The echo performance of DVB-T receivers

Ranulph Poole
BBC Research and Development

This article introduces a model to describe the way in which a single echo gives rise to an equivalent noise floor (ENF) in a DVB-T system. Once the ENF is known, it is possible to calculate the equivalent noise degradation (END) of the system. The article also shows that the model can readily be extended to include multiple echoes. Agreement between the predictions of the model and practical measurements is shown to be good.

Much effort has been expended over the past few years in quantifying the effects of signal impairments in DVB-T systems. Most transmitter distortions, at least, can be thought of as possessing equivalent amounts of Gaussian noise. This model is especially convenient because equivalent noise powers can be added together to give a total noise power. At the input to the receiver, the equivalent noise of the transmitter adds to the thermal noise introduced by the antenna and front-end circuitry. The effect is a slight reduction in the service area of the transmitter.

It would be helpful if the idea of equivalent noise power could be extended to propagation problems. A much-advertised advantage of the DVB-T system is its immunity to multipath, or echoes. Unfortunately, until now the only ways available of assessing the system performance have been by means of computer simulation and practical measurement. Neither of these offers a good understanding of the mechanism.

This article attempts to fill the gap by providing a simple model based on the concept of equivalent noise. It shows that the predictions of the "single echo" model agree well with experimental results. It then extends the model to cover multiple echoes.

For the sake of argument, the DVB-T "UK" modulation mode has been used throughout — that is, 64 QAM, code rate 2/3, guard interval 7 µs and 2K FFT. However, the model is easy to extend to the other modulation modes.

Theory of echo tolerance

The DVB-T system was specifically designed with echo tolerance in mind. In the UK, the DVB-T signal includes a 7 µs guard interval within the overall 231 µs symbol period. Any echo with a delay of less than 7 µs relative to the direct signal path cannot cause intersymbol interference. Most of the echo signal adds coherently to the direct signal, but a small amount of power is lost within the guard interval.

Although a short-delay echo apparently adds useful signal power [1], it also has the adverse effect of creating an uneven channel response. The signal is then more difficult to demodulate, and a greater signal-to-noise ratio is needed at the receiver input.

1. Note, however, that a *very* short delay can give rise to "flat fading".

A receiver can generally withstand a 0 dB echo within the guard interval, assuming that the transmission path is reasonable in other respects. If the echo delay exceeds the guard interval, a fraction of each delayed symbol adds incoherently to the direct signal. This noise-like intersymbol interference results in the tolerance of the receiver falling rapidly with increases in the delay.

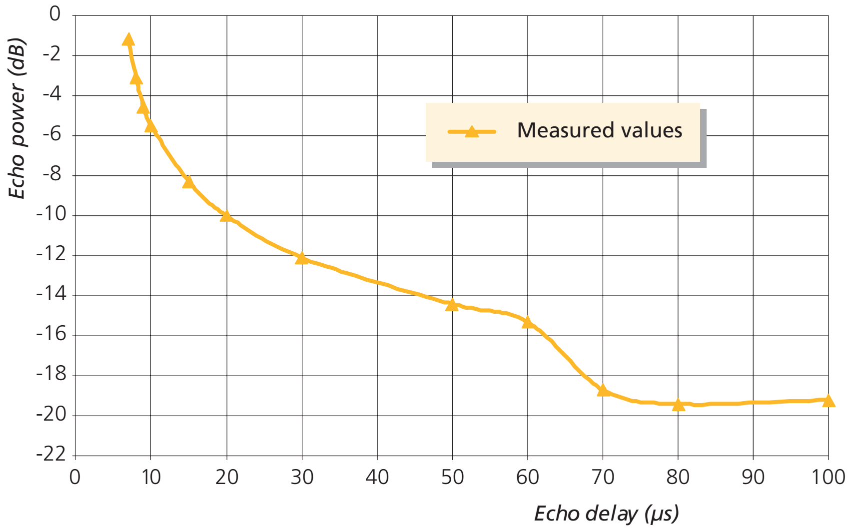

Figure 1
A typical echo tolerance characteristic.

Fig. 1 shows a typical characteristic, where the plot represents the maximum tolerable echo versus delay. The sharp fall beyond 60 µs is a function of the channel equalizer. Since only one COFDM carrier in three provides the equalizer with useful information, the maximum equalizable delay is a third of the active symbol period. If the signal cannot be equalized, the entire echo power appears as noise.

Both mechanisms — intersymbol interference and channel difficulty — add their own amounts of equivalent noise. The contributions are calculated as follows.

Intersymbol interference

Suppose the power of the direct signal is unity, and the echo has power P_{echo} and delay τ_d. The active symbol period is 224 µs, and the guard interval τ_g (7 µs). Because the echo adds coherently for $(224 + \tau_g - \tau_d)$ µs in each active symbol period, the power of the *coherent* echo component is given by:

$$P_{echo}\{(224 + \tau_g - \tau_d)/224\}^2 \qquad \text{for } \tau_d > 7\ \mu s,$$

and $$P_{echo} \qquad \text{for } \tau_d \leq 7\ \mu s.$$

The fraction $\{(224 + \tau_g - \tau_d)/224\}$ is squared because, where signals are coherent, their amplitudes must be added. The power of the *incoherent* echo component — the intersymbol interference — is the difference between the total echo power and the coherent echo component:

$$P_{echo} - P_{echo}\{(224 + \tau_g - \tau_d)/224\}^2 \qquad \text{for } \tau_d > 7\ \mu s,$$

and $$0 \qquad \text{for } \tau_d \leq 7\ \mu s.$$

Later in this article, the intersymbol interference is designated M. It amounts to approximately $0.009 \times P_{echo}$ per 1 µs beyond the guard interval. As will be seen, intersymbol interference is generally the more important of the two impairment mechanisms.

Channel difficulty

Quantifying the channel difficulty requires more thought. Errors in the channel response do not generate "real" noise; rather they increase the effect of noise already present at the receiver input. The additional noise is "virtual".

This virtual noise, R, can be calculated with the help of a computer simulation. Each COFDM carrier is ascribed a power in accordance with the channel response. Equal amounts of noise are added to the carriers, resulting in a carrier-to-noise (C/N) distribution function. The bit error ratio (BER) for each carrier is calculated from the standard formula for 64 QAM, hence giving a BER distribution function. Averaging this gives an overall BER.

The channel is first calibrated with a flat response. Noise is added until the BER reaches an appropriate reference value, BER_{REF}, and the overall value of C/N , C/N_{REF}, is noted [2]. Next, the carrier amplitudes are modulated by the appropriate channel response. Once again, noise is added until BER_{REF} is reached, and the new value of C/N noted. The ratio of the two values of C/N gives the equivalent noise degradation (END).

Finally, R, which equals the equivalent noise floor (ENF), is calculated from the following relationship:

$$ENF = (1 - 1/END) / (C/N_{REF})$$ (see *Footnote* 3)

Perhaps surprisingly, the equivalent noise turns out to be closely proportional to the power of the echo. If C/N_{REF} is taken to be 77.6 (18.9 dB), R is about $0.0093 \times P_{echo}$.

This value of R is approximate for several reasons. For instance, the effect of the Viterbi decoder has been ignored. In principle, by favouring the larger COFDM carriers, the decoder could improve the system performance as the echo power increases. Residual noise and the behaviour of the channel equalizer also influence R. These factors are difficult to determine, but experiments confirm the simple formula derived above.

Note that the intersymbol interference M always exceeds R, provided that the echo delay exceeds the guard interval by more than about 1 µs. This is a convenient fact, because it implies that R does not generally need to be known to great accuracy.

Noise buckets and echoes

A convenient concept for quantifying the effect of signal impairments is the “noise bucket”. In essence, the reasoning behind the noise bucket is as follows. A DVB-T demodulator can only provide a valid data-stream if the signal C/N exceeds a certain level, C/N_{REF}. Conventionally, C/N_{REF} corresponds to a post-Viterbi BER of 2×10^{-4}. This BER is designated BER_{REF}.

The quantity N_{REF}/C — the maximum allowable amount of noise relative to the signal power — can be thought of as defining the size of a bucket. In an otherwise ideal system, the bucket starts to fill with thermal noise as the signal level at the input to the receiver decreases. If the system is not ideal, various impairments contribute to the bucket, thus leaving less room for the thermal noise. The extra contributions create an equivalent noise floor (ENF), and a greater signal must be transmitted to overcome the noise. The fractional increase in transmitter power is the equivalent noise degradation (END). ENF is usually quantified in dBc, and END in dB.

The noise bucket concept is illustrated in *Fig. 2*, where an “ideal” system is shown on the left, and an impaired one on the right [4].

2. Because no account is taken of the Viterbi decoder, BER_{REF} is not the post-Viterbi value of 2×10^{-4} normally quoted, but the equivalent “raw” BER of 5×10^{-2}.
3. This value of C/N_{REF} must be the actual value for the receiver in question, not the theoretical value for 64 QAM. Typically, the actual figure is about twice the theoretical. The *implementation margin* of the receiver is said to be 3 dB.
4. Note that, even though the presence of an echo increases the “wanted” signal from D to D + E, the bucket size is taken to be constant. The usual convention is to relate the bucket to the total signal power, D + E. However, for the purposes of the present discussion, a constant bucket size is much more convenient. Either convention gives the correct results, provided that the various noise contributions are scaled appropriately.

The diagram gives a strong clue as to how an echo noise contribution can be measured. Firstly, the size of the bucket Q and the system noise S must be eliminated. Suppose that the amount of Gaussian noise needed to "top up" the bucket is:

A_0 when S is the only impairment present, and

A_1 when both S and the echo contributions M + R are present.

Then

$S + A_0 = Q,$

and

$S + A_1 + M + R = Q.$

Eliminating Q and S gives:

$R + M = A_0 - A_1.$

Hence the total of the echo contributions is simply the difference between two noise levels.

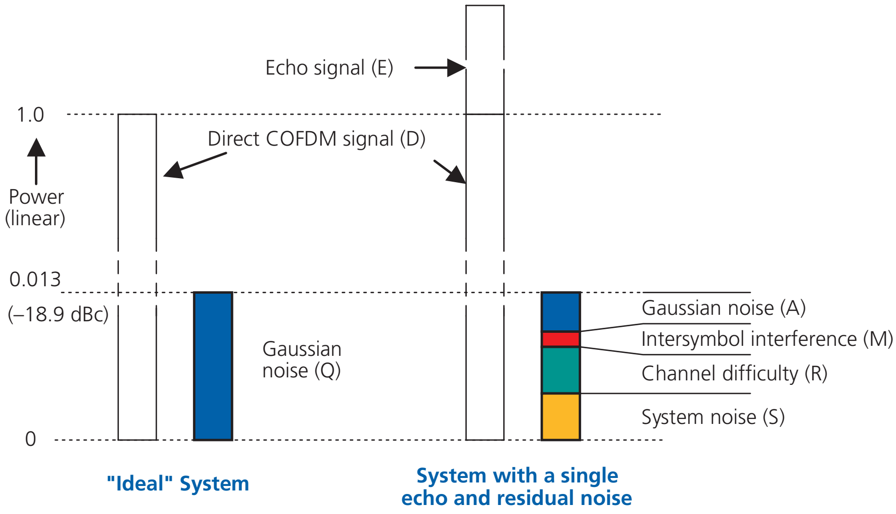

Figure 2
Illustration of the noise bucket concept.

Secondly, contributions R and M must be separated. The trick here is to note that echoes within the guard interval only introduce R, whereas long-duration echoes predominantly introduce M. Thus, for a short-duration echo,

$R = A_0 - A_1 .$

This value of R can be substituted into $R + M = A_0 - A_1$, when making measurements on longer duration echoes, so giving a value for M.

Because M is generally by far the greater contribution, for echoes outside the guard interval, a small error in R makes little difference.

These ideas are easy to extend to situations where two (or more) echo signals are present. In the comparison between theoretical and practical results that follows, the procedure will be to calculate the ENFs resulting from single echoes and combinations of echoes. The experimental work naturally yields ENDs, and so these must be converted into ENFs by using the formula quoted earlier.

Once the practical values of R and M have been obtained, as above, they may be compared with the calculated values.

Experimental arrangements

The experimental arrangements for measuring R and M are straightforward, and the essential elements are shown in *Fig. 3*.

The DVB-T signal is generated by a broadcast-quality modulator, then upconverted to UHF. It passes through an echo simulator, which allows up to five echo paths to be added. A coupler then combines the DVB-T signal with the output of a noise source. An adjustable attenuator provides adjustment of the noise level. The combined signal passes to a high-quality monitoring receiver, which provides a direct read-out of BER.

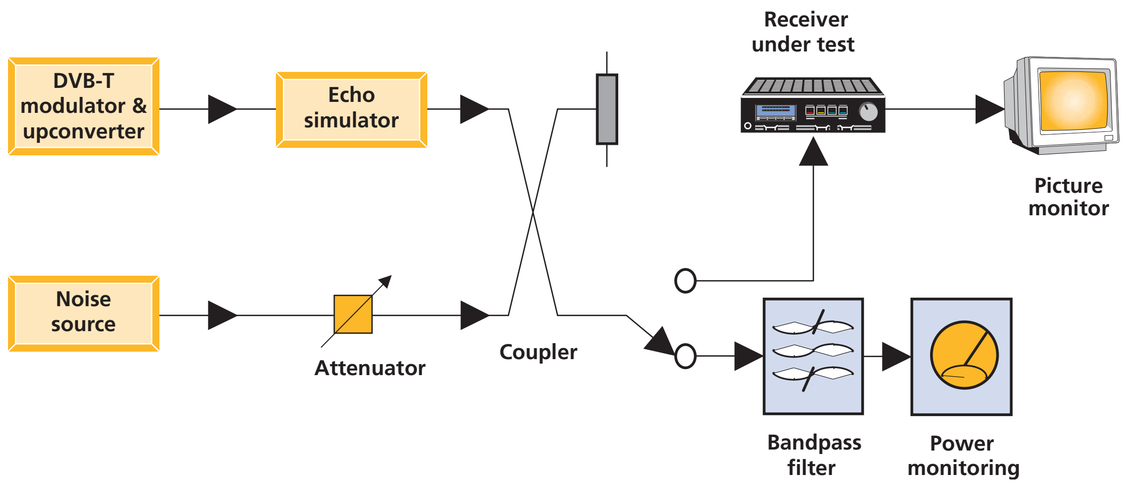

Figure 3
Experimental arrangement for measuring END.

Most of the measurements involve the difference between two noise attenuator settings. Firstly, the noise attenuator is set for BER_{REF} in the absence of any echo. The echo or echoes are then introduced, and the attenuator setting increased until once again BER_{REF} is achieved. The difference corresponds to the END (in dB). Finally, the formula

$$ENF = (1 - 1/END)/(C/N_{REF})$$

is used to convert END into ENF.

C/N_{REF} is found by using the bandpass filter and power meter shown in *Fig. 3*. The filter has a passband of about 4 MHz at the centre of the channel, hence allowing through equal portions of the noise and DVB-T signals to be compared.

Five different echoes were defined for practical tests, as detailed in *Table 1*.[5] The plan was to measure the noise contributed by each echo, and then to combine pairs of echoes and then measure the total noise. The expectation was that the total noise would equal the sum of the contributions.

Not all the experimental results are presented here; the article would be excessively unwieldy if they were. However, members of the UK Digital Television Group may gain access to the full details of the tests through their website [1][2].

Table 1
The echo tests performed.

Echo details	
Echo 1	0.53 µs
Echo 2	0.92 µs
Echo 3	9.87 µs
Echo 4	13.03 µs
Echo 5	50.01 µs

Experimental results

Short-duration echoes

Firstly, the relationship between echo power and echo noise was explored for echoes falling within the guard interval. With the echo disabled, the noise attenuator was set so that the noise corresponded to BER_{REF}. The attenuation was then increased in steps of 0.1 dB and, for each step, a note was made of the echo level corresponding to

5. The delay values were chosen so that the corresponding channel response exhibited an integral number of ripples over the width of the COFDM ensemble. Doing this ensured that the total signal power equalled the direct signal plus echo signal powers.

BER_{REF}. The equivalent "virtual" noise of the echo was calculated as already described. *Fig. 5* shows the results for the 0.5 µs echo.

The plot shows that the equivalent noise power R is indeed closely proportional to echo power. Also, the results agree with the earlier prediction that R amounts to 0.0093 of the echo power. At high echo levels, the equivalent noise is slightly less than predicted, possibly thanks to the power of the Viterbi decoder.

The results for the second short-duration echo are not shown, as they were almost identical.

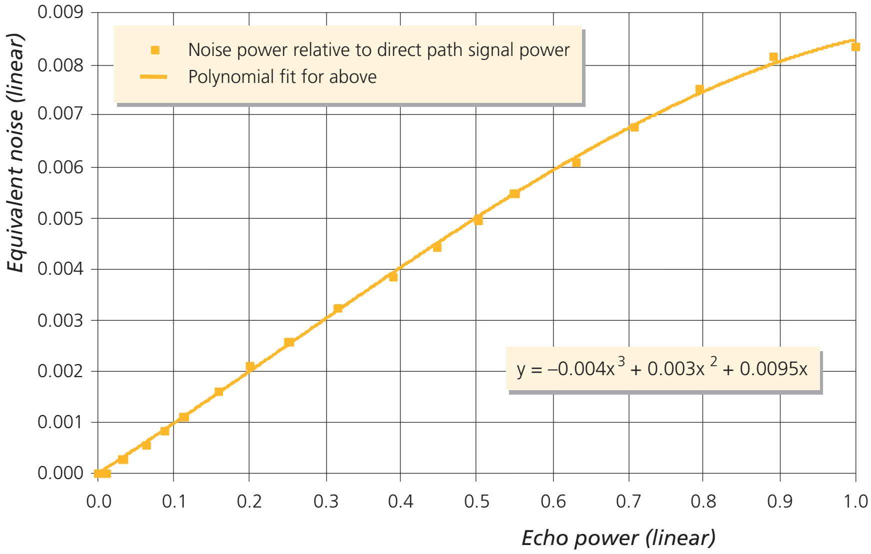

Figure 5
Equivalent noise introduced by the 0.5 µs echo.

There are many ways in which measurements involving both echoes could be performed. The method adopted was to adjust the noise attenuator setting for BER_{REF} in the absence of echoes. The noise attenuation was then backed off by a fixed amount — say 1 dB — and the echo levels adjusted so as to achieve BER_{REF} once again. A measurement run would involve Echo 2 being increased from zero in convenient steps. At each step, Echo 1 would be adjusted for BER_{REF} and its value noted. The run would continue until Echo 1 reached zero. *Fig. 6* shows the results for 1 dB noise back-off.

The magenta-coloured line (right-hand y-axis) shows the equivalent noise of the two echoes together. Of course, the value remains constant since the test is defined by the fixed 1 dB END. The blue points (left-hand y-axis) show the combinations of echo powers corresponding to BER_{REF}. Because the two noise contributions behave as if they were generated independently, it is possible to draw a good straight line through the points. The implication is that the total echo power corresponding to 1 dB END remains constant at about 0.26.

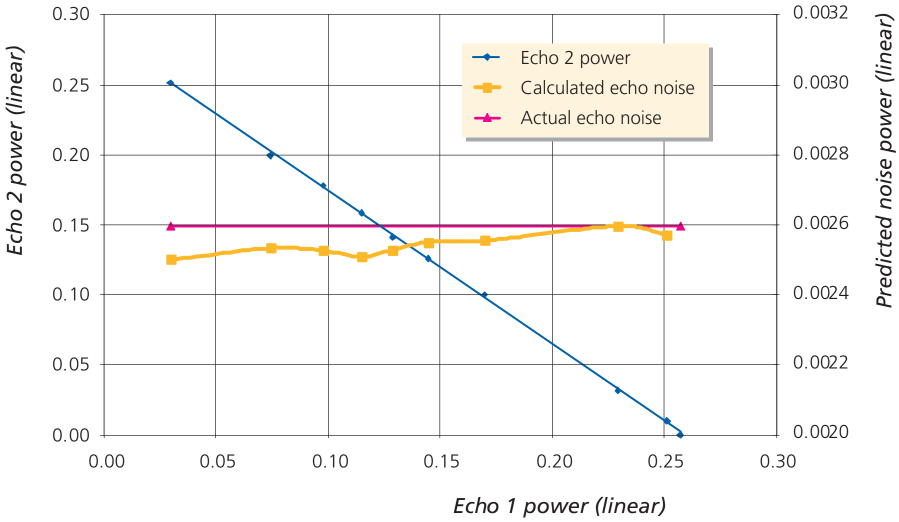

Figure 6
Short-duration echo powers corresponding to 1 dB END.

If the total echo noise is now calculated by using the formula derived for R, the result is the yellow line (right-hand y-axis). This corresponds closely to the magenta line.

When the above exercise is repeated for increasing ENDs, the linearity of the noise-generation mechanism remains good until the point where the peak echo power exceeds the direct signal power. Nulls then appear in the channel response, and the effect of the Viterbi metrics becomes marked. Generally, the receiver is more tolerant under these conditions than was predicted by the simple model.

Longer-duration echoes

Secondly, the relationship between echo power and equivalent noise was determined for echoes falling outside the guard interval. The practical measurements were made in just the same way as before, whilst the calculated noise was taken as the sum of M and R; that is,

$$P_{echo}\{(224 + \tau_g - \tau_d)/224\}^2 + 0.0093.P_{echo} .$$

Fig. 7 shows the results [6]. The data points represent the measured results whilst the straight lines show the calculated noise. In general, there is good agreement between practice and theory. Agreement improves as the echo duration increases, since the proportion of virtual noise — which is not known so accurately — decreases. The relative importance of the longer duration echoes is evident.

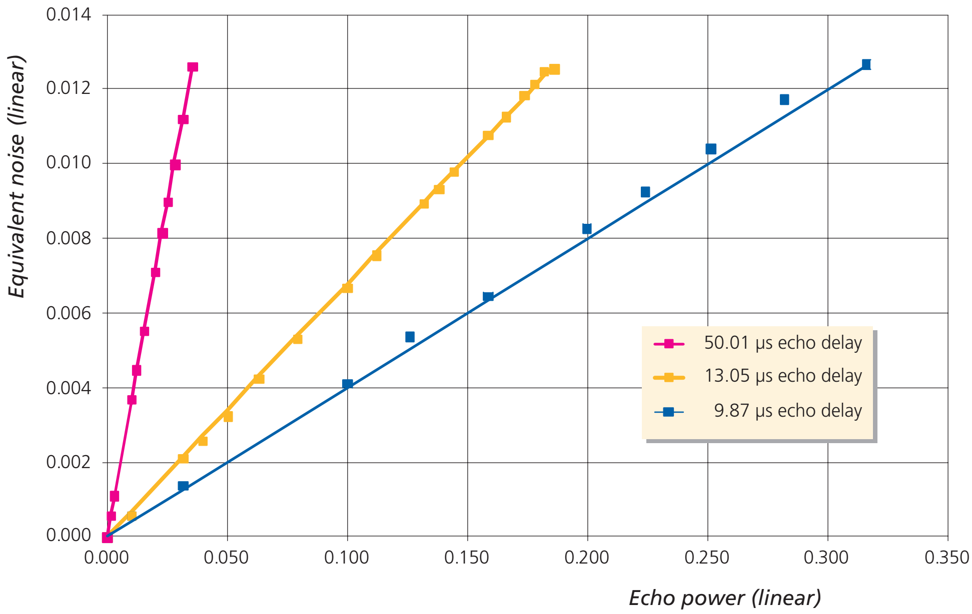

Figure 7
Equivalent noise introduced by longer-duration echos.

It remains to check that the contributions from pairs of echoes add linearly. *Fig. 8* was derived in the same way as *Fig. 6*, except that the two echoes selected were those of 9.87 µs and 13.03 µs duration. Once again, the experimental procedure was to vary the relative echo powers in such a way as to maintain a constant total noise power — in this case corresponding to 3 dB END.

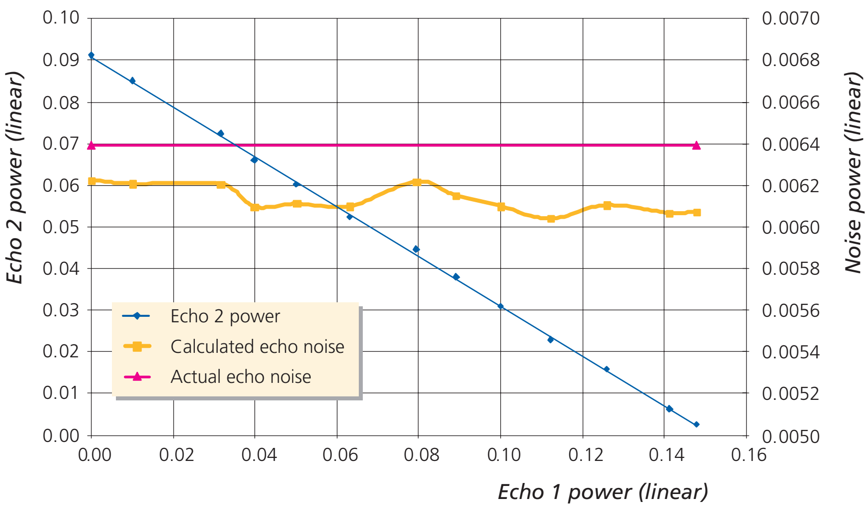

Figure 8
Medium-duration echos corresponding to 3 dB END.

Despite the large amount of noise being introduced by the echoes, the system remains closely linear: the sum of the theoretical noise contributions agrees well with the actual total. Agreement between the theory and measurements remains good when other echo pairs are selected [1].

6. The guard interval was taken as 6.5 µs, to allow for a slight synchronization offset in the demodulator.

Multiple-echo tests

The model can now be put to use to predict the END that results from a “real” multiple echo signal. A good example is a test currently proposed by the DTG [3]. Details of the five echoes are given in *Table 2*, together with their expected noise contributions.

The total ENF corresponds to a true END of 2.72 dB, assuming that C/N_{REF} equals 19 dB. (“True” means that the END is related to the *total* signal power.) Measurements made on two actual receivers gave ENDs of 2.97 dB and 2.77 dB. The agreement is good, and is better still if other sources of system noise are taken into account.

Table 2
Multiple-echo test signal.

μs	dB	M	R
5	9	0	0.001171
14	22	0.000398	0.000059
35	25	0.000797	0.000029
54	27	0.000844	0.000019
75	28	0.001585	0
	Totals:	0.003624	0.001278

Summary

This article has introduced a model to describe the way in which a single echo gives rise to an equivalent noise floor (ENF) in a DVB-T system. Once the ENF is known, it is possible to calculate the equivalent noise degradation (END) of the system. The article has also shown that the model can readily be extended to include multiple echoes. Agreement between the predictions of the model and practical measurements is good.

According to the model, the noise associated with a single echo may be calculated as follows:

- The noise equivalent of intersymbol interference is about 0.009 times the echo power for every microsecond that the echo delay exceeds the guard interval. Within the guard interval, there is no noise contribution.
- The noise equivalent contributed by channel difficulty is about 0.0093 times the echo power, irrespective of the echo delay.
- Long delay echoes — those beyond the limit of the channel equalizer’s capability — contribute their full power as noise.

__Ranulph Poole__ received a degree in physics from Oxford University in 1974. In that year he joined BBC Transmitter Operations, where he was involved with the maintenance of a wide range of broadcast equipment. He moved to BBC Design and Equipment Department in 1989, to assist with the development of PAL television test equipment and the introduction of Nicam sound.

Since 1994, Mr Poole has been working in BBC Research and Development on the performance requirements for DVB-T transmission equipment. He has been an active member of the UK Digital Television Group and the ACTS VALIDATE project.

Provided that the echo is more than about 5 μs outside the guard interval, the channel difficulty component is negligible. Within the guard interval, however, the channel response is the only significant factor.

Whatever the mechanism, the noise contributions are closely proportional to the echo power. The linear relationship implies that the noise associated with a multiple echo should equal the sum of the noise components of the individual echoes. Experiment supports this idea, provided that the peak echo power does not exceed the direct signal power.

The article finishes by showing how to calculate the performance of an “ideal” receiver, when presented with a multiple-echo test signal.

System noise has not been considered. Where this is appreciable, the effect of the echo contributions is greater than that predicted by the simple model; that is, the measured END is greater. Since this article was written, the model has been refined to include such noise [2]. Good predictions are now possible for typical domestic equipment.

Table 3
Glossary of abbreviations.

Abbreviation and Term		Notes
BER	Bit error ratio	BER_{REF} is 2×10^{-4} post Viterbi; approximately equivalent to 5×10^{-2} "raw" or pre-Viterbi.
C/N	Ratio of total carrier power to total noise power in bandwidth of COFDM ensemble	C/N_{REF} corresponds to BER_{REF}
COFDM	Coded Orthogonal Frequency Division Multiplex	The modulation scheme used for DVB-T
dB	Decibel	A measure of relative power level
dBc	Power in dB relative to carrier power	
DVB-T	Digital Video Broadcasting — Terrestrial	The European digital television system
END	Equivalent noise degradation	The increase in transmitter power needed as a result of an impairment. Generally expressed in dB.
ENF	Equivalent noise floor	The amount of noise, "virtual" or "real", introduced by an impairment. Generally expressed in dBc.
FFT	Fast Fourier transform	Signal processing for moving from representation in time to representation in frequency domain
M	"Real" echo noise	Intersymbol interference
P_{echo}	Echo power	Relative to the direct signal power
QAM	Quadrature amplitude modulation	
R	"Virtual" echo noise	Channel difficulty
µs	Microsecond	
τ_g	Guard interval	Expressed in µs
τ_d	Echo delay	Expressed in µs

Acknowledgement

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The above references are available to all members of the UK Digital Television Group.