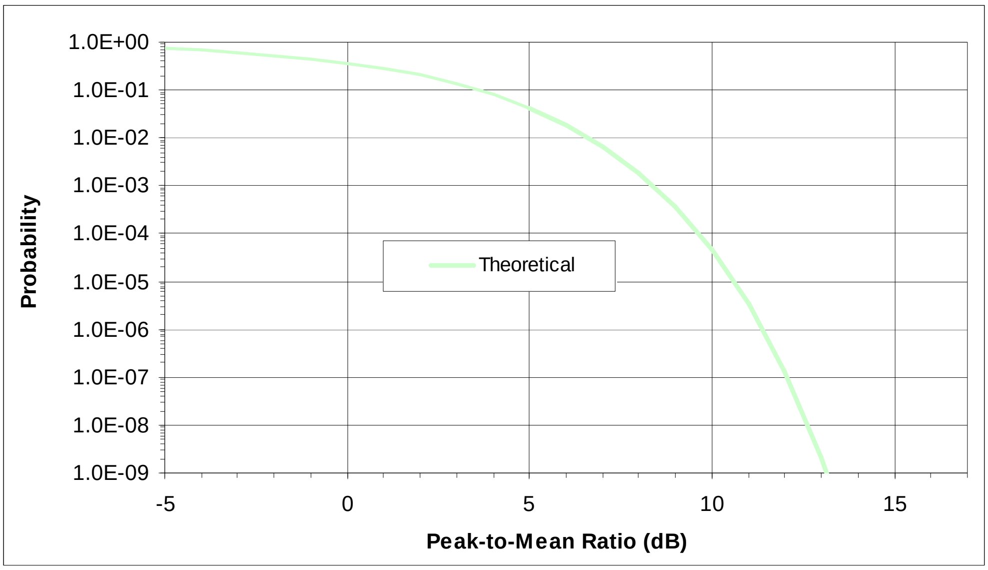

Figure 10: Exceedance Probability Plot for a Rayleigh Distribution

Appendix 2: A Simulation of Peak-to-Mean Regrowth in Filters

Contributed by Peter Moss

Background

With the impending expansion of DVB-T networks in the run-up to switchover, the question has been raised as to the likely peak envelope powers which may occur in COFDM service combiners. Although a particular amplifier may have a maximum envelope power output which can be reasonably easily determined, it is well known that subsequent filtering can cause re-growth of previously limited peaks. Consequently it was decided to model the process of clipping and filtering in MATLAB, and below is a description of the m-file code. Note that the signal is assumed to possess a Rayleigh envelope — an approach that Appendix 1 confirms as valid.

Description

The sequence of events within the code can be summarised thus:

1. Read parameters 'time_len', 'env_thres', 'trials'
2. for each trial, proceed as:
3. define random complex vector (Rayleigh envelope) of length ' time_len'
4. Interpolate vector to 4x 'time_len'. *This provides Nyquist range for distortion products & filtering.*
5. Find peak. Add to running total of 'initial_peak' register
6. Clip to envelope level 'env_thres'
7. Filter to original bandwidth
8. Find peak. Add to running total of 'restored_peak' register
9. Divide contents of 'initial_peak' and 'restored_peak' registers by 'trials'

Actual m-file

The m-file is reproduced below:

```
%This function predicts peak-to-mean recovery after clipping and filtering
%parameters are time vector length and envelope clip threshold
%Outputs initial peak-to-mean (linear voltage units), post-clipping value
%(should be as entered) and post-re-filtering value

function [] = clipfilter(time_len,env_thres,trials)

initial_peak=0;
clipped_peak=0;
restored_peak=0;
[b,a]=cheby1(7,0.03,0.25);
tic
for m=1:trials
    x=randn(time_len,1);
    y=randn(time_len,1);
    z=(x+y*i)/sqrt(2);  %define Rayleigh random vector

    z_interp=interp(z,4,10,0.99); % define filter taps to oversample &
interpolate

    z_filt=filter(b,a,z_interp);

    initial_peak=initial_peak+max(abs(z_filt));

    for m=1:4*time_len   %clip
        if abs(z_filt(m))>env_thres
            z_filt(m)=env_thres*z_filt(m)/abs(z_filt(m));
        end
    end
```

```
    clipped_peak=clipped_peak+max(abs(z_filt)); %only here as check, should
of course be deterministic

    z_filt=filter(b,a,z_filt);  % re-filter

    restored_peak=restored_peak+max(abs(z_filt));

end
toc
avg_initial_peak=initial_peak/trials
avg_clipped_peak=clipped_peak/trials
avg_restored_peak=restored_peak/trials
```

Regrowth Statistics *(Contributed by Chris Nokes)*

The above treatment indicates the increase in peak-to-mean ratio (PMR) that can be expected when a COFDM signal passes through a bandpass filter. However, it says nothing about the statistics of such a signal. For instance, for peak signal levels just below the PMR limit, the exceedance probability (EP) might be greater than that of an unclipped signal — clearly an undesirable situation. To find out, a further simulation was carried out.

The plots below show the exceedance probabilities for unclipped, clipped, and clipped and filtered DVB-T signals. As in Section 4, the filtering is 7th-order Chebychev. There is no evidence that the statistics of the clipped and filtered DVB-T signal are particularly unfriendly.[10]

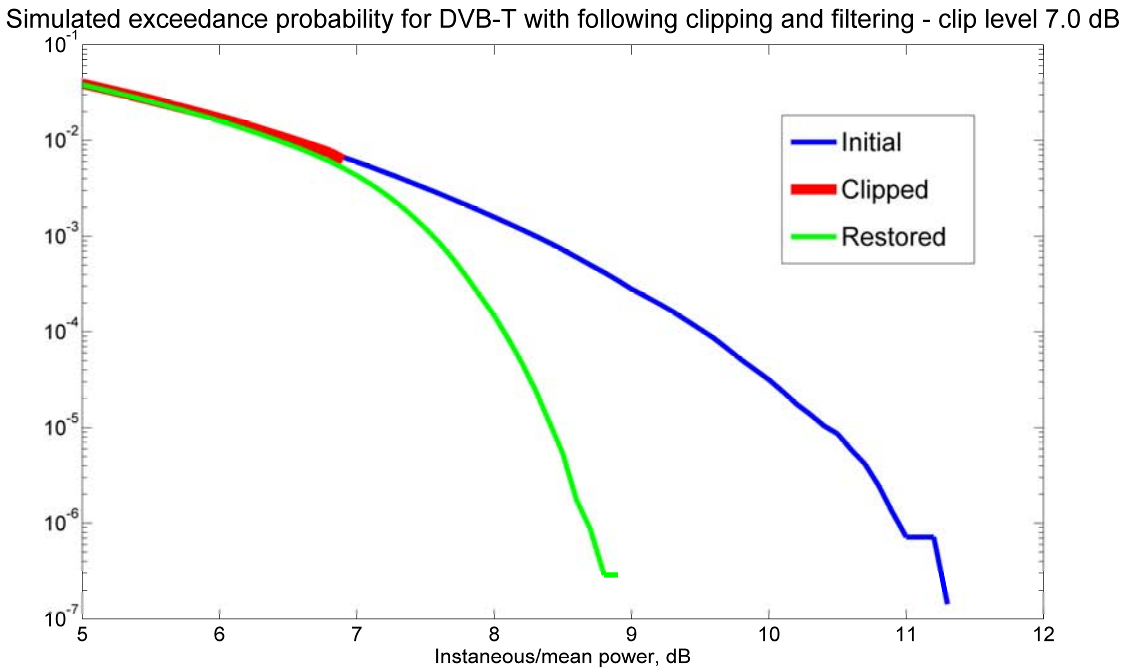

Figure 11: EP Plots for Unclipped, Clipped and Clipped and Filtered DVB-T Signals

[10] The strange kinks in the curves at very low EPs are the result of limited computational power, and are not 'real'.