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Digital television services:
equivalent noise floors and equivalent noise degradation

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Abstract

This White Paper originally appeared as an internal BBC R&D Report in 1997, before the start of regular digital television transmissions. The aim of the work described in the document was to discover the best way of quantifying typical impairments introduced by the transmission system. It was hoped that the individual impairments could be added in a convenient way to provide a measure of the total impairment. Fortunately, this proved to be true.

Although both the theory and practice of COFDM systems have moved on considerably since those early days, the author believes that the original work is still of interest. In particular, the concepts of equivalent noise floor (ENF) and equivalent noise degradation (END) may not be widely known outside organisations such as the Digital Television Group. Also, the reader may find it comforting that these abstract concepts have direct application to measurements in the real world.

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Digital Television Services: Equivalent Noise Floors and Equivalent Noise Degradation

1. Introduction

In 1997, before the start of regular DVB-T broadcasts, the Digital Television Group considered options for specifying the performance of COFDM transmission equipment. It was desirable that the method chosen should allow the equipment manufacturer maximum freedom to juggle the quality and costs of the individual items within the transmission chain, and so arrive at the most economic solution. For example, a transmitter's local oscillator phase noise and power amplifier non-linearity could have been specified individually in such a way as to ensure satisfactory overall performance. It made more sense, however, to specify the overall performance alone, and to allow the transmitter manufacturer to decide the relative levels of the various impairments.

This report gives a simple account of the concept of equivalent noise degradation (END), and describes some laboratory tests as illustrations. The signal impairments considered are local oscillator phase noise, amplifier non-linearity and amplitude response ripple. Impairments that result in large group delay errors — some multipath conditions, for instance — are not suitable for such treatment; the main concern then is erosion of the guard interval.[1]

2. Theory

The diagram below shows, in essence, how END measurements are performed.

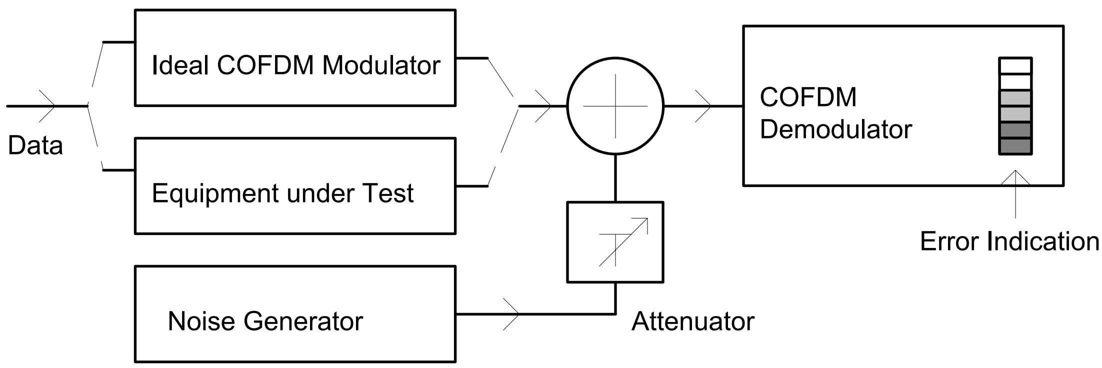

Figure 1: Measurement of Equivalent Noise Degradation

The level of noise added to the output of the ideal COFDM modulator is increased until a 'reference' bit error ratio (BER_{ref}) is measured at the output of the demodulator. A convenient figure is 2×10^{-4} following the Viterbi decoder.[2] The level of noise relative to the COFDM signal is recorded. Now the equipment under test is substituted for the ideal modulator, and the new relative noise level giving the same error rate is recorded. Because any impairments within the equipment under test reduce the tolerance of the demodulator to noise, the second figure will be less. The ratio of the two figures — or the difference in dB — is the END.

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1 The original report referred to the END as 'loss of noise margin', or LONM — the term END did not exist at the time. Although the report says that END (or LONM) is not suitable for quantifying impairments involving long delays, later work on echoes has shown this statement to be pessimistic; see Reference **[1]**, for instance.

2 At this BER, the output of the Reed-Solomon decoder is quasi error-free. An increase in noise level of about 1 dB would be necessary to produce regular errors.

It is not obvious from the above how the ENDs of individual impairments may be combined to give an overall END, but the diagram below provides some understanding. For the sake of argument, assume that the demodulator provides BER_{ref} with a carrier-to-noise ratio (C/N) of 20 dB.

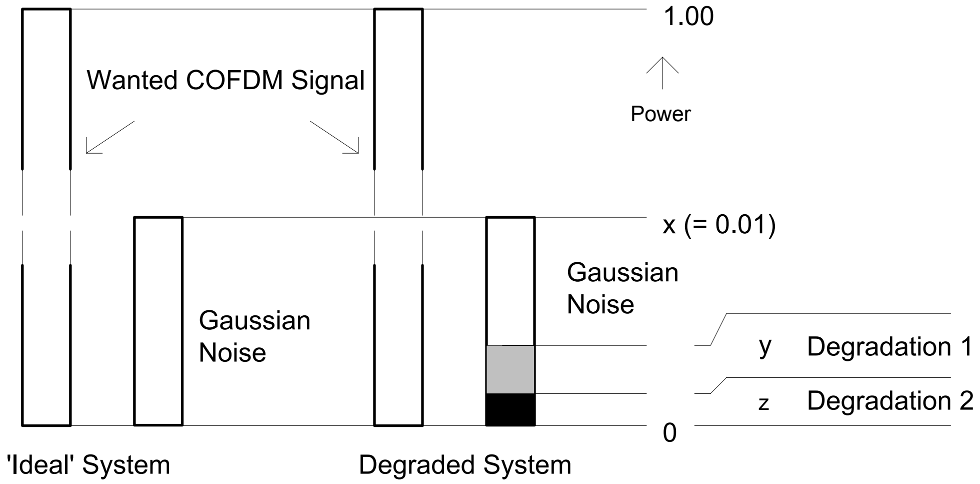

Figure 2: Comparison of an 'Ideal' System with One Including Noise-like Impairments

The left-hand part of Figure 2 illustrates the 'ideal' system. The noise level shown is that required for BER_{ref} at the output of the demodulator. If noise-like impairments are now added, as shown in the right-hand part of Figure 2, the amount of Gaussian noise necessary to cause the same error rate is evidently less. The overall END is defined as:

$$\frac{(\text{COFDM power/Gaussian noise power})_{\text{degraded system}}}{(\text{COFDM power/Gaussian noise power})_{\text{ideal system}}}, \text{ or } \frac{(\text{Gaussian noise power})_{\text{ideal system}}}{(\text{Gaussian noise power})_{\text{degraded system}}},$$

since the COFDM power is the same in both cases.

Normally, the END is expressed in dB:

$$END_{dB} = 10 \log_{10}(\text{Gaussian noise power})_{\text{ideal system}} - 10 \log_{10}(\text{Gaussian noise power})_{\text{degraded system}}$$

It follows that measuring the END is simply a matter of introducing the impairment(s) and noting the change of noise attenuator setting required to maintain BER_{ref}.[3]

Figure 2 actually shows two noise-like impairments, with powers y and z, contributing to an overall impairment of y + z. The overall END is given by

$$END_{dB\ total} = 10 \log_{10} \{x / (x - (y + z))\}.$$

The sum of the two individual contributions to the END is

$$\begin{aligned} END_{dB\ 1} + END_{dB\ 2} &= 10 \log_{10} \{x / (x - y)\} + 10 \log_{10} \{x /(x - z)\}, \\ &= 10 \log_{10} \{x / (x - y)\} \{x /(x - z)\}, \\ &= 10 \log_{10} \{x^2 / (x^2 - xy - zx + zy)\}. \end{aligned}$$

If y and z are both small, the product zy can be neglected; therefore

$$\begin{aligned} END_{dB\ 1} + END_{dB\ 2} &= 10 \log_{10} \{x^2 / (x^2 - xy - zx)\}, \\ &= 10 \log_{10} \{x / (x - (y + z)\}. \end{aligned}$$

Thus $$END_{dB\ 1} + END_{dB\ 2} = END_{dB\ total}.$$

In other words, *for small ENDs*, the total END equals the sum of the individual ENDs.

[3] Assuming, of course, that introducing the impairment does not affect the power of the COFDM signal.

The quantities x and y are often known as the equivalent noise floors or ENFs of the impairments, and are generally quoted in dB with respect to the COFDM power. For the system just discussed, an ENF of –20 dBc would give rise to BER_{ref}.

The relationship between END and ENF is shown in **Appendix 1**. BER_{ref} is taken as corresponding to a C/N of 20 dB,[4] but it is simple to rescale the x-axis for different C/Ns. For example, if the C/N for BER_{ref} equals 17 dB, 3 dB should be subtracted from the 'Interferer Level' scale.

3. Experimental Set-up and Method

Laboratory measurements were carried out to check that small ENDs could, in practice, be added to provide an overall END. The experimental set-up was essentially that shown in Figure 1, but with further details as given in **Figure 3** below. Note that the modulator itself is taken to be 'ideal', and that the impairments are introduced subsequently.

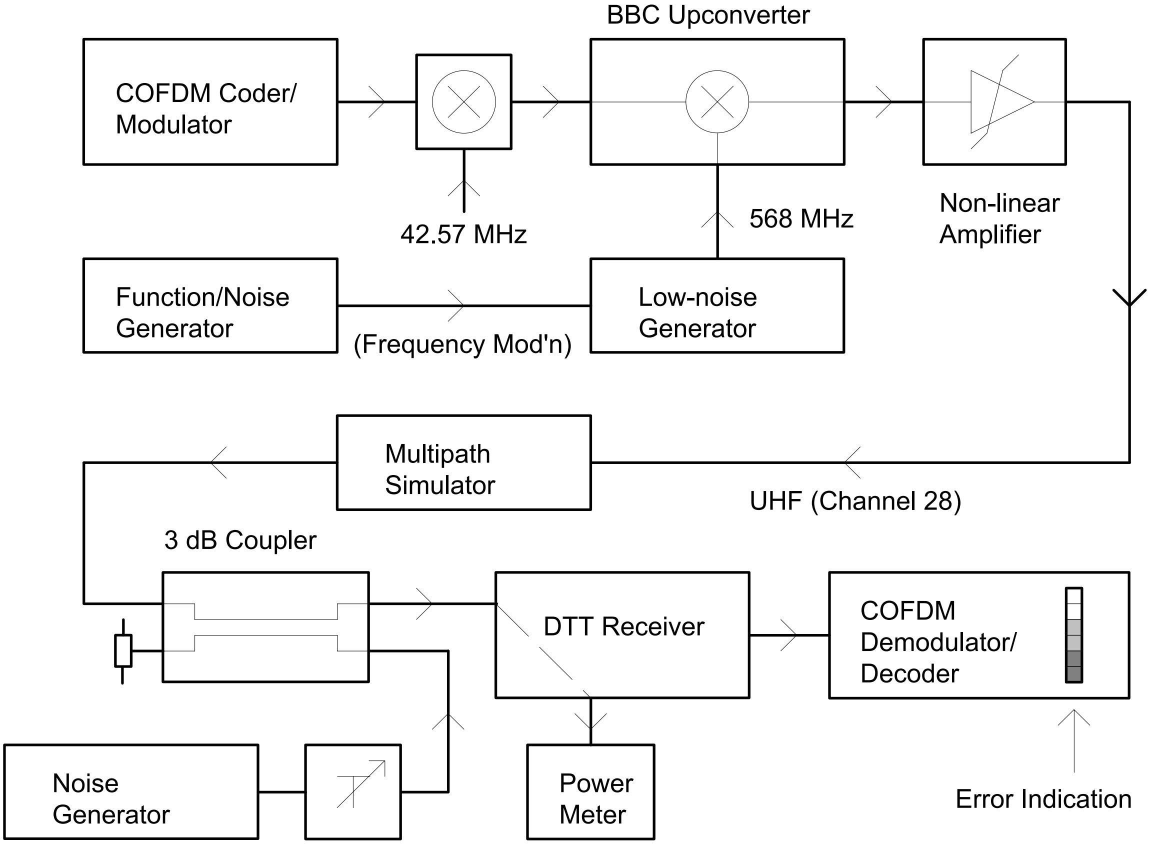

Figure 3: Experimental Arrangement for Checking END Theory

To make an END measurement, the noise source attenuator setting was first decreased in 0.1 dB steps until the first six LEDs of the error indication bargraph were lit.[5] The signal impairment was then introduced, and the additional attenuation required to achieve the same BER was noted. This corresponded to the END. In general, a particular impairment type was initially added at low level and then increased in steps, hence allowing END to be plotted versus impairment level.

[4] This figure is representative of what may be expected from a practical demodulator, assuming that it is set up for the DVB-T option of 64 QAM, rate 2/3, fractional guard interval 1/32. As stated at the end of Section 3, the measured value for the BBC demodulator, when set up in this way, was 19.5 dB. At the time of making the measurements — 18th April, 1997 — common phase-error correction was not being used.

[5] Corresponding to the reference BER of 2×10^{-4} following the Viterbi decoder.

The impairments were introduced as follows:

- ***Phase Noise.*** The (UHF) local oscillator of the COFDM upconverter was a high-quality signal generator which, in itself, introduced negligible phase noise. However, it possessed an FM input, and applying white noise here would result in a phase noise spectrum falling at 6 dB per octave — a reasonable approximation to the spectrum of a free-running noisy oscillator. It was also straightforward to introduce other modulating signals if required.
- ***Non-linearity.*** The output of the COFDM upconverter was passed through a broadband UHF amplifier. The signal level provided by the upconverter was sufficient to cause this amplifier to overload. By adjustment of variable attenuators at both the input and the output, the amount of non-linearity — and hence the level of intermodulation products (IPs) — could be varied over a wide range whilst maintaining the COFDM output power constant.
- ***Amplitude Response Ripple.*** The multipath simulator provided an amplitude response ripple by adding an 'echo' path of about 1 μs delay to the direct signal. The peak-to-peak ripple was set by adjustment of the echo path's power. Of course, the power of the echo path has an effect on the total signal power, and it is important to remember this when quoting the END.

When making END measurements, the power of the COFDM signal must be monitored. This is because varying the impairment is likely to change the power. As it was hoped to determine the END to an accuracy of 0.1 dB, there were practical difficulties, the most serious of which was the introduction of spurious signals by the multipath simulator.[6] Initially, therefore, power levels were measured after the receiver input channel filter, as shown in Figure 3. However, spurious signals were still troublesome, and it was found better to monitor the COFDM power at the *input* of the simulator. A calculated allowance was then made for the power of the echo channel.

The first stage was to determine the performance of the system in the absence of any signal impairments; that is, the C/N corresponding to BER_{ref} at the output of the demodulator. To do this, the signal applied to the demodulator input was examined with a spectrum analyser. The noise source attenuator was set so that the analyser display indicated the individual COFDM and noise signals to possess identical powers per unit bandwidth. This attenuator setting was noted. The attenuation was then increased until the BER_{ref} was achieved. The difference in attenuator settings represented the C/N required — 19.5 dB, in this case.

During the END measurements that followed, it was sufficient to ensure that the COFDM signal power did not change as a result of increasing the impairment level — or to know if a small change had occurred, so that an allowance could be made. There was no need to know the absolute C/N.

4. Experimental Results — Individual Impairments

The first step was to check the repeatability of the measurements. The noise level was increased slowly several times until the sixth LED of the error display flashed once every five seconds or so. In each case the same position of the 0.1 dB step attenuator was noted, which indicated that repeatability of each measurement should be within 0.05 dB. When small amounts of impairment were added, the repeatability remained as good, but this was not so where the END was large. Then the added noise was of low power relative to the impairment, and a larger fractional change was needed for a given change in the error display. In the plots that follow, error bars of ±0.1 dB are shown. Probably these are pessimistic for small ENDs and optimistic for large ones.

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[6] The spurious signals were mainly local oscillator and an image COFDM ensemble, both close in frequency to the wanted COFDM signal.

Phase Noise

As mentioned before, phase noise was introduced by applying white noise to the FM input of the upconverter local oscillator. This resulted in the phase noise spectral density falling off at 6 dB per octave. To calibrate the system, the generator was set to give an indicated 1 kHz FM deviation. The actual phase modulation was then measured with a modulation analyser, and found to be 0.07 radians mean or 0.24 radians quasi-peak.[7] Altering the amount of phase modulation was simply achieved by changing the generator deviation setting.

Figure 4, below, shows END plotted as a function of quasi-peak phase deviation. *Note that this plot applies only to this particular demodulator, for this particular modulation mode, and should* not *be taken as typical of demodulators in general.*

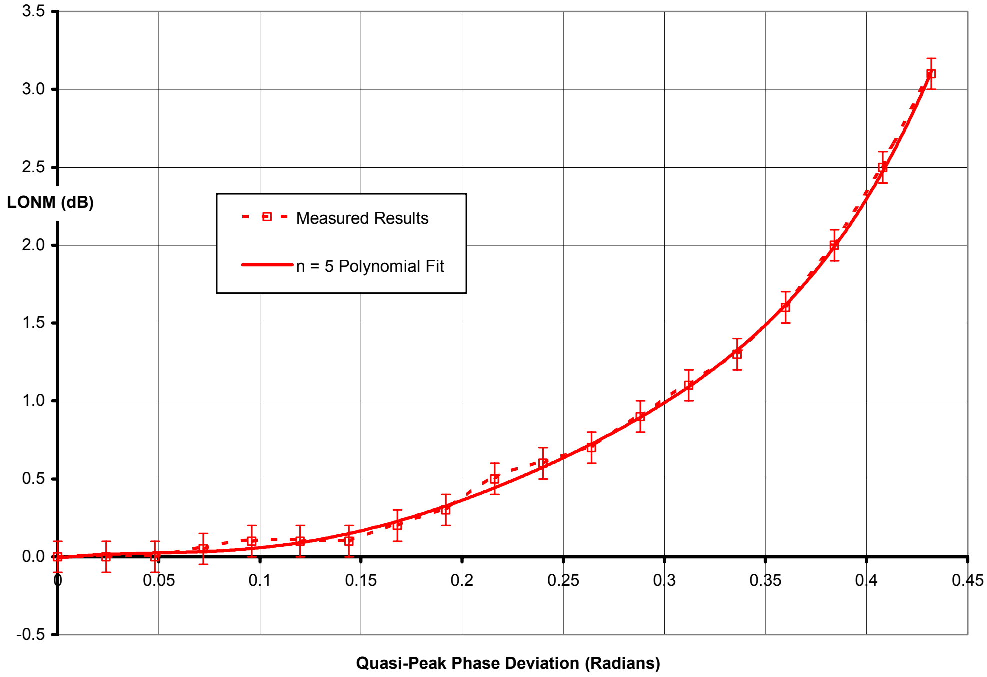

Figure 4: END (LONM) versus Local Oscillator Phase Noise Deviation

In addition to the experimental figures, a polynomial best fit is also shown. In effect, the best fit improves the accuracy of the figures by interpolating between the 0.1 dB step attenuator settings. This feature will become important when discussing the addition of small ENDs.

Non-linearity

Non-linearity was introduced by overdriving an amplifier at the output of the COFDM upconverter. The non-linearity was controlled by means of an attenuator at the amplifier input. An output attenuator then allowed the output power to be kept at its reference value. The non-linearity was quantified by measuring the level of intermodulation products (IPs), relative to the wanted signal, at 500 kHz beyond the edge of the COFDM ensemble.[8] These figures are the ones appearing in the following plot, but it should be remembered that the IPs appearing *within* the ensemble — not directly measurable — are the ones responsible for END. They are approximately 2 dB greater.

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[7] With a 50 Hz highpass filter selected. The analyser lowpass filtering had no detectable effect.

[8] There was some discussion about the spectrum analyser resolution bandwidth that should be used when making such measurements. The problem is that, although the IPs appear noise-like, their statistics are not Gaussian. In consequence, the apparent IP level relative to the wanted COFDM signal is affected by the analyser bandwidth. 100 kHz was used during the measurements.

Figure 5, below, gives the END plotted as a function of IP level. Again, a polynomial best fit is shown. Comparison with the chart in **Appendix 1** indicates that the results are much as would be expected, assuming the demodulator achieves BER_{ref} at 20 dB C/N.

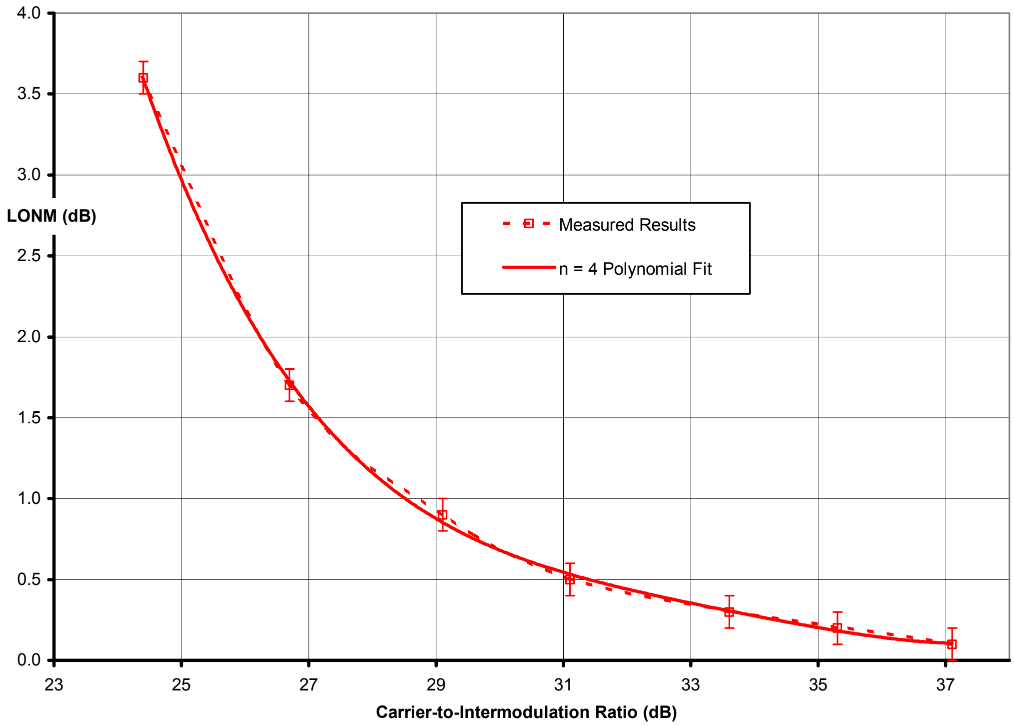

Figure 5: END (LONM) versus Carrier-to-Intermodulation Product Level

Amplitude Ripple

It may not be obvious why amplitude ripple can be considered a noise-like process, so contributing to the END of a system. Hence a few words of explanation are given here.

A convenient way of introducing amplitude ripple is to add a short duration echo to the wanted COFDM signal. As an example, suppose the relative power of the echo is –20 dB, and its delay is 0.5 µs. The relative echo amplitude is then 1/10, and the spectrum of the overall signal varies in amplitude between 0.9 and 1.1, a ripple of about ±1 dB. The period of the ripple is 1/(0.5 µs), or 2 MHz. When noise is added to the signal, the presence of the echo increases the signal-to-noise ratio during the peaks and decreases it during the troughs. There is a corresponding reduction in BER during the peaks, but this is more than balanced by the increase during the troughs.

A second factor is that the overall power of the signal is increased by the presence of the echo — in this case by 0.043 dB.

Figure 6 overleaf shows END plotted, in red, as a function of echo amplitude. An echo delay of 1.45 µs was used, this value giving 11 complete ripples within the 7.6 MHz bandwidth of the COFDM ensemble. There was no reason to suppose that the END would be greatly affected by the number of ripples, but a further set of measurements was made with a delay of 2.9 µs. The results are shown as green points. Although the number of ripples has doubled, the two sets of points are nearly coincident.

Table 1, underneath Figure 6, shows the relationship between echo amplitude and peak-to-peak ripple. Figure 6 and Table 1 demonstrate that quite large amplitude ripples are necessary to cause appreciable END.

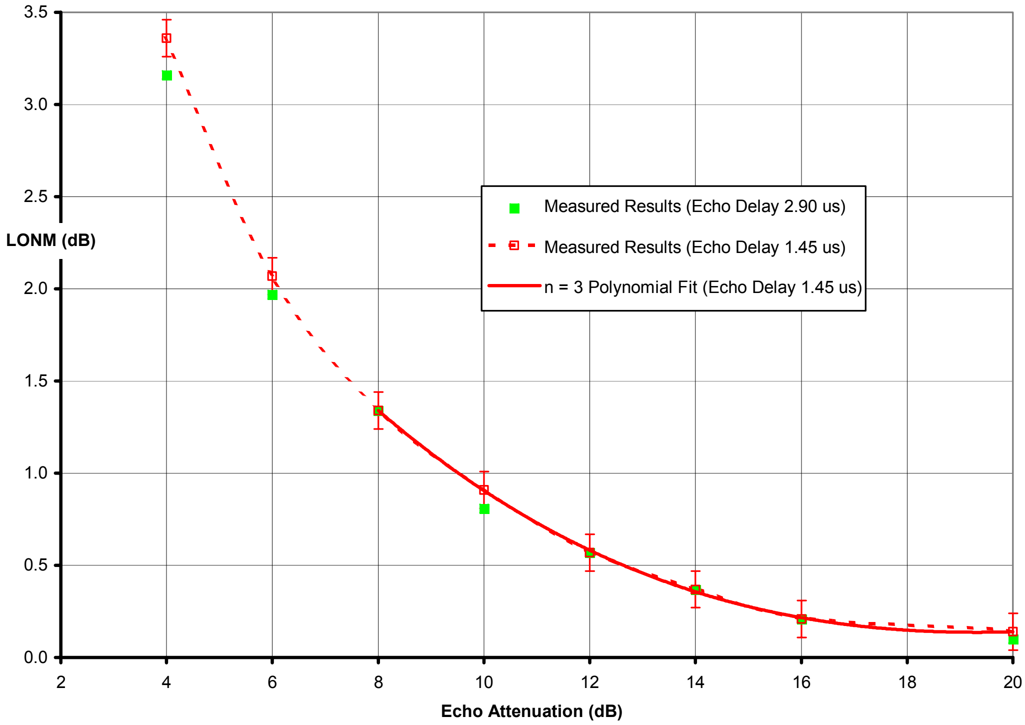

Figure 6: END (LONM) versus Echo Attenuation

Echo Attenuation (dB)	**Amplitude Ripple** (dB, peak-to-peak)
∞	0
20	1.743
16	2.777
14	3.513
12	4.459
10	5.688
8	7.320
6	9.570

Table 1: Relationship between Echo Attenuation and Amplitude Ripple

5. Experimental Results — Combinations of Pairs of Impairments

After the above results were obtained for the individual impairments, the impairments were grouped together in pairs and the END measurements repeated. The intention was to demonstrate that the sum of two individual ENDs equalled the overall END. For any given pair of impairments, there were many different combinations of ENDs that could have been selected. For example, 0.5 dB overall END could have been achieved by including 0.1 dB of one and 0.4 dB of the other; it could also have been achieved with 0.25 dB of each. It was decided to make the two ENDs as nearly equal as convenient.[9]

After selecting such a pair of ENDs, the overall END was measured in the same way as before. By repeating the measurements for different pairs of ENDs, a plot could be made of overall END versus the sum of the individual ENDs. It was possible to 'improve' the accuracy of the individual ENDs by taking them from Figures 4 to 6, as the polynomial fits helped remove some of the experimental error. The estimated error in the sum of the individual ENDs is 0.1 dB. **Figure 7** shows the results for a combination of amplitude ripple and non-linearity:

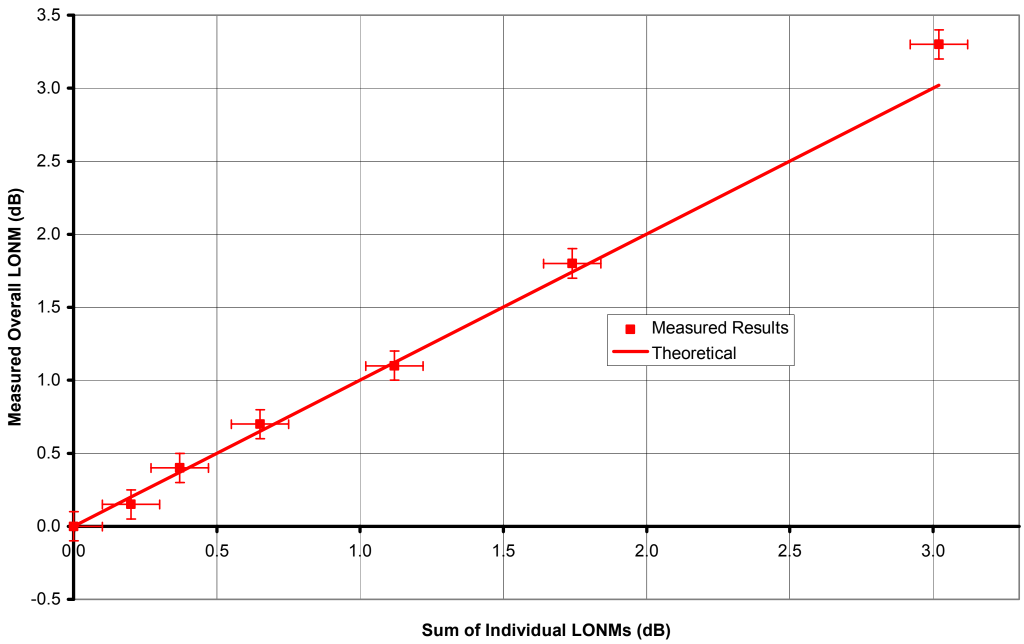

Figure 7: Overall END (LONM) *versus* Sum of Individual ENDs
(Amplitude Ripple and Non-linearity)

Of course, there is no need to carry out a best fit on the data, as the plot should be a straight line, y = x; the straight line is shown above as 'theoretical'.

Figures 8 and **9** overleaf are similar, but with the ENDs being contributed by non-linearity and phase noise, and amplitude ripple and phase noise, respectively. All three plots show good agreement with the theoretical straight line.

[9] Only a finite number of measurements were made, and so it was not always possible to select *exactly* equal values.

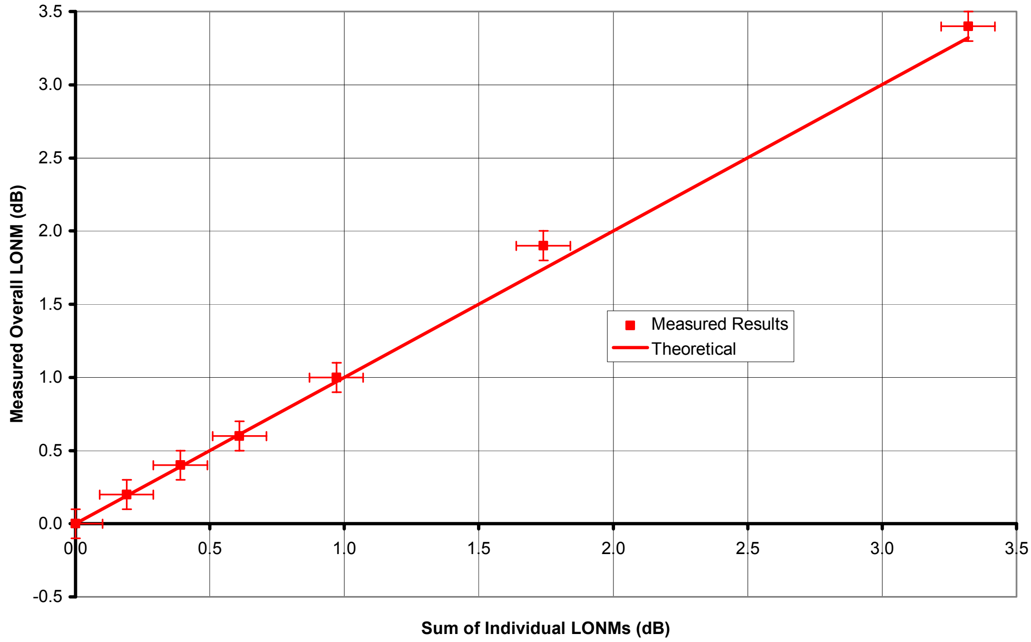

Figure 8: Overall END (LONM) *versus* Sum of Individual ENDs
(Non-linearity and Phase Noise)

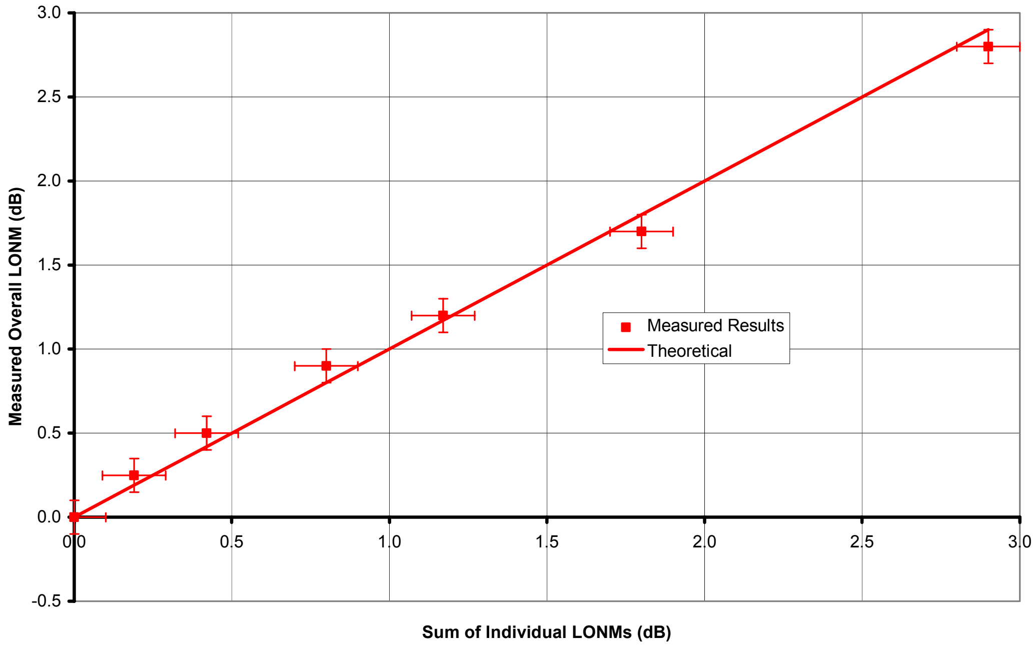

Figure 9: Overall END (LONM) *versus* Sum of Individual ENDs
(Amplitude Ripple and Phase Noise)

6. Experimental Results — Combination of All Three Impairments

Finally, all three impairments were introduced simultaneously in nearly equal quantities, resulting in **Figure 10** below. The error in the sum of the individual ENDs has been taken to be 0.15 dB. Again, the plot shows good agreement with the theoretical straight line.

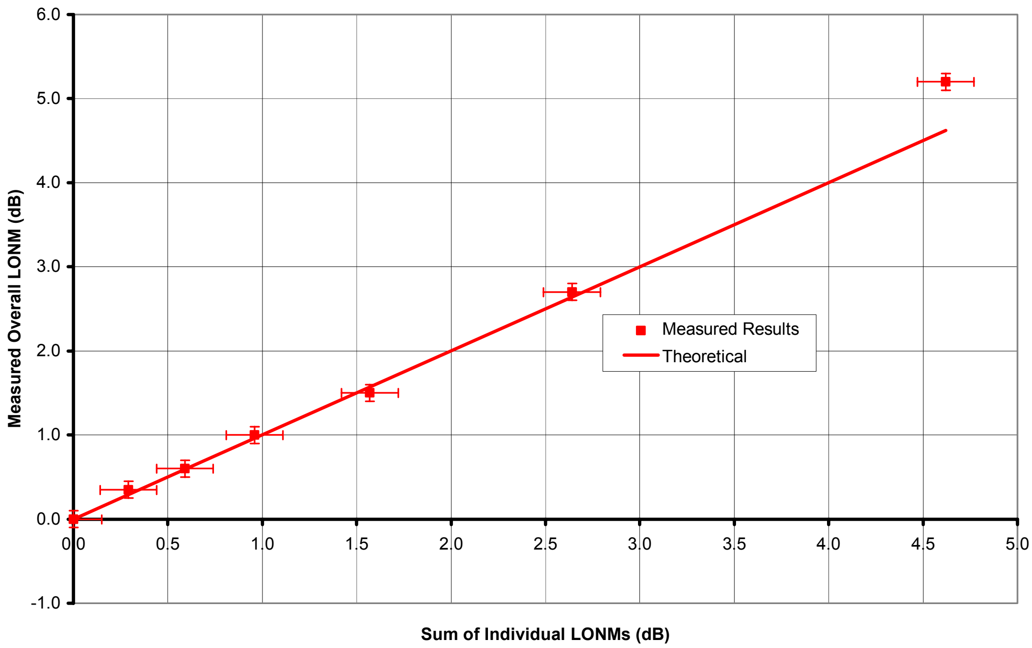

Figure 10: Overall END (LONM) *versus* Sum of Individual ENDs
(Amplitude Ripple, Non-linearity and Phase Noise)

7. Conclusion

The work described above has confirmed that, within experimental accuracy, the total equivalent noise degradation (END) in a COFDM system *does* equal the sum of the individual contributions. Hence the concept of END is appropriate for characterising the performance of COFDM transmission equipment. There are two conditions for the equality to be true:

- The overall END must not exceed 3 dB.
- The same demodulator must be used when measuring the overall END and the individual contributions. This is because the END associated with a particular impairment may depend on the design of the demodulator.

8. Reference

1. POOLE, R H M, 2003. 'Echoes, Doppler and DVB-T Receivers: Some Theory and Practice.' BBC R&D WHP 054.

Appendix 1: Relationship Between END and ENF

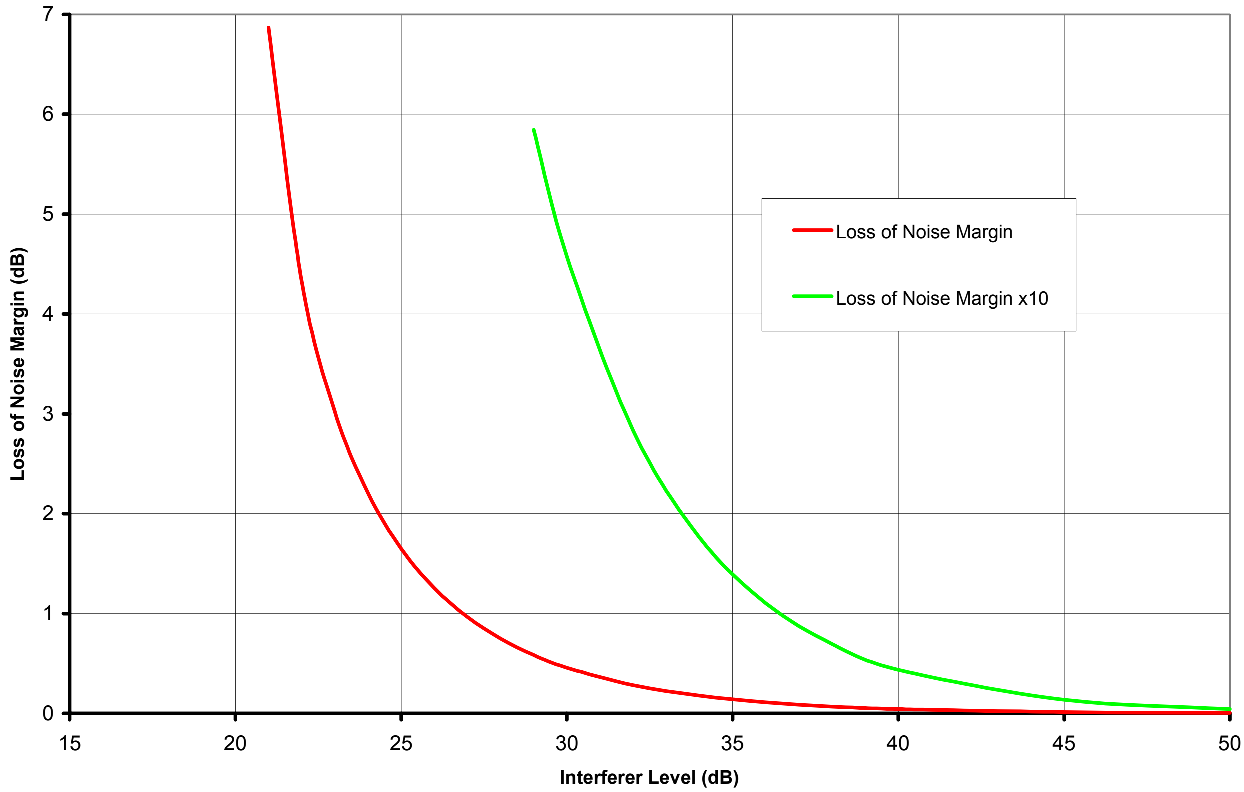

Chart 1: Loss of Noise Margin (END) versus Noise-like Interferer Level (ENF)
(Assuming BER_{ref} is achieved at a C/N of 20 dB)