DTT comparison of 64-QAM with 16-QAM

— co-channel interference from PAL, echoes and impulsive interference

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This article collates the results of comparing the performance of the two DVB-T modes currently in use in the UK – namely, 64-QAM rate 2/3 and 16-QAM rate 3/4, both using 2K carriers with a 7μs guard interval. Three different sources of impairment were measured: (i) co-channel interference from an analogue PAL signal, (ii) multipath propagation resulting in one echo inside or outside the guard interval and (iii) impulsive interference.

The results are presented in a novel manner as "noise bucket" plots. These plots are used to quantify the improvement in performance that can be achieved with 16-QAM rate 3/4 over 64-QAM rate 2/3.

In June 2002, a series of field trials were carried out from the Crystal Palace transmitter in London to evaluate the relative merits of the different DVB-T modes being considered for the re-launch of DTT in the UK. Two modes of particular interest were (i) the mode used since the start of service in November 1998, 64-QAM, rate 2/3, and (ii) 16-QAM rate 3/4, which had been used for engineering trials in 1997 [1]. Both are 2K modes with a guard interval duration of 7μs, which corresponds to $^1/_{32}$ of the OFDM symbol duration. The Independent Television Commission (ITC) has now mandated these two DVB-T modes for use in the UK. In the following, and for brevity, these modes will be referred to as 64Q and 16Q, respectively.

This article presents a performance comparison between these two modes in the presence of three different types of impairment:

- co-channel interference (CCI) coming from an analogue PAL transmitter;
- multipath propagation resulting in one echo located inside or outside the guard interval (echoes delayed by 3.5μs and 14μs respectively);
- impulsive interference (II).

A number of DVB-T receivers were used for the CCI and multipath tests, whereas just one DVB-T receiver – exhibiting a typical performance – was used for the II tests. The results collected here quantify the improvement in performance that is achieved with the 16Q mode compared with the 64Q mode.

The final report issued by the Digital Television Group (DTG) [2], documenting the mode trials of June 2002, included several II performance comparisons between 64Q and 16Q as submitted by the different partners collaborating in those tests. In some instances however, the results of the II tests were difficult to compare and even to analyse. Besides, although an improvement in II performance was noticed when switching from 64Q to 16Q in both the subjective and objective in-home measurements carried out by the BBC, this was not so clear-cut in the results reported by other partners.

Two different types of impulsive noise scenarios are analysed in this article. First, some field measurements of real-traffic II are presented. These measurements did not make it to the final report in [2] for lack of time to process them. Second, a compilation of different laboratory measurements is presented using both real captured II and some preliminary test waveforms which were considered within the DTG as a test suite for II [1].

1. Measurement methodology

1.1. Co-channel PAL and multipath

Measurements were made on ten different DVB-T receivers, according to DTG measurement guidelines. When making measurements, the now favoured approach within the DTG is to measure the point of failure [2] rather than the reference BER [3] condition. This is the case for all the measurements presented here. For an Additive White Gaussian Noise (AWGN) channel, the difference between the degradation criterion for reference BER and failure is typically 1.3 dB. For CCI coming from a PAL transmission, the best estimate for this difference between criteria is 2 dB.

By making several Equivalent Noise Degradation (END) measurements, it has been possible to present the results in a novel manner as "noise bucket" plots. For the case of CCI arising from PAL, this is a plot of C/N versus C/I. For multipath channels with one echo, C/I is replaced by the echo attenuation relative to the main signal path. The asymptotic values of such a plot are the familiar AWGN C/N performance (no added interference) and the infinite END protection ratio performance (no added noise). It should be noted that the values of C/N used here refer to carrier power C and AWGN N at the receiver input.

It is worth mentioning that the convention followed here to obtain the carrier power C, when an echo is present, is to include the echo power. This can be done by actually measuring the total channel power with a modern spectrum analyser. Alternatively, if the system is calibrated with no echoes (main path only), then the total channel power can be calculated by performing a vector sum.[4]

1.2. Impulsive interference

For the field measurements, a BBC survey vehicle, equipped with a mast fitted with a log-periodic antenna, was used in areas where traffic interference was abundant. For each location, one or more antenna orientations were used to try and vary the amount of traffic interference getting into the receiver. The number of UnCorrectable Errors (UCEs) on the MPEG-2 transport stream and the number of times the receiver's Forward Error Correction (FEC) decoder lost sync were averaged over a one minute period.

An objective ranking system, reminiscent of the subjective one used in [2], was established to quantify the results. Namely, for each receiving set-up, the two modes 64Q and 16Q were ranked according to *Table 1*.

Table 1
Ranking system used to evaluate traffic II performance

	Ranking
Less than 1 UCE/min	1
Between 1 and 100 UCE/min	2
Sync errors and between 0 and 30 UCE/min	3
Sync errors and more than 30 UCE/min	4

Two types of laboratory measurements were done. For the first one, we used real II waveforms captured at baseband (centred around 4.57 MHz and with a 7.61 MHz bandwidth) as part of a rather large II measurement campaign. For the second one, we employed a preliminary II test suite proposed within the DTG. Two different ways of presenting the results are used. In both, the wanted signal level C remains fixed. When using captured II

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1. It is important to stress that a standard DVB-T receiver was used throughout all the tests with no countermeasures available to mitigate impulsive interference.
2. "Failure" criterion, as used from here onwards, means the onset of uncorrectable errors within the transport stream resulting in picture artefacts.
3. The reference BER (BERref) adopted for DVB-T is 2×10^{-4} after the inner (Viterbi) decoding, which corresponds to Quasi-Error-Free (QEF) operation after the outer Reed-Solomon decoding. QEF is defined as a transport stream BER of less than 10^{-11} – equivalent to about one error per hour.
4. A useful trick here for a single echo is to set the centre carrier relative phase to 90°. This avoids "flat" fade or variation due to a non-integer number of cycles in the channel frequency response. Thus a 0 dB echo will always increase the carrier power by 3 dB regardless of the delay.

data, a plot of C/N versus C/I, corresponding to the visual onset of UCE, is used. Thus for each level of II, there is a certain amount of Gaussian noise N that we have to add in order to bring the DVB-T receiver close to its failure point. Note that when no II interference is added, we are effectively measuring the AWGN C/N performance of the receiver.

The methodology followed with the preliminary DTG II test suite was different. No additional Gaussian noise was added and the C/I corresponding to 1 UCE per minute was recorded. The test suite comprised a set of seven trains of pulses, which differed in the number of pulses and the statistical distribution of the spacing between pulses. All pulses had the same amplitude and duration (250ns).

These waveforms were used to gate a source of wideband white Gaussian noise and the resulting signal was combined with the wanted signal. Regarding the computation of the interfering power, first the average power of the ungated noise source, measured over the DVB-T bandwidth of 7.61 MHz, were noted. This value was then divided by $224/\tau$ to obtain the gated noise power I, with $224\mu s$ being the useful OFDM symbol period and τ the "effective" burst duration given by the number of pulses multiplied by the pulse duration. More details can be found in *Section 2.3.3.*

2. Results

2.1. CCI from PAL

Fig. 1 shows C/N versus C/I plots for a PAL co-channel interferer for the two modes under consideration. A comparison of the average curves can be seen in *Fig. 2*.

With very low levels of interference, the performance is asymptotic to that of an AWGN channel. Here the C/N values are about 18 and 13.5 dB for 64Q and 16Q, respectively. The difference ΔC/N at the limit is 4.5 dB. For extreme levels of interference, 16Q shows about a 1.5 dB improvement over 64Q at the limit. However, it is far more informative to see how ΔC/N varies as a function of impairment level. In *Fig. 2*, ΔC/N is marked for a C/I value of 1 dB. Here, ΔC/N is about 7 dB – considerably more than the AWGN channel value of 4.5 dB. The variation of ΔC/N as a function of impairment level is shown in *Fig. 3*.

By presenting the results as shown in *Fig. 3,* it can be seen that, for severe to moderate PAL CCI (2 to 7 dB C/I say), 64Q requires 7 to 5.5 dB greater C/N than 16Q.

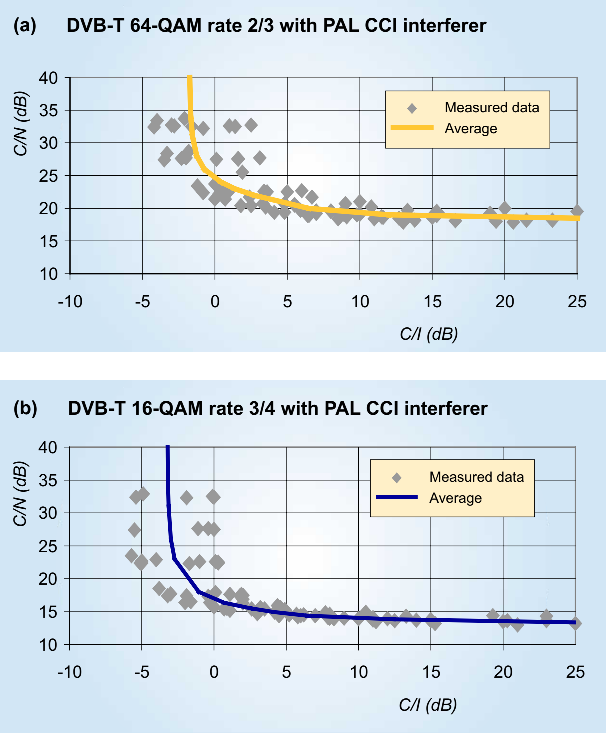


Figure 1
All measured PAL CCI data for modes (a) 64Q and (b) 16Q

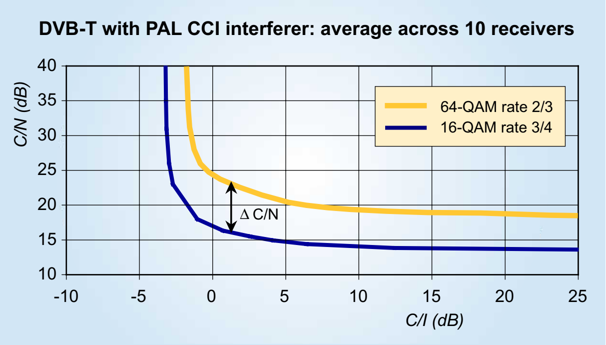


Figure 2
Average PAL CCI results for modes 16Q and 64Q

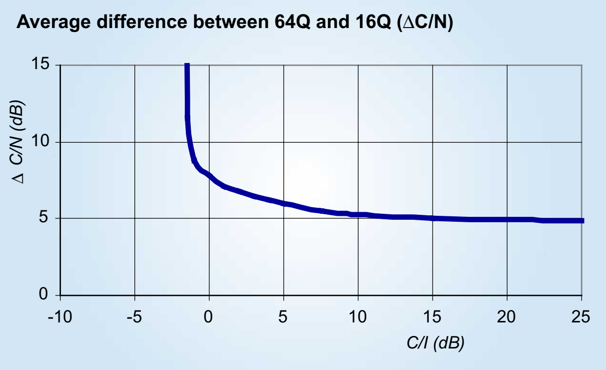


Figure 3
Additional C/N required for 64Q compared with 16Q

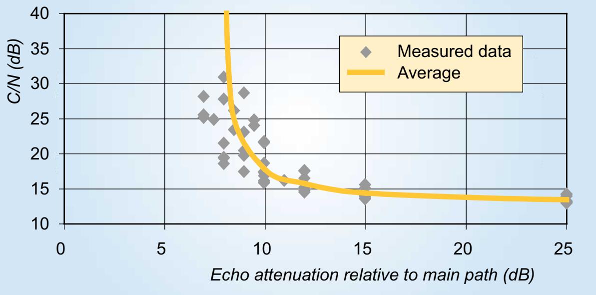
2.2. *Multipath channels with just one echo*

Plots of C/N versus relative attenuation of a 3.5*µ*s echo within the guard interval for modes 64Q and 16Q are shown in *Figs 4a* and *4b* respectively. *Fig. 4c* shows a comparison of the averaged results. Analogous plots for a 14*µ*s echo outside the guard interval are shown in *Fig. 5*.

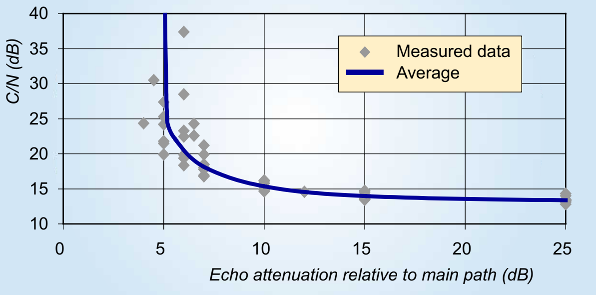
For very low echo levels, the performance of the DVB-T system is asymptotic to that of an AWGN channel. C/N values in this region are about 18 dB for 64Q and 13.5 dB for 16Q.

For extreme 3.5*µ*s echo levels (5 to 0 dB relative attenuation – see *Figs 4a* and *4b*), 16Q degrades at a slightly greater rate than 64Q because of the weaker code rate, although at the 0 dB limit, 64Q still requires 3 dB greater C/N than 16Q. For the 14*µ*s echo, the maximum relative attenuation is less than 0 dB because this is outside the guard interval. At the limit, 16Q shows about 3 dB improvement over 64Q.

(a) DVB-T 64-QAM rate 2/3 with 14µs echo



(b) DVB-T 16-QAM rate 3/4 with 14µs echo



(c) DVB-T with 14µs echo: average across 10 receivers

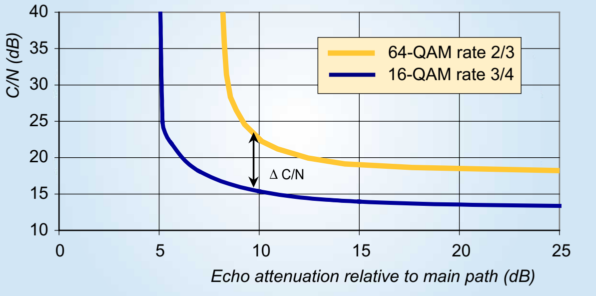
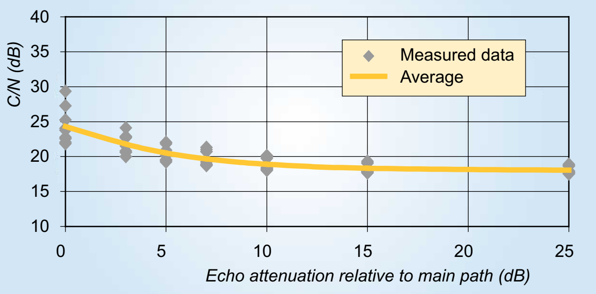
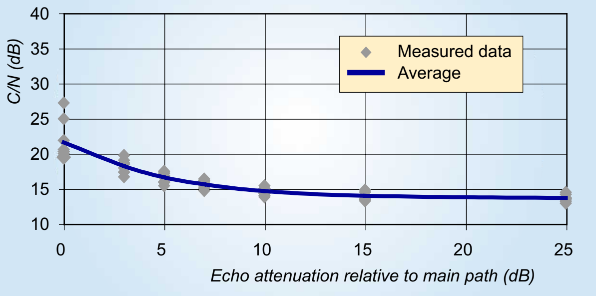


Figure 5
All measured data for a 14µs echo for modes (a) 64Q and (b) 16Q. A comparison of average results is shown in (c).

(a) DVB-T 64-QAM rate 2/3 with 3.5µs echo



(b) DVB-T 16-QAM rate 3/4 with 3.5µs echo



(c) DVB-T with 3.5µs echo: average across 10 receivers

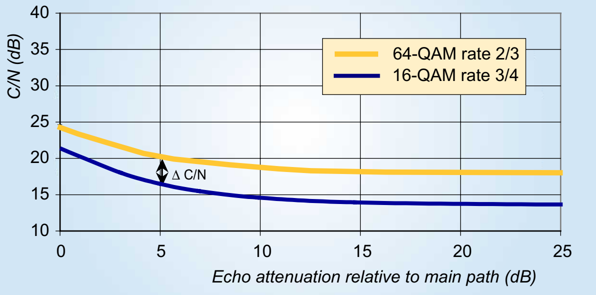


Figure 4
All measured data for a 3.5µs echo for modes (a) 64Q and (b) 16Q. A comparison of average results is shown in (c).

It is very informative to see how ΔC/N varies as a function of echo level. In *Fig. 4c*, ΔC/N is marked for a 3.5*µ*s echo attenuation value of about 5 dB. In this case, ΔC/N is about 4 dB – slightly less than the AWGN channel value of 4.5 dB. Analogously, we measure a ΔC/N of about 7.5 dB for a 14*µ*s echo attenuation of 9.5 dB (see *Fig. 5c*). This difference is considerably greater than the Gaussian value of 4.5 dB.

The variation of ΔC/N as a function of echo level, for both modes, are shown in *Figs 6a* and *6b*. Presenting the results in this fashion allows us to easily see the additional C/N requirements for 64Q compared to 16Q for all values of echo attenuation.

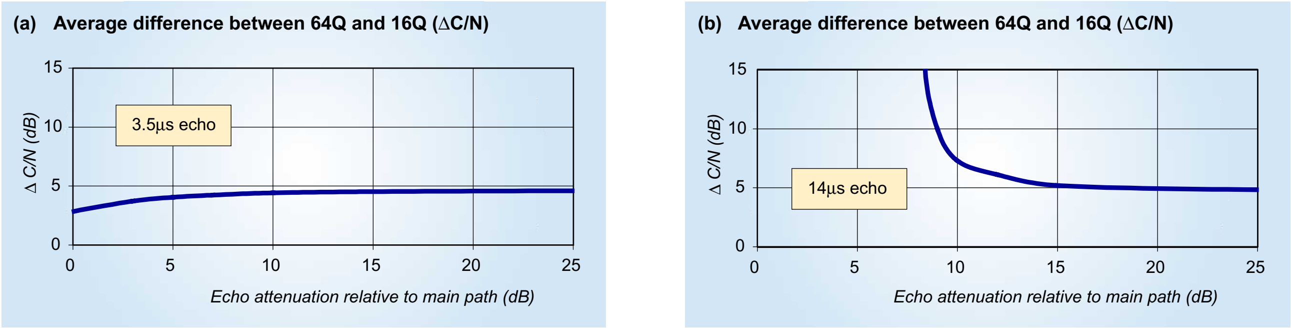


Figure 6
Additional C/N required for 64Q compared with 16Q as a function of the relative echo attenuation for (a) a 3.5µs echo and (b) a 14µs echo

2.3. Impulsive interference

2.3.1. Traffic impulsive interference

Table 2 shows for each location and measuring configuration the objective rankings (see *Table 1*) obtained for DVB-T transmission modes 64Q and 16Q. In the bottom row, an average of all 27 measurements for each mode is shown. The improvement in performance achieved with 16Q is apparent. The receiver operating in 64Q lost sync (ranking = 3 or 4) at 23 locations whilst, in comparison, the receiver tuned to the 16Q channel lost sync only at 13 locations. In practice, sync losses are much more disruptive to the viewer than picture and audio artefacts caused by UCEs. Note also that for every single measurement, mode 16Q usually outperforms mode 64Q.

Table 2
Objective rankings for traffic II and modes 64Q and 16Q

	Ranking	
Location	**64Q**	**16Q**
1, meas. 1	4	3
1, meas. 2	3	2
1, meas. 3	3	2
1, meas. 4	1	1
1, meas. 5	3	3
2, meas. 1	4	1
2, meas. 2	4	3
2, meas. 3	3	3
2, meas. 4	4	1
2, meas. 5	4	3
2, meas. 6	4	3
2, meas. 7	2	1
2, meas. 8	4	2
2, meas. 9	4	4
3, meas. 1	4	4
3, meas. 2	4	3
3, meas. 3	4	1
3, meas. 4	2	1
3, meas. 5	3	1
3, meas. 6	4	3
3, meas. 7	3	1
3, meas. 8	1	1
3, meas. 9	3	1
3, meas. 10	4	4
4, meas. 1	4	3
4, meas. 2	4	4
5, meas. 1	3	1
MEAN	3.3	2.2

2.3.2. Captured impulsive interference

Figs 7 to *10* show C/N versus C/I plots for four typical impulsive interference sources found in the real world. When no II is present in the system, the C/N asymptotically approaches the value associated with the AWGN failure point which, for the receiver used in these tests, is 17.7 dB and 13.6 dB, for 64Q and 16Q respectively. Thus, the improvement of 16Q over 64Q for an AWGN channel is approximately 4 dB, much as expected.

As II is introduced in the system, the gap between the two curves remains roughly constant until the system performance starts to be determined by the impulsive noise instead of the Gaussian noise. This area corresponds to the bend in the yellow curves associated with 64Q. When, for this mode, we have that most of the noise bucket is filled with II (vertical asymptote), 16Q still allows for more than a 10 dB increase in noise power before the receiver fails. When II is the only source of impairment (C/N tends to infinity), we can measure the raw improvement in C/I obtained with a change to 16Q, corresponding to the difference between the vertical asymptotes. This is shown in *Table 3*.

Table 3
C/I improvement for 16Q measured using captured II data

Captured II source	**ΔC/I (dB)**
Central heating	4
Traffic	7.5
Switching relay	4.4
Light switch	4

Obviously, this improvement is lower-bounded by the 4 dB measured for an AWGN channel. As the peak-power

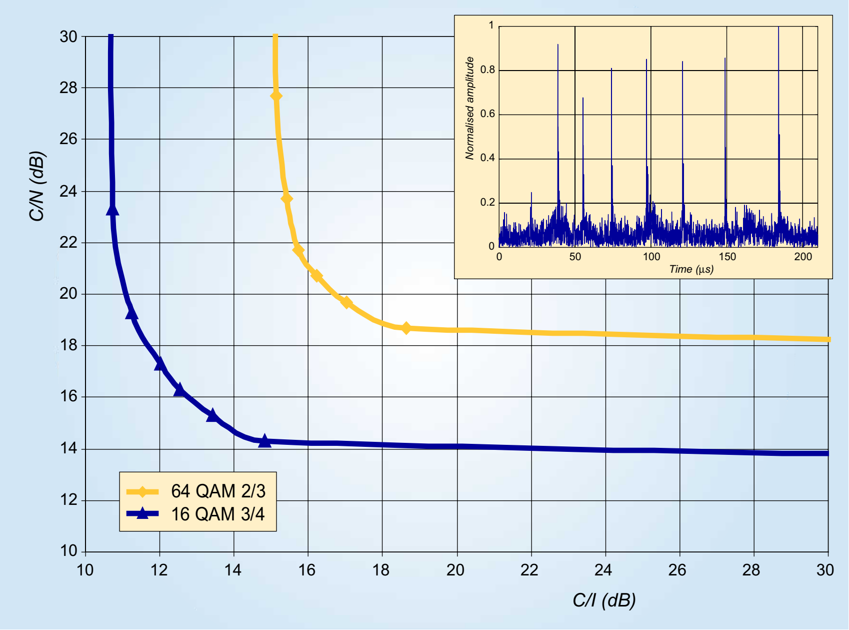


Figure 7
C/N v. C/I for the II shown in the inset plot captured from a central heating boiler

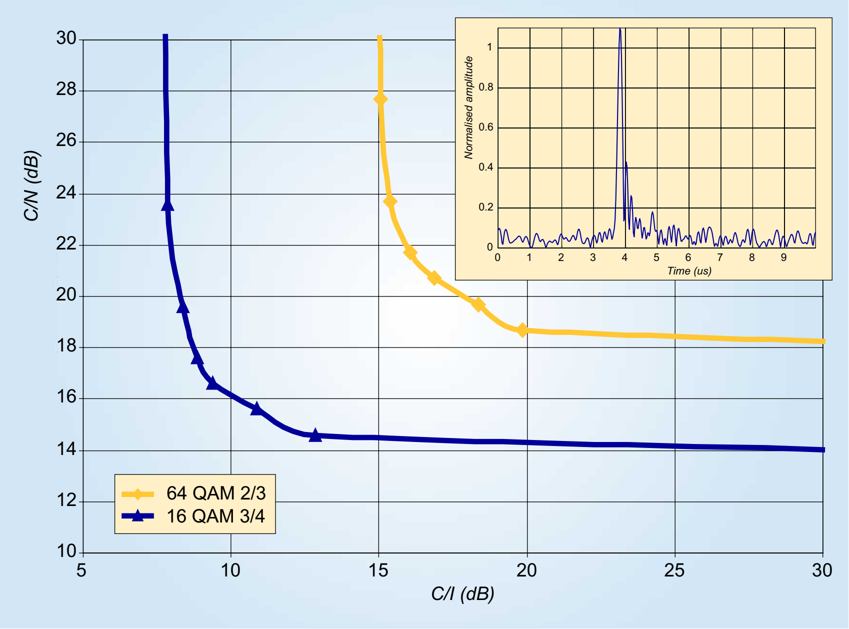


Figure 8
C/N v. C/I for the traffic II shown in the inset plot

to mean-power ratio of the II is increased (e.g. traffic interference), clipping effects start to take place in the receiver and a greater advantage of up to 8 dB in interference power can be obtained from a change to 16Q.

2.3.3. Preliminary suite of test waveforms proposed within the DTG

The DTG test suite is formed by seven trains of pulses with 1, 2, 6, 10 or 20 pulses per burst [5]. These bursts of pulses are repeated every 10ms. The spacing between pulses depends on the actual source of interference that

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[5] At the time these measurements were made, the DTG was refining and simplifying the preliminary test suite. The finally-proposed suite of test waveforms, along with further results, will be the subject of a future article.

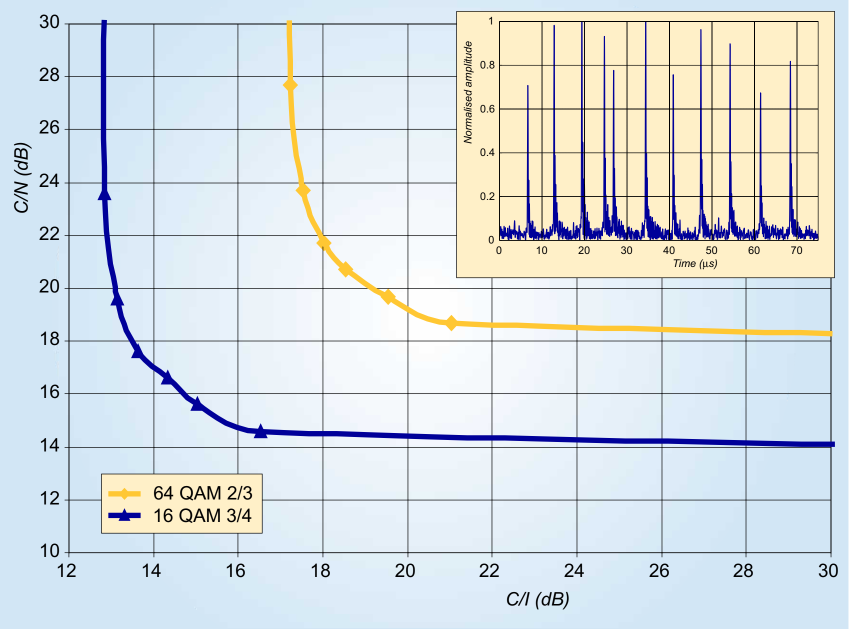

Figure 9
C/N v. C/I for the II shown in the inset plot. This was captured from a contrivance used to generate II by continually switching a relay.

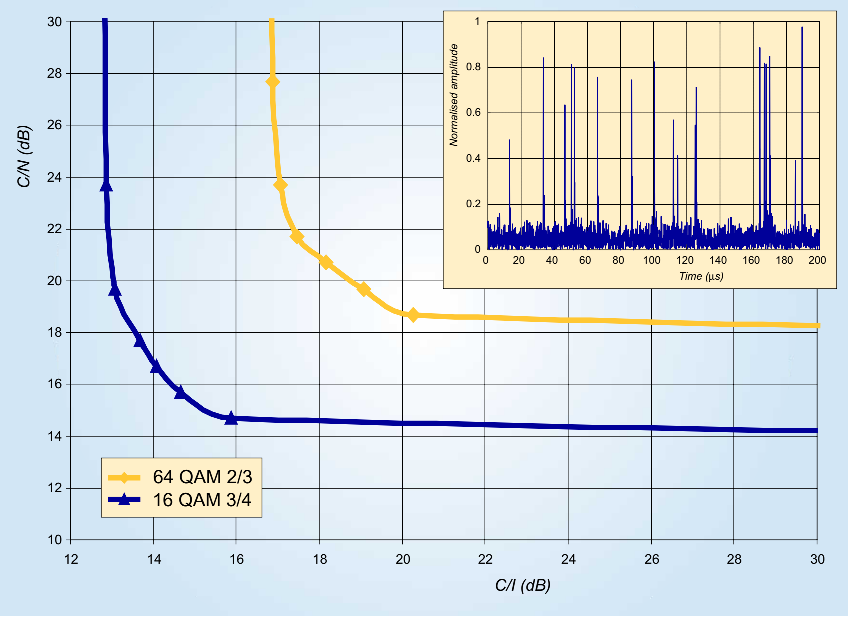

Figure 10
C/N v. C/I for the II shown in the inset plot as generated by a light switch

the train of pulses is mimicking, and is given by a nominal value plus some uniformly distributed dithering. These parameters were obtained as a result of a thorough statistical analysis performed on more that 200 captures taken from an assorted set of II sources (such as light switches, boilers, domestic appliances and traffic). As mentioned before, II is simulated by switching an AWGN source with these trains of pulses. *Table 4* gives a brief description of each test profile.

For the sake of completeness and to account for other sources of II which do not easily fall into the train-of-pulses model, the test suite also includes two gated AWGN profiles. One of them uses a 100μs pulse to gate the AWGN once every millisecond, whereas the other profile gates the noise once every 10ms using a 750ns pulse.

Table 4
II profiles used in the preliminary DTG test suite

Number of pulses per burst	Pulse spacing (μs)
1	æ
2	2 ± 0.5 7.5 ± 2.5 25 ± 20
6	25 ± 10
10	12.5 ± 2.5
20	1.5 ± 0.5

Table 5
C/I improvement for 16Q using the preliminary DTG test suite

Effective duration τ (μs)	Gating signal description	ΔC/I (dB)	$\overline{\Delta C/I}$ (dB)
0.25	1 pulse	8.9	8.9
0.5	1 pulse	7.0	7.0
0.5	2 pulses PS = 2 ± 0.5	6.9	
0.5	2 pulses PS = 25 ± 20	7.1	
0.5	2 pulses PS = 7.5 ± 2.5	7.1	
0.75	1 pulse	7.0	7.0
1.5	1 pulse	6.5	6.3
1.5	6 pulses	6.1	
2.5	1 pulse	5.2	5.3
2.5	10 pulses	5.4	
5	1 pulse	4.1	4.2
5	20 pulses	4.4	
14 to 18	100μs pulsated PS = 1.5 ± 0.3	4.2	4.2
100	1 pulse	4.1	4.1

A summary of the results obtained using the preliminary DTG test suite is shown in *Table 5*. In the first column, the effective useful duration of the II waveforms is shown. The second column briefly describes the type of waveform (whether the gating signal is just a single pulse or a train of pulses with pulse spacing PS). In the third column, the advantage of 16Q over 64Q is expressed as the difference in C/I values corresponding to 1 UCE per minute.

Finally, the last column shows the improvement averaged over all waveforms having the same effective duration τ. The performance of a standard DVB-T receiver in the presence of II can be described using this single parameter.

The performance of the DVB-T receiver for both 64Q and 16Q depends on the effective duration of the II, regardless of the number of gating pulses we use to synthesize it. For small τ, the improvement for the 16Q mode is rather substantial (between 7 and 9 dB when less than 0.5% of the useful OFDM symbol is corrupted). As τ increases, the mode change from 64Q to 16Q results in a smaller improvement, until the AWGN lower bound is reached.

Conclusions

In this article, a collection of performance measurements has been presented for the two DVB-T modes currently in use in the UK:

- **64Q** (64-QAM rate 2/3, 2K and $^1/_{32}$ guard interval);
- **16Q** (16-QAM rate 3/4, 2K and $^1/_{32}$ guard interval).

Only three types of impairment have been considered – co-channel PAL interference, multipath channels with a single echo (inside or outside the guard interval) and impulsive interference.

The results have been presented in a novel manner as “noise bucket” plots, i.e. a plot of (i) C/N versus C/I for CCI from a PAL transmitter and for impulsive interference, and (ii) C/N versus relative echo attenuation for multipath channels.

John Salter joined the BBC in 1969 and moved to the RF Group of the BBC Designs Department in 1972. Here he became involved in the design of transmission and reception equipment for ancillary broadcast services. Later, within the BBC Development Group, he designed monitoring and re-broadcast systems for both FM radio and PAL television. In 1994, the BBC Research and Development departments combined and he started work on digital broadcasting, initially testing DAB receivers then working on new DVB-T systems. He designed the analogue transmission and reception equipment required for the BBC's DVB-T pilot service. He was also involved with the ACTS VALIDATE project as well as the DRiVE project for which he provided measurement data for spectrum co-existence studies.

Mr Salter is an active member of the UK Digital Television Group. He is currently Chairman of the UK DTG RF Sub-Group, whose work includes RF performance issues and test procedures.

José Lago-Fernández received a degree in telecommunications engineering in 1998 from the University of Vigo, Spain. He then spent two years as a research assistant within the Communication Technology Department at the same university, where he looked into DVB-T network planning issues. He joined BBC Research & Development in 2000 where he is currently an R&D engineer in the Transmission Systems Group. In 2002, he collaborated in the field trials leading to the change of the DVB-T transmission mode in the UK. His research interests lie in the RF aspects of digital terrestrial television, impulsive interference and hardware designs for digital wireless receivers.

For all levels of PAL co-channel interference and 3.5μs and 14μs echo attenuation, the 64Q mode clearly requires a greater C/N than the 16Q mode.

A few values have been extracted from *Figs 3*, *6a* and *6b* and are shown in *Table 6*. This table illustrates how much more C/N is required for 64Q compared with 16Q for each different sort of impairment.

Regarding impulsive interference, a transmission mode change from 64-QAM rate 2/3 to 16-QAM rate 3/4 would bring the much desired benefit of having a more robust system against II. This has been verified with field measurements of traffic interference and lab measurements using both real captured II data and a preliminary suite of test waveforms proposed within the DTG:

- *Field measurements* show that, for a given receiving location, 16-QAM 3/4 is less prone to suffer from traffic II than 64-QAM 3/4. Given the nature of the experiment, it is difficult to extract a figure in dB but it is certain that the number of disruptions per minute is smaller for the more rugged DVB-T mode.
- *Lab measurements* using the onset of UCE or one UCE per minute as failure criteria, confirmed that 16-QAM 3/4 is able to withstand between 4 and 9 dB more II than 64-QAM 3/4. The exact figure depends on the effective duration of the interference relative to the useful OFDM symbol period.

Table 6
Additional C/N required for 64Q compared with 16Q for (top) a co-channel analogue PAL interferer, (middle) a 3.5µs echo and (bottom) a 14µs echo

C/I (dB)	ΔC/N (dB)
∞ (AWGN channel)	4.5
20	5.0
7	5.5
2	7
-2	∞ (64Q failed, 16Q OK)
Echo relative attenuation (dB)	**ΔC/N (dB)**
∞ (AWGN channel)	4.5
5	4.0
0	3.0
Echo relative attenuation (dB)	**ΔC/N (dB)**
∞ (AWGN channel)	4.5
20	5.0
10	7.5
8	(64Q failed, 16Q OK)
5	N/A (16Q failed)

Abbreviations

AWGN	Additive White Gaussian Noise	**DVB-T**	DVB - Terrestrial
BER	Bit-Error Ratio	**END**	Effective (or Equivalent) Noise Degradation
C/I	Carrier-to-Interference ratio	**FEC**	Forward Error Correction
C/N	Carrier-to-Noise ratio	**II**	Impulsive Interference
CCI	Co-Channel Interference	**OFDM**	Orthogonal Frequency Division Multiplex
DTG	Digital Television Group	**QAM**	Quadrature Amplitude Modulation
DTT	Digital Terrestrial Television	**QEF**	Quasi-Error-Free
DVB	Digital Video Broadcasting	**UCE**	UnCorrected Error

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