

Sysblocks

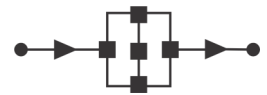
Communications and digital radio techniques



MATRIX

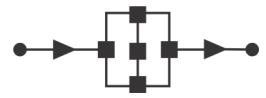
CP6125

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Communications and digital radio techniques

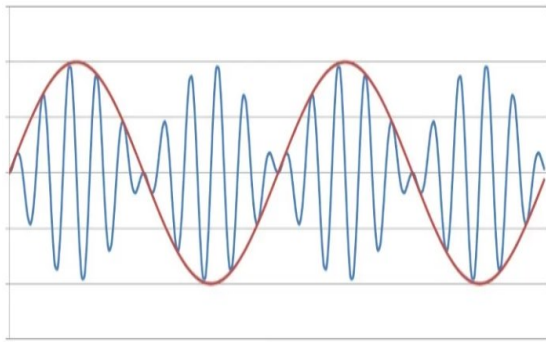
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Worksheet 1

Amplitude modulation

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Sound waves have a limited transmission range. They can get confused with other sound waves if we use 'baseband' transmission. Modulated onto an electronic carrier signal, they can be transmitted further and separated from other 'conversations'. Modulation means modifying a characteristic of the carrier - its frequency, amplitude or phase - using the information contained in the data signal.

About the program

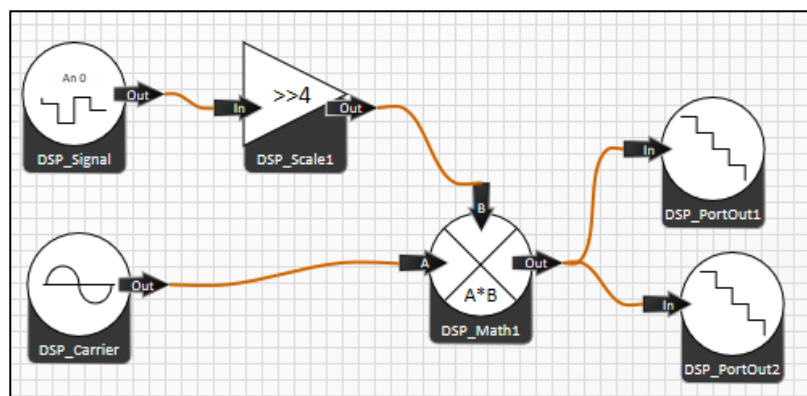
In this program, a signal from input 'IN0' is used to amplitude-modulate (AM) a carrier signal, by multiplying the two together. Two outputs are provided - one for connection to a demodulator while the other is connected to an oscilloscope.

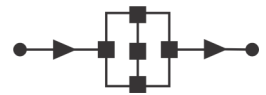
The 12-bit signal from the Input ADC is right-shifted by 4 bits to give it an 8-bit depth.

The carrier Wave Generator has an amplitude of 256, giving it an 8-bit depth also.

Multiplying these two 8-bit signals together gives a 16-bit result.

Project layout:



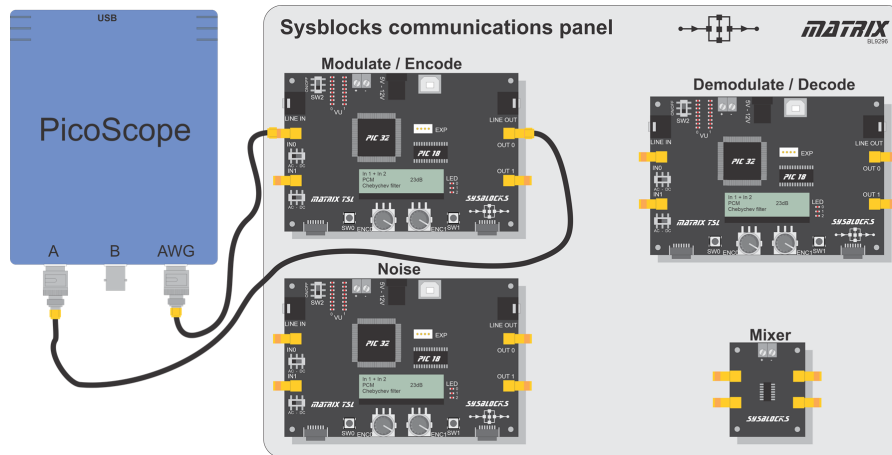


Worksheet 1

Amplitude modulation

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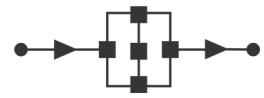
Hardware / firmware:



Firmware	Transmitter - Wk 1 - AM Modulation.fcfx
Inputs	IN0 - AWG signal
Outputs	Transmitter OUT0 - Modulated signal
Oscilloscope	CHA - $\pm 5V$ DC
	Time - $500 \mu s/div$
	AWG - Sine 1kHz, 1V

Over to you:

- Set up the hardware as shown. Ensure that the switch next to input 'IN0' is set to 'AC'.
- View the signal on Picoscope.
With no input signal, the output is a constant 25kHz carrier signal.
- Set the PicoScope 'AWG' to generate a sinusoidal wave with an initial frequency of 1kHz.
- Observe the modulated signal as you then vary its amplitude and frequency.
- Change the waveform shape of the signal and notice the effect on the modulated signal.
- Add a 'spectrum view' to the Picoscope and change the timebase to 10ms/div.
With no input signal, the spectrum shows a single peak representing the 25kHz carrier.
Two other peaks are visible around 15kHz above and below the carrier, resulting from the digitisation of the carrier wave.
- Switch on the 'AWG' output, with a frequency set to 1kHz.
- Observe the two peaks resulting. One peak is 1kHz above the carrier and one is 1kHz below. These are known as sidebands.
- Alter the amplitude and frequency of the 'AWG' signal. Observe the effect on the spectrum.
- Set up the 'AWG' to sweep frequencies from 100 Hz to 5 kHz.
- Look at the spectrum analyser output. As the modulating signal increases in frequency, the two peaks move away from the carrier in opposite directions.
- Notice what happens when you change the shape of the waveform.



Worksheet 1

Amplitude modulation

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Challenges

1. Signal levels:

The ADC input component has its 'Auto Adjust' property set to 'No'. As a result, it gives a full-scale output of 12-bits rather than the 16-bit indicated by the 'signed int' data type. The output is then right-shifted by 4-bits giving it a bit depth of 8-bits. Then the multiplier has two 8-bit depth inputs and so produces a 16-bit output. Experiment with this balance:

- What happens if the carrier is increased to 10 bits (by increasing its 'Amplitude' property) and the signal is reduced to 6 bits (by changing the Scaler 'Initial Integer Scaler' property)?
- How does shifting the input signal affect the modulation depth?

Compare this with the effect of changing the amplitude of the signal.

2. Interrupt frequency:

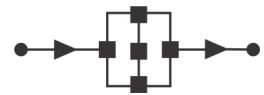
The interrupt frequency is controlled by 'Timer1'. This runs on a clock frequency of 200MHz, meaning one clock pulse is counted every 5ns.

When it reaches the 'rollover' value, set in the 'Interrupt' icon properties in the 'Main' macro, it triggers the 'ISR' macro, resets and starts counting again. A rollover setting of 1227 means that this happens every $1227 \times 5 = 6135\text{ns}$, giving an interrupt frequency of 162.999kHz.

On each interrupt, the DSP_Signal component causes the waveform generator to output the next step in the waveform. There are 163 steps and so each carrier cycle takes $6135 \times 163\text{ns}$ (roughly 1ms), giving a waveform frequency of 999.995Hz.

The DSP_Carrier component is configured with a multiplier of 25.0013. This changes the carrier frequency to 25kHz. Modify the numbers used. For example:

- change the timer rollover to 1600 to give an interrupt frequency of 125kHz.
- change the number of samples to 125 to give a generator frequency of 1kHz which, when multiplied by exactly 25, gives 25kHz.



Worksheet 1

Amplitude modulation

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Challenges

3. Look at the carrier signal in the spectrum view and compare it with the previous version. There are more artefacts in the spectrum. Why is this?

The digitised carrier is not a pure sinusoidal wave but has steps in it. Fourier analysis states that a wave that such a wave can be constructed from a series of sinusoidal waves.

Using a sample frequency that is not an exact multiple of the carrier frequency means that the number of samples in each cycle is constantly changing and so the Fourier series changes from cycle to cycle. The quantisation error energy is spread across the spectrum rather than being in one place. Ideally we want to keep the spectrum as flat as possible as any artefacts in the spectrum will be audible when demodulated.

So what?

The mathematical identity

$$\sin f_1 \times \sin f_2 = \frac{1}{2} [\cos (f_1 - f_2) - \cos (f_1 + f_2)]$$

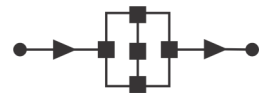
predicts that amplitude modulation will produce two sidebands.

Multiplying together two sinusoidal signals of frequencies f_1 and f_2 produces two components with frequencies equal to the sum and difference of f_1 and f_2 (plus a phase difference.)

The transmitted information is duplicated in the sidebands and so, in practice, one can be filtered out, producing what is known as single-sideband AM transmission.

The change in carrier amplitude produced by AM is measured as the depth of modulation. For example, if the carrier amplitude varies by 50% above (and below) its unmodulated level, the depth of modulation, m , is 0.5.

The maximum desirable value for m is 1.0. With this, the carrier amplitude can reach zero. Beyond this, an effect known as overmodulation risks distorting the signal when the transmission is demodulated.



Worksheet 2

AM demodulation

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Amplitude modulation (AM) takes the original signal spectrum and creates two copies of it, one above the carrier frequency and one below. These are known as sidebands.

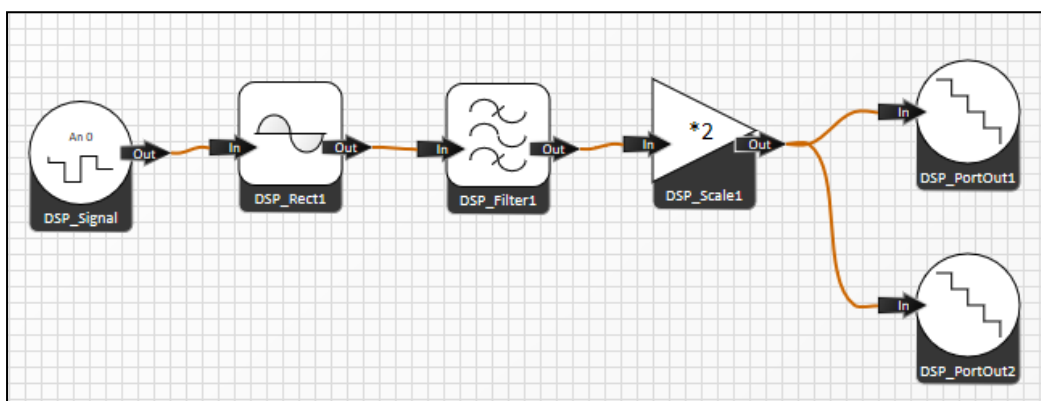
Demodulation transfers the signal spectrum back to its original location in the frequency spectrum.

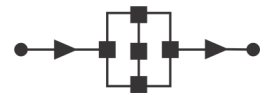
About the program

This program takes the amplitude-modulated signal, from the last worksheet, and reconstructs the original modulating signal. This is done by rectifying and filtering the AM signal in much the same way as in a simple analogue receiver.

The first block samples the ADC input. The next, the DSP rectifier, flips the negative part of the signal positive. Then the DSP filter, configured as a bandpass filter with cut-off frequencies at 36Hz and 5kHz, filters high frequencies, to remove the carrier, and low frequencies, to remove the DC component added during rectification. The signal is then scaled, (multiplied by two in this case,) to compensate for the reduction in dynamic range caused by the rectification. The signal is then outputted via two DACs, allowing the use of stereo speakers or headphones.

Project layout:



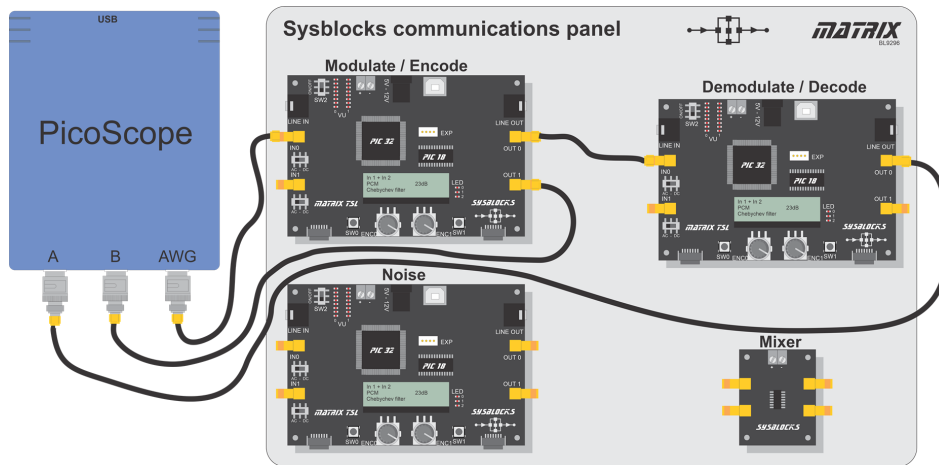


Worksheet 2

AM demodulation

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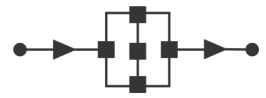
Hardware / firmware:



Firmware	Transmitter Wk 1 - AM Modulation.fcfx
	Receiver Wk 2 - AM Demodulator.fcfx
Inputs	Transmitter IN0 - AWG signal
Outputs	Transmitter OUT0 - Modulated signal
	Transmitter OUT1 - Modulated signal
	Receiver OUT1 - Reconstructed signal
Oscilloscope	CHA - $\pm 5V$ DC
	CHB - $\pm 5V$ DC
	Time - 500 μs /div
	AWG - Sine 1 kHz, 0.5V

Over to you:

- View the demodulated signal on Picoscope channel A. How well is it reproduced?
- Increase the amplitude of the original modulating signal.
What happens to the demodulated output signal at higher amplitudes?
- Change the frequency of the original signal.
What happens to the demodulated signal as the frequency goes up?
- Take a series of measurements of amplitude and frequency of the demodulated signal. Use them to create a graph of amplitude vs frequency and measure the receiver bandwidth.
- Change the waveform shape of the original modulating signal.
How well are other shapes reproduced?
- Add a 'Spectrum view' to the Picoscope and change the timebase to 10ms/div.
With no input signal, the 25kHz carrier is visible in the modulated signal.
- Switch on the 'AWG' and observe that a 1kHz sinusoidal signal produces peaks above and below the carrier and also at 1kHz in the spectrum of the demodulated signal.
- Set up the 'AWG' to sweep frequencies from 100Hz to 5kHz.
As the signal frequency increases, the peaks move away from the carrier in the spectrum view. However, only a single peak is seen in the demodulated output signal.



Worksheet 2

AM demodulation

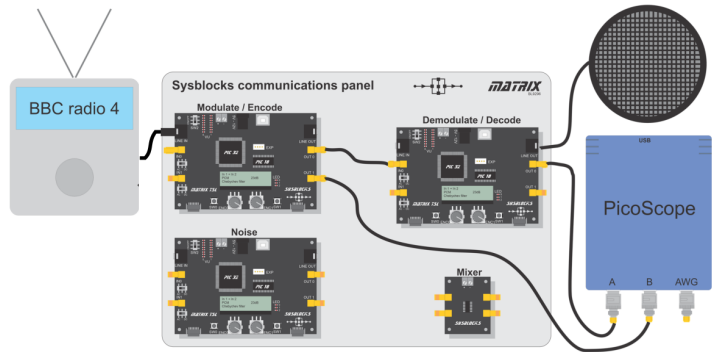
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Challenge

- Download 'Wk 1 - AM Mod - line in.fcfx' to the left-hand Sysblock. This is the same as the previous program - but uses the AN1 line input via the 3.5mm audio jack.
- Connect this to an audio source such as a laptop or phone headphone socket.
- Use an app or a website such as <https://onlinetonegenerator.com/> to generate test signals.
- Repeat a few tests to prove that the system works as it did when connected to the Wave Generator.
- Play music through the system and note the quality of the output. What factors affect this quality?
- Compare speech and music, or music of different genres.

(Note - mobile phone jack connectors are sometimes 4 pole and may need a special cable.)

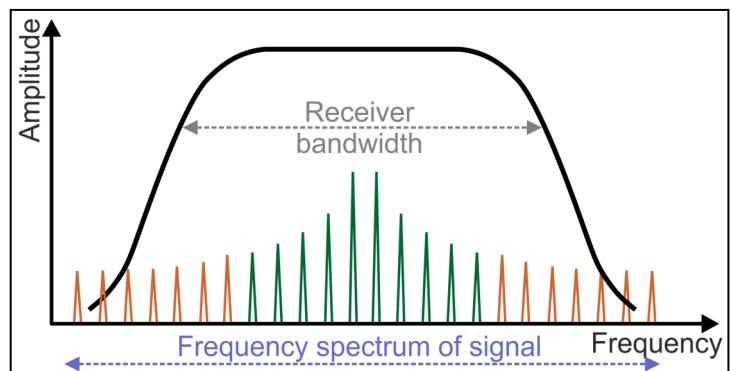
Hardware / firmware:

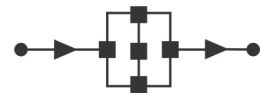


Firmware	Transmitter Wk 1 - AM Mod - line in.fcfx
	Receiver Wk 2 - AM Deodulator.fcfx
Inputs	Transmitter line in - Radio or audio signal
Outputs	Transmitter OUT0 - Modulated signal
	Transmitter OUT1 - Modulated signal
	Receiver OUT1 - Reconstructed signal
Oscilloscope	Receiver line out - Speaker
	CHA ± 5 volts DC
	CHB ± 5 volts DC
	Time: 500 μ s/div
	AWG: Sine 1 kHz, 0.5V

So what?

The receiver bandwidth determines the fidelity of the signal received. The diagram shows the frequency spectrum of a signal and the effect of the receiver's bandwidth. Only the frequency components shown in green will be reproduced accurately in the receiver output.

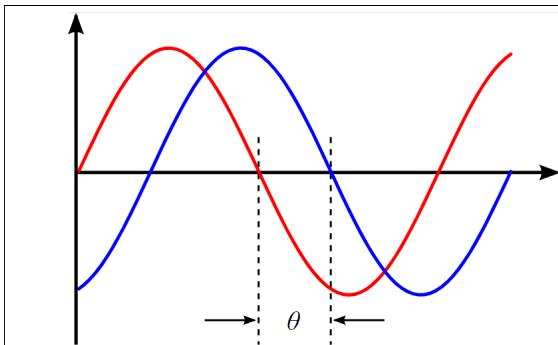




Worksheet 3

Phase-locked loop

Communications and digital radio techniques



The Phase-Locked Loop (PLL) is a basic element in many modern electronic systems.

Its function is to create an output signal having a frequency controlled by an input signal.

It is used mainly in modulators/demodulators and in clock generation and frequency multiplication.

About the program

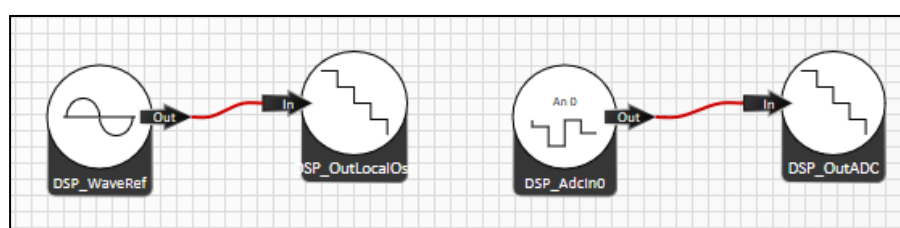
A digital phase-locked loop typically consists of a numerically-controlled oscillator (NCO), loop filter and phase detector.

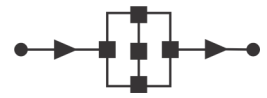
The phase detector compares the PLL input signal with that generated by the NCO and then outputs a signal indicating the phase difference between them. The loop filter then uses this to generate a signal voltage (the 'error' signal) which adjusts the frequency of the NCO output until it locks onto the input frequency. The result - an output frequency equal to that of the input, shown by a constant phase shift (which could be zero) between them.

The program implements this mainly in code rather than by using DSP blocks. An interrupt samples both the incoming signal from the input block and the NCO signal, created by a DSP Wave Generator. It compares each sample with the previous to find where each signal crosses zero. The simplest (but coarse) measure of phase difference is the number of samples between these zero crossing points. It is improved by estimating how far through each sample period the zero crossing occurred. The resulting scaled 'error' signal at the output is used to adjust the NCO oscillator frequency to keep the phase difference constant, i.e. keep the two signals at the same frequency. As the frequency of the SysBlocks input signal changes this 'error' signal should go up and down in sympathy with it.

The program allows adjustment of the centre frequency of the local oscillator, (the NCO) i.e. the NCO frequency when there is no input signal, and of the bandwidth, (which determines the phase difference range that the PLL can handle) to match the range of the input signals.

Project layout:



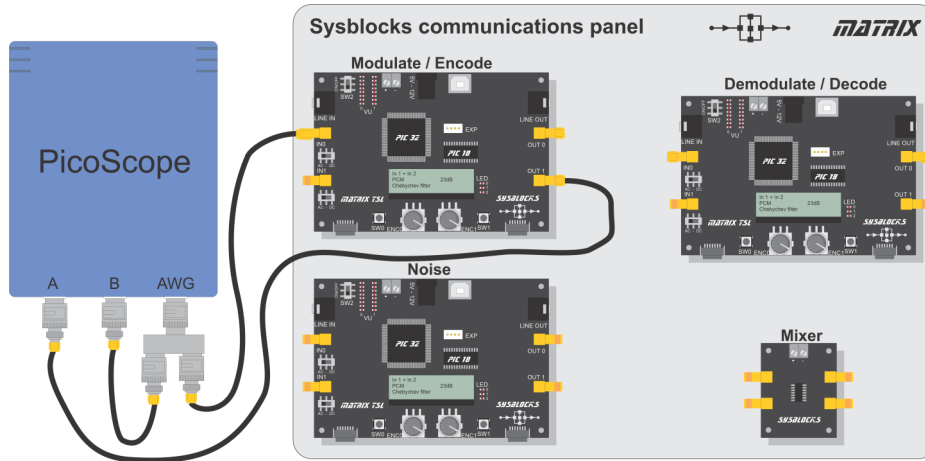


Worksheet 3

Phase-locked loop

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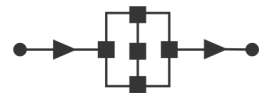
Hardware / firmware:



Firmware	Transmitter Wk 3 - PLL.fcfx
Inputs	Transmitter IN0 - AWG signal
Outputs	Transmitter OUT0 Phase error signal
	Transmitter OUT1 Phase error signal or NCO signal
Controls	Transmitter ENCO - Select a parameter to adjust
	Transmitter ENC1 - Adjust selected parameter
Oscilloscope	CHA ±5V DC
	CHB ±5V DC
	Time - 20 μs/div
	AWG: Sine 25 kHz, 1.0V

Over to you:

- Set up the hardware as shown earlier. Ensure that the switch next to input 'IN0' is set to 'AC'.
- Use the encoders to set the NCO centre frequency to 25kHz and bandwidth to 2.5kHz.
- 'OUT0' always outputs the 'error' signal. 'OUT1' provides either the NCO signal or the 'error' signal, depending on the encoder settings. Use the encoders to set the reference output to 'On' to select the NCO signal from 'OUT1'.
- Set the PicoScope 'AWG' to generate a sinusoidal wave with frequency 25kHz, amplitude 1.0V and offset 0V.
- Examine the Picoscope trace for the signal from 'OUT1' to verify that the PLL output and AWG signals have the same frequency and a constant phase difference i.e. are locked.
- Confirm this by looking at the trace for the signal from 'OUT0' - a horizontal trace means a constant phase difference.
- Reduce the input frequency to 24kHz.
Is the output still locked? What has happened to the phase difference between the signals?
- Progressively reduce the input frequency in steps of 2.5 kHz.
At what point does the system stop locking?
- Increase the frequency in the same way to find the upper limit of locking.



Worksheet 3

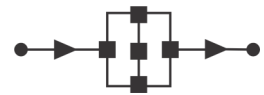
Phase-locked loop

Communications and digital radio techniques

Over to you.....

- Change the bandwidth setting to 5kHz.
How do the upper and lower locking limits change?
- Use the cursors on the Picoscope display to estimate the phase offset between the waves.
- Measure these values for a range of input frequencies and bandwidth settings.
Copy the following table and complete it with your results.
- On the same set of axes, plot graphs of phase offset against frequency for each value of bandwidth.

Input frequency /kHz	Phase Offset		
	BW = 2.5 kHz	BW = 5.0 kHz	BW = 10 kHz
15	No Lock		
17.5	No Lock		
20	No Lock		
22.5			
25			
27.5	No Lock		
30	No Lock	No Lock	
32.5	No Lock	No Lock	



Worksheet 3

Phase-locked loop

Communications and digital radio techniques

Challenges:

Measuring PLL performance:

- 1. Lock-in Time** - the time taken for the PLL to acquire a lock. (The system is in lock when the phase difference signal output at 'OUT0' is constant.)
- 2. Step Response** - how quickly the PLL responds to a step change in frequency.

1. Lock-in time:

- This uses the AWG editor to generate a signal having a flat line followed by a burst of a sine wave.

You can set this up with a Picoscope as follows:

start frequency - 25kHz;
amplitude - 1V, offset - 0V;
triggers - active;
cycles per trigger - 25.

- On the Picoscope trace, you will see a delay following the first cycle of the sinusoidal signal before the PLL locks onto it (relatively constant phase difference). This delay is the lock-in time. Estimate this lock-in time.

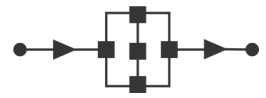
2. Measuring step response:

- The frequency step change can be achieved, using the Picoscope 'AWG' in sweep mode. Set the start and stop frequencies to the two desired points and the frequency step value to the difference between them, to give only one step.

For example:

start frequency - 25 kHz,
stop frequency - 26 kHz,
frequency increment - 1kHz,
increment time interval -10ms.

- As the frequency steps, so does the phase difference signal from the Sysblocks board, on OUT0.
- Set the trigger on Picoscope to the phase difference channel at a voltage mid-way between the two levels. How long after the input frequency changes is the output stable?
- Is there a difference between the result for a rising transition and that for a falling transition?



Worksheet 3

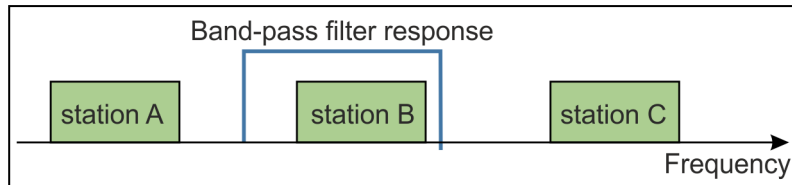
Phase-locked loop

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So what?

A simple AM radio uses a band-pass filter to select signals around the frequency of the chosen transmitting station and reject others.

The process does not have to be precise, as long as the filter passes most of the desired signal and rejects most of the unwanted signals.



Though its response is not centred on it, the above filter passes station B but rejects A and C.

Frequency modulation and other advanced modulation schemes require a precise frequency reference. It would be difficult to construct a local reference frequency that was accurate enough. The phase-locked loop offers an easy means of obtaining an accurate reference signal matching the oscillator frequency used at the transmitter.

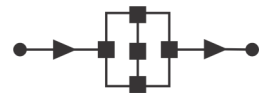
The PLL causes the output of the NCO to vary, controlled by the detected phase. Since phase difference is between 0 and 360° , the PLL is designed so that a specific range of frequencies is covered by this range. If the incoming signal lies outside this range, then the PLL will fail to lock.

Once the PLL locks onto a signal, it stays locked on and mirrors any changes in the incoming signal frequency.

The performance of the PLL, measured by its lock-in time and step response, place limits on the modulating signal that can be used. The better the PLL performance, the higher the bandwidth or data rate that can be demodulated.



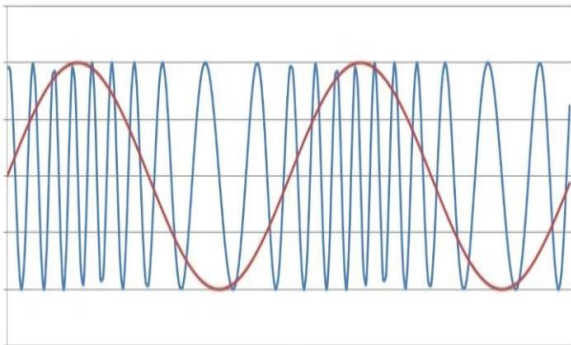
Two phase-locked loops with different bandwidths around a centre of 25 kHz



Worksheet 4

Frequency modulation / demodulation

Communications and digital radio techniques



Their resistance to amplitude variations and noise gives frequency-modulated signals, (FM) a higher signal-to-noise ratio (SNR) and better signal quality. Moreover, superior frequency response means that FM signals can transmit a wider range of frequencies, allowing transmission of high-fidelity audio signals in both mono and stereo.

About the program

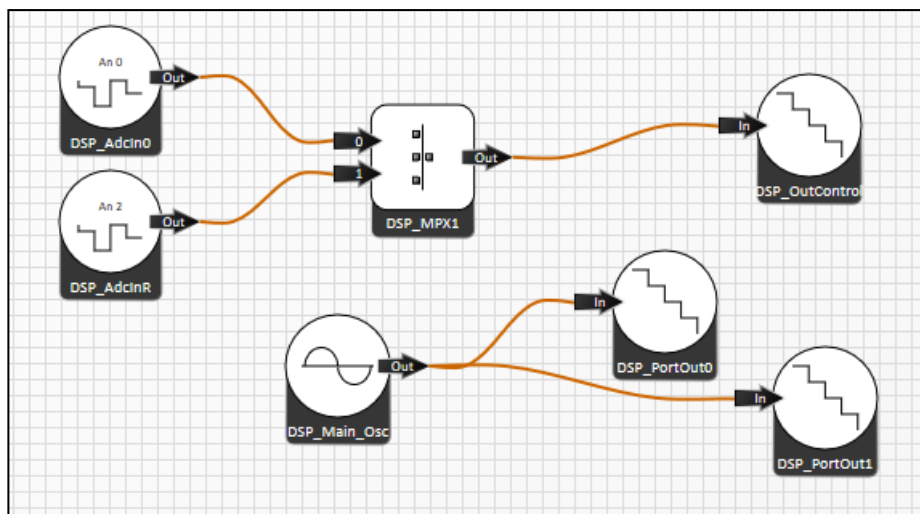
The FM program samples the incoming signal and adjusts the output of the Wave Generator to generate a signal with a frequency proportional to that sample voltage, a frequency-modulated output signal, in other words.

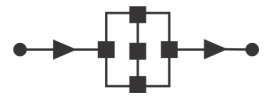
This program converts voltage to frequency, whereas the PLL program studied in the previous worksheet gave us a conversion from frequency to voltage. Putting the two programs together, we can modulate and demodulate FM audio signals - we have a FM communication system.

The bandwidth of this system can be adjusted to demonstrate its effect on quality, which is far from hi-fi but good enough to demonstrate the principle.

1. Frequency modulation

Project layout:



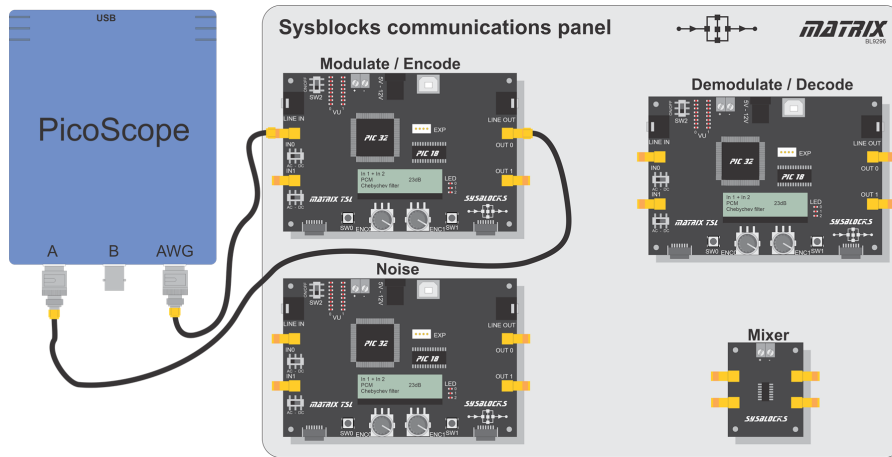


Worksheet 4

Frequency modulation / demodulation

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Hardware / firmware:

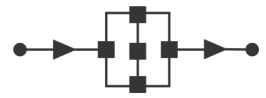


Firmware	Transmitter Wk 4 - FM Modulator.fcx
Inputs	Transmitter IN0 - AWG signal
Outputs	Transmitter OUT0 - Frequency modulated signal
Controls	Transmitter ENC0 - Select a parameter to adjust
	Transmitter ENC1 - Adjust selected parameter
Oscilloscope	CHA $\pm 5V$ DC
	Time: 50 $\mu s/div$
	AWG: DC

Over to you:

- Set up the hardware shown above. Ensure that the switch next to input 'IN0' is set to 'DC'.
- The program parameters are set to:
source = 'IN0', carrier frequency = 25.0kHz and bandwidth = 5.0kHz.
- Set the wave-type of the Picoscope AWG to 'DC voltage', to output a steady, unvarying voltage. Add a measurement of the frequency of channel **A** to the display and observe the output frequency as the DC voltage is altered.
- The output frequency should be proportional to the input voltage with a slope that depends on the selected bandwidth. Copy and complete the following table and use the results to plot graphs of output frequency against input voltage for the three bandwidth settings all on the same axes.

Input voltage	Output frequency		
	BW = 2.5kHz	BW = 5.0kHz	BW = 10.0kHz
0.5			
1			
1.5			
2			



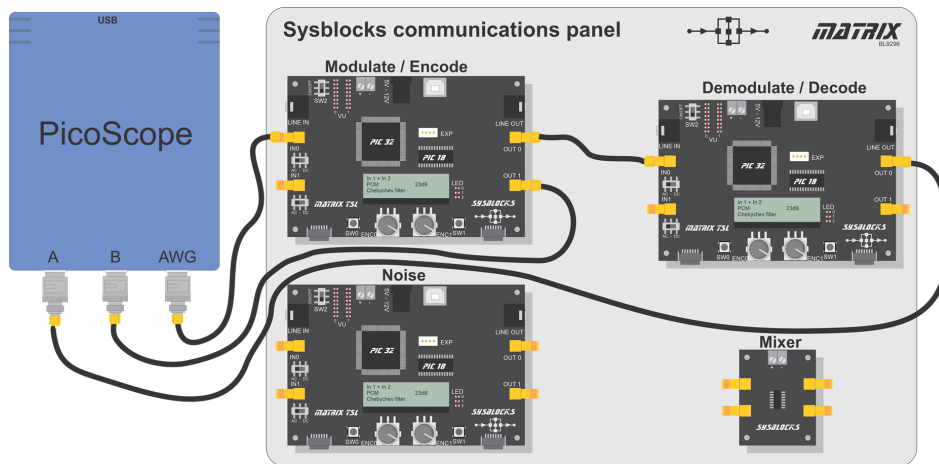
Worksheet 4

Frequency modulation / demodulation

Communications and digital radio techniques

2. Frequency Modulation and Demodulation

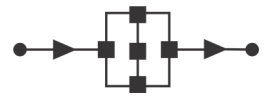
Hardware / firmware:



Firmware	Transmitter Wk 4 - FM Modulator.fcfx
	Receiver Wk 3 - PLL.fcfx
Inputs	Transmitter IN0 - AWG signal
Outputs	Transmitter OUT0 - PLL output
Controls	Transmitter ENCO - Signal source
	Transmitter ENC1 - Frequency
	Receiver ENC1 - Frequency
Oscilloscope	CHA $\pm 5V$ DC
	CHB $\pm 5V$ DC
	Time: 50 μs /div
	DC 1V

Over to you:

- Set up the hardware shown above. The left-hand Sysblocks board acts as the FM modulator while the other, with the PLL program from the previous worksheet, acts as a demodulator.
- Set the centre frequency of each board to 25kHz and the bandwidth to 10kHz.
- Set the Picoscope 'AWG' to output a DC voltage of 1V.
- Configure Picoscope to display measurements of:
 - the DC average of channel A;
 - the frequency of channel B.
- Investigate the effect on these of increasing the 'AWG' output in steps up to 2V.



Worksheet 4

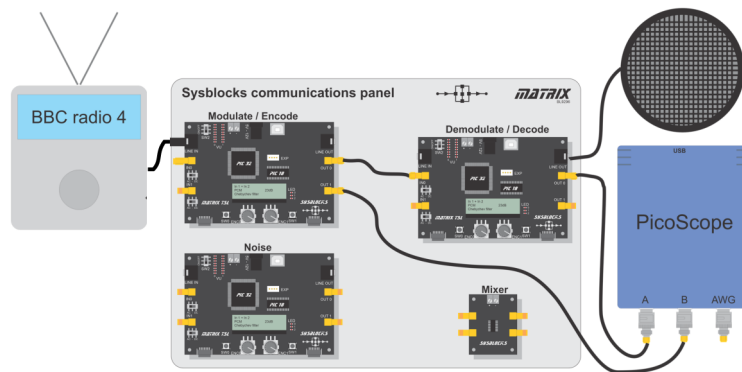
Frequency modulation / demodulation

Communications and digital radio techniques

Challenges:

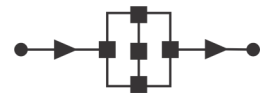
- Investigate what happens when the IN0 input is time-varying (AC) rather than constant DC.
 - Change the coupling switch next to 'IN0' to 'AC'.
 - Set the Waveform Generator to produce a 100Hz sinusoidal wave with amplitude of 0.5V.
 - Investigate:
 - how well the input signal is reproduced at the output;
 - the effect of increasing the frequency of the input signal;
 - the effect of increasing the amplitude of the input signal;
 - the effect of adjusting the system bandwidth.
- Replace the input source with a source of 'real' audio signals.

Hardware / firmware:



Firmware	Transmitter Wk 4 - FM Modulator.fcfx
	Receiver Wk 3 - PLL.fcfx
Inputs	Transmitter Line in Audio source - e.g. radio
Outputs	Transmitter OUT0 PLL output
	Receiver Line out Speaker
	Receiver OUT0 Audio out
Controls	Transmitter ENC0 Signal source
	Transmitter ENC1 Frequency
	Receiver ENC1 Frequency
Oscilloscope	CHA ±5 volts DC
	CHB ±5 volts DC
	Time: 50 μs/div
	DC, 0.5V

- Use the left hand rotary knob to change the source for the modulator to 'Jack'. This changes the signal source to AN1 on the 3.5mm jack socket.
- Connect an audio source such as the headphone socket of a laptop or radio.
- Test the system to show that it still works as when connected to the Wave Generator.
- Play music and speech through the system and notice the quality of the output.
- Use the Encoder knobs to adjust the carrier frequency and the bandwidth on both the transmitter and receiver. What factors affect the quality of the output?



Worksheet 4

Frequency modulation / demodulation

**Communications and
digital radio techniques**

So what?

Choosing the most appropriate bandwidth for a communication channel is not straightforward as there are conflicting demands.

The wider the bandwidth:

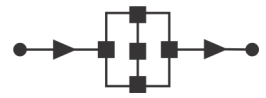
- the greater the data rate it can transmit;
- the better the quality of speech and music transmission.

The narrower the bandwidth:

- the greater the number of radio stations that can broadcast within a particular region of the electromagnetic spectrum;
- the greater the number of signals that can be multiplexed onto a communication channel.

The bandwidth of a communication channel depends on factors like:

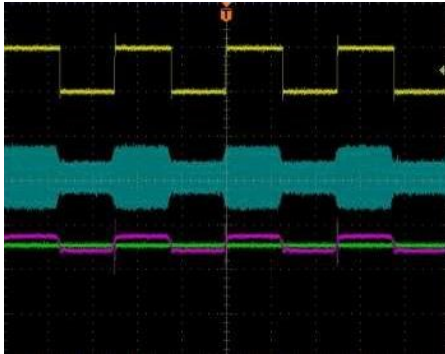
- the medium used;
- the length of the channel;
- the quality of the channel components;
- the signal-to-noise ratio.



Worksheet 5

Digital AM - OOK and ASK

Communications and digital radio techniques



The modulation techniques studied so far have combined an analogue signal with a carrier wave. Next, we examine ways of combining digital data with a carrier. The first looks at two techniques that use amplitude modulation, known as OOK (on-off keying) and ASK (amplitude-shift keying).

About the program

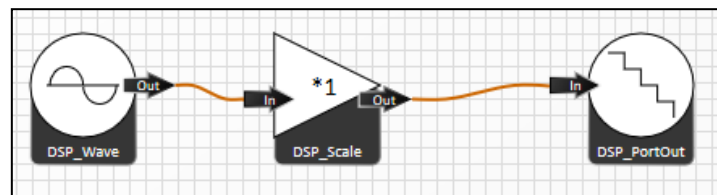
The transmitter modulates a stream of test data onto a carrier wave using either on-off keying (OOK) or amplitude shift keying (ASK). The carrier frequency is fixed at 15kHz and the data rate at 500 bits per second.

The modulated wave from the transmitter is then rectified and filtered by the receiver to recover the data. This is sampled and the program averages the samples over each symbol period to determine the data that was transmitted. The result is then shown on the LCD display at the end of the transmission.

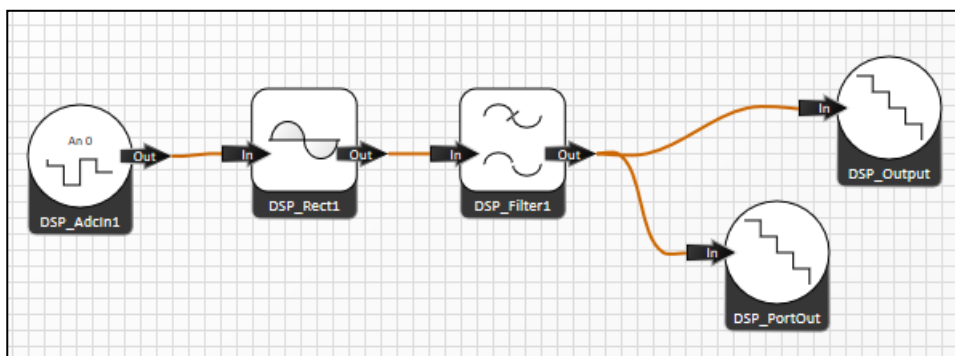
The test data is the string: {1,1,0,0,1,1,0,1,0,1,1,1,0,1,0,0,0,1,1,1,0,0,1,1,0,1,1,0,1,1,0,1,1,0,1}

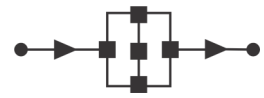
Project layout:

The transmitter



The receiver



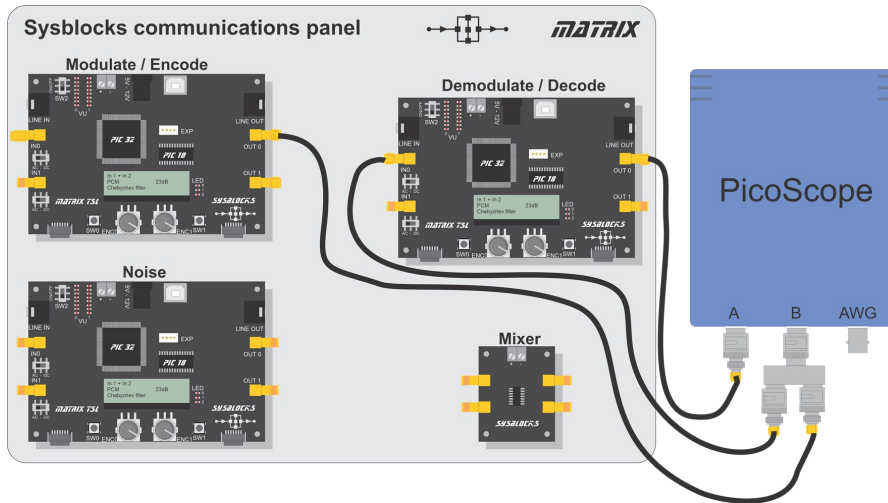


Worksheet 5

Digital AM - OOK and ASK

Communications and digital radio techniques

Hardware / firmware:

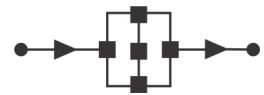


Firmware	Transmitter Wk 5 - ASK - Transmitter.fcfx
	Receiver Wk 5 - ASK - Receiver.fcfx
Outputs	Transmitter OUT0 - Modulated output signal
	Receiver OUT0 - Demodulated output signal
Controls	Transmitter ENCO - Selects between OOK and ASK
	Transmitter ENC1 - Triggers a transmission
	Transmitter SW0 - Sends data
	Receiver SW0 - Arms the receiver
Oscilloscope	CHA ±5V DC
	CHB ±5V DC
	Time: 5ms/div

Over to you:

1. OOK:

- Set up the hardware.
- Use transmitter encoder 'ENC0' to select the OOK modulation type.
- Set the Picoscope to trigger on the rising edge of channel **B** with the threshold set to 2V.
- Press switch 'SW0' on the receiver board to arm it - 'LED2' will come on.
- Press 'SW0' on the transmitter board to send the data. Both modulated and demodulated waves are shown on the Picoscope.
- Use cursors to select part of the trace containing a single bit modulated as a '1', i.e. a section with a period of 2ms where the modulated wave amplitude is at its maximum level.
- Add a measurement to show the DC average voltage of channel **A** between the rulers.
- Use the cursors again to select part of the trace containing a '0'.
- Again add a measurement to show the DC average of channel A.
- The transmitted data is displayed on the LCD display.



Worksheet 5

Digital AM - OOK and ASK

Communications and digital radio techniques

Over to you.....

2. ASK:

- Next, change the modulation type from OOK to ASK and repeat the same procedure.
- Note the difference in the waveforms.
- Copy and complete the following table:

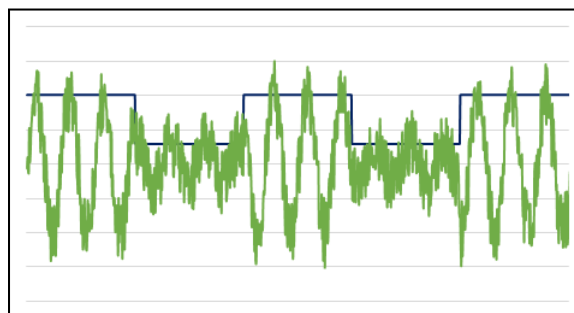
Symbol	DC Average / V	
	OOK	ASK
0		
1		

- Add a spectrum view to the Picoscope and compare the spectra produced by the two types of modulation . Which one has the wider bandwidth?

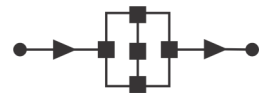
So what?

The receiver program used in this worksheet is very similar to the demodulator in worksheet 2. There, the signal modulated an analogue carrier whereas here it modulates a digital carrier. The system design assigns an amplitude to each symbol . For just two symbols, '0' and '1', the simplest approach assigns an amplitude of zero (fully off) to '0' and the maximum amplitude (fully on) to '1' . This is on-off keying (OOK) - very easy to decode since the signal is either there or not.

In the program provided, there is a choice between OOK and ASK, another form of modulation. Like OOK, this assigns the maximum amplitude to the symbol '1' but an amplitude of roughly one third to the symbol '0'. ASK has a slightly lower bandwidth because the two symbols are closer together. However, the closer the symbols are, the more difficult it is to decode a noisy signal. In our ASK system, an amplitude of two-thirds could either be a '0' plus some noise or it could be a '1' minus some noise.



With noise present, it is harder to distinguish symbols



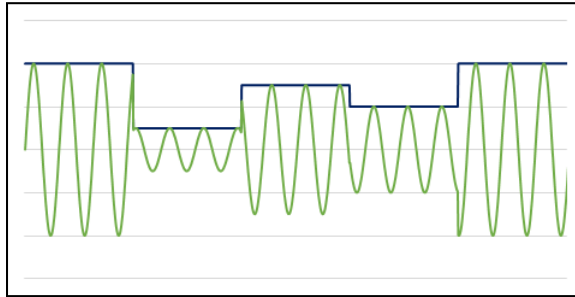
Worksheet 5

Digital AM - OOK and ASK

Communications and digital radio techniques

So what.....

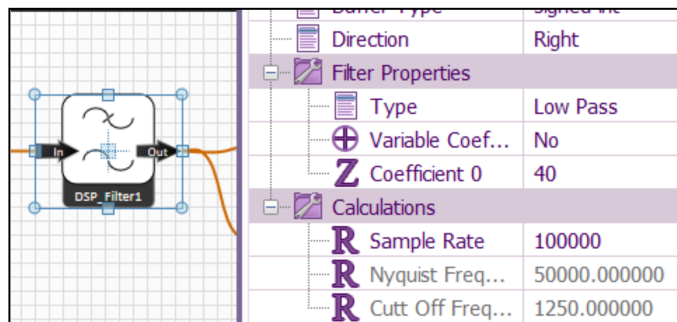
It is possible to encode more than two symbols. For example, four separate symbols could be encoded as one, two, three or four quarters of maximum amplitude, giving twice the data rate of a binary keying scheme. However the greater the number of symbols, the harder it becomes to distinguish between the different levels and the less tolerant is the system to noise



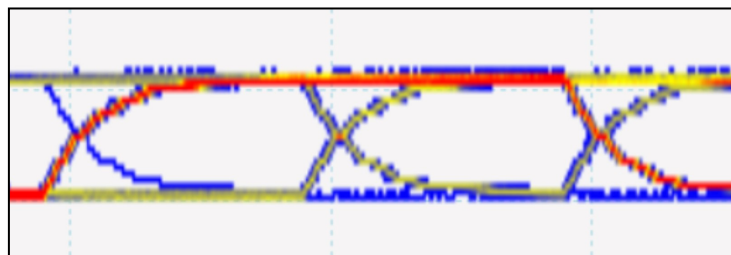
ASK signal with four levels encoding four symbols

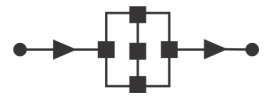
Challenges:

- The shape of the demodulated output signal depends on the value chosen for the coefficient in the low-pass filter in the receiver, used to filter out the carrier signal. Experiment with changing the value of this coefficient. Notice the effect on the output signal.



- Set Picoscope into persistence mode. Trigger the transmitter several times to produce an 'eye diagram' showing the shape of the received data stream.





Worksheet 6

Digital FM - frequency-shift keying

Communications and digital radio techniques



First used in teleprinters in the 1950s, frequency-shift keying (FSK) uses different frequencies to represent logic '0' and '1'. The choice of frequencies depends on factors such as the distance the signals must travel. For long distances, the difference in frequencies needs to be greater to reduce errors. This is another example of an analogue carrier used to transmit digital data.

About the program

The transmitter modulates data onto a carrier using FSK. The output is the 'raw' 25kHz carrier wave when no data is transmitted. With data present, the frequency is shifted up or down by 2kHz depending on the symbol being transmitted. The data rate is fixed at 500 bits per second.

The receiver uses the PLL techniques described earlier to estimate phase difference between the carrier and the incoming signal. An interrupt running at 180kHz samples both the incoming signal and the carrier wave. The program looks for zero crossing points and counts the number of samples between them. It also estimates how far through the sample the crossings occurred.

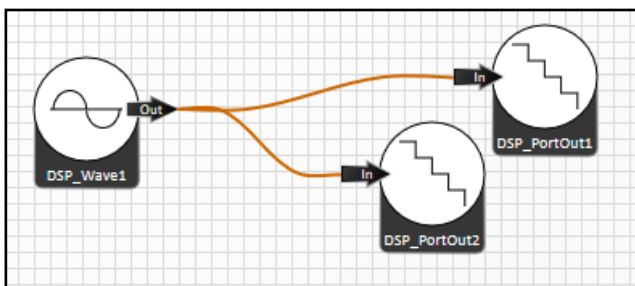
This phase difference controls the local oscillator (Wave Generator) frequency, available at output 'OUT0'. The average phase difference over the duration of the symbol determines what data was transmitted. This is then shown on the LCD display at the end of the transmission.

The test data is the string: -

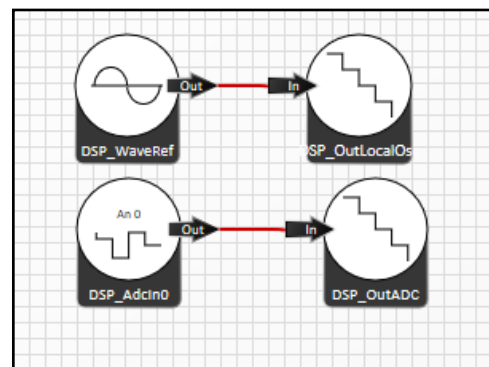
{1,1,0,0,1,1,0,1,0,1,1,1,0,1,0,0,0,1,1,1,0,0,1,1,0,1,1,0,1,1,0,1}

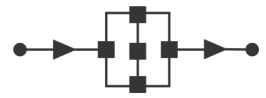
Project layout:

The transmitter



The receiver



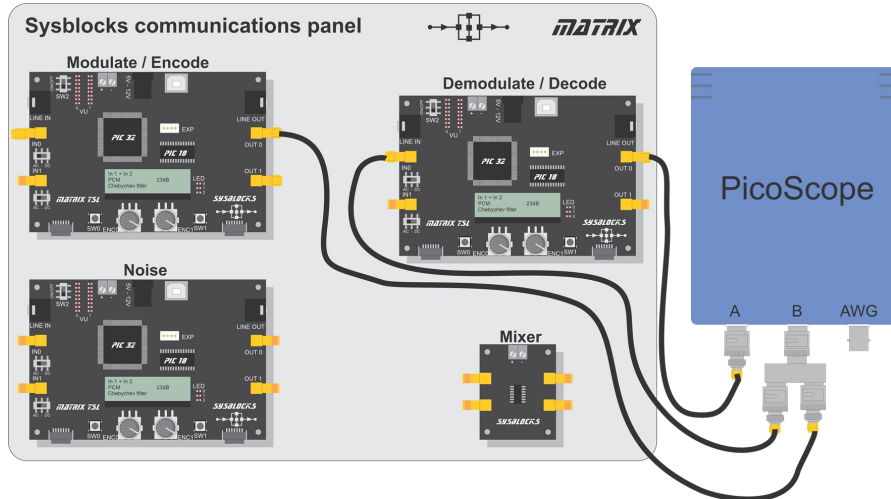


Worksheet 6

Digital FM - frequency-shift keying

Communications and digital radio techniques

Hardware / firmware:



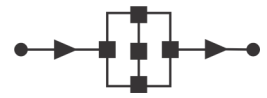
Firmware	Transmitter Wk 6 - FSK Transmitter.fcx
	Receiver Wk 6 - FSK Receiver.fcx
Outputs	Transmitter OUT0 - FSK modulated signal
	Transmitter OUT1 - FSK modulated signal
	Receiver IN0 - FSK modulated signal
	Receiver OUT0 - Demodulated output signal
Controls	Transmitter SW0 - Sends data
	Receiver SW0 - Arms the receiver
Oscilloscope	CHA $\pm 5V$ DC
	CHB $\pm 5V$ DC
	Time: $50\mu s/div \rightarrow 1ms/div \rightarrow 5ms/div$

Over to you:

- Set the Pico-scope to trigger on channel B, threshold 1.5V and rising-edge triggered.
- Set the timebase to $50\mu s/div$ initially.
- Channel **B** shows the carrier wave (constant frequency) produced by the transmitter.
- Channel **A** shows the phase difference between this and the signal (almost constant).
- Measure the frequency of the carrier and the DC average of the phase error signal.
- Now set the Picoscope to trigger on channel **A** and change the timebase to $1ms/div$.
- Press switch 'SW0' on the receiver board to arm it - 'LED2' will come on.
- Press switch 'SW0' on the transmitter board to send the data packet . Picoscope should capture the data.
- Measure the frequency of the transmitted signal and the DC average voltage of the phase error signal for both a '1' and a '0'.

Copy the following table and use the results to complete it:

Symbol	Frequency /kHz	DC Average /V
None		
0		
1		



Worksheet 6

Digital FM - frequency-shift keying

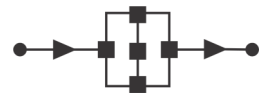
**Communications and
digital radio techniques**

Over to you.....

- Change the timebase to 5ms/div. Add a spectrum view to the Picoscope display. Without a trigger, the scope shows the unmodulated 25kHz carrier.
- Set the trigger to channel **A** and press switch 'SW0' on the transmitter board to send a burst of data to the receiver.
- The spectrum now shows two peaks, one on each side of the fundamental and separated from it by a gap of 2kHz.

Challenges:

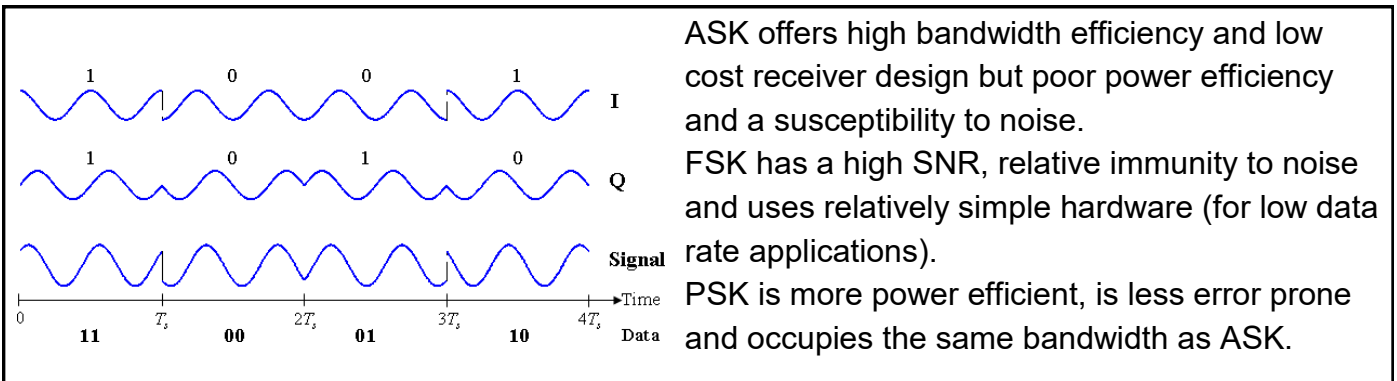
1. Put the Picoscope into persistence mode. Trigger the transmitter several times to produce an 'eye diagram' showing the shape of the received data stream.
2. Low frequency FSK is used for sending data over voice channels. An example is the Bell 103 modem standard, still used in shortwave and amateur radio. Similar technology was used in the past for storing computer data on audio cassette tapes. Design and construct a system to demonstrate this use of FSK.



Worksheet 7

Digital modulation - phase-shift keying

Communications and digital radio techniques

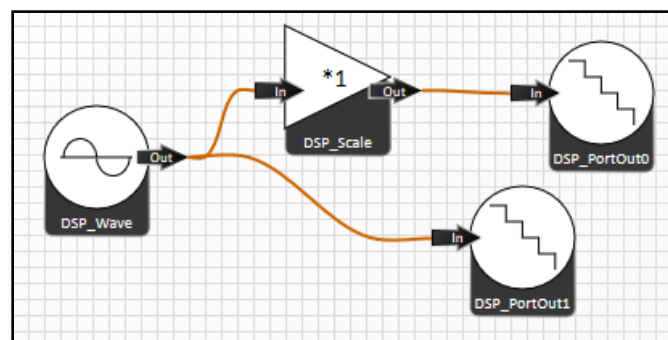


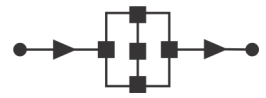
About the program

This program implements the simplest form of phase-shift keying (PSK), known as binary phase-shift keying (BPSK), which transmits two binary symbols.

As before, the program sends a stream of data when switch 'SW0' is pressed. It also provided a continuous output of each symbol to aid analysis, using encoder 'ENC0'. This selects between a steady output phase of 0^0 , a steady output phase of 180^0 and an output of a data stream with 0 and 1 represented by the two phases.

Project layout:



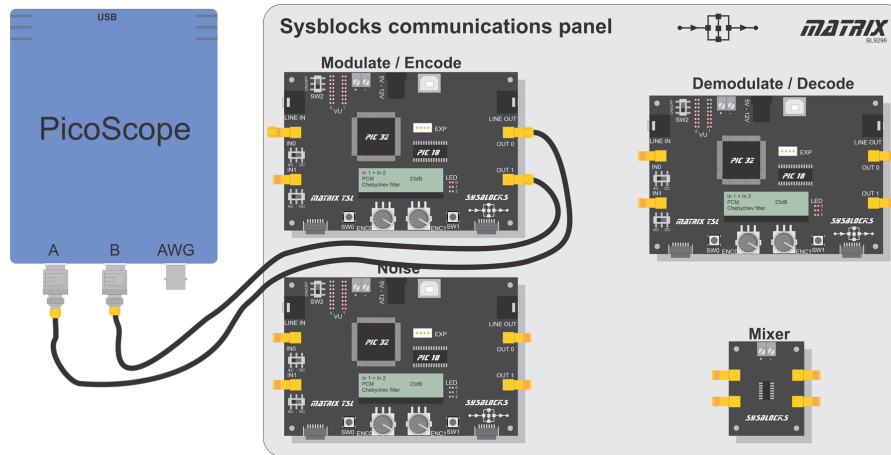


Worksheet 7

Digital modulation - phase-shift keying

Communications and digital radio techniques

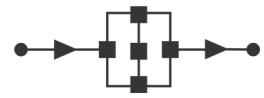
Hardware / firmware:



Firmware	Transmitter Wk 7 - PSK Transmitter.fcx
Outputs	Transmitter OUT0 - Phase modulated signal
	Transmitter OUT1 - reference signal
Controls	Transmitter ENC0 - Selects output mode
	Transmitter SW0 - Triggers data transmission
Oscilloscope	CHA ±5V AC
	CHB ±5V AC
	Time: 200 μs/div

Over to you:

- Set up the hardware as shown above. Picoscope channel **A** shows the PSK modulated signal and channel **B** the unmodulated sinusoidal carrier.
- Use encoder 'ENC0' to select a phase difference of 0° - the two waveforms are identical.
- Now select a phase difference of 180° - the two waveforms are exactly out of phase.
- Use encoder 'ENC0' to select 'data'.
- Hold down switch 'SW0' to see the phase difference change as the data is transmitted.
- Recall the following identities from trigonometry :
 1. $\cos(\omega t) \times \cos(\omega t) = \frac{1}{2} [1 + \cos(2\omega t)]$ (i.e. a DC term plus a double frequency term.
 2. $\cos(-\omega t) = -\cos(\omega t)$
 3. $\cos(\omega t) \times \cos(-\omega t) = -\frac{1}{2} [1 + \cos(2\omega t)]$ (i.e. the same as the first identity but inverted.)
 4. $\cos(\omega t) \times \sin(\omega t) = \frac{1}{2} \sin(2\omega t)$ a double frequency but with no DC component.
- Click on the 'Tools' tab and add a 'Math channel' to the Picoscope display to show 'A*B'. Observe the result of multiplying the two waves together.
- Verify that the 'Math channel' display shows the expected results for the first three identities. (The fourth identity is not relevant here but will become important soon.)



Worksheet 7

Digital modulation - phase-shift keying

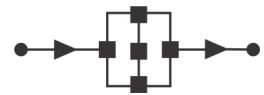
Communications and digital radio techniques

Challenge:

- Add a spectrum view to the Picoscope display.
- Select 'Data' with ENC0 and press switch SW0 to transmit a stream of data.
- Compare the spectrum of the continuous outputs with that of a data stream.
- Why does the latter occupies more bandwidth than the continuous output?
- What might be done to reduce it?

So what?

- An obvious way to demodulate the PSK modulated signal would be to filter out the double frequency component, leaving the DC component, either positive or negative. Unfortunately, the reference waveform is not available in most real systems.
- We have seen that we can encode data by modulating a signal's amplitude or frequency. Here we have demonstrated that it is possible to use the phase of the signal as a means of encoding the data.
- We have used the Picoscope to demonstrate that multiplying the signal with a reference signal provides a means of demodulating it. In a real system, the reference signal would not be so readily available. In worksheet 3, we saw that a phase-locked loop (PLL) can be used to lock a local oscillator to a sampled signal. Going forward, we shall use a PLL to create the reference signal that will be multiplied by the sampled signal



Worksheet 8

Quadrature generator

Communications and digital radio techniques



As we progress to more sophisticated modulation schemes, we introduce a new DSP component, the quadrature generator. This component generates a wave and also outputs the same wave phase shifted by 90° , i.e. in quadrature phase. This is equivalent to generating a cosine wave and its corresponding sine wave.

About the program

Any modulated sinusoidal signal can be synthesized from two sinusoidal waves that are 90° out of phase, known as ‘in quadrature phase’. In **Quadrature Amplitude Modulation**, (QAM), two such components, one sinusoidal and the other cosinusoidal, have the same frequency, f . The sinusoidal signal is known as **Q** and the cosinusoidal signal as **I**.

Mathematically they can be represented by the equations:

$$I = A_I \cos (2\pi ft) \text{ and } Q = A_Q \sin (2\pi ft)$$

The components may be amplitude modulated, i.e. A_I and A_Q may vary with time.

In the transmission process, these components are combined together.

To demodulate them, the received signal is multiplied by :

1. a cosinusoidal signal with the same frequency as the original carrier, to give the signal:

$$\frac{1}{2}(A_I + A_I \cos (4\pi ft) + A_Q \sin (4\pi ft))$$

which is then filtered to remove the high frequency ($4f$) components, leaving $\frac{1}{2} A_I$ from which the original amplitude, A_I , of the **I** component can be obtained;

2. a sinusoidal signal with the same frequency as the original, resulting in the signal:

$$\frac{1}{2}(A_Q - A_Q \cos (4\pi ft) + A_I \sin (4\pi ft))$$

which is filtered, leaves $\frac{1}{2} A_Q$, giving the original amplitude, A_Q , of the **Q** component.

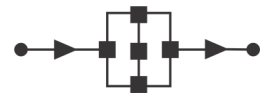
In this program, a quadrature generator outputs two 5kHz sinusoidal waves with a fixed phase difference of 90° between them. These are designated **I** and **Q**, standing for “In-Phase” and “Quadrature”. Mixing these in various strengths controls the phase of the output.

Sysblocks ‘OUT1’ output delivers the **I** reference signal. This never changes.

The ‘OUT0’ output provides a multiple of **I** plus a multiple of **Q** as dictated by the encoders.

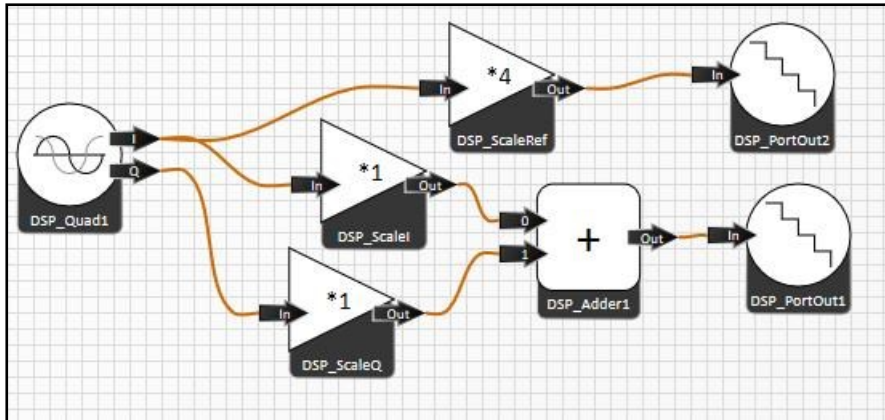
Worksheet 8

Quadrature generator

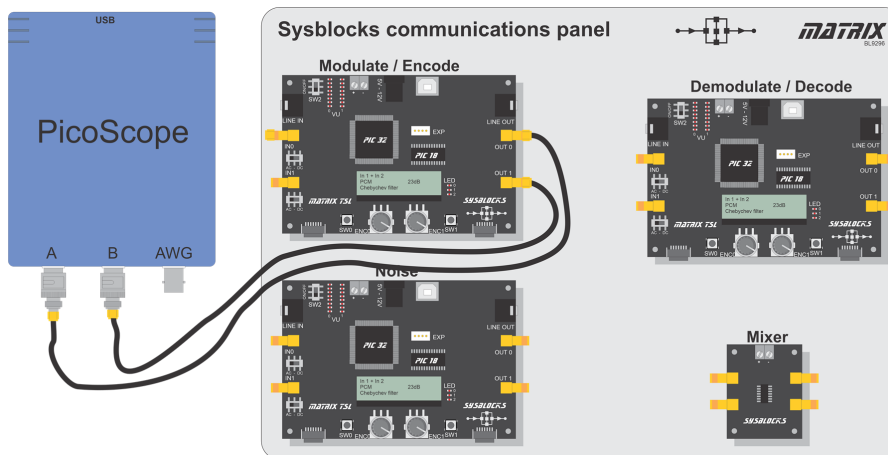


Communications and digital radio techniques

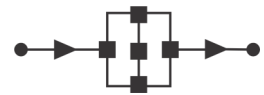
Project layout:



Hardware / firmware:



Firmware	Transmitter Wk 8 - Quadrature Generator.fcfx
Outputs	Transmitter OUT0 - Mixed I and Q Signal
	Transmitter OUT1 - Fixed reference signal
Controls	Transmitter ENC0 - Sets I output level
	Transmitter ENC1 - Sets Q output level
Oscilloscope	CHA ±5V AC
	CHB ±5V AC
	Time: 200 μs/div
	Trig: Ch B, 0V



Worksheet 8

Quadrature generator

Communications and digital radio techniques

Over to you:

- Set up the hardware as shown.
Make sure that Picoscope channels A and B are set to AC coupling.
- The encoders select the amplitudes of **I** and **Q** in arbitrary units, from -3 to +3.

The first tasks look at the effect on phase of combining **I** and **Q** signals in various proportions.

1. Set 'OUT 0' to be an addition of **I** = +3 and **Q** = 0.
Check that the reference signal at 'OUT 1' and the multiple signal at 'OUT0' are identical.
2. Set **I** = 0 and **Q** = +3.
Check that the two outputs are 90⁰ phase shifted.
3. Set **I** = -3 and **Q** = 0.
Check that the outputs are 180⁰ out of phase.
4. Set **I** = 2 and **Q** =2.
What is the phase difference now?

The next tasks aim to confirm the trigonometric identities given in worksheet 7. According to these, the product **A * B** produces a sinusoidal wave with twice the frequency along with a DC offset.

- Add a Math channel to the Picoscope to show **A * B**.
- Use the Picoscope tools to measure the frequency and DC offset of the signal shown on the Math channel.
- Do these confirm the trigonometrical predictions?

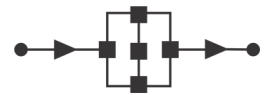
The next tasks study the effect of each of the **I** and **Q** signals in isolation.

- Set the **Q** scale to zero and study the effect of varying the **I** scale.
- Copy and complete the table below and use the results to plot a graph of A*B average voltage against **I** scale value.

Scale I	A * B Average
-3	
-2	
-1	
0	
1	
2	
3	

- Now set the **I** scale to zero and study the effect of varying the **Q** scale.

You should find that the **Q** scale has negligible effect on the DC average.



Worksheet 8

Quadrature generator

Communications and digital radio techniques

Challenge

- Finally we are going to look at the result of some specific values of **I** and **Q** scales.

For each pair of values, measure:

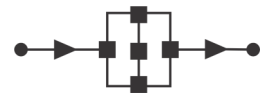
- the phase difference between **A** and **B**;
- the amplitude of the “**A * B**” Math channel;
- and the DC Offset (mean) of the Math channel.

(Notice that the Picoscope has a phase measuring utility.)

- Copy and complete the table with your results.

Scale I	Scale Q	Phase A → B	A * B Amplitude	A * B DC Average
3	0			
2	2			
0	3			
-2	2			
-3	0			
-2	-2			
0	-3			
2	-2			

- Plot a graph of Scale **I** versus Scale **Q**.
- Draw a line from each point to the origin.
 - How does the phase measured between **A** and **B** compare to the corresponding angle between the plotted point and the **I** axis?
 - How does the measured amplitude of **A * B** compare with the length of the line?
 - How does the DC average compare with the scale **I** values?
 - What would happen if the reference signal came from the **Q** component rather than the **I** component (i.e. 90° different)?



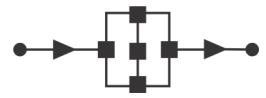
Worksheet 8

Quadrature generator

Communications and digital radio techniques

So what?

- Using the trigonometric identities given in worksheet 7:
 - 'cosine x cosine' gives an AC component at twice the input frequency and a DC offset.
 - 'sine x cosine' (i.e. waves have a 90^0 phase shift between them,) gives the same AC component at twice the frequency but does not give a DC component.
- When we multiply the mix of **I** and **Q** with the reference **I** signal we find that the resulting DC offset is directly proportional to the scaling applied to the **I** value used but unaffected by the **Q** signal.
- The result means that we could modulate data on to the **I** component and decode it with this system. At the same time, we could modulate data onto the **Q** component without affecting the **I** component or its data stream at all.
- Looking at the last graph, the points where **I** is +3 and -3 while **Q** is zero correspond with the two symbols that used in Binary Phase Shift Keying (BPSK) – 0 and 180^0 . (Later we show that the other six points on the graph could also be used as data symbols.)
- The eight points plotted on the graph almost lie on a circle. They are not quite on a circle because the distance from the origin to the point (2,2) is (from Pythagoras) $\sqrt{(2^2+2^2)} = \sqrt{8} = 2.83$. In order for the points to be exactly on a circle, point (2,2) should really be $(\sqrt{4.5}, \sqrt{4.5}) = (2.12, 2.12)$. However, these values are a close approximation.
- By adjusting the amounts of the sine and cosine signals that are added together, we can create a wave with any phase offset relative to the in-phase reference signal **I**. In the software provided, the phase angle can be set in steps of 45^0 . If finer adjustment of the two scales were available, then finer phase adjustment would be possible.



Worksheet 9

Quadrature receiver

Communications and digital radio techniques



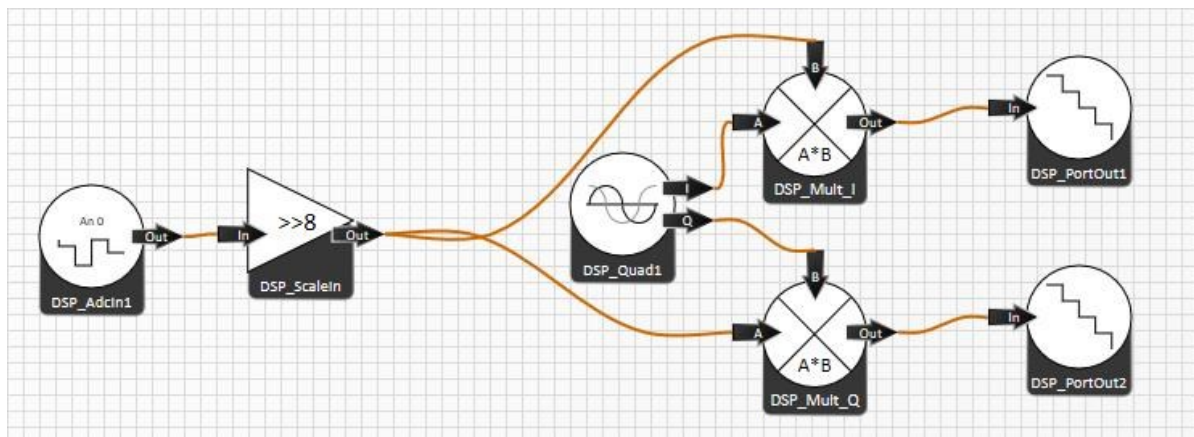
The previous worksheet examined the behaviour of a quadrature generator and the effect of multiplying a mix of the outputs with a reference signal.

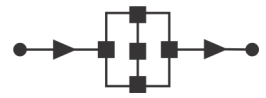
This worksheet looks at a receiver with a quadrature generator as its local oscillator, giving us the ability to decode the levels of both the transmitted in-phase and quadrature signals.

About the program

In this program, a local quadrature generator uses a digital phase-lock loop to lock its frequency to an incoming reference signal. The program then multiplies the incoming signal, separately, by the **I** and **Q** outputs of the local oscillator, to show the effects of the **I** and **Q** signals on the **I** and **Q** outputs of the receiver.

Project layout:



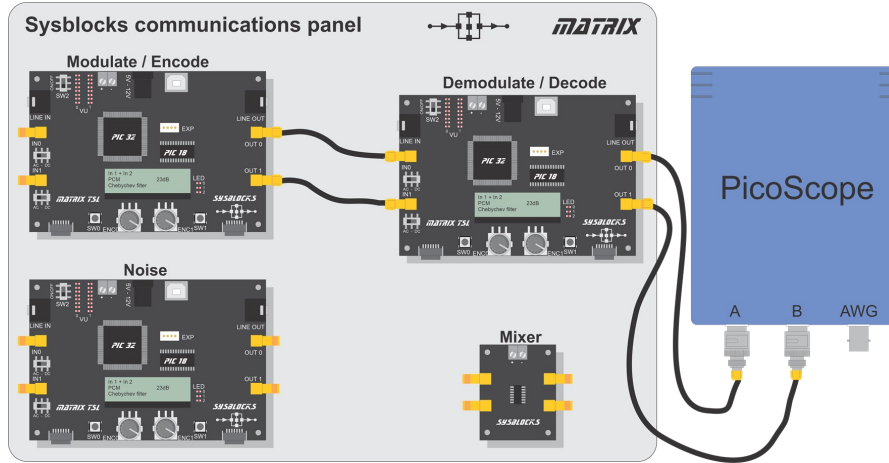


Worksheet 9

Quadrature receiver

Communications and digital radio techniques

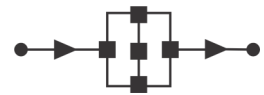
Hardware / firmware:



Firmware	Transmitter Wk 8 - quadrature generator.fcx
	Receiver Wk 9 - quadrature receiver.fcx
Outputs	Transmitter OUT0 - Quadrature modulated signal
	Receiver OUT0 - I level signal
	Receiver OUT1 - Q level signal
Controls	Transmitter ENCO - Selects modulation type
	Receiver ENCO - Selects modulation type
Oscilloscope	CHA $\pm 5V$ DC
	CHB $\pm 5V$ DC
	Time: 2ms/div

Over to you

- Set up the hardware as shown. The Picoscope inputs are DC coupled. Picoscope Channel **A** shows the result of multiplying the quadrature generator modulated signal with the **I** signal of the local oscillator. Channel **B** shows the result of multiplying the signal by the **Q** signal from the local oscillator.
- Set up Picoscope to measure the DC average of each of these signals.



Worksheet 9

Quadrature receiver

Communications and digital radio techniques

Over to you.....

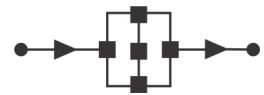
- Adjust the **I** and **Q** scales of the quadrature generator to check that the **I** setting affects only the DC offset of the **I** output and that the **Q** setting affects only the DC offset of the **Q** output. (If both scales are set at 3 or -3, the signal saturates and the output signals are distorted.)
- Next, set the **Q** scale to zero and vary the **I** scale as shown in the following table.
- Copy and complete it with the resulting measurements.

Scale I	Scale Q	DC Average of I	DC Average of Q
-3	0		
-2	0		
-1	0		
0	0		
1	0		
2	0		
3	0		

- Now, set the **I** scale to zero and vary the **Q** scale as shown in the next table.
- Copy and complete it with the resulting measurements.

Scale I	Scale Q	DC Average of I	DC Average of Q
0	-3		
0	-2		
0	-1		
0	0		
0	1		
0	2		
0	3		

- Use these results to plot a graph showing DC Average voltage versus Scale value for both **I** and **Q** on the same axes.



Worksheet 9

Quadrature receiver

Communications and digital radio techniques

- Now set the I and Q scales to the values used in the last task of the previous worksheet. Copy and complete the table with the resulting measurements.

Scale I	Scale Q	DC Average of I	DC Average of Q
3	0		
2	2		
0	3		
-2	2		
-3	0		
-2	-2		
0	-3		
2	-2		

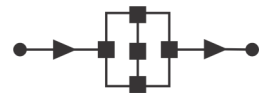
- Plot graphs of the DC average voltages versus **I** and **Q** on the same axes. Compare the results to those of the previous worksheet.

Challenge

- Place the Picoscope into X-Y mode. The display will show a small circle.
- Alter the levels of **I** and **Q** in the signal and observe how the size and position of the circle change. Determine the rules that connect the size and position to the **I** and **Q** levels. How does this relate to the results of the previous exercise, particularly the DC averages graph?

So what?

- In the previous worksheet, we used a Math channel of the Picoscope to multiply our signal by the **I** reference signal. The resulting DC average was proportional to the level of the **I** component in our signal but unaffected by the level of the **Q** signal.
- In this worksheet, we use the Sysblocks DSP system to do the multiplication. We create both **I** and **Q** reference signals in the receiver. As a result, we can measure the DC offset for both **I** and **Q** components and thus decode the levels of both in the received signal from the transmitted signal.



Worksheet 10

Quadrature detector

Communications and digital radio techniques



So far, in examining the quadrature encoded signals, we focussed on the DC average voltage but not on the AC component. The latter can be removed by adding a filter to the receiver.

This leaves just the DC average voltage, the signal that is carrying the transmitted information.

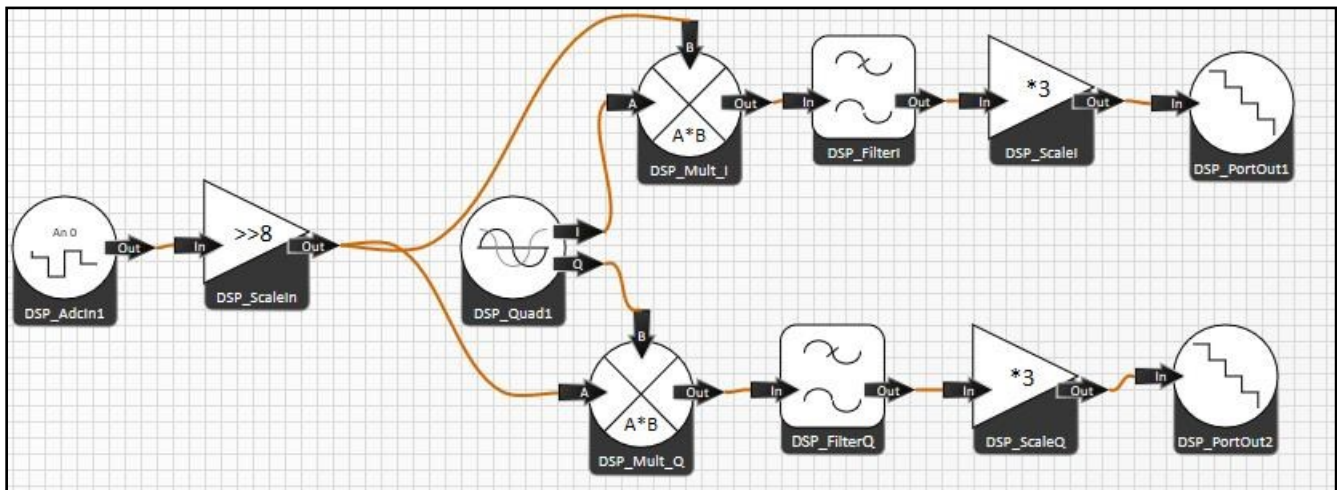
About the program

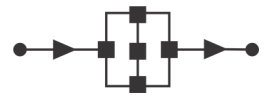
This program builds on the previous one, adding filters after the multipliers in the detector. A scale component added after the filter increases the dynamic range of the output.

As before, it uses a PLL to lock the local generator to a reference signal.

The program is tested using the same quadrature generator as before.

Project layout - receiver:



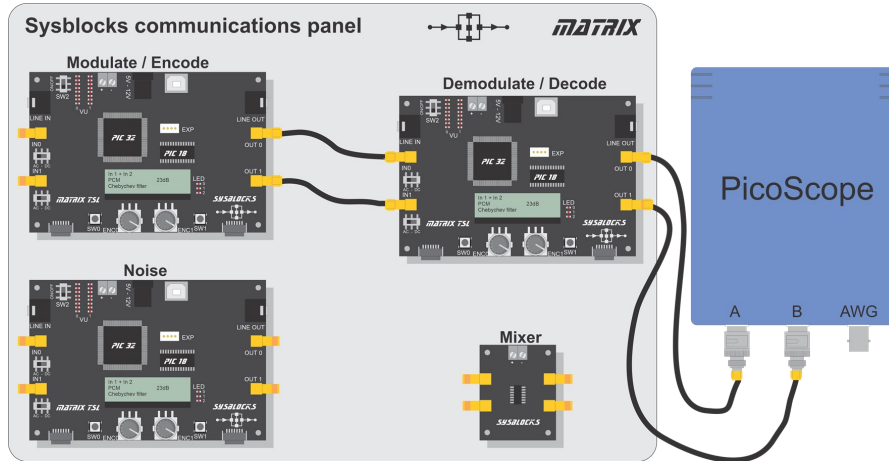


Worksheet 10

Quadrature detector

Communications and digital radio techniques

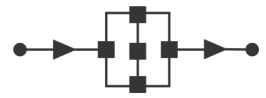
Hardware / firmware:



Firmware	Transmitter Wk 8 - Quadrature Generator.fcfx
	Receiver Wk 10 - Quadrature Detector.fcfx
Outputs	Transmitter OUT0 - Mixed I and Q Signal
	Transmitter OUT1 - Fixed reference signal
	Receiver OUT0 - Input multiplied by local I
	Receiver OUT1 - Input multiplied by local Q
Oscilloscope	CHA $\pm 5V$ DC
	CHB $\pm 5V$ DC
	Time: 100 μs /div

Over to you:

- Set up the hardware as shown above. The Picoscope inputs are DC coupled. Notice that the two channels are virtually flat lines with very little AC component.
- Adjust the scales of **I** and **Q** on the quadrature generator board. Check that the resulting level of channel **A** is:
 - proportional to the scale of the **I** component;
 - unaffected by the scale of the **Q** component.
 Check that the opposite is true for channel **B**.
- Place the Picoscope in X-Y mode. The display should show a small dot.
- Adjust the scales of **I** and **Q** and observe how the dot moves.



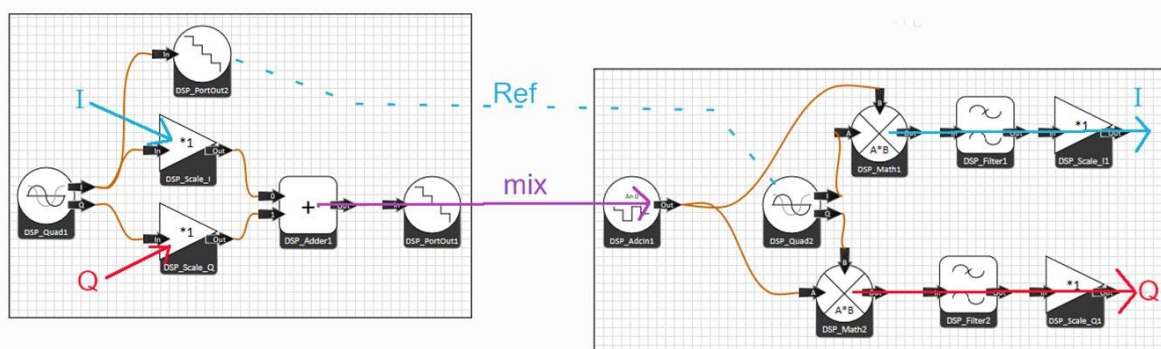
Worksheet 10

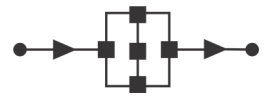
Quadrature detector

Communications and digital radio techniques

So what?

- At this point, our detector can decode two independent signals that are modulated onto the same carrier wave. At the transmitter, **I** and **Q** signals are combined into one signal. At the receiver, this signal is multiplied by the two outputs of a quadrature generator and filtered to recover the **I** and **Q**. Two signals are mixed into one, transmitted, then unmixed.
- Here, we still use a separate reference signal to lock the local quadrature generator. In the next worksheet, the modulated wave is used to lock the local oscillator, using a Phase-Locked Loop, even though its phase is constantly changing.





Worksheet 11

Coherent detector and QPSK

Communications and digital radio techniques



This worksheet looks at a practical quadrature transmission system.

The transmitter uses a serial data stream, saving the tedious task of adjusting **I** and **Q** scales manually, with the encoders. The receiver uses the mixed quadrature signal instead of the reference signal to lock the local quadrature generator.

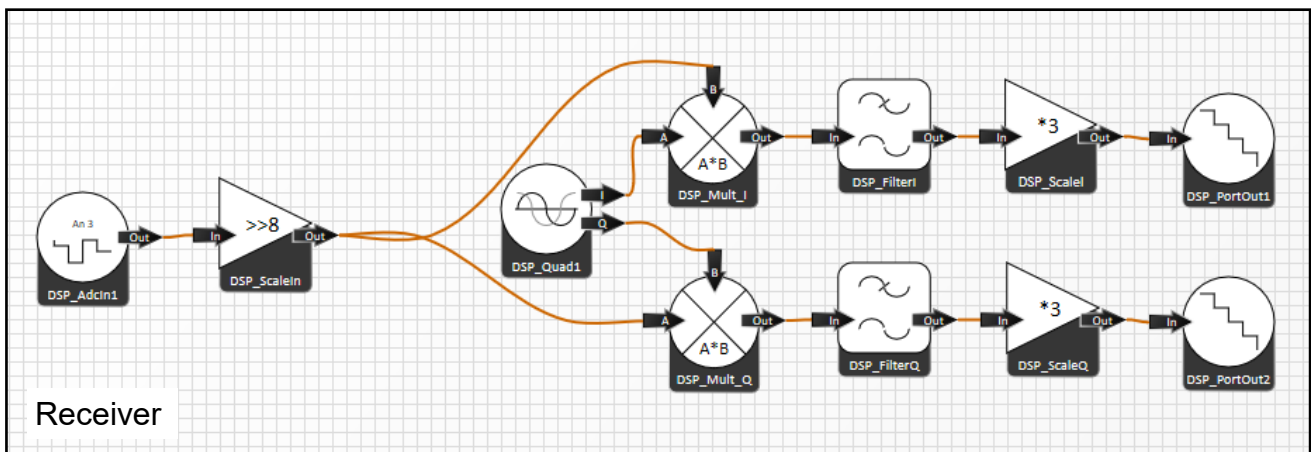
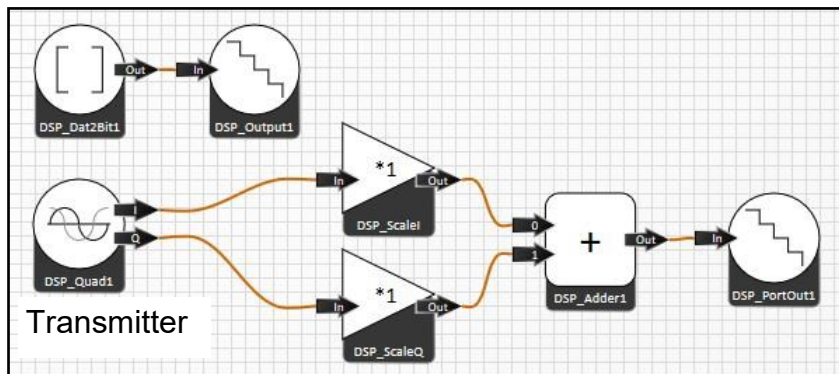
It includes a look at BPSK and at variations of a modulation scheme known as Quadrature Phase Shift Keying (QPSK).

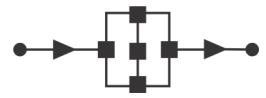
About the program

The transmitter is similar to that used in the previous worksheets but this time it includes a Data2Bit component, which converts a test string of data into a stream of bits. A flowchart macro reads that stream and uses it to modulate the scale components.

The receiver program is similar to that used previously except that, this time, the modulated signal is used to lock the local generator rather than the reference signal.

Project layout:



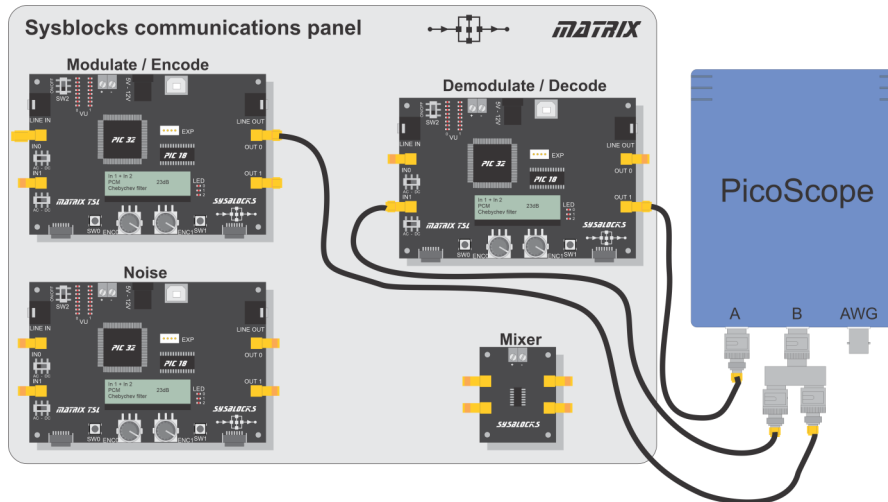


Worksheet 11

Coherent detector

Communications and digital radio techniques

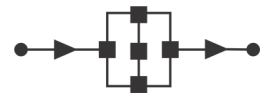
Hardware / firmware:



Firmware	Transmitter Wk 11 - X-PSK transmitter.fcfx
	Receiver Wk 11 - Coherent Detector.fcfx
Outputs	Transmitter OUT0 - Quadrature modulated signal
	Receiver OUT0 - I level signal
	Receiver OUT1 - Q level signal
Controls	Transmitter ENCO - Selects modulation type
	Receiver ENCO - Selects modulation type
Oscilloscope	CHA ±5V DC
	CHB ±5V DC
	Time: 2ms/div

Over to you:

- Set up the hardware as shown.
- Rotate the encoders so that both Sysblocks boards display 'Carrier' on both LCD screens. Picoscope channel **B** shows an unmodulated 5kHz carrier wave. Look at channel **A**, what does it show?
- Rotate the encoders so that both displays show '4-QPSK'.
- Set the Picoscope to trigger on channel **A** at a level of 1.6V.
- Stop the oscilloscope to freeze the display.
- Channel **A** is now showing recovered data while channel **B** is showing the phase-modulated carrier wave. Look closely at the modulated wave just before the data signal changes level. Are there any discontinuities in the modulated wave that do not change the data signal?
- Rotate both encoders so that the displays show '8-PSK'.
- Increase the time base of the oscilloscope to 10 ms/div.
- Look at the two signals now. The modulated signal still has a constant amplitude but the data signal now shows five distinct levels. Explain why this is so?



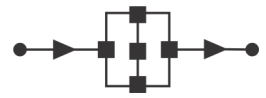
Worksheet 11

Coherent detector

Communications and digital radio techniques

So what?

- Ideally, channel **A** would give a flat line, showing a constant DC level, for an unmodulated carrier. In this system, however, two other components are observed:
 - a ripple at 10kHz, (twice the carrier frequency), because the low pass filter does not remove all of the double frequency component;
 - a lower frequency signal fluctuation because the PLL does not lock perfectly.
- With 4-QPSK, channel **A** shows data recovered from the **I** part of the modulation. (Data recovered from the **Q** part can be viewed at 'OUT1' if wished.)
Phase changes caused by data changing, create discontinuities in the modulated signal. The data signal does not respond immediately because the filter slows its response. Since data is modulated onto both **I** and **Q**, some discontinuities do not change the **I** signal. (If a four-channel oscilloscope is available, both **I** and **Q** outputs could be observed.)
- In binary phase shift keying (BPSK), phase angles of 0° and 180° represent two binary symbols. In quadrature phase shift keying (QPSK), more phase angles occur, representing more symbols. For example, 4-QPSK uses four symbols, 90° apart, so that each symbol carries two bits of information. Similarly 8-PSK uses eight different symbols, 45° apart.
- In theory, using smaller and smaller phase intervals between symbols allows us to carry even more data bits per symbol. In practice, this is limited by the difficulty in distinguishing one symbol from another. For instance, 360-PSK would be possible only if we could reliably detect a 1° phase shift.
- In BPSK, the phase angle of the signal jumps by 180° when data changes state. The NCO design used earlier would not cope and the PLL would not remain locked on. It is modified so that a phase angle, '**p**', produces the same NCO frequency as a phase angle ('**p** + 180° '). As before, small changes in phase angle cause the NCO to change to keep it locked on. However, phase difference changes of 180° , caused by data changing state, produce no change in NCO frequency. The incoming signal can jump back and forth by 180° and the PLL continues to function just as if the signal had a constant phase.
- With 4-QPSK, the signal can jump in phase angle steps of 90° . Again, the NCO design is modified to accommodate this. Similarly, for 8-PSK, the design is modified to have eight locking points at intervals of 45° .
- Although phase changes can be detected, the system cannot tell which symbol represents zero phase. In BPSK, for example, the system can distinguish between two symbols but, in this example program, there is no mechanism for deciding which denotes '1' and which '0'. Hence, a BPSK signal may be decoded either correctly or inverted. In a practical system, each message would have a known starting pattern to overcome this.



Worksheet 12

Quadrature Amplitude Modulation

Communications and digital radio techniques



Quadrature modulation can be used to encode information onto the phase of a signal. This worksheet looks in greater detail at how the modulated signal is decoded. It also introduces another modulation scheme in which the amplitude of the signal is modulated at the same time as the phase.

About the program

The programs are the same as for the previous worksheet.

The transmitter again includes a Data2Bit component that converts a string of test data into a stream of bits.

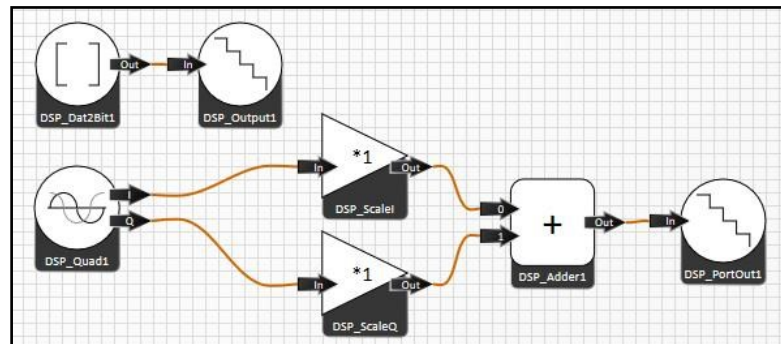
The receiver again uses the modulated signal to lock the local generator.

This time, the oscilloscope is connected to the **I** and **Q** outputs of the detector.

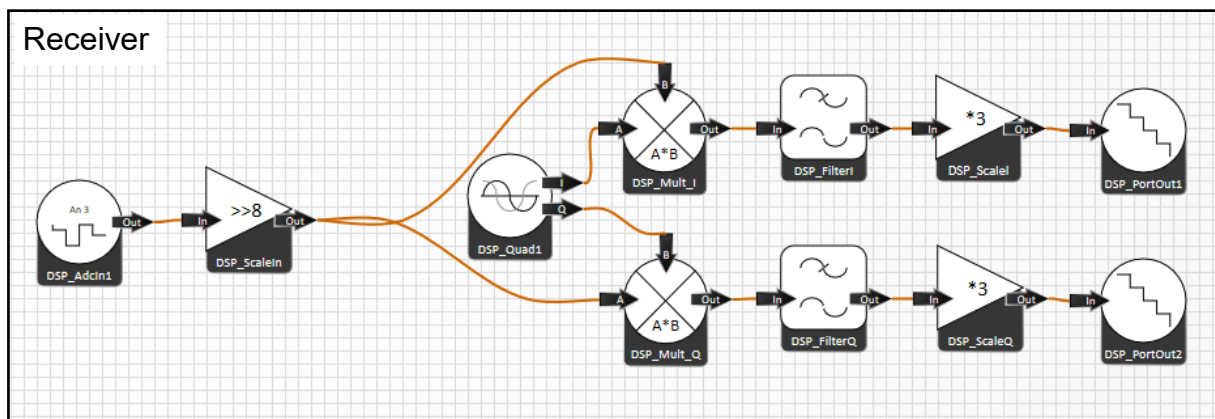
Project layout:

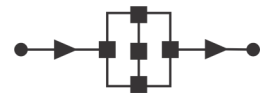
As for previous worksheet

Transmitter



Receiver



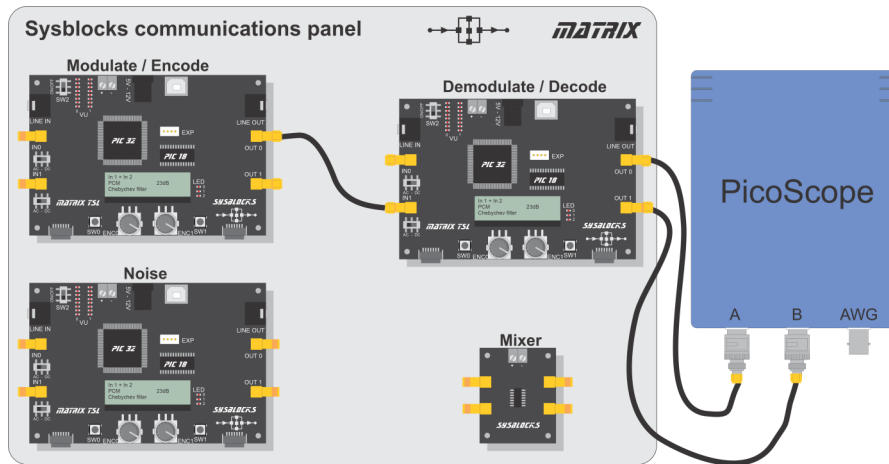


Worksheet 12

Quadrature Amplitude Modulation

Communications and digital radio techniques

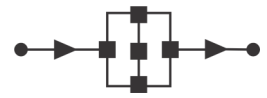
Hardware / firmware:



Firmware	Transmitter Wk 11 - X-PSK transmitter.fcfx
	Receiver Wk 11 - Coherent Detector.fcfx
Outputs	Transmitter OUT0 - Quadrature modulated signal
	Receiver OUT0 - I level signal
	Receiver OUT1 - Q level signal
Controls	Transmitter ENCO - Selects modulation type
	Receiver ENCO - Selects modulation type
Oscilloscope	CHA $\pm 5V$ DC
	CHB $\pm 5V$ DC
	Time: 10 ms/div 10ms/div

Over to you:

- Set up the hardware as shown above.
- Rotate the encoders to set both transmitter and receiver to 'Carrier'.
- Check that a stable output signal is obtained.
- Add an X-Y view to the oscilloscope. The display should show a small dot.
- Rotate both encoders so that the LCD screens show "BPSK".
One output shows a recovered data stream and the other a fairly flat DC level.
- The data stream has two levels which correspond to the two intense spots on the X-Y plot.
Make a sketch of the X-Y plot.
- Rotate the encoders so that both LCD screens show "4-QPSK".
Both traces now show parts of the recovered data stream.
- Since the **I** and **Q** parts each have two states, there are now four possible symbols.
Make a sketch of the new X-Y plot.
- Rotate the encoders so that both LCD screens show "8-PSK".
Compare the X-Y plot to the graphs of **I** and **Q** scales in worksheet 8 and **I** and **Q** DC averages in worksheet 9. Make a sketch of this X-Y plot.



Worksheet 12

Quadrature Amplitude Modulation

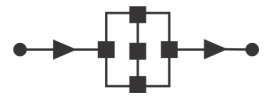
Communications and digital radio techniques

So what?

- The X-Y plot of the 8-PSK modulation scheme shows eight symbols arranged in a ring. The symbols all lie at a fixed distance from a central point because the amplitude of the modulated signal is kept constant.

Challenge:

- Now rotate the encoders so that the LCD screens show “*-QAM”. In this scheme, both the phase and amplitude of the modulated signal are changed. Make a sketch of the X-Y plot and compare it to the QPSK schemes.
- There are two more schemes available - “16-QAM A” and “16 QAM B”. Investigate these. The 16-QAM schemes are not so easy see. Increase the timebase of the Picoscope and freeze the display to make it easier to sketch the plots.



Worksheet 13

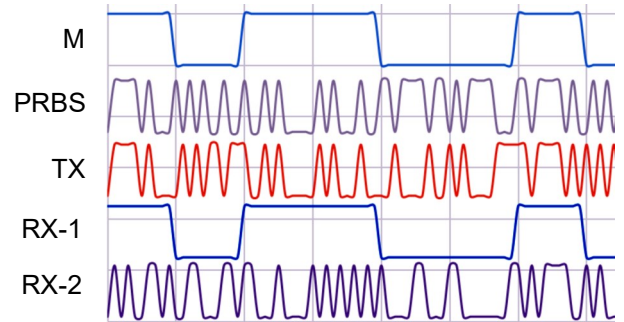
Direct-sequence spread spectrum

Communications and digital radio techniques

In **direct-sequence spread spectrum (DSSS)** communication, the transmitter multiplies the message by a **pseudo-random binary sequence (PRBS)** of 1's and -1's. The **PRBS**, has a higher frequency than the message bit rate, gives a higher signal bandwidth.

The receiver multiplies the received signal by the same **PRBS**. As $1 \times 1 = 1$ and $-1 \times -1 = 1$, **PRBS**'s at the transmitter and receiver cancel each other out.

If the receiver used a different **PRBS**, they would not cancel and the received signal would appear as noise.



DSSS Signals

- M – message signal to be transmitted
- PRBS – higher bandwidth sequence
- TX – M and PRBS combined for transmission
- RX-1 – received signal x same PRBS
– message recovered
- RX-2 – received signal x different PRBS
– message not recovered

1. DSSS transmission

About the program

This program modulates a data stream onto a 20kHz carrier signal using ASK modulation. The data stream can be modified by a PRBS at 2, 4, 8, 16 or 32 times the rate of the data stream.

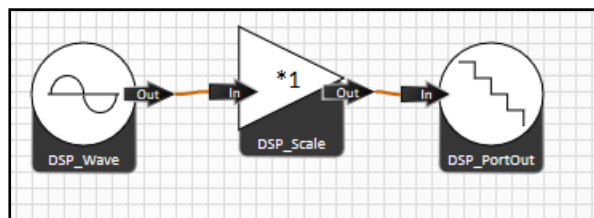
The seed (initial value) of the PRBS can be selected between four different options.

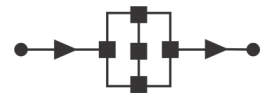
A transmission is triggered when 'SW0' is pressed.

The modulated signal appears at output 'OUT0'.

Output 'OUT1' provides a baseband representation of the data stream, generated in software.

Project layout:



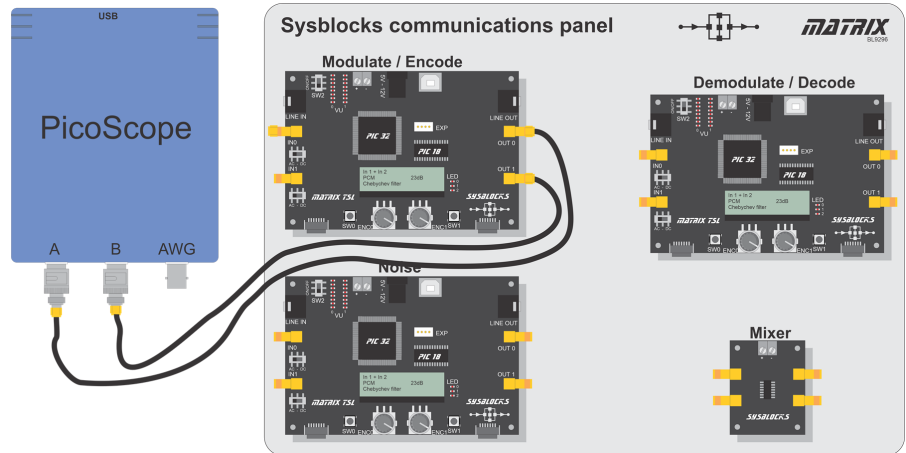


Worksheet 13

Direct-sequence spread spectrum

Communications and digital radio techniques

Hardware / firmware:



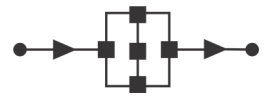
Firmware	Transmitter Wk 13 - Tx DSSS.fcx
Outputs	Transmitter OUT0 - Modulated signal
	Transmitter OUT1 - Data stream for reference
Controls	Transmitter ENC0 - Selects the DSSS multiplier
	Transmitter ENC1 - Selects the DSSS seed
Oscilloscope	CHA $\pm 5V$ DC
	CHB $\pm 5V$ DC
	Time: 20ms/div

Over to you:

- Set up the hardware as shown.
- Notice the traces with DSSS turned off.
- Set the Picoscope trigger to 'Single' mode to capture a single trace.
- Press 'SW0'
- Compare the data signal and the modulated output signal.
- Turn on the DSSS and observe the effect on the traces as the multiplier is increased.
- Add a spectrum view to the oscilloscope and observe how the bandwidth of the output increases as the DSSS multiplier increases.

So what?

- With DSSS turned off, it is easy to see the data modulated onto the output signal. The effect of DSSS is to add a pseudo-random element to the modulated output. It is not possible to recognise the original data stream.
- Looking at the spectrum view you can see that when DSSS is turned on the energy in the signal is spread across the spectrum.



Worksheet 14

DSSS decoding

Communications and digital radio techniques



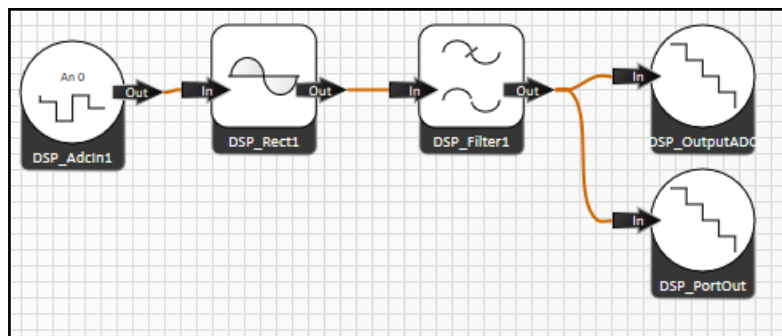
In examining quadrature encoded signals, we have been interested in the DC average but not the AC component. We can remove the AC component by adding a filter to the receiver. This will leave us with just the DC average that is carrying the information.

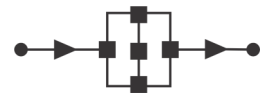
About the program

This program decodes an incoming ASK modulated signal by rectifying and filtering it. The signal is sampled to recover a bit stream. The result can be modified using the same PRBS as in the transmitter.

As with the transmitter, the PRBS seed and the PRBS rate can be selected. When they match the settings of the transmitter, the original data stream is recovered. Where the rate or seed are different, the data stream is not recovered.

Project layout:



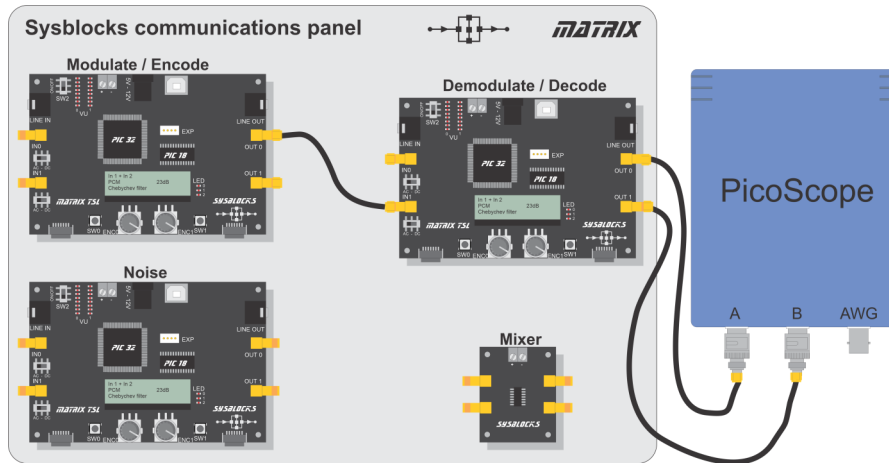


Worksheet 14

DSSS decoding

Communications and digital radio techniques

Hardware / firmware:



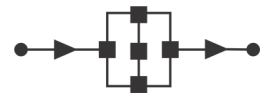
Firmware	Transmitter Wk 13 - Tx DSSS.fcfx
	Receiver Wk 13 - Rx DSSS.fcfx
Outputs	Transmitter OUT0 - Modulated signal
	Transmitter OUT1 - Data stream for reference
	Receiver OUT0 - Decoded data
	Receiver OUT1 - Reference signal
Controls	Transmitter ENC0 - Selects the DSSS multiplier
	Transmitter ENC1 - Selects the DSSS seed
	Receiver ENC0 - Selects the DSSS multiplier
	Receiver ENC1 - Selects the DSSS seed
Oscilloscope	CHA ±5V DC
	CHB ±5V DC
	Time: 20ms/div

Over to you:

- Set up the hardware as shown.
- With both transmitter and receiver showing 'DSSS Off', trigger a transmission and capture the outputs of the receiver on the oscilloscope.

So what?

- Trace **A** shows the decoded data. If you can, make this a reference waveform so that you can compare the following results.
- Trace **B** shows the incoming data before multiplication by the PRBS to recreate the original waveform
- Compare the decoded data output to the demodulated output. Note that the data output is delayed by half a bit-time because the sampling to identify the data happens in the middle of each symbol period. Save the decoded data as a reference waveform on Picoscope.



Worksheet 14

DSSS decoding

Communications and digital radio techniques

Over to you:

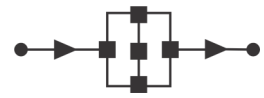
- Change the setting of both boards to 'DSSS x8' with a key of 932. This sets the PRBS frequency to 8 times the data frequency with a key of 932.
- Verify that the original data is still decoded correctly. Note that, while the decoded data is the same, the demodulated output shows the effect of modification by the PRBS. Without the decoded output, it would be impossible to decode the original signal.
- Make the key at the receiver different from that of the transmitter. Observe the effect on the decoded data.

So what?

- Both transmitter and receiver have a key that can be set by rotating the encoder 'ENC1'. Four options are provided for the key, (although any value could have been used.)

Challenge:

- Try the other values and also try changing the key at the transmitter. Observe that the data is successfully decoded only when the keys at the transmitter and receiver match. Since both use the same sequence generator, the receiver can predict the sequence if it is given the correct starting value.
- The PRBS frequency can be set to 32 times the data rate. This means that a new bit from the PRBS is generated 32 times for every bit of data. At this rate it is hard to see any pattern in the demodulated signal. Without the correct key, the signal appears to be simply noise.
- Use the technique outlined in worksheet 5 to obtain 'eye diagrams' for the demodulated signal for different PRBS speeds. Notice the appearance of jitter at high PRBS speeds.



Worksheet 15

A digital communications system

Communications and digital radio techniques



Now that we have looked at different modulation schemes, examined how PLLs work, and investigated how data is transmitted, it's time to put it all together to see how it works in sending digital data packets.

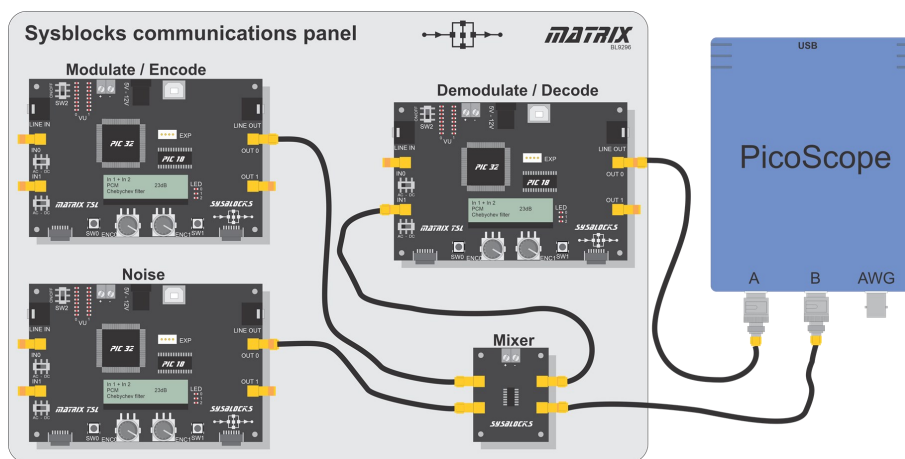
The digital communications software application allows you to set up a number of modulation schemes and packet types so that you can examine the parameters and trade-offs of various modulation types.

About the programs

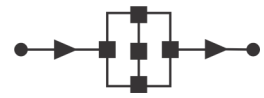
Three firmware programs are needed: 'Transmitter', 'Receiver' and 'Noise'. They use the Digital Communications software to set up a communications systems based on one of the following:

- On Off Keying (OOK),
- Amplitude Shift Keying (ASK),
- Frequency Shift Keying (FSK),
- Bi Phase Shift Keying (BPSK),
- Quadrature Phase Shift Keying (QPSK),
- 8 Phase Shift Keying (8PSK).

Hardware / firmware:



Firmware	Transmitter Wk 15 - App Transmitter.fcx
	Receiver Wk 15 - App Receiver.fcx
	Noise Wk 15 - App Noise.fcx
Outputs	Transmitter OUT0 - Modulated data
	Noise OUT0 - Noise
	Receiver OUT0 - I signal
	Receiver OUT1 - Q signal
Controls	Noise ENC0 - Noise level
Oscilloscope	CHA ±5V AC
	CHB ±5V AC
	Time: 200 ms/div



Worksheet 15

A digital communications system

Communications and digital radio techniques

Over to you:

1. Introductory exploration:

- Set up the hardware/ firmware as shown on the previous page.
- Set up the Picoscope to trigger on 'OUT0' of the receiver, the I signal. Make sure that both channels **A** and **B** are AC-coupled.
- Connect the Transmitter and Receiver Sysblocks and Picoscope to the PC using USB leads.
- Open the Digital Comms software. Read the Reference section to learn how to use it.
- On the Digital Comms panel, configure the transmission settings as follows:
 - Carrier frequency: 5kHz
 - Baud rate: 150 baud
 - Preamble length: 2 cycles
 - Group length: 4
 - Modulation scheme: OOK

For a baud rate of 150, symbol period = 6.7ms.

Depending on the modulation method used, one symbol may carry more than one bit of data.

For example, 4-PSK transmits two bits per symbol, so the bit rate = 2 x baud rate.

- Set the transmission string to 'abcdefghijklmnop' i.e. 16 bytes of data.
- Send the data and check that it is received correctly.

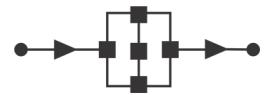
- Vary the data and observe the effect on the Picoscope traces.

- Vary the Preamble Length. Observe the effect on Revert to a preamble length of 2 cycles.

- Vary the Group Length. Measure the transmission time for the group lengths shown in the table. Copy the table and complete it with your measurements.

Group Length	Transmission time
4	
8	
16	
32	

- Return the group length to 4.



Worksheet 15

Communications systems

Communications and digital radio techniques

Over to you.....

2. Message transmission time:

- Keep the transmission settings shown on the previous page. Add rulers to the Picoscope traces and use them to measure the transmission time for the whole data packet using each of the modulation schemes given in the table.
- Copy and complete the following table with your measurements:

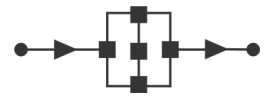
Modulation scheme	OOK	ASK	FSK	BPSK	QPSK	8PSK
Packet transmission time in ms						

3. Transmission errors:

- With the same transmission settings, use encoder 'ENC1' on the Noise Generator panel to vary the level of noise inputted into the mixer.
- For each 'Scale' setting, measure the Bit Error Rate (BER) for each type of modulation. Copy and complete the following table with your results:

Noise level Scale value	BER /%					
	OOK	ASK	FSK	BPSK	QPSK	8PSK
0						
1						
2						
3						
4						
5						
6						

Note - noise is a random occurrence and so the BER readings can vary. Check this for yourself by resending the data a number of times.



Worksheet 15

A digital communications system

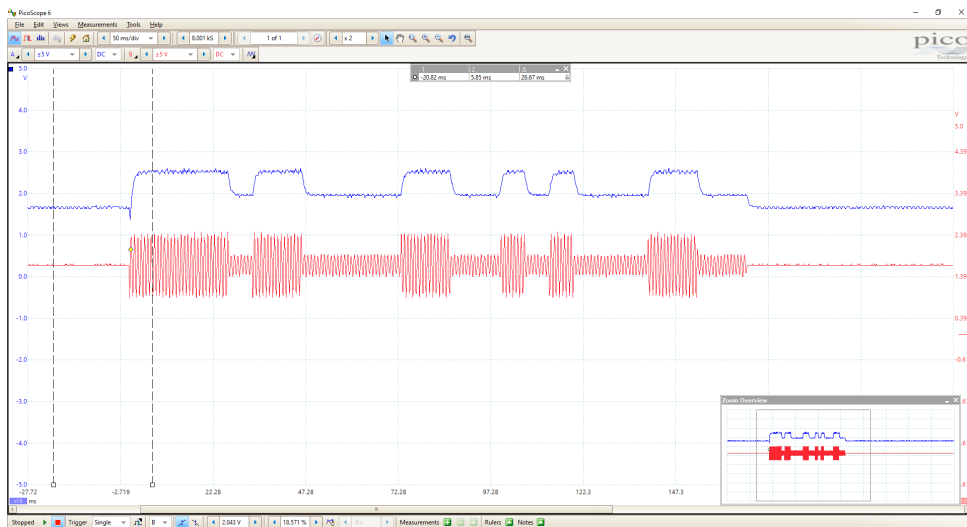
Communications and digital radio techniques

Challenges

1. Configure the transmission settings as follows:

- Carrier frequency: 5kHz
- Baud rate: 150 baud
- Preamble length: 4 cycles
- Group length: 8
- Modulation scheme: ASK
- Transmission string 'zx'

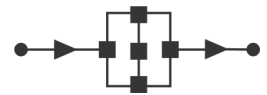
• Use Picoscope to capture an image, like the one below, showing the decoded output from 'OUT1' of the transmitter (blue) and the transmission from the mixer board (red)



• Mark on

- the symbol clock;
- the 0's and 1's that make up the transmission packet; using the information in the Reference section.

it:



Worksheet 15

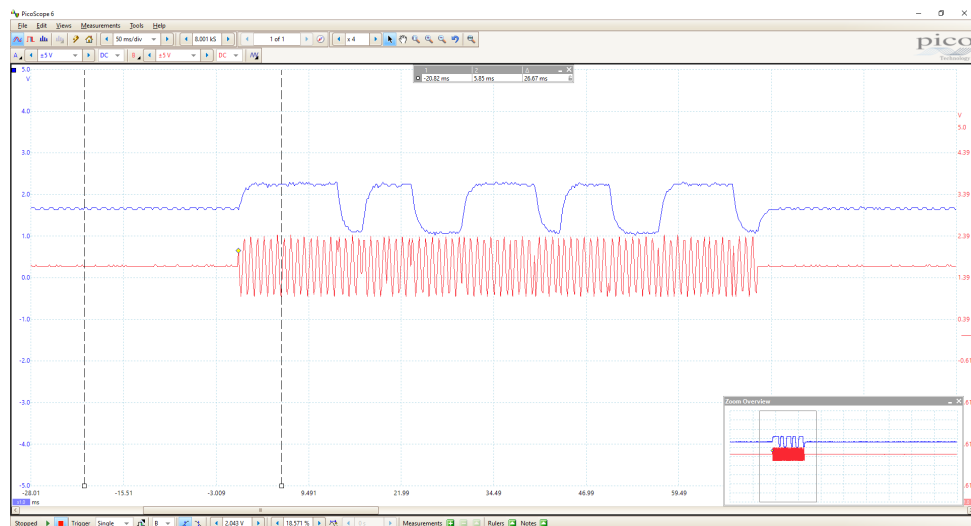
A digital communications system

Communications and digital radio techniques

Challenges.....

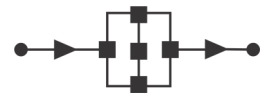
2. Now alter the transmission settings as follows:

- Carrier frequency: 5kHz
 - Baud rate: 300 baud
 - Preamble length: 4
 - Group length: 4
 - Modulation scheme: QPSK
 - Transmission string 'ab'
- Use Picoscope to capture an image like the one below which shows the decoded output from 'OUT1' of the transmitter (blue) and the transmission from the mixer board (red)



- As before,
- the symbol clock
 - the 0s and 1s that make up the transmission packet

mark on this:



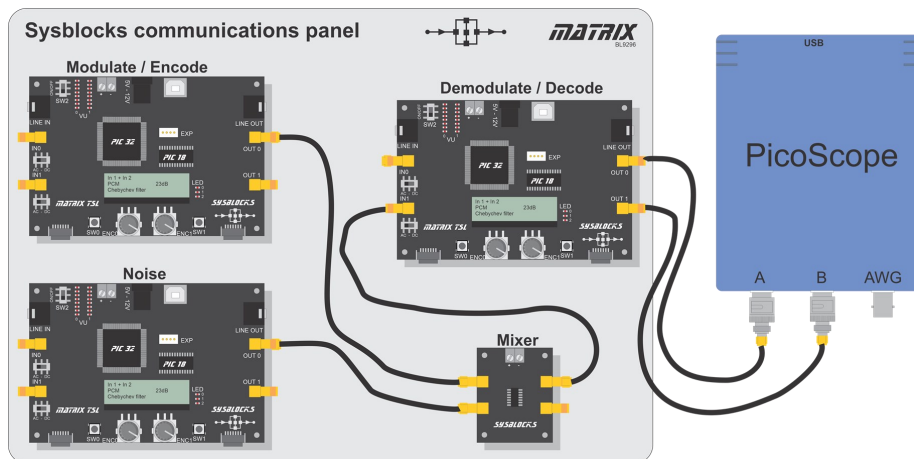
Worksheet 15

Communications systems

Communications and digital radio techniques

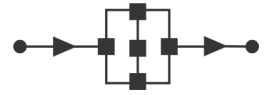
Challenge.....

- Change the connections as shown in the following diagram so that the I and Q outputs are connected to PicoScope.



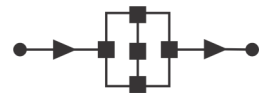
Firmware	Transmitter Wk 15 - App Transmitter.fcfx
	Receiver Wk 15 - App Receiver.fcfx
	Noise Wk 15 - App Noise.fcfx
Outputs	Transmitter OUT0 - Modulated data
	Noise OUT0 - Noise
	Receiver OUT0 - I signal
	Receiver OUT1 - Q signal
Controls	Noise ENC0 - Noise level

- Set up an X-Y plot view.
- Change the modulation scheme to:
 - BPSK,
 - then QPSK
 - and then 8PSK.
- Compare the constellation diagram for each of these.
- Add noise from the noise generator and see the effects on the constellation diagram.



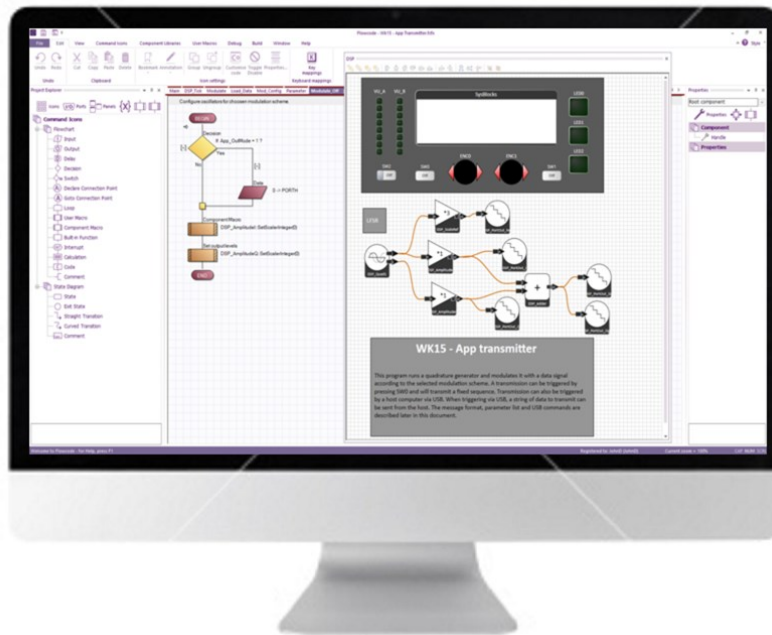
Communications and digital radio techniques

Reference



Flowcode software

Communications and digital radio techniques



Digital communications systems are a mixture of hardware and software.

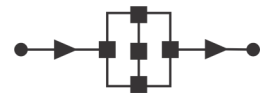
Flowcode software is needed for and is an important part of this course. However, students do not need to know the fine details of how to use it to benefit from the course - they just load the programs and compile them to the Sysblocks boards.

To do this:

- in Explorer double click on a program to load it;
- select BUILD from the top menu;
- select COMPILE TO TARGET.

The programs are easy to follow as they are written as flow charts and can be the basis for further projects. All programs provided for the course are open source and are fully editable - including the communications software.

Students can use Flowcode to construct programs for embedded systems, for PCs and for mobile devices using browser technology. It allows programs to be constructed using a variety of programming techniques including pseudocode, C, flow charts, state diagrams and data-flow diagrams. (The advantage of data-flow diagrams is that the results resemble diagrams used to describe communications systems in text books.)



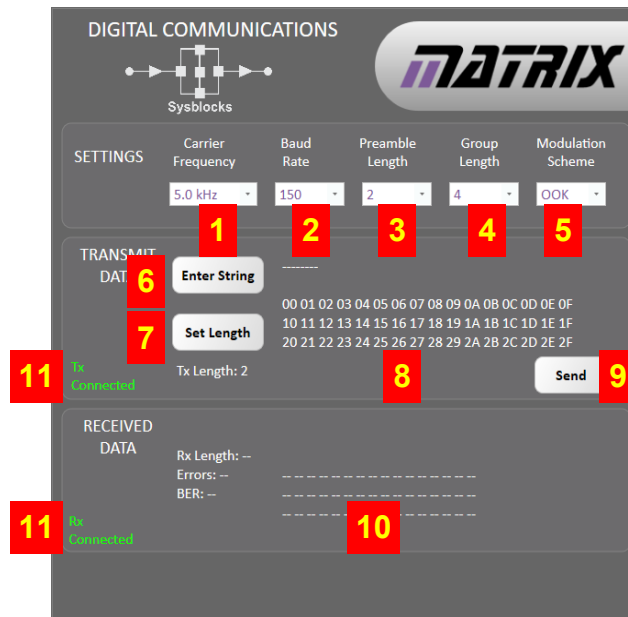
Digital communications software

Communications and digital radio techniques

'Digital_comms_app.exe' is freely available from the Matrix web site. It is written using Flowcode software is open source and fully editable. USB drivers are not needed.

To use it:

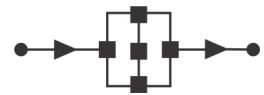
- unpack the software from the ZIP file;
- run the file: 'Digital_comms_app.exe'.



The controls and displays are:

1. Carrier frequency - alters the carrier frequency for the transmission.
Data rate and carrier frequency are not linked.
A higher carrier frequency is more difficult for the PLL to lock onto.
2. Baud rate - controls the frequency of the data transmission.
Baud is the number of changes in data per second, i.e. the number of symbols per second, so:
$$\text{symbol period} = \text{duration of one symbol} = \text{time between data changes} = 1/\text{baud}$$

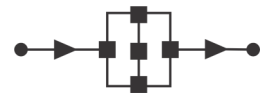
For a baud rate of 150, symbol period = 6.7ms.
Depending on the modulation method, one symbol may carry more than one bit of data.
3. Preamble length - is the number of cycles at the start of the transmission.
Higher carrier frequencies may need a longer preamble length to allow the PLL to lock.



4. Group length - the number of sampling periods in a data transmission cycle.
This is the number of data symbols sent before a stop symbol and then a start symbol. These symbols flag up the beginning of the next group and are used to resynchronise the receiver and transmitter. Even a slight error between their clocks causes the receiver to sample too early or too late rather than in the middle of a symbol. Over time, this clock error builds up so that the receiver eventually samples the wrong symbol.
A group length of two never causes a problem as the receiver resynchronises every couple of symbols. However, this is inefficient since half the time is spent transmitting stop and start symbols.
A group length of sixty-four is more efficient but, unfortunately, by the end of a group, the clock error has been multiplied 64 times. Longer groups transmit data quicker, but sampling timing drift with respect to the bit pattern may give errors at the end of the group.
5. Modulation scheme.
6. String to be transmitted - when you enter a string the 'Length' parameter is updated.
7. Length of the string data.
8. Hex data to be transmitted.
9. 'Send' button - initiates data transmission.
10. Hex data received.
11. Text fields indicate USB connections are in place for transmit (Tx) and receive (Rx).

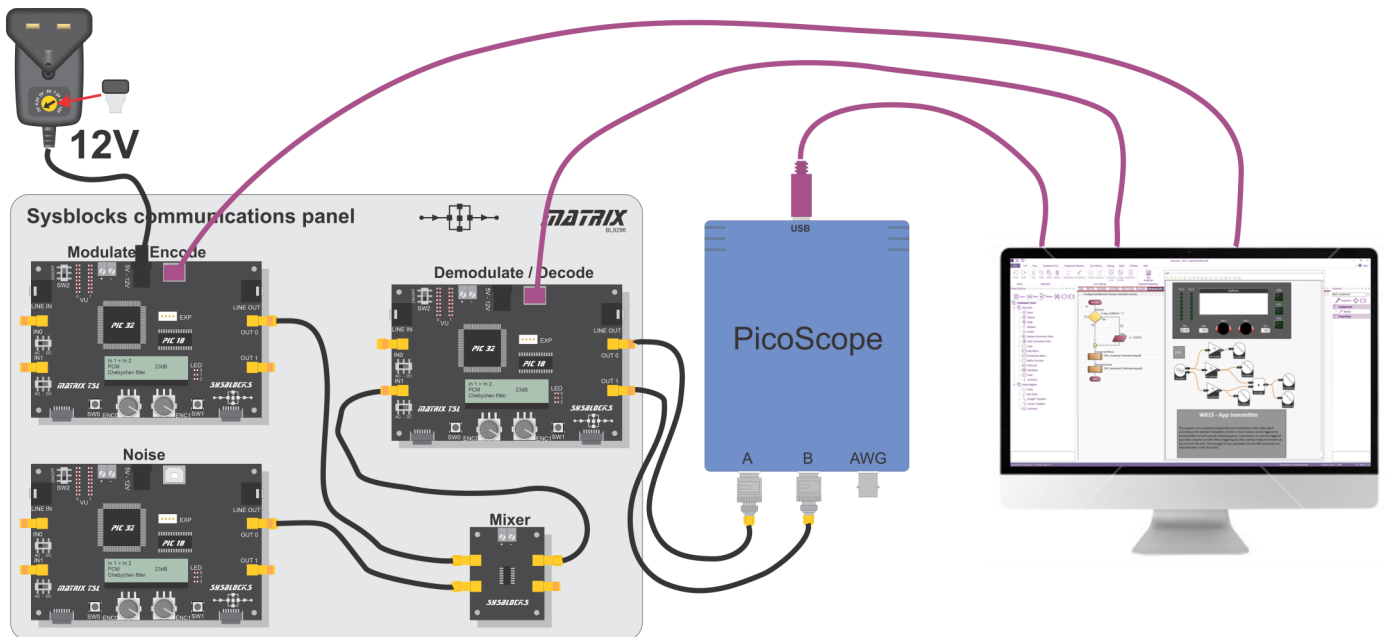
Instructions for use:

- 1) Connect the hardware - see hardware instructions
- 2) Alter the communication settings
- 3) Set up a transmission string
- 4) SEND the data - the receiver will automatically receive it and update the screen.



Digital communications hardware/firmware

Communications and digital radio techniques



The Digital Communications application allows students to carry out investigations in digital communications.

For a variety of modulation schemes, they can:

- see packet construction;
- create constellation diagrams;
- view Bit Error Rates (BER) with different noise conditions.

The hardware set up is shown above.

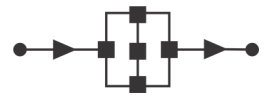
To set this up:

- compile Flowcode file ' Wk15 - App transmitter.fcfx' into the Transmitter Sysblock;
- compile Flowcode file ' Wk15 - App receiver.fcfx' into the Receiver Sysblock;
- compile Flowcode file ' Wk15 - App noise generator.fcfx' into the Noise Sysblock;
- connect Sysblocks and the Picoscope;
- connect the Transmitter, Receiver and Picoscope to the computer using USB leads;
- start the software application 'BER app.exe'.

(No drivers are needed for Sysblocks but the system requires a 12V power supply.)

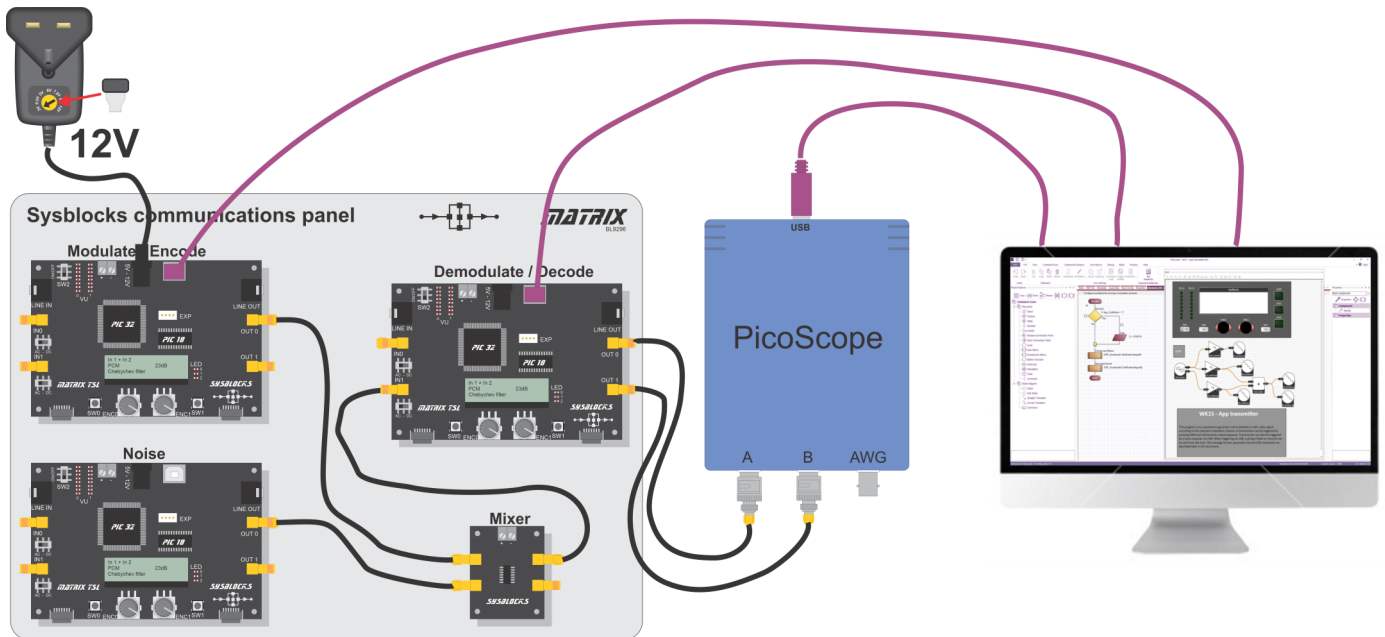
The Receiver ('Demodulate / decode') Sysblock then gives **I** and **Q** signals on outputs 'OUT0' and 'OUT1' respectively. To create constellation diagrams, students need both **I** and **Q** signals on Picoscope.

The Mixer has two outputs which are connected together, allowing students to look at **I** signals from the Receiver and the transmitted waveforms at the same time, a really useful tool in understanding the transmission.



Connecting hardware to the PC

Communications and digital radio techniques



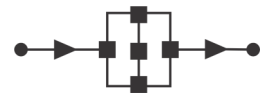
The diagram above shows three USB connections between the PC and:

- Transmitter;
- Receiver;
- Picoscope.

Flowcode software manages these connections and the computer.

When the Digital Communications software is loaded, it checks that there is a connection to each of the Sysblocks Transmitter and Receiver boards.

You need to connect these boards to the computer USB inputs before starting the Digital Communications software.

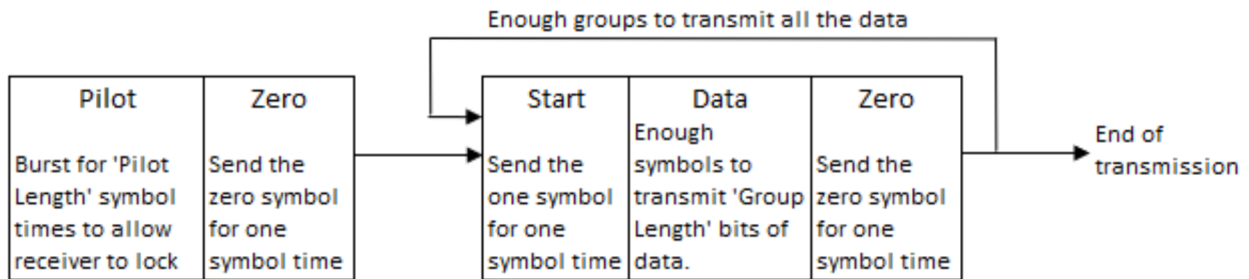


Digital comms packet structure

Communications and digital radio techniques

In this system, time is defined in terms of 'symbols' and so the inverse of the baud rate. This gives us a virtual 'symbol clock' in the firmware.

The Digital Comms application sends packets of data. At the start of each, a burst of carrier waves for a number of symbol clock periods allows the PLL to lock on to the carrier.



The software then transmit data in groups, each preceded by a '0' and then a '1'. This initial '01' information allows the receiver firmware to deduce the centre sampling point of the symbol.

There is always a variance/drift between transmitter symbol 'clock' and receiver symbol 'clock'. Shorter groups of data minimise this variance, make sampling more accurate, and reduce the Bit Error Rate.

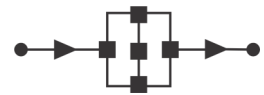
After the zero and start bits the first group is transmitted. Then, following another start and zero bit, the next group is transmitted and so on until the transmission is complete.

The Digital Comms application allows you to set the baud rate, the length of the initial carrier burst, the Preamble and the group length. You can also dictate the data string transmitted.

Here is an example of a data packet having just two bytes of data:

- One symbol = one bit (OOK,ASK,FSK or BPSK)
- Preamble length = 2 bits
- Group length = 4 bits
- Tx Length = 2 bytes

Pilot Preamble	Zero 0	Start 1	Data 4 bits of data	Zero 0	Start 1	Data 4 bits of data	Zero 0	Start 1	Data 4 bits of data	Zero 0	Start 1	Data 4 bits of data	Zero 0
----------------	--------	---------	---------------------	--------	---------	---------------------	--------	---------	---------------------	--------	---------	---------------------	--------



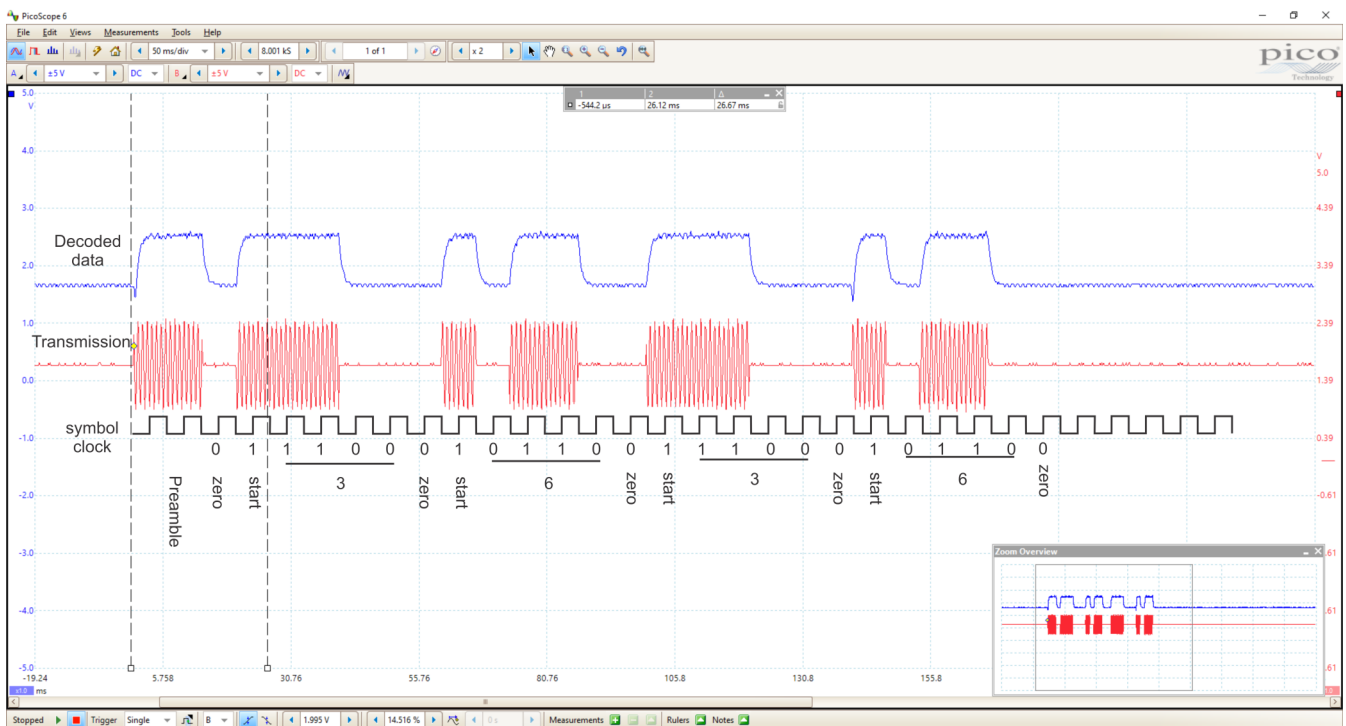
Digital comms packet structure

Communications and digital radio techniques

Example One symbol = one bit (OOK,ASK,FSK or BPSK)
 Preamble length = 2 bits
 Group length = 4 bits
 Tx Length = 2 bytes

Pilot Preamble	Zero 0	Start 1	Data 4 bits of data	Zero 0	Start 1	Data 4 bits of data	Zero 0	Start 1	Data 4 bits of data	Zero 0	Start 1	Data 4 bits of data	Zero 0
----------------	--------	---------	---------------------	--------	---------	---------------------	--------	---------	---------------------	--------	---------	---------------------	--------

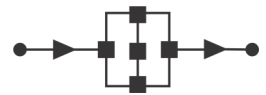
The Picoscope trace shows how this relates to the actual transmission between Transmitter and Receiver (red trace) and the Receiver output (blue trace).



We have superimposed on this image the virtual symbol clock and the data transmitted in each symbol period.

This trace shows an On Off Keying (OOK) transmission of the letters 'cc'.
 In ASCII, 'c' is hex 63, i.e. two bytes - 6 and 3 - or binary 0110, 0011.

The lowest bit of the low nibble, 0011, is transmitted first (i.e. appears at the right-hand end of the trace.)

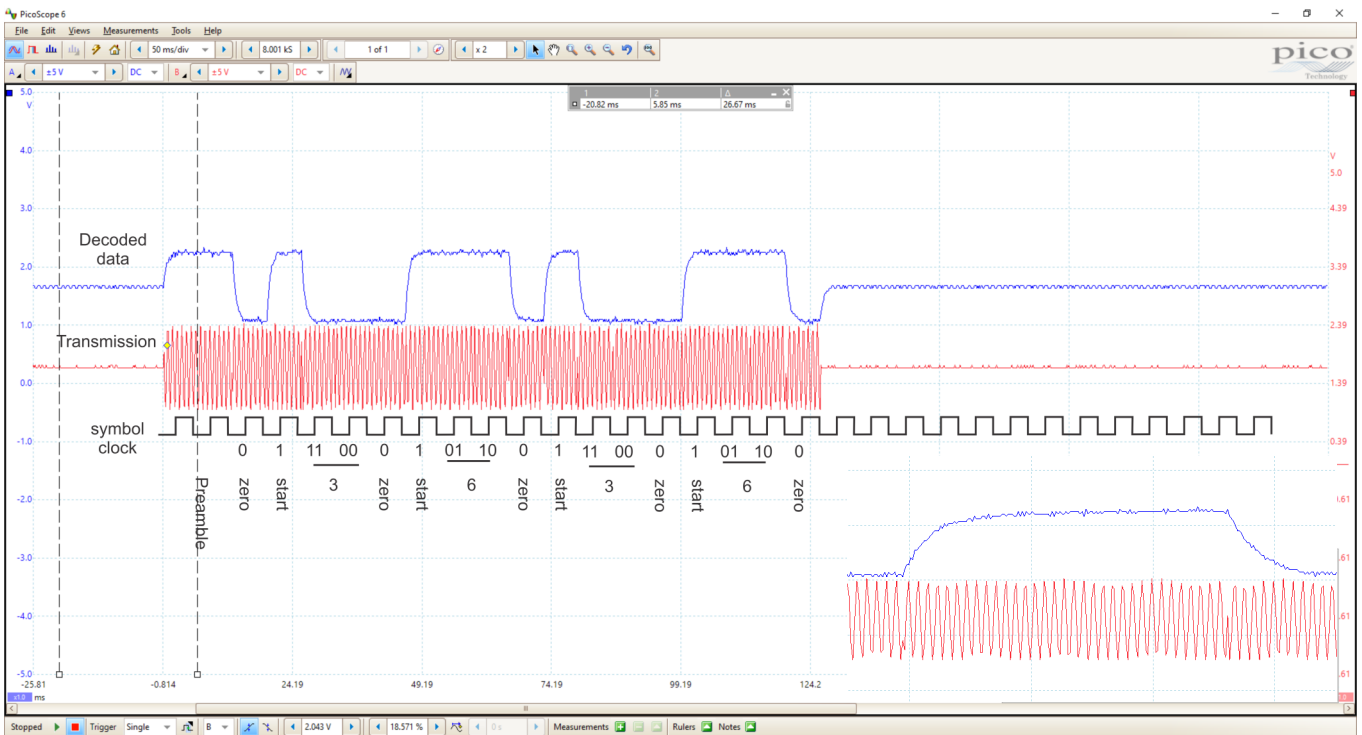


Digital comms packet structure

Communications and digital radio techniques

Example One symbol = two bits (QPSK)
 Preamble length = 2 bits
 Group length = 4 bits
 Tx Length = 2 bytes

Pilot	Zero	Start	Data	Zero	Start	Data	Zero	Start	Data	Zero	Start	Data	Zero
Preamble	0	1	2 symbols, 4 bits	0	1	2 symbols, 4 bits	0	1	2 symbols, 4 bits	0	1	2 symbols, 4 bits	0

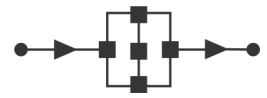


The same transmission of 'cc' looks very different using QPSK .

Here a phase change in a symbol period is used to transmit one of: '00', '01', '10', or '11'.
 This makes the transmission shorter.

It's hard to see the phase transitions on the main trace.
 You can just make them out in the magnified insert, at bottom right.

Version control



**Communications and
digital radio techniques**

15 02 24 First release