Modelling impulsive interference in DVB-T

— statistical analysis, test waveforms and receiver performance

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Until now, gated Gaussian noise has been widely recognized as the only calibrated tool available to measure impulsive interference performance in a DVB-T system. Recently, a working group within the Digital Television Group, led by BBC R&D, carried out a series of theoretical and practical studies to devise a representative set of test waveforms for impulsive interference.

The result of this work was the proposal of a group of new "gated-squared" Gaussian noise tests, together with some recommendations for test methods and measurement equipment. Arising from this work came the realization that the impulsive noise performance of a DVB-T receiver equipped with no specific counter-measures can be determined from the effective duration of the burst of noise.

Impulsive Interference (II) has been an elusive phenomenon which cast a shadow on the initial launch of Digital Terrestrial Television (DTT) in the UK in 1998. The lack of a suitable time-interleaving scheme in the DVB-T specification makes the system rather sensitive to sources of interference of an impulsive nature. Strategies for improving the performance of DTT in the presence of impulsive noise have met with varying success. One reason for this is the unavailability of a DTT model for II that can be used by set-top box and demodulator chip manufacturers to develop new II countermeasures.

In October 2001, a working group within the Digital Television Group (DTG) led by BBC R&D and formed by Sony, Philips, Rohde & Schwarz, Zarlink and STMicroelectronics was set up. Other invited parties included Roke Manor Research and the Radiocommunications Agency. The aims were to propose a set of test waveforms and methods which could be used to faithfully represent the effect that II has on DTT.

This article reports on the work done by the BBC as a member of the DTG II working group from October 2001 to October 2002. Basically, our contribution to the group consisted of two main areas of work: (a) the capture and statistical analysis of real impulsive interference in order to come up with a simulation model for II, and (b) a campaign of laboratory measurements to validate and simplify the proposed model. These measurements were also used as an assessment of the key parameters determining the performance of DTT when affected by II.

What is impulsive interference?

Impulsive interference (or noise) is usually described in the literature as a process characterized by bursts of one or more short pulses whose amplitude, duration and time of occurrence are random [1]. The inter-arrival time of these pulses is generally assumed to be greater than the time constants of the measuring system. This does not introduce any restrictions and simply means that individual pulses can be resolved by the system.

There are many potential sources of impulsive interference in a domestic DTT installation. Among them we have house appliances (washing machines, dish washers, food mixers, irons, ovens, kettles, electric razors, drills, etc.), central heating thermostats, light switches and ignition systems (traffic, lawn mower, etc). The first three types can affect the DTT receiver through ingress into the downlead and/or flylead. The use of properly screened cables and mains outlets is of paramount importance here. Also, the use of a balun antenna reduces the coupling considerably. Ignition interference is received by the rooftop aerial and cannot be eliminated so easily.

Impulsive noise models for systems operating at low frequencies have been proposed by the ITU [1]. These models are based on measurements of median levels of interfering noise. However, at higher frequencies as used in DTT, high peak levels of interference may adversely affect reception even though the measured median level does not rise above the background noise. This is why a fresh approach was needed to characterize impulsive noise in the UHF band.

Mathematically, impulsive interference is usually modelled as a train of pulses [2][3]

$$n(t) = \sum_i A_i P_{w_i}(t - \tau_i) \qquad \text{Equation (1)}$$

where the amplitude A_i, duration W_i and arrival time τ_i of each pulse is a random variable whose distribution is *a priori* unknown. The parametric model above is fully defined when we establish the statistical distribution of the three parameters characterizing each pulse.

The RF bandwidth of impulsive interference is typically much greater than that of the measuring system [1][4]. The shape of the pulses is therefore determined by the impulse response of the actual receiving or measuring system. In [2] the arrival times are modelled using a gamma distribution, and an exponentially decaying unit step is used as a typical pulse. The choice of statistical distribution for each parameter therein seems rather arbitrary since it is based on models which are either too specific or excessively theoretical. The applicability of these results to DTT is thus rather limited.

In [5], the model in *Eq. (1)* is used to characterize impulsive interference in the UHF bands using a 10 MHz measurement bandwidth. In this study, no suitable probability distribution could be reliably fitted to the measured pulse amplitudes and time spacing between pulses. A similar statistical analysis in the VHF/UHF bands using a 10 kHz measurement bandwidth and a time resolution of 50 μs was presented in [6]. In this case only vehicle ignition noise was considered. The time spacing between consecutive pulses was observed to be uniformly distributed between 5 and 15 ms.

Capturing impulsive interference

In order to gather a sufficiently large set of captured II data, we used a capture system which takes 200 ms snapshots of an 8 MHz clean DTT channel, filtered and down converted to 2nd IF (central frequency 4.57 MHz and 7.61 MHz bandwidth). The captured waveforms span several hundred OFDM symbols. Data is sampled at 40 MHz using a 12-bit Analogue-to-Digital converter that gives a time resolution of 25 ns [1].

More than two hundred captures were taken at several households and also at locations where traffic interference could be detected. A 200 ms capture contains the impulsive noise waveform responsible for triggering the capture system. This waveform may consist of one or several impulsive events. A new impulsive event starts when the time elapsed between this event and the previous one is greater than the “recovery time” of the receiver. This is the time it takes the receiver to reacquire lock after having lost synchronization because of an error event. Sample waveforms for each of the categories that make up the complete set of captures can be found in [7].

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1. A similar capture system with a measurement bandwidth of 10 MHz is proposed in [1].

The statistics of impulsive interference

A sentence that summarizes the chaotic nature of impulsive interference is “no two impulsive events are the same”. Trying to characterize it statistically using a complex model may thus sound too ambitious. Instead, it seems more plausible to use a simple model to characterize II as seen by a DTT receiver at IF, that is, to model II once it has been downconverted and band limited to 8 MHz.

As detailed in [7], all captured data was classified and catalogued as belonging to one of the following categories:

- central heating types 1, 2 and 3;
- cooker ignition;
- dishwasher;
- light switches being turned off;
- fluorescent and incandescent light switches being turned on;
- traffic interference types 1, 2 and 3.

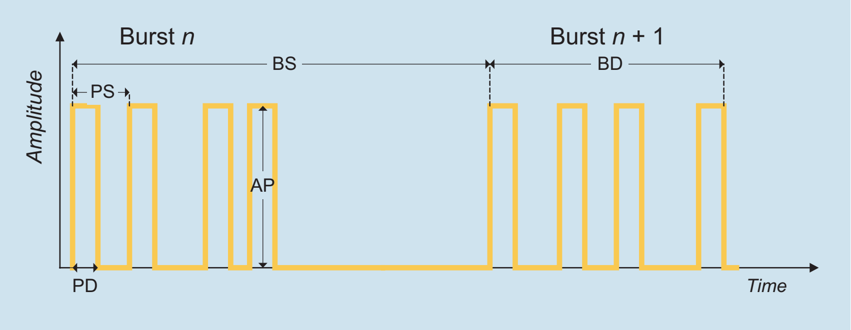

Figure 1
Parametric model for impulsive noise used in the capture data fit

To each of these groups of captures we tried to fit the statistical model shown in *Fig. 1*, which is similar to that proposed in *Eq. (1)*. An impulsive event comprises one or more bursts. Each of these bursts contains a number of pulses. The pulse amplitude AP is assumed to be constant [2]. PS is the spacing between pulses within the same burst and equals the distance between arrival times in *Eq. (1)*. PD and BD denote the duration of a pulse and a burst, respectively. BS represents the spacing between consecutive bursts.

Adjusting a statistical distribution to each of the six parameters AP, PD, PS, BD, BS and the event duration proved rather involved, given the great variation in the data histograms [7]. In view of this, and after several brainstorming sessions within the DTG II working group, the following conclusions and compromises were reached:

- **Pulse amplitude is to be held constant within an impulsive event**. It proved almost impossible to glean any information from the pulse amplitude distributions. The actual amplitude level of the simulated interferer can be varied to change its total power.
- **Pulse duration is assumed constant and is fixed at 250 ns**. Elementary pulses within a burst are shaped by the impulse response of the tuner. This response spreads the energy of the incoming short impulses over about 200 to 350 ns. If we accept the rising times of the edges at the input to the aerial to be negligible when compared with the duration of the tuner’s impulse response, then fixing PD at 250 ns does not imply a loss of generality in our model.
- **PS follows a uniform distribution.** Again no statistical distribution could be fitted to the PS histograms and therefore uniform distributions with suitably chosen lower and upper limits are used.
- **A burst is not allowed to last more than a useful OFDM symbol (224 μs in the UK)**. As far as DVB-T is concerned, bursts longer than this can be treated as Gaussian noise. It also seemed more appropriate to express the duration of a burst as a number of pulses per burst rather than a time duration.

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[2] In reality, the pulse amplitude varies greatly within the same capture but in an apparently unpredictable way [7].

- **BS is fixed at 10 ms**. It was agreed to use a fixed burst spacing so that by the time a new impulsive burst hits the receiver the effect of previous bursts has long died away. This spacing is consistent with the repetition period of engine ignition interference [6].
- **The observation period determines the duration of the impulsive event.** A new burst is generated every 10 ms and this is repeated until the observation period chosen for the measurements elapses.

Preliminary recommendation for impulsive noise tests

Once the bulk of captured data has been analysed, we are in a position to propose a preliminary set of test waveforms conforming to the template shown in *Fig. 1*. The basic requirements for these waveforms as agreed within the II working group are:

- they must be representative of actual interference, albeit somewhat tailored to the peculiarities of the DVB-T system:
- they must be easily reproducible, repeatable and should yield the same results regardless of who uses them;
- test and measurement equipment must be readily available to the user.

Tables 1 and *2* gather the nine test waveforms initially proposed within the DTG II working group. These waveforms were used in many DVB-T performance tests carried out in the laboratory, a summary of which is presented in the next section. A more complete compilation of results can be found in [7].

Table 1
Preliminary impulsive noise test waveforms. Burst spacing is fixed at 10 ms and pulse duration is 250 ns.

Noise type	Type of capture accounted for	Pulse spacing (µs)	Burst duration (pulses per burst)	Minimum and maximum burst duration (µs)	Effective burst duration τ_E
N1	CH type 2	25 ± 10	6	75.25 → 175.25	1.5 µs
N2	CH type 3	2 ± 0.5	2	1.75 → 2.75	500 ns
N3	Cooker ignition	1.5 ± 0.5	20	19.25 → 38.25	5 µs
N4	Dishwasher type 2 & Lights off type 2	12.5 ± 2.5	10	90.25 → 135.25	2.5 µs
N5	Fluorescent lights on	25 ± 20	2	5.25 → 45.25	500 ns
N6	Traffic 3A	7.5 ± 2.5	2	5.25 → 10.25	500 ns
N7	Traffic 3B	N/A	1	N/A	250 ns

Table 2
Complementary table for impulsive noise test based on gated Gaussian noise

Noise type	Type of capture accounted for	Burst duration	Burst spacing
GN1	Dishwasher type 1B	100 µs	1 ms
GN2	Canal+ recommendation scaled down for 2K	750 ns	10 ms

The pulse spacing in *Table 1* is uniformly distributed and is expressed as a mid-range value plus or minus a “dither” factor. Burst duration is measured in number of pulses per burst. From the bounds on PS we can work out the minimum and maximum burst durations in µs. Contrary to BD, which includes the time spacing between pulses, the effective burst duration τ_E is defined as the number of pulses per burst, times the pulse duration. That is, τ_E represents the total amount of time the interference is "on". *Table 2* completes the tests in *Table 1* with two gated Gaussian noise tests. This type of test has been widely used in the past [4]. Test GN2 is a modified version of the specification for impulsive interference made by Canal + [3].

Experimental results

In this section we summarize the results regarding the performance of DVB-T in the presence of impulsive interference. The aim of these laboratory measurements was twofold:

1) To validate the use of the test waveforms and to further reduce the number of waveforms needed to realistically simulate II.
2) To compare the II performance of the two DTT modes currently used in the UK — 64-QAM, rate 2/3, guard interval 1/32 with 2K carriers, and 16-QAM, rate 3/4, guard interval 1/32 with 2K carriers. A more comprehensive comparison of these two modes (including some II results not presented here) can be found in [8].

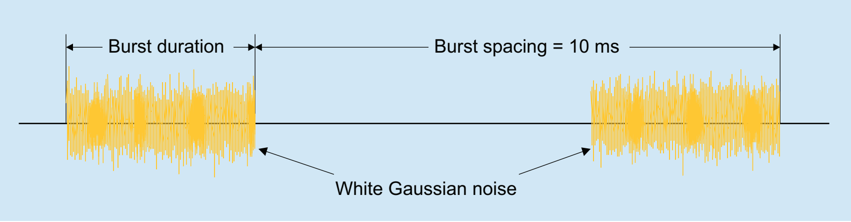

Figure 2
Classic Gated Additive White Gaussian Noise (GAWGN) test waveform

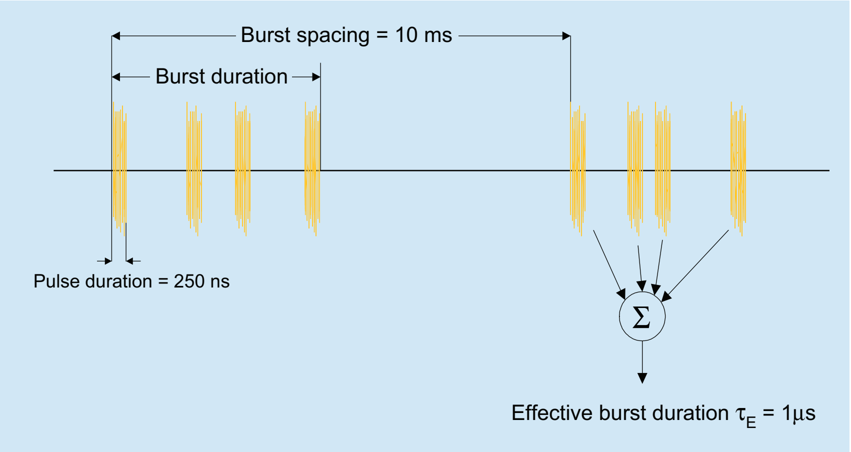

Figure 3
'Gated squared' AWGN (G2AWGN) test waveforms

Two types of tests were performed. In the first one we used a train of pulses to gate a source of Additive White Gaussian Noise (AWGN). *Fig. 2* illustrates the classic approach to this kind of test where bursts contain just one pulse (as in *Table 2*). *Fig. 3* shows what we call "gated-squared" Gaussian noise tests (G^{2}AWGN). The name comes from the fact that pulses within a burst can be seen as a *second* gating of the classic GAWGN waveform of *Fig. 2*. The test waveforms in *Table 1* were generated using G^{2}AWGN.

For the second type of tests we used II captures (previously downconverted to complex baseband) in combination with a Rohde & Schwarz's vector signal generator SMIQ. The SMIQ contains an I/Q Arbitrary Waveform Generator (AWG) with an external PC software application that can be used to download arbitrary waveforms to the SMIQ. These waveforms are stored in the non-volatile memory of the SMIQ and provide I/Q signals to drive the SMIQ's IQ modulator. The AWG in the SMIQ cyclically repeats the I/Q waveforms.

Results with SMIQ + II capture waveforms

The setup for this type of tests is shown in *Fig. 4*. Attenuator A is used to set the level of the useful DVB-T signal C. The SMIQ upconverts the complex baseband II captures to the UHF channel,

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[3] Contribution to the DTG II working group from Philips.

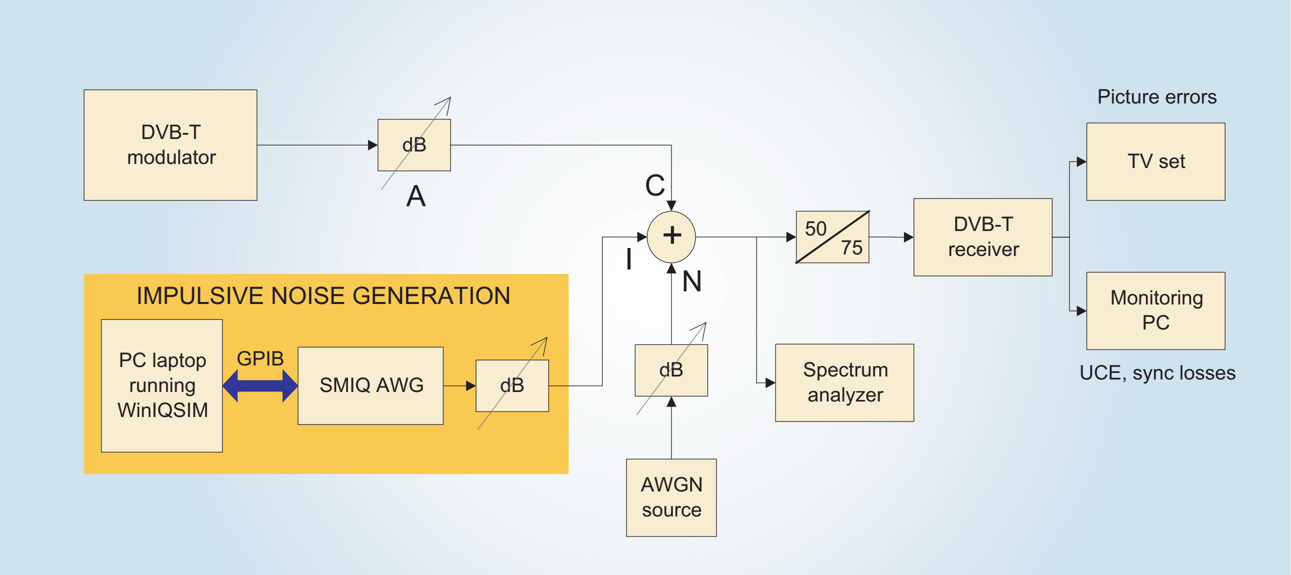

Figure 4
Set-up for measurements using capture waveforms

where the DVB-T signal is located. Another source of Gaussian noise N is also added to the DVB-T signal. The channel power measurement option of a spectrum analyser is used to measure the average power of the different signals. A DVB-T receiver decodes the received signal, providing a running count of the number of UnCorrectable Errors (UCEs) and receiver sync losses. Picture errors on the decoded picture can be spotted on a TV set.

Pulses in the capture waveforms correspond to the impulse response of the complete downconversion process (from the aerial input to complex baseband). For our laboratory measurements we chose four representative capture waveforms from the capture database (central heating, traffic, spark generator and light switch).

Performance results are presented here in a novel way used before in [8]. The wanted DTT signal level at the input to the DVB-T receiver remains fixed at –50 dBm (see *Footnote 4* on page 9). For each level of impulsive interference (I) we add enough Gaussian noise (N) to make the DVB-T receiver fail. The failure criterion used is the onset of visual errors on the decoded picture. The observation period is 1 minute. By plotting C/N versus C/I we include in one plot the AWGN C/N performance of the receiver (asymptote corresponding to increasing C/I), the C/I performance for the II capture in question (asymptote when no additional noise is added) and the performance when both Gaussian noise and impulsive noise are present in the system.

The power level shown on the SMIQ display I corresponds to the average taken over the total duration of the downloaded waveform, which in this case corresponds to BS = 10 ms. To allow for comparison between C/N and C/I, we define the so-called windowed C/I. Given the value of I, the windowed C/I is referred to the useful OFDM symbol duration using:

$$\left(\frac{C}{I}\right)_W = C - I + 10\log\left(\frac{T_U}{10^{-2}}\right) \qquad \text{Equation (2)}$$

... where $T_U = 224 \times 10^{-6}$ s for the UK modes.

The 6 dB II performance gain predicted by the “energy bucket” theory [9] when changing from a 2K to an 8K mode is not accounted for by the windowed C/I because the interfering power is normalized with respect to the useful OFDM symbol duration (the 6 dB comes from the fourfold increase in window duration).

Figs 5 and 6 show C/N v. windowed C/I plots for the two DTT modes currently radiated in the UK. A first generation BBC DVB-T receiver without II countermeasures was used for these measurements. Plots for another three DVB-T modes can be found in [7]. As II is reduced in the system, the C/N asymptotically approaches the value associated to the AWGN failure point which, for the receiver

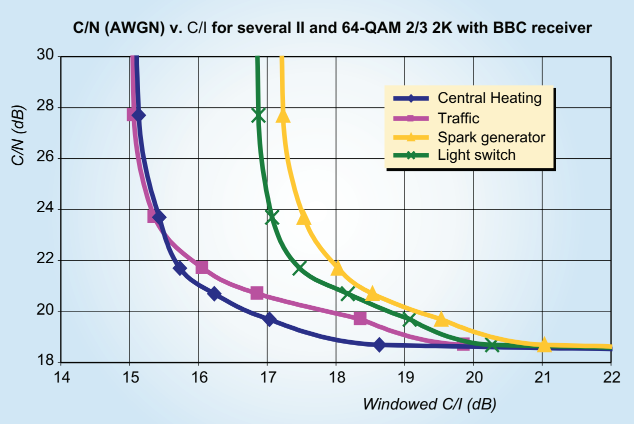

Figure 5
C/N v. windowed C/I plots for the “old” UK mode and four capture waveforms

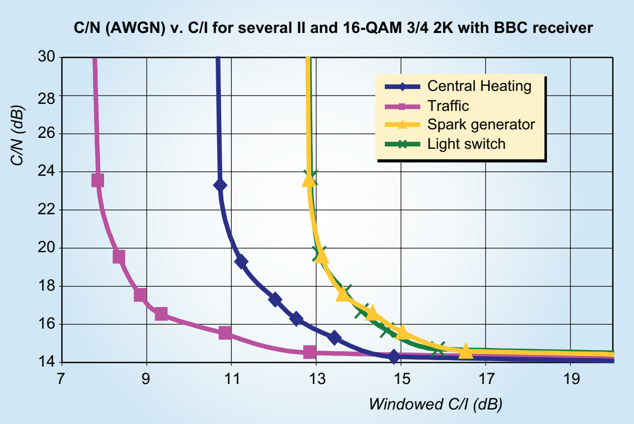

Figure 6
C/N v. windowed C/I plots for the “new” UK mode and four capture waveforms

used in these tests, is 17.6 dB for 64-QAM rate 2/3 (old UK mode) and 13.3 dB for 16-QAM rate 3/4 (new UK mode). Thus, the improvement of the new UK mode over the old UK mode for an AWGN channel is approximately 4 dB, much as expected.

As II is added, performance starts to be dominated by it. This area corresponds to the bends in all curves. When most of the noise bucket in the old UK mode is filled with II (vertical asymptotes), the new UK mode still allows for an increase in I 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 the mode change which is obviously lower bounded by the 4 dB measured for an AWGN channel. For captures with very high peak-to-mean ratios, clipping effects start to take place in the receiver and an improvements of up to 8 dB can be obtained with the new UK mode.

The major drawback of this approach to II testing is the limited isolation of the SMIQ (~54 dB). When the peak-to-mean ratio of the II is very high, noise from the SMIQ’s Digital-to-Analogue converter breaks through, filling the noise bucket of the receiver. A second limitation is the 20 MHz

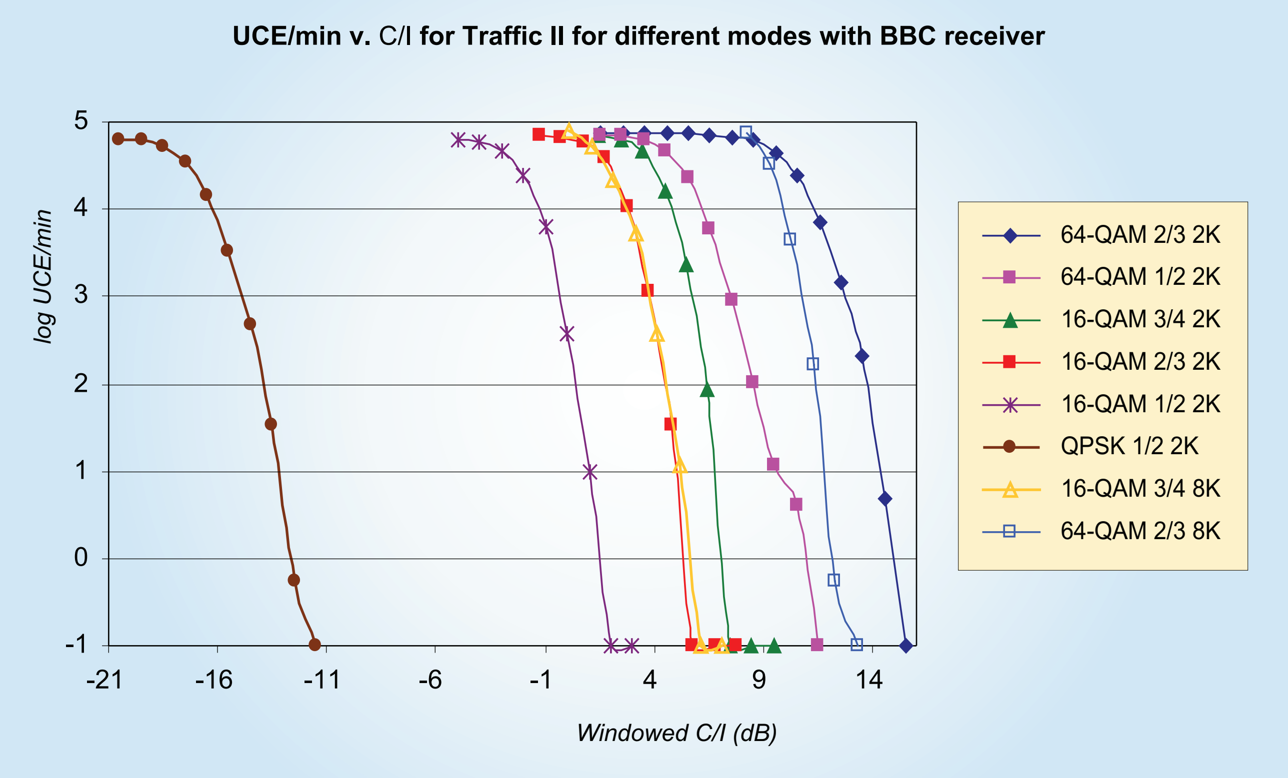

Figure 7
Number of UCEs per minute versus windowed C/I for several DVB-T modes using a traffic interference capture waveform

bandwidth of the interfering signal. To be truly representative and for testing and developing a UHF DTT receiver, the interferer bandwidth should cover the entire UHF band.

Fig. 7 presents some results for traffic interference in a different way. No additional Gaussian noise is used this time, and the number of UCEs per minute is noted for each level of interference. The failure criterion is 1 UCE per minute (0 on a log scale). *Table 3* shows a comparison of the AWGN C/N values for picture failure and the analogous C/I values extracted from *Fig. 7*.

Table 3
Comparison of Gaussian *C/N* performance and *C/I* performance for a typical traffic capture waveform. A BBC receiver was used.

DVB-T mode GI = 1/32	AWGN C/N 2K (8K)	Traffic capture C/I 2K (8K)	C/N – C/I (dB) 2K (8K)
64-QAM 2/3	17.7 (17.6)	15.3 (11.4)	2.4 (6.2)
64-QAM 1/2	14.7 (14.5)	11.3 (N/A)	3.4 (N/A)
16-QAM 3/4	13.5 (13.3)	7.4 (6)	6.1 (7.3)
16-QAM 2/3	12.2 (12.1)	5.7 (N/A)	6.5 (N/A)
16-QAM 1/2	10 (10)	1.9 (N/A)	8.1 (N/A)
QPSK 1/2	4.6 (4.5)	–13.3 (N/A)	17.9 (N/A)

The advantage of going from 2K to 8K for the two UK modes ranges from 1.5 to 4 dB. To this value we have to add another 6 dB that is not accounted for in the windowed C/I. The disparity between the AWGN C/N and the C/I for traffic is greater for more robust modes. For these modes, we need very high peak interference levels to break the system.

Preliminary test waveforms results

Fig. 8 shows the laboratory setup for this kind of tests. The main differences from the one in *Fig. 4* are that no extra source of Gaussian noise is used and that the power of the impulsive interferer is

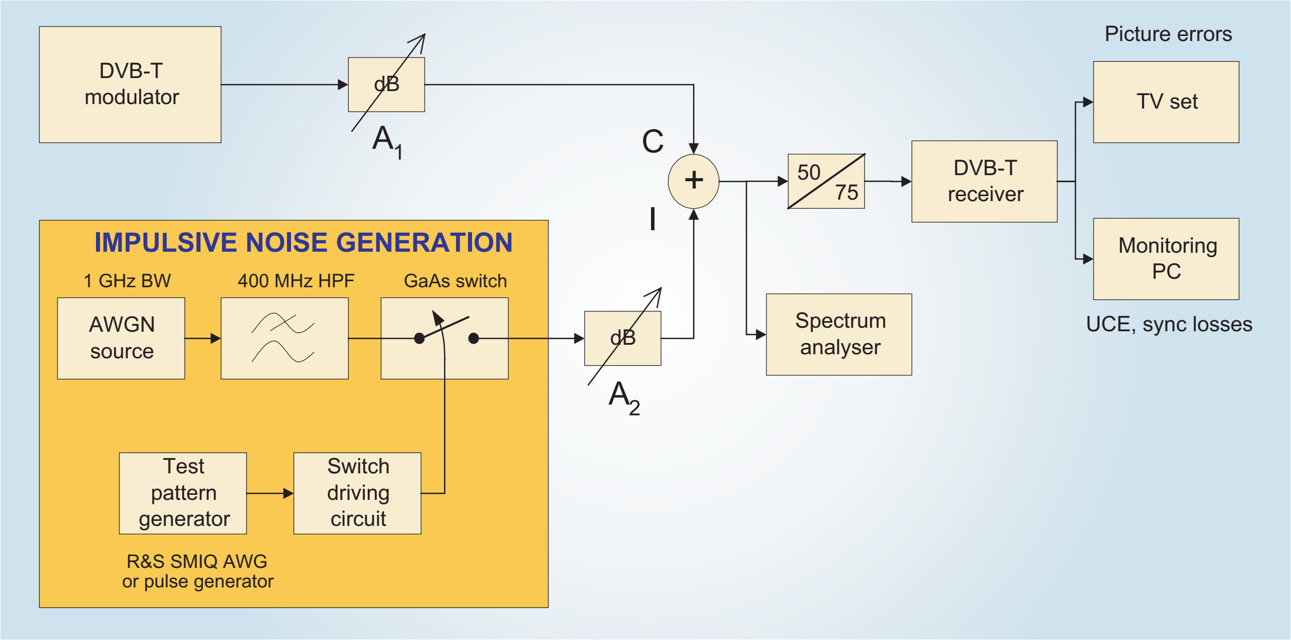

Figure 8
Set-up for GAWGN and G2AWGN measurements

Abbreviations

16-QAM	16-state Quadrature Amplitude Modulation	**G(2)AWGN**	Gated (squared) AWGN
64-QAM	64-state Quadrature Amplitude Modulation	**IF**	Intermediate-Frequency
AWG	Arbitrary Waveform Generator	**II**	Impulsive Interference
AWGN	Additive White Gaussian Noise	**OFDM**	Orthogonal Frequency Division Multiplex
BD	Burst Duration	**PD**	Pulse Duration
BS	Burst Spacing	**PS**	Pulse Spacing
C/I	Carrier-to-Interference ratio	**QAM**	Quadrature Amplitude Modulation
C/N	Carrier-to-Noise ratio	**UCE**	UnCorrectable Error
DTG	Digital Television Group	**UHF**	Ultra High Frequency
DTT	Digital Terrestrial Television	**VHF**	Very High Frequency
DVB-T	Digital Video Broadcasting – Terrestrial		

now controlled using variable attenuator A_2. The useful DVB-T signal level after the matching pad is fixed at –60 dBm [4].

The impulsive noise generation block consists of a wideband source of Gaussian noise, a 400 MHz high-pass filter that eliminates low-frequency noise, a high-isolation GaAs switch and a test pattern generator. The circuit that drives the switch sets the pulses coming from the test pattern generator to the right logic levels so as to control the switch. The pattern generator can be a simple pulse generator for GAWGN or the SMIQ AWG for G^{2}AWGN. In the latest implementation, output I of the SMIQ is used directly to drive the switch control circuit. The GaAs switch is Minicircuits model ZFSWHA-1-20 with an upper operating frequency of 2 GHz and a typical isolation at UHF of 65 dB.

The computation of the windowed C/I performance is done as follows:

1) With the spectrum analyser's channel power option, we adjust A_1 for a useful DTT power of C = –54 dBm measured within the DVB-T bandwidth of 7.61 MHz (the matching pad inserts another 5.7 dB of attenuation).
2) With the GaAs switch closed (ungated Gaussian noise), we adjust A_2 at arbitrary reference level A_{REF} and measure the corresponding interference level, $I = I_{REF}$, using a 7.61 MHz measurement bandwidth.

We then gate the noise source using the chosen test pattern and find the attenuation level A for attenuator A_2 corresponding to 1 UCE per minute.

The calculation of the windowed C/I is then done as follows:

$$\left(\frac{C}{I}\right)_W = C - I_{REF} + A - A_{REF} + \underbrace{10\log\left(\frac{T_U}{\tau_E}\right)}_{TF} \qquad \text{Equation (3)}$$

... where the logarithmic term TF is the so-called "tolerance factor", τ_E is the burst effective duration and T_U is the OFDM symbol duration (224 μs for the UK).

Table 4 shows a compilation of C/I performance results for different test patterns for the two UK modes. Interference is grouped according to its effective burst duration. The number of pulses per burst depends on whether the waveform is generated using gated (just one pulse) or gated-squared AWGN.

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[4] Initially, a figure of –50 dBm was proposed within the II working group. This is the same value suggested for other DTG DVB-T test setups. It was later felt that –60 dBm would make II measurements easier (less interfering power needed to make the receiver fail) without affecting the results, since the receiver is still well above its sensitivity point for picture failure (less than –81 dBm for 16-QAM 3/4 and –77 dBm for 64-QAM 2/3, measured with a BBC receiver).

Table 4
Overall C/I performance for the new and old UK modes for the preliminary set of test waveforms (shaded in dark blue). Results for other test patterns with different effective burst durations and pulse spacings are also included. The pulse duration is fixed at 250 ns

			C/I (dB)	
Waveform description	**Number of pulses per burst**	**Effective burst duration τ_E (μs)**	**64 QAM rate 2/3**	**16 QAM rate 3/4**
Continuous 50ns burst	1	0.05	15.7	1
Continuous 100ns burst	1	0.1	17.5	3.6
Test waveform N7	1	0.25	18.3	9.4
Continuous 500ns burst	1	0.5	18.9	11.8
Test waveform N2	2	0.5	18.6	11.7
Test waveform N5	2	0.5	18.8	11.8
Test waveform N6	2	0.5	18.8	11.7
Test waveform GN2	1	0.75	18.3	11.6
Average of 5 different pulse spacings	3	0.75	18.2	11.3
Continuous 1μs burst	1	1	18.2	11.3
Average of 5 different pulse spacings	4	1	17.9	11.7
Continuous 1.5μs burst	1	1.5	18.4	11.9
Test waveform N1	6	1.5	18.3	12.2
Continuous 2μs burst	1	2	17.8	12.4
Average of 5 different pulse spacings	8	2	17.7	12.3
Continuous 2.5μs burst	1	2.5	17.9	12.7
Test waveform N4	10	2.5	17.8	12.4
Continuous 4μs burst	1	4	17.4	12.5
Three different pulse spacings	16	4	17.1	12.4
Continuous 5μs burst	1	5	17.2	13.1
Test waveform N3	20	5	16.9	12.6
Continuous 8μs burst	1	8	16.8	12.6
Three different pulse spacings	32	8	16.4	12.2
Total burst duration of 100μs as GN1 but with uniform PS of 1.5 ± 0.3μs	57 to 71	14 to 18	16.2	12.1
Continuous 25μs burst	1	25	16.5	12.2
Three different pulse spacings	100	25	16	11.7
Test waveform GN1	1	100	16.1	12
Two different pulse spacings	400	100	15.8	11.4

For the test waveforms in *Table 1* and *Table 2*, several realizations with different pulse spacings were downloaded to the SMIQ and the average C/I performance was recorded. Other waveforms with a different number of pulses were generated so as to sweep through the range of effective burst durations. For a given τ_E, several realizations of the basic train of pulses, with different pulse spacing, were tested and the average performance was taken. This value is compared with the C/I performance for a continuous burst with the same effective duration.

In *Table 5* the results of *Table 4* are averaged for each effective burst duration. Measurements for durations greater than an OFDM symbol are also shown. From these two tables we can conclude that the II performance of a DTT receiver with no II countermeasures can be explained in terms of the effective duration of the interference. For a given τ_E and interference level, the peak-to-mean power ratio remains constant as does the total energy within an OFDM symbol. The C/I performance of a receiver will be the same regardless of how the energy within the OFDM symbol is distributed. This is a simple extension of the energy bucket theory [9].

Table 5
Averaged windowed C/I performance for the two UK DTT modes for different effective burst durations. The right-most column represents the C/I improvement for the new UK mode with respect the old UK mode.

Effective burst duration τ_E (μs)	$\overline{C/I}$ for 64 QAM rate 2/3	$\overline{C/I}$ for 16 QAM rate 3/4	$\overline{\Delta C/I}$ (dB)
0.05	15.7	1.0	14.7
0.1	17.5	3.6	13.9
0.25	18.3	9.4	8.9
0.5	18.8	11.8	7.0
0.75	18.3	11.4	6.9
1	18.1	11.5	6.6
1.5	18.3	12.0	6.3
2	17.8	12.3	5.5
2.5	17.8	12.5	5.3
4	17.2	12.5	4.7
5	17.1	12.8	4.3
8	16.6	12.4	4.2
16	16.2	12.1	4.1
25	16.3	12.0	4.3
100	16	11.8	4.2
200	16	11.7	4.3
300	16.1	11.9	4.2
500	16.8	12.4	4.4
1000	17.3	13.1	4.2
5000	17.6	13.4	4.2

The right-most column in *Table 5* shows the average II improvement obtained from the change of DTT mode in the UK. This improvement ranges from approximately 4 dB for AWGN, to more than 10 dB for impulsive interference with very high peak-to-mean ratios.

In *Fig. 9* we show the plots of windowed C/I performance versus effective burst duration for the two UK modes. The AWGN performance of the BBC receiver is also shown as solid lines. As τ_E

increases, the C/I asymptotically approaches the AWGN C/N. For bursts shorter than an OFDM symbol but longer than 0.5 μs, the C/I performance is roughly within a 2 dB neighbourhood of the Gaussian performance. For pulses shorter than 0.5 μs, clipping occurs in the front end and the behaviour of the receiver departs from the Gaussian performance.

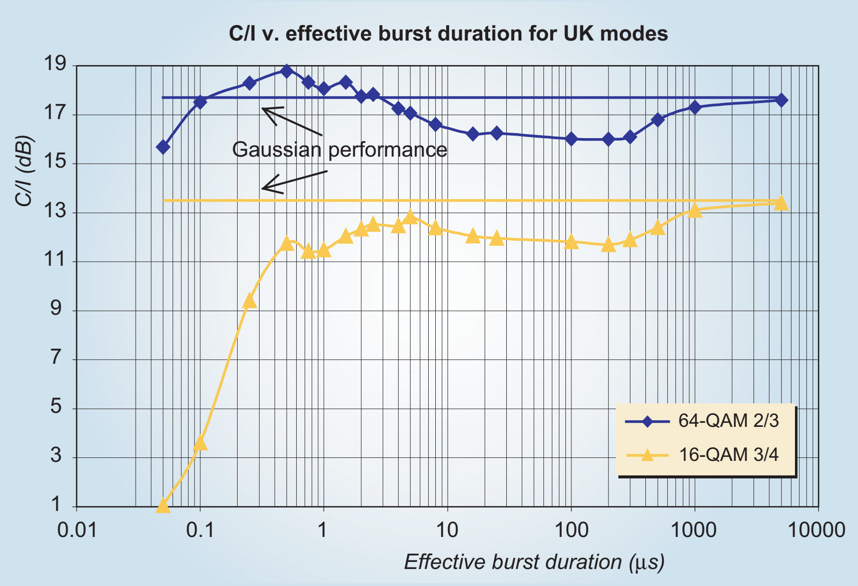

Figure 9
Windowed C/I versus effective burst duration

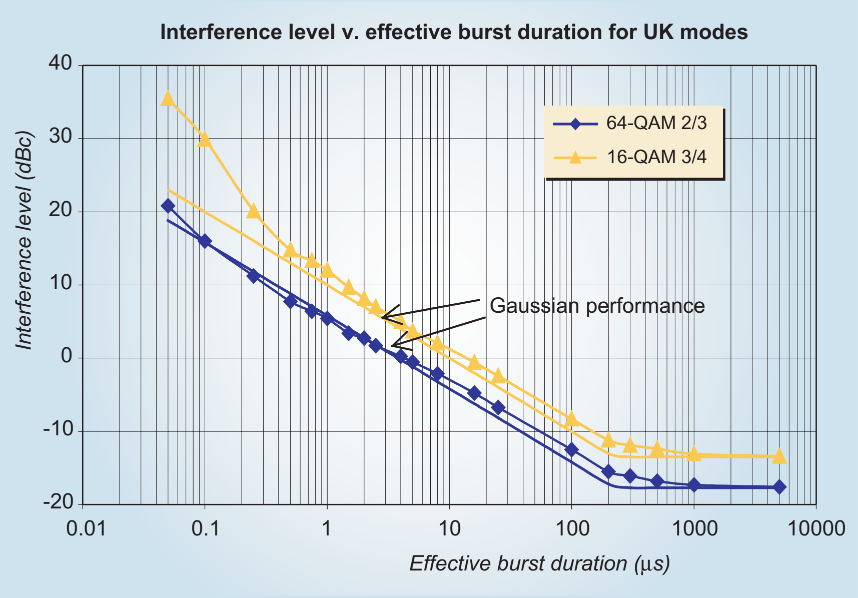

Figure 10
Impulsive interference level versus effective burst duration

The same results are plotted in *Fig. 10* but now the *amplitude* of the interferer is referred to the carrier level. The departure from Gaussian performance is more clearly seen in this figure. The straight line for effective burst durations of less than an OFDM symbol period has a –3 dB-per-octave characteristic. That is, doubling the burst duration implies halving the burst amplitude. For effective burst durations greater than an OFDM symbol period, the amplitude approaches that for a Gaussian channel.

The main advantage of using the test setup in *Fig. 8* to simulate II is that the wide flat power spectrum of the generated interference makes for a fairly easy power calibration and performance measurement. Also, the randomness introduced by the source of noise partly counters the deterministic generation of the test patterns using SMIQ's arbitrary waveform generator. With gated Gaussian noise, we can recreate the basic characteristics of impulsive interference – *wideband spectrum* and *high peak-to-mean power ratio*.

DTG impulsive noise test waveforms

From the discussion in the previous section, it should be now apparent that the effective duration of the burst of Gaussian noise is the parameter that defines the performance of a DTT receiver with no II countermeasures. Based on this result, the DTG II working group agreed on a further simplification of the set of test waveforms proposed in the section "Preliminary recommendation for impulsive noise tests" *(on page 4)*. The test patterns that were finally proposed for II are shown in *Table 6*.

A new test with 40 pulses per burst is included to account for longer burst durations. Also the number of pulses per burst has been slightly modified so as to have a set of evenly-spaced effective durations covering the different performance areas in *Fig. 9*. Test GN1 has been left out of the final proposal because it has the same effect as Gaussian noise. Similarly, test GN2 has been discarded because those in *Table 6* cover it.

Table 6
Final set II test waveforms proposed by the DTG II working group. The waveform definition is shown in *Fig. 1*. The pulse spacing should be uniformly distributed between the minimum and the maximum pulse spacing.

Test	Pulses per burst	Similar preliminary test	Minimum pulse spacing (µs)	Maximum pulse spacing (µs)	Effective duration (µs)	2k tolerance factor TF (dB)
1	1	N7	N/A	N/A	0.25	29.5
2	2	N2, N5, N6	1.5	45	0.5	26.5
3	4	N1	15	35	1	23.5
4	12	N4	10	15	3	18.7
5	20	N3	1	2	5	16.5
6	40	æ	0.5	1	10	13.5

The pulse duration is 250 ns and the burst spacing is 10 ms. A possible setup for carrying out the measurements is that shown in *Fig. 8*. The DTT signal power at the receiver's aerial input should be set at –60 dBm. The failure criterion is either 1 uncorrectable error per minute (objective) or no picture errors spotted on the decoded picture for one minute (subjective). The choice of equipment used to generate the train of pulses that is gating the AWGN source is left unspecified.

For bursts spaced 10 ms, within a one-minute observation period we have at least 6,000 different bursts with varying pulse spacing. The receiver has therefore no means of predicting which specific test pattern it will be attacked with at any particular time. This prevents the design of II countermeasures aiming at passing the tests for just a few pre-chosen combinations of spacings between pulses.

Looking at *Fig. 9*, we can see that Gaussian C/N performance can be used as an initial target value for windowed C/I performance of II waveforms. The tolerance factor of *Table 6* is the amount of gated Gaussian noise we can add to the noise level corresponding to the AWGN performance without reaching the failure point. The tolerance factor is independent of modulation mode, receiver implementation margin and degradation criterion. Note, however, that it does depend on the length of the useful OFDM symbol (FFT mode).

For instance, let us assume that the Gaussian performance of a receiver for picture failure is 20 dB for a certain DVB-T mode. The anticipated picture failure point for test waveform 6 should correspond to an ungated noise power equal or greater to –20 dBc + 13.5 dB = –6.5 dBc. A receiver with measures to counter impulsive interference should be expected to perform better than that.

Conclusions

This article has presented the work carried out by the BBC as leading member of the working group set up within the DTG to study impulsive interference. The aim of this group was to propose a set of realistic and repeatable tests to assess the performance of a DTT receiver suffering from impulsive interference.

As a result of the statistical analysis of a large amount of captures of impulsive interference, we concluded that an effective yet not too simplistic way of simulating impulsive noise was using the well-known gated Gaussian noise model. We have introduced a variation on this model which is the use of a train of gating pulses with constant amplitude and duration but whose spacing is uniformly random. This simulation model has been renamed "gated-squared" Gaussian noise model.

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The finally agreed set of tests consists of six waveform patterns with different numbers of 250 ns pulses which are randomly spaced. These waveforms gate a wideband source of Gaussian noise and must be repeated every 10 ms. The suggested observation period is one minute and the failure criterion is that there can be no more than 1 uncorrectable error per minute. An alternative subjective criterion when this figure is not available is the onset of errors on the decoded picture. We also presented a possible impulsive interference test setup, including the type of equipment needed and a recommended measurement method.

The campaign of laboratory measurements that was used to validate the use of the proposed test waveforms to simulate impulsive interference also yielded other results:

- A 4 to 10 dB improvement in impulsive interference performance obtained with the change from the old UK DTT mode (64-QAM, rate 2/3, 2K and 1/32 guard interval) to the new UK mode (16-QAM, rate 3/4, 2K and 1/32) was measured.
- It was shown that we need just a single parameter to determine the impulsive noise performance of a DTT receiver equipped with no special countermeasures. For pulsed impulsive interferers, receiver performance depends on how many samples of a particular OFDM symbol are affected by the interference, not on how many pulses are present or how they are distributed in the time domain.

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