DMT Waveform Generation

Introduction

In this lab you will use Matlab to compute the sample values of a DMT symbol conforming (somewhat) to the G.992.1 ADSL standard, output the waveform from an AWG and use a 'scope to measure the signal's power and spectrum.

DMT (Discrete Multi-Tone) is the name used in the ITU ADSL standards for OFDM (Orthogonal Frequency Division Multiplexing). OFDM is a modulation technique that reduces the symbol rate by modulating data onto "sub-carriers" (sometimes called "tones"). This reduction in symbol rate allows guard times to be inserted between symbols with a relatively small reduction in the symbol rate. These guard times allow the inter-symbol interference (ISI) to decay between symbols.

DMT is used on ADSL systems to avoid the ISI that would be caused by reflections from bridge taps and other discontinuities in the local loop.

The format of the downstream DMT signal is defined in Section 7 of ITU standard G.992.1. For simplicity we will limit ourselves to generating a single DMT symbol rather than the complete superframe. We will also set the subcarrier phases to random values rather than using them to carry data.

ADSL DMT Symbols

The G.992.1 downstream signal is an OFDM signal with subcarriers spaced 4.3125 kHz apart. As can be seen from the PSD masks, the subcarriers at the low-frequency end aren't used because they are reserved for the voice signal. Some subcarriers at the high end may also not be used.

The subcarrier spacing is the inverse of the symbol duration. In addition, a guard time containing a cyclic (periodic) extension of the symbol is placed between each symbol.

Waveform Specification

Your DMT signal should include subcarriers between the frequencies 1AB kHz and 9CD kHz where ABCD are the last four digits of your BCIT ID number. For example if your BCIT ID is A00123456 then you should include all subcarriers that fall within the range 134 kHz and 956 kHz.

Each subcarrier should be set to the same amplitude (magnitude) and to a phase chosen randomly from values between 0 and 2π.

The standard requires that a synchronization subcarrier be included in each symbol at subcarrier 64 (with numbering starting at 0). This subcarrier is not modulated (the amplitude and phase are constant) which allows it to used for synchronization. Set it to a phase of 0.

Finally, Section 7.12 of G.992.1 defines the required cyclic prefix as: *The last 32 samples of the output of the IDFT ... shall be prepended to the block of 512 samples...*

DMT Signal Probability Distribution

The DMT (OFDM) signal is the sum of about 200 sine waves ("subcarriers" or "tones") whose amplitudes and phases are determined by the data being transmitted (QAM modulation). The summing of a large number of different signals results in a signal whose voltages have a Gaussian probability distribution.

While we can predict and measure the RMS voltage, the Gaussian distribution has no minimum or maximum voltage. There will therefore always be some samples that fall outside the range the AWG can generate.

When driving a 100 Ω load, the AWG output is limited to a range of about ± 6 V. You should configure the AWG to use these as the high and low voltage levels. If some of the samples exceed these values they will be clipped, resulting in distortion.

The G.992.1 specification requires that the clipping probability be $< 10^{-7}$ but in this lab we will tolerate a higher clipping probability.

Sample Matlab Code

We start by generating an array m containing 1's in the array elements corresponding to subcarriers that will be used for data and 0 elsewhere.

The following Matlab code demonstrates the use of comparison and logical operations to generate an array of truth values (1 for true, 0 for false):

```
N=256 ;
n=0:N-1 ;
f=4.3125*n ;
m=n( f>134 & f<956 & n ~= 64 ) ;
```

The subsequent Matlab code subscripts the array x using the array of logical values m, computed above, rather than using array indices.

We can generate the (complex) subcarrier values using the complex exponential: $Ae^{j\theta}$ is a complex value with amplitude A and phase θ. The rand function generates an array of random numbers. The synchronization subcarrier (64) is also initialized by the code below.

```
A=0.1;
x=zeros(2*N,1) ;
x(m)=A*exp(j*2*pi*rand(length(m),1)) ;
x(65)=A;
```

A property of the Fourier Transform of a real signal is that the real part has even symmetry and the imaginary part has odd symmetry. To generate a real signal we must ensure the symmetry conditions in the frequency domain are met. To do this we use an array that is twice as long as the number of frequency components (512 instead of 256) and make a copy, in reverse order, of the complex conjugates of the positive-frequency subcarrier values. This ensures the symmetry required to end up with real samples after the inverse FFT. We also have to scale the output of the inverse FFT[1] and remove any small imaginary portion of the sample values that sometimes result from rounding errors in the inverse FFT computation:

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[1] The Matlab ifft function includes a scaling factor of $\frac{1}{N}$.

```
x(2*N-n)=conj(x(n+2)) ;
y=N*ifft(x) ;
y=real(y) ;
```

Finally, we add on the cyclic prefix by copying the last 32 samples to the start of the array:

```
y=[y(481:512);y] ;
```

We can compute the RMS voltage as the standard deviation of the waveform:
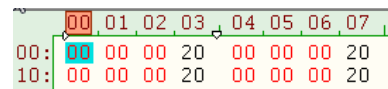
```
std(y)
```

The sample values should be saved to a USB drive using the instructions below for creating .RAF files.
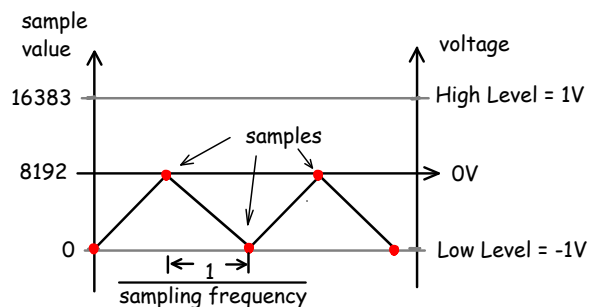
Creating AWG Files

We need to write the sample values to a file in a format that the AWG can read. The Rigol DG1000Z AWG can read CSV or text files with a special header as well as binary files in the RAF (Rigol AWG File?) format documented on page 2-75 of the user manual. We will create an RAF format file for this lab.

An RAF file consists of a sequence of 16-bit sample values in little-endian byte order. Each sample value is an unsigned integer between 0 and 16383 ($2^{14} - 1$) corresponding to the configured low and high levels respectively.

For example, if the AWG was configured for a low level of -1 V and a high level of +1 V and the RAF file contained values alternating between 0 and 8192:

then the output would be a triangle (or square) wave with levels of -1V and 0V:

<image_ref_caption>sample value / voltage diagram showing High Level = 1V at 16383, 0V at 8192, Low Level = -1V at 0, with samples and 1/sampling frequency marked.</image_ref_caption>

The following Matlab code creates a .RAF file from the vector x.

First the sample voltages in x are scaled so they fall in the range 0 to 16383. The variables vhi and vlo should be the High and Low voltages configured into the AWG.

```
s=floor(16384*((x-vlo)/(vhi-vlo)));
s=min(16383,max(0,s)) ;
```

Then the sample values are written to a file as 16-bit integers in lsb-first byte order[2]:

```
f=fopen('filename.RAF','w')
fwrite(f,s,'int16','l')
fclose(f)
```

Procedure

Create a .RAF file containing the DMT signal described in the waveform specification section above and save it your USB drive.

Use the cable with clip leads to connect the AWG Channel 1 output to a resistor and a 'scope probe as shown:
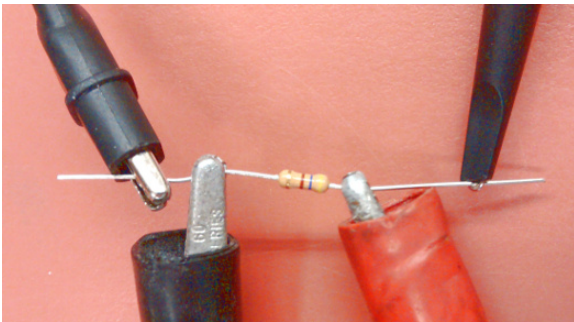

Configure The AWG

- Press [Utility] [Set To Default] [OK] to reset the AWG to it's default settings.

- Press [Utility] [Channel Set] [Output Set]

- Press [Imped] until Load is selected, enter the load impedance on the keyboard (e.g. 100) and then press the button with the appropriate units (e.g. Ω). This configures the load impedance so that the output levels will be calibrated.

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[2]Note that the last argument to fwrite() is a lower-case letter 'l', not the digit one. Omit this argument if using Freemat.

- Press [Arb] to select Arbitrary waveform output.

- Press [Arb Mode] until SRate (sample rate mode) is selected. Note: to access this and some of the following buttons you may need to press [▽] (gray key on the bottom) to toggle between two sets of menus.

- Plug your USB drive into the USB socket on the front of the AWG. You should see the message USB device detected and the USB icon (⯈⥱) will appear on the display.

- Press [Select Waveform] [Stored Wforms].

- Press [File Type] [Arb File]

- Press [Browser] until Dir is selected.

- Use the knob to highlight drive D: (the USB drive).

- Press [Browser] until File is selected.

- Use the knob to highlight your .RAF file.

- Press [Read] and you should see the message Completed! Arb Wave data have been read.

- Press [Arb] to return to the Arb menu.

- Press [Srate] and enter the ADSL sample rate on the keyboard.

- Press [Ampl] until HiLevel is highlighted.

- Enter the voltage that should be output for the maximum sample value (16383).

- Press [Offset] until LoLevel is highlighted.

- Enter the voltage that should be output for the minimum sample value (0).

- Press [Output1] to turn on the Channel 1 output.

Measurements

Configure the 'scope to view a duration covering one symbol. Use AC coupling and remember to configure the probe ratio. Use the $\boxed{\text{SINGLE}}$ button to capture one sweep or adjust the trigger level to obtain a stable display. Use the Measurement menu to display the RMS voltage. Compare this to your predictions. Take a screen capture.
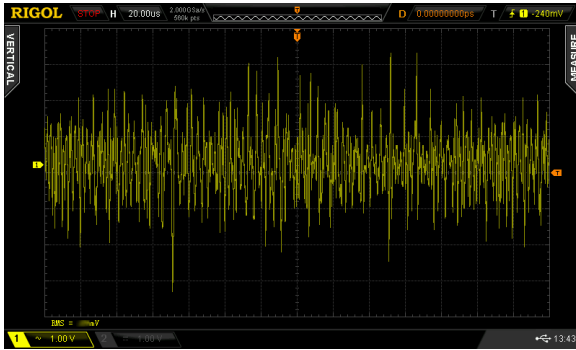
Enable the $\boxed{\text{MATH}}$ trace showing the FFT operation to view the spectrum of the signal. Set the vertical scale to 5 dB/division. Adjust the Horizontal scale to show a frequency range covering the ADSL signal bandwidth.

Use the Cursor menu to set up two vertical (X) cursors on the frequency (Math) display showing the range of frequencies containing subcarriers. Compare to your predictions. Take a screen capture.

Pre-Lab Report

Submit the answers to the following questions to the appropriate dropbox on the course web site. Do this before the lab.

- What sampling rate is assumed in the ADSL specification?

- What is the duration of one DMT symbol plus its cyclic prefix?

- Based on your BCIT ID number, what subcarrier frequency range do you need to generate? What changes do you need to make to the code above to ensure this?

- If the subcarrier amplitude, set by the value of the variable A in the code above, is 0.1 V and the load impedance is 100 Ω, what is the power spectral density (PSD) in units of dBm/Hz? How does this compare to the PSD limit in G.992.1?

- How many bytes will be written to the .RAF file?

- Assuming the DMT signal power is the sum of the subcarrier powers,[3] what RMS voltage do you expect to measure?

- Write the Matlab code required to create and save *your* .RAF file and save it to a text file (e.g. with Notepad++). But don't just copy the code above – it won't work without changes. Include a copy of this code in your pre-lab report and bring the file with you to the lab.

Lab Report

Submit your post-lab report to the appropriate dropbox on the course web site. Your report should contain:

- the identification information asked for in previous labs,

- the Matlab code you used to generate the DMT waveform, including any corrections you made in the lab, and

- the time- and frequency-domain screen captures described in the Procedure section.

- A comparison of the predicted and measured RMS voltages and the predicted and measured range of subcarrier frequencies.

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[3]When independent signals are added, their powers (not voltages) add up.