VDSL2 radiation and its signal characterisation

Overview

The EMC committee of the Radio Society of Great Britain has been monitoring sources of RFI for many years. A particular problem for HF communications is that the density of modern digital equipment in the home is ever increasing. In many cities it is now virtually impossible to receive any but the strongest HF transmissions.

It is normally assumed that below 30 MHz testing for conducted emissions is sufficient to ensure compatibility. In the case of equipment that is not explicitly intended to transmit over air it is further assumed that only the equipment and not its cabling needs testing. In the case of network ports this judgement appears to be based on the assumption that the cabling is able to carry the intended signals without excessive emission.

There are various Digital Subscriber Line (xDSL) standards in use in the UK. These range from ADSL1 using frequencies up to 1.1MHz through VDSL2 up to 17.664MHz in the UK, and a few installations of the new G.Fast which has versions that go up to hundreds of MHz.

Our investigations have shown that the biggest problem for HF communications at present is VDSL2. This has been difficult to prove as often VDSL2 broadband interference goes unrecognised since it looks like background noise. This is not surprising as any characteristic of a communication system that is distinguishable from white noise represents inefficiency in the use of the spectrum. Since VDSL2 is broadband and can approach the Shannon limit over its entire bandwidth it is difficult to identify. This has in the past misled Ofcom into the conclusion that there is no problem with VDSL2 as all one sees is what looks like (elevated) background noise.

RFI survey setup

Measurements are typically made in RSGB members' gardens using a broadband magnetic loop such as a Wellbrook ALA1530 and the RF signals captured to a wave file (.wav) using a software defined radio (SDR). SDRs are used as they are commonly available to members and with the correct processing can produce good relative results. The sampling rates of the recording can be as low as 96KHz but 2MHz or more will produce clearer results provided the host PC doesn't drop any samples. These wave files are then processed using the software Lelantos I have developed. This paper explains how this is done and describes some of the key results.

How to detect VDSL2 RFI.

To detect modern digital communications signals such as VDSL2 within an RF recording one needs to understand the coding techniques used and any aspects of them which are less random. There are two key features of a VDSL2 signal that are not fully random. These are Sync symbols and the Cyclic Extension.

A VDSL2 system typically has 4096 carriers and has a typical symbol rate of 4000/second. Each symbol carries of the order of 10,000 bits spread over the carriers. Of these symbols 256 out of every 257 carry data. The 257th is the same structure but is a sync symbol. All these symbols appear random. The data symbols have been scrambled with a pseudo random sequence. However the sync symbol is a fixed pseudo random sequence and is nominally the same every time. Thus if one can find this sync symbol one can in principle detect this within background noise and thus measure the strength of the VDSL2 signal relative to the noise. However this signal is not strong being only 1/257th of the total VDSL2 noise power.

Before anything else can be achieved one needs to align one's measurement system not only with the xDSL symbol rate but with its timing. An xDSL system starts up with a training phase during which timing parameters are exchanged and symbol alignment is established. This alignment is then maintained to high accuracy using digital phased locked loops relative to a crystal reference. It is not practical for a remote measurement system to obtain this information directly.

To obtain symbol alignment, one can make use of the second non-random feature of an xDSL system. This is the cyclic extension mechanism. This forms the core of the current measurement system as follows.

An introduction to Cyclic Extension.

In any communication system which encodes data into symbols a limiting factor is inter symbol interference. This results from dispersion in the media such that signals arrive spread out in time relative to when transmitted. To avoid these signals impinging on the following symbol one needs to leave gaps between symbols to allow time for the transient response “ringing” of the line to die down. In an xDSL system Discrete Multi-Tone (DMT) symbols are constructed using an Inverse Fast Fourier Transform (IFFT). For VDSL2 this typically generates 4096 carriers at 4.3125 KHz spacing. The individual carriers are modulated with (scrambled) data using Quadrature Amplitude Modulation (QAM). Thus each individual symbol looks like a random mush with a potential frequency spectrum from DC to 4.3125KHz*4096 = 17.664MHz (depending on which carriers are used). 17.664MHz is the top of Band Plan 998ADE17 as used by BT Infinity.

If the signal were to drop to zero immediately during the inter-symbol gaps this would cause distortion leading to inter channel interference. To avoid this the symbols are extended, and their envelopes smoothed to minimise harmonic distortion.

The Cyclic Extension mechanism

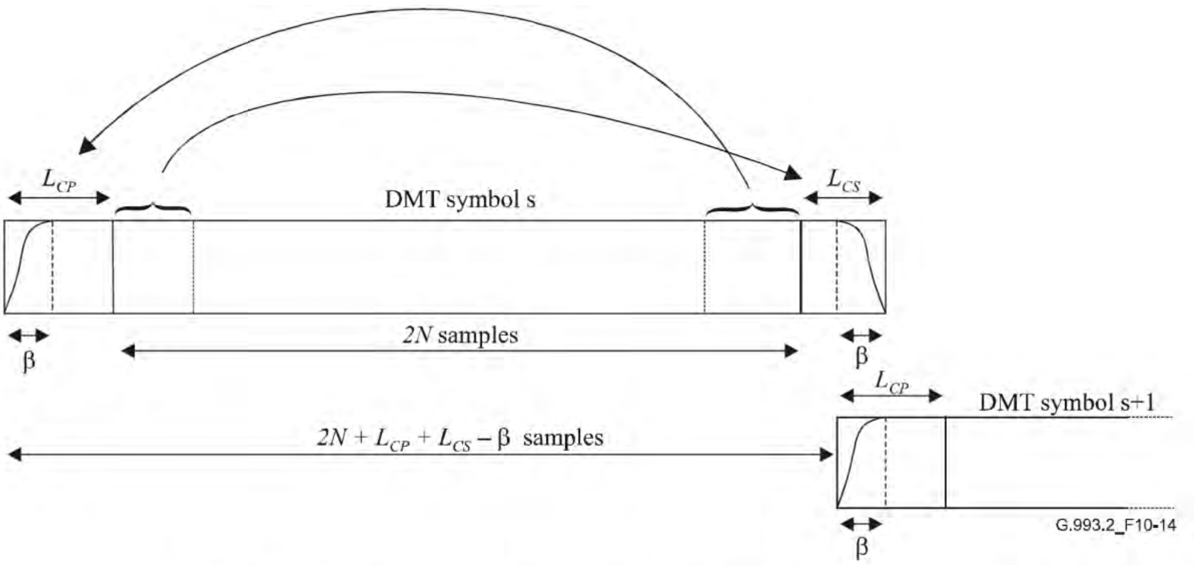


Figure 10-14 – Cyclic extension, windowing and overlap of DMT symbols

Figure 10-14 is derived from the freely available VDSL2 G.993.2 specification. In this figure N corresponds to the number of carriers. For a typical VDSL2 system this is 4096. The symbol generated by the complex IFFT will have 2N=8192 time domain samples (2N corresponds to the Nyquist rate). This is the un-extended symbol length. The diagram shows that part of the end of the DMT symbol is copied and appended to the beginning of the symbol as Lcp. Similarly part of the beginning of the DMT symbol is copied and appended to the end of the symbol as Lcs. Lcp and Lcs are the cyclic prefix and cyclic suffix.

In order to provide the smoothing of the envelopes Lcs and Lcp are overlapped during a period β. There is a gradual fade done during the period β between one symbol and the next so there will be no noticeable join between symbols. (This contributes to the difficulty of detection without suitable software.)

The length of the cyclic extension CE is Lcs + Lcp - β. The VDSL2 specification allows for a varying length of CE and says that the duration of the overlap β is vendor dependant. The length of the CE is negotiated during initialisation of the xDSL line. It is exchanged during negotiation in units of (un-extended symbol length=2N)/64. Though values from 2 to 16 are permitted only support for the value 5 is mandatory. A value of 5 results in the usual symbol rate of 4000 symbols per second. 4.3125KHz (channel spacing) * 64/(64+5) = 4000. This is the value used in practice everywhere.

Detection of the Cyclic Extension

The cyclic extension provides us with both the symbol alignment information and a method of measuring the strength of the interfering xDSL signal.

To detect the cyclic extension in a signal from an SDR we need to do a correlation between the signal recorded by the SDR and a point on the same recording exactly one un-extended symbol period later, since the xDSL signals will be the same and genuine noise will not. To achieve this, we need to construct a digital delay of the correct duration.

Once we have this we need to do the correlation over a window of the length of the cyclic extension CE. The un-extended symbol period is 1/4312.5 seconds = 231.884us. The extended symbol period is 1/4000 = 250us. Thus the length of the CE is 250 - 231.884 = 18.116us.

Processing the signals from an SDR

On some common SDRs and, in particular, the FUNcube Dongle PRO+ the maximum sample rate is 192K of stereo signals (In phase and Quadrature) or equivalent to 384K combined sampling rate resulting in a 192K Bandwidth. In terms of VDSL2 one un-extended symbol time = 231.884us = 89.043 SDR samples at 384K. The correlation window = 18.116us = 6.95 samples at 384K

Producing the delay

For the rather common sampling rate of 192K stereo 89.043 samples can be rounded to 89 but that's not a general solution for other sampling rates. An error of 0.043 samples corresponds to a phase error of about 8 degrees for the highest in band xDSL channel being measured (the Nyquist rate being half the sample rate). That's a fairly negligible error so on the early versions of the software this technique was used, and the error calibrated out. In the current version of Lelantos a software filter is used to give the exact non-integral delay for whatever sampling rate is being processed.

The correlation

Once one has derived the direct and delayed samples the correlation itself is in principle straightforward. All that is required to achieve this is to multiply the direct samples with their corresponding delayed counterparts and sum them over the number of samples in the width of the CE.

Finding the symbol alignment

The outputs from the correlation are noisy. To overcome this Lelantos averages the results over many symbols. Since we don't know the alignment yet Lelantos does this correlation for every possible symbol position. The position that emerges with the highest correlation is our correct alignment. However, there is an additional problem. The sampling rate of the SDR will not be perfectly calibrated relative to that of the VDSL2. When averaging over typically 10,000 symbols there will be alignment drift during the averaging process. To overcome this Lelantos repeats the correlation above that it did for every possible phase alignment also for errors in sampling rate from -25 PPM to +25 PPM. It plots the variation in the highest correlation with sampling error in order to find the correct PPM error. Once it has determined this it then plots the variation in the correlation for different symbol alignments at the known PPM sampling error rate. The resulting graph should have clear peaks during the cyclic extension. Lelantos aligns the trace to show one symbol time with a CE peak at each end.

Measuring the Ratio of VDSL2 noise to background noise.

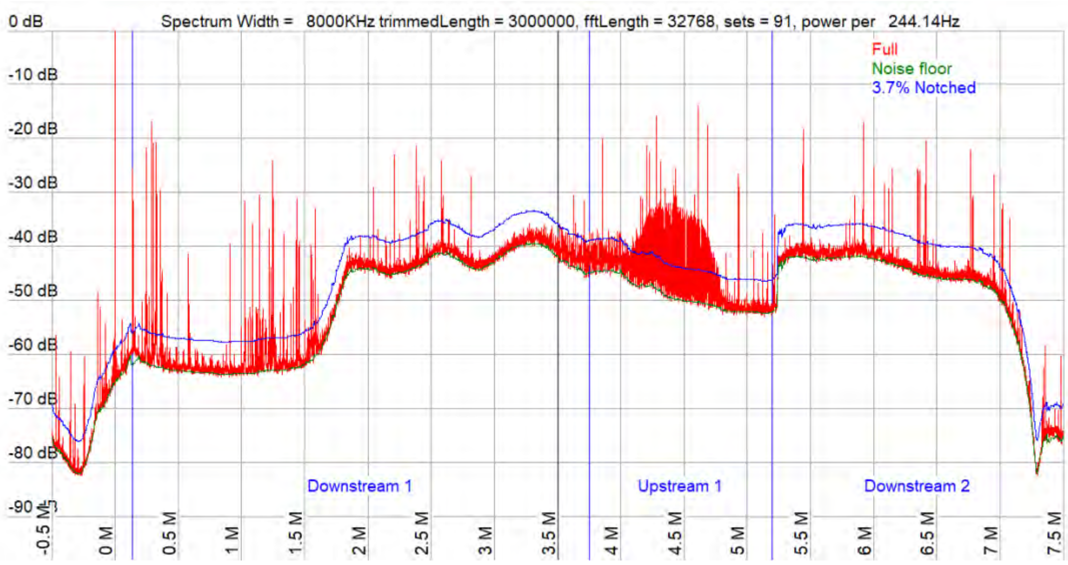
While doing the correlation above Lelantos also takes the squares of the samples with themselves this resulting in the RMS value of all signals. Once we know the symbol alignment we can square root both the correlation sum and the self product sum at the correct alignment. The ratio of the two is the ratio of the RMS values of the VDSL2 signal to the (VDSL2 + background noise) signal. Lelantos then calculates and reports the ratio of the RMS values of the VDSL2 signal to the other signals.

Accuracy check.

To check that the results are correct Lelantos also contains a VDSL2 signal and noise generator. It can generate VDSL2 signals with any ratio of VDSL2 signal to other noise and with any VDSL2 PPM symbol rate error.

Typical Lelantos measurements

Lelantos produces plots of the correlations. There are several parameters adjustable by the user but Lelantos can determine suitable defaults after analysing the wave file. All the graphs below were auto generated this way. They are all generated from wave files recorded in the same RSGB member's rear garden. The loop was placed in the centre of the lawn 12 metres from the house rear wall. The nearest phone lines were from a pole at the front 50 metres away beside the road. The drop wires run from this to the houses in the street. Behind the house are open fields but there is a low voltage overhead power line at the rear 20 metres from the loop at the nearest.



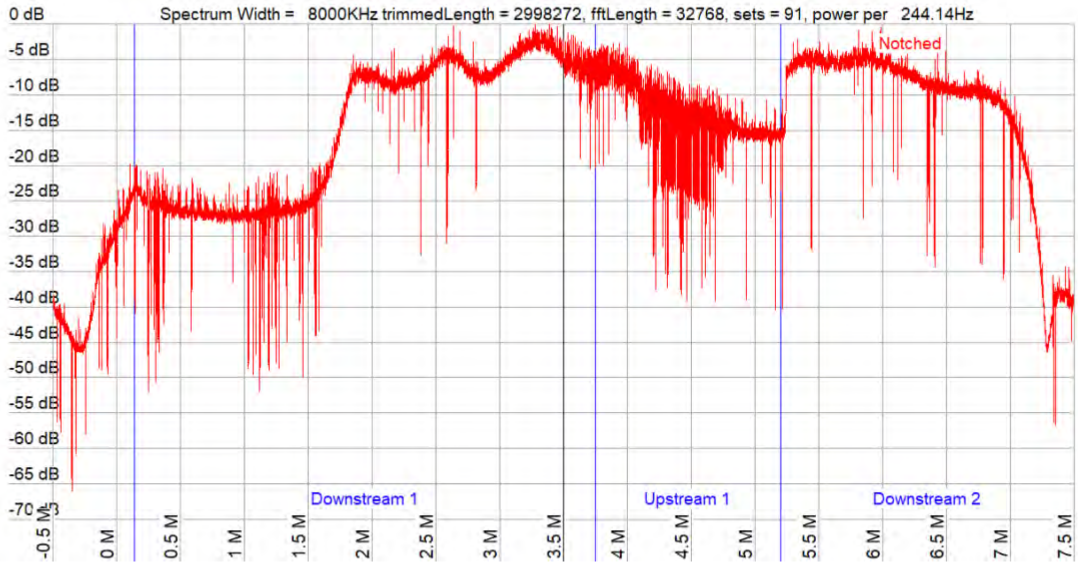
Graph 1

Several 8MHz bandwidth recordings were made using an SDR Play RSP1 connected to the loop. On Graph 1 the red line shows the spectrum of a recording centred on 3.5MHz. The vertical blue lines show the boundaries between the VDSL2 bands. Upstream 1 starts at 3.75 MHz and Downstream 2 starts at 5.2 MHz. One can already see that the spectrum has a 10dB discontinuity at 5.2 MHz where the VDSL2 RFI has raised the noise floor.

To isolate and measure the VDSL2 signals Lelantos needs to do the correlation explained above. However, one can see that there are a lot of strong narrow band signals / RFI. Some of them are 30 to 60 dB above the noise floor. If any of these are harmonically related to the VDSL2 symbol rate they will impair the correlation. To avoid this, we need to remove these strong narrowband signals so that we can do a broad band correlation on everything else.

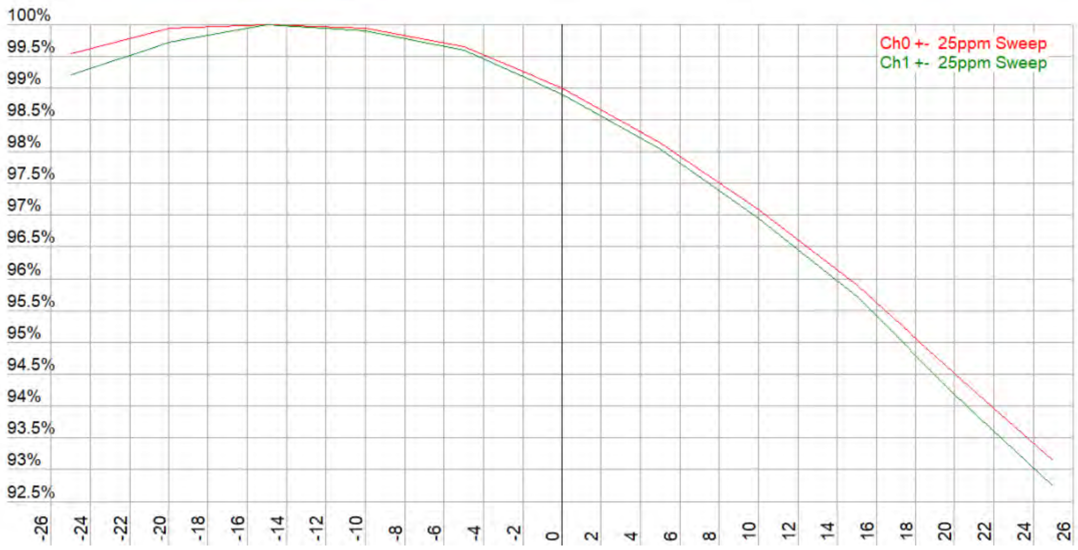
To achieve this Lelantos constructs a mask to define the frequencies to be notched out. The green line on Graph 1 shows the noise floor that Lelantos has determined. The blue line marks a threshold 6dB above the local noise floor. All frequencies where the red spectrum is above this 6dB line are to be masked out. The blue text top right says that 3.7% of the total bandwidth will be notched out. This will enable the broadband correlation to be done but will have negligible impact on the results.

Graph 2 shows the resulting spectrum after the signals to be masked have been notched out. The vertical axis is scaled so that the strongest component is 0dB. You should be able to see that all the narrow peaks in Graph 1 are narrow troughs in Graph 2.



Graph 2

Now that we have a suitable signal to analyse we can do the correlation. As a confidence check the two notched (I/Q) channels are correlated separately.

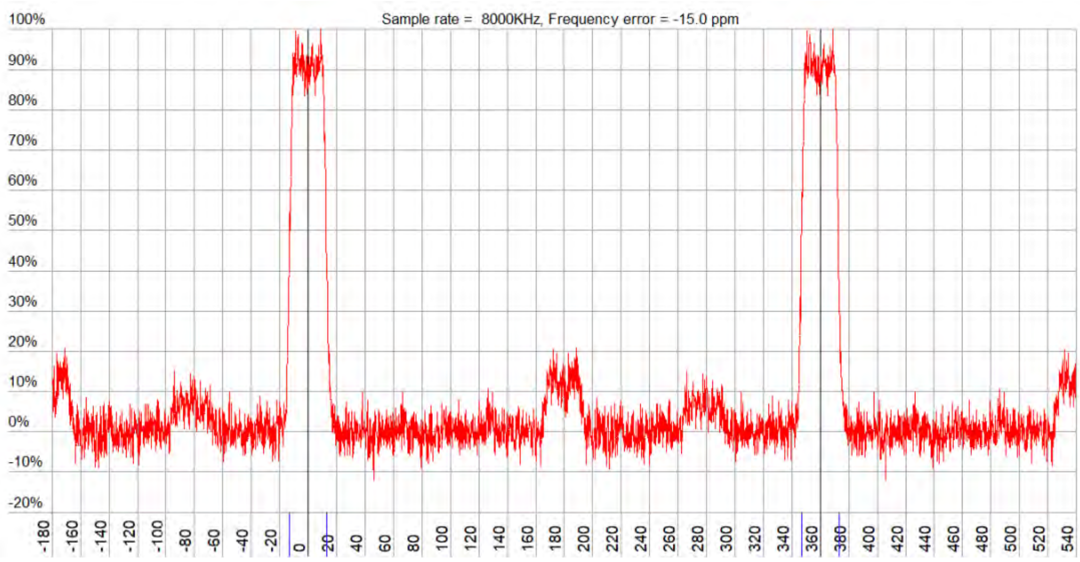


Graph 3

Remember that due to calibration errors (predominantly in the SDR rather than the VDSL2) we need to allow for symbol rate errors during the correlation. Graph 3 shows the variation in correlation with frequency for each channel. In this case they closely agree that the error is -15ppm. As explained above the correlation peaks during the Cyclic Extension. Graph 4 shows the variation of the correlation with time. The horizontal axis is 2 VDSL2 symbol times long is marked in degrees.

At 0 degrees you can see a very clear peak. This peak repeats at 360 degrees. The expected width of the cyclic extension is shown with the two blue lines on the horizontal axis, so it is undeniable that this is VDSL2. The VDSL2 data symbol occupies the gap between the two peaks. Being random it has virtually zero correlation.

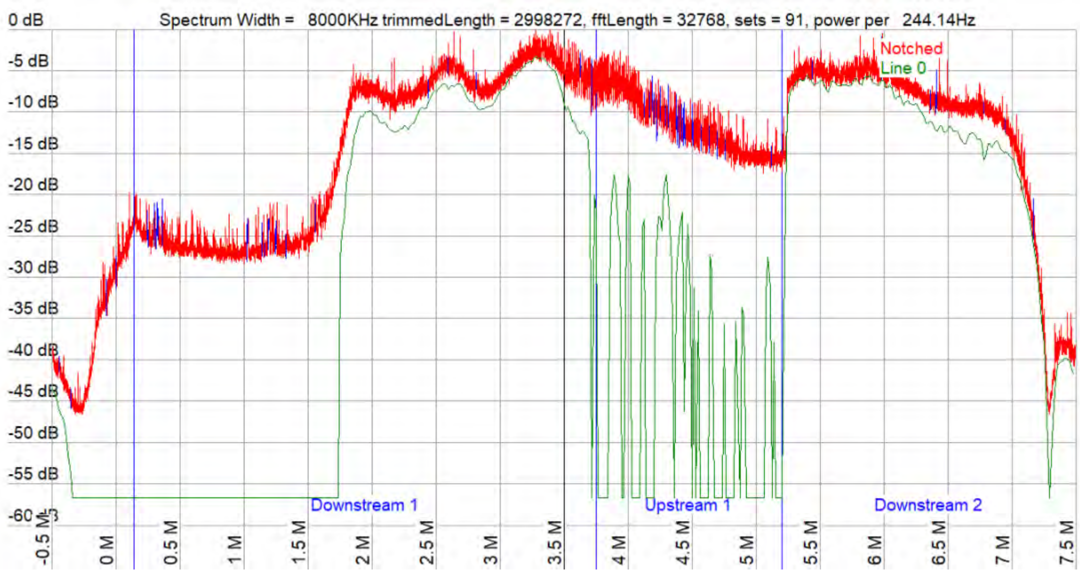
You can see a much smaller peak at 180 Degrees and one smaller still at 280 degrees. These are other VDSL2 lines that are further away or have better balance so show lower RFI. Though at the same symbol rate their symbol timing is not aligned. If the loop antenna is moved one can in fact measure the radiation pattern of each line separately.



Graph 4

Having synchronised up to the symbol timing one can extract the waveforms during each cyclic extension and do a spectrum analysis of their correlation. This is done over many symbols in the wave file to get sufficient separation of the spectrum from other noise.

In Graphs 5,6 & 7 three 8MHz wave files are all analysed in this way so that the entire spectrum of the VDSL2 RFI can be seen. For each the green line shows the spectrum of only the line producing the strongest RFI. The red line is the total spectrum so contains the contributions of all lines so is in places slightly higher.

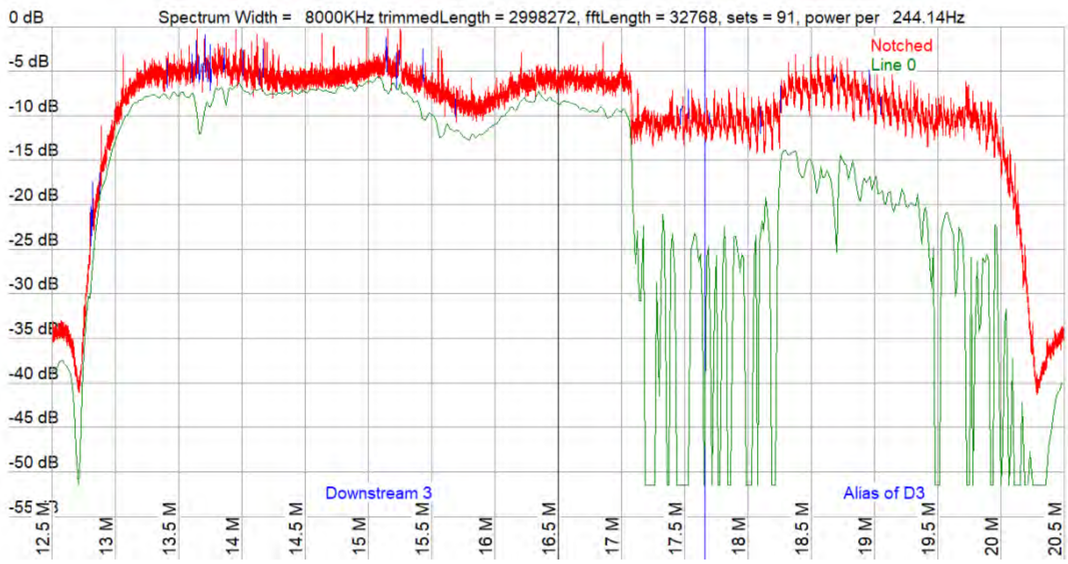


Graph 5

Graph 5 shows the spectrum of the VDSL2 RFI up to 7MHz. You can clearly see that the VDSL2 band Downstream 1 is in use from 1.75MHz up to its limit at 3.75MHz. Upstream 1 should run from 3.75MHz to 5.2MHz. However, it is either very weak, well balanced, or not in use. Above 5.2MHz Downstream 2. The cause of the step in the red spectrum at 5.2 MHz is now obvious.

Graph 6

Downstream 2 is shown continuing on Graph 6 up to 8.5MHz where there is a dip corresponding to the guard band. Beyond this Upstream 2 raises the noise floor all the way up to 12MHz. Again, at 12MHz there is a dip for the guard band. Downstream 3 starts at 12MHz and continues to the next graph.



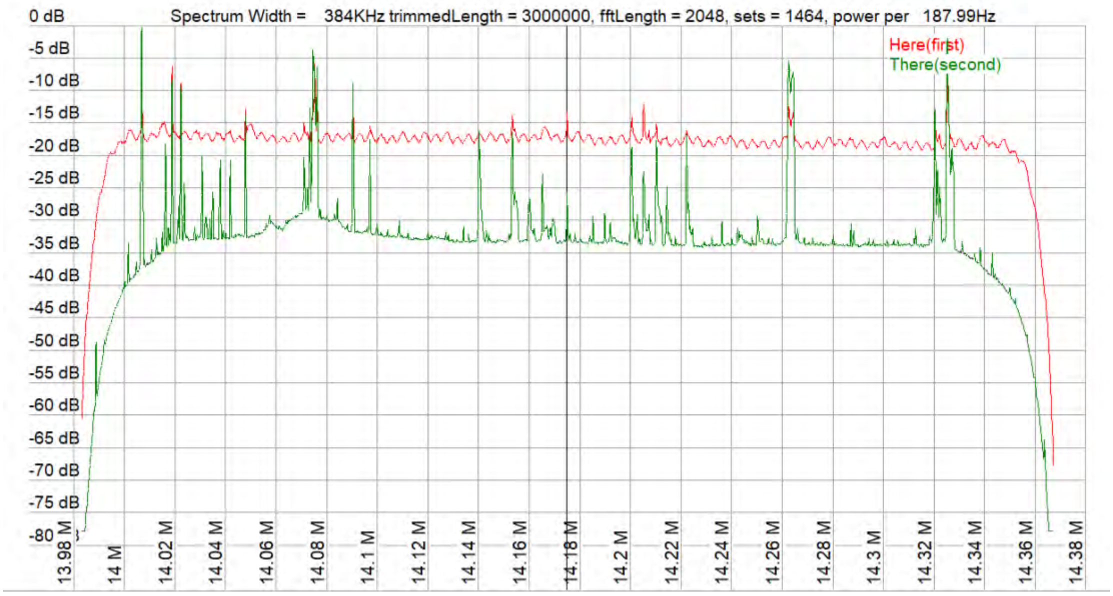
Graph 7

Downstream 3 runs from 12MHz to the highest usable frequency. In this case 17.1MHz. However, there are clearly extraneous VDSL2 signals well above this. The theoretical limit for this VDSL2 band plan is 17.664MHz. VDSL2 symbols are generated using an Inverse Fast Fourier transform (IFFT) and then output via a D/A converter. In Graph 7 one can clearly see that the D/A converter is running at a sampling rate of 2*17.664MHz such that the Nyquist rate is 17.664MHz. This results in frequencies below 17.664MHz aliasing above that. The VDSL2 equipment at the exchange end may have only a crude analogue roofing filter giving the 4dB suppression of this alias.

Comparison of measurement sites

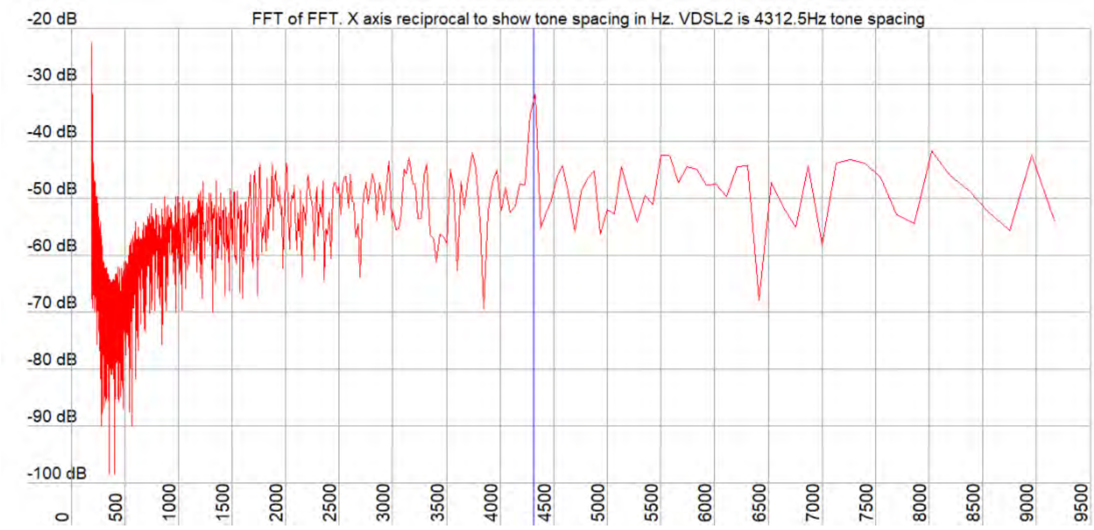
To illustrate the Harmful interference that the VDSL2 is generating we set up a second identical listening station in a farmer's field outside the village. We then made simultaneous recordings in the Amateur bands on both stations.

Graph 8 shows a comparison of the signals recorded on the two stations on the 14MHz band. The red (here) line shows the signals in the member's garden. The green (there) line shows the signals in the farmer's field. It is very clear that most of the signals seen in the field are totally obstructed in the member's garden. One can in fact see the ripple in the red line corresponding to the 4.3125KHz VDSL2 channel spacing.



Graph 8

To make it clear that this ripple is indeed the VDSL2 channels Graph 9 shows the spectrum of that spectrum. There is a very clear peak at 4.3125KHz marked with the blue line.



Graph 9

Summary

A software tool Lelantos has been developed that can be used to identify and measure the relative strengths and spectrum of VDSL2 RFI and desired signals. It can detect and compare the signals from multiple simultaneous VDSL2 lines. The tool also allows comparisons of recordings made at the same time, one being of the receiver obstructed by VDSL RFI and the other in a quiet environment close-by. Lelantos runs on windows so that it can easily be made available to the RSGB's members.

Conclusions

Surveys show that these results are typical for about half of those responding to survey and are not just the result of unusual line faults. It is undeniable that VDSL2 is causing harmful interference in most areas of the country. This was predicted when the VDSL2 standard was developed and accordingly the standard mandates that the equipment can be configured to notch out 16 selectable frequency bands. The amateur radio bands for each region are listed in the standard as frequencies to be notched and it is left up to the operator to select the appropriate notches. In the UK no notches are being applied.

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