

PCM ENCODING

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PCM ENCODING

ACHIEVEMENTS: *introduction to pulse code modulation (PCM) and the PCM ENCODER module. Coding of a message into a train of digital words in binary format.*

PREREQUISITES: *an understanding of sampling, from previous experiments, and of PCM from course work or a suitable text. Completion of the experiment entitled **Sampling with SAMPLE & HOLD** (in this Volume) would be a distinct advantage.*

ADVANCED MODULES: *PCM ENCODER*

PREPARATION

PCM

This is an introductory experiment to pulse code modulation - PCM.

The experiment will acquaint you with the PCM ENCODER, which is one of the TIMS Advanced Modules. This module generates a PCM output signal from an analog input message.

In this experiment the module will be used in isolation; that is, it will not be part of a larger system. The formatting of a PCM signal will be examined in the time domain.

A later experiment, entitled *PCM decoding* (in this Volume), will illustrate the recovery of the analog message from the digital signal.

In another experiment, entitled *PCM TDM* (within *Volume D2 - Further & Advanced Digital Experiments*), the module will be part of a system which will generate a two-channel pulse code modulated time division multiplexed system (PCM TDM).

PCM encoding

The input to the PCM ENCODER module is an analog message. This must be constrained to a defined bandwidth and amplitude range.

The maximum allowable message bandwidth will depend upon the sampling rate to be used. The Nyquist criterion must be observed.

The amplitude range must be held within the ± 2.0 volts range of the TIMS ANALOG REFERENCE LEVEL. This is in keeping with the input amplitude limits set for all analog modules.

A step-by-step description of the operation of the module follows:

1. the module is driven by an external TTL clock.
2. the input analog message is *sampled* periodically. The *sample rate* is determined by the external clock.
3. the sampling is a *sample-and-hold* operation. It is internal to the module, and cannot be viewed by the user¹. What is held is the *amplitude* of the analog message *at the sampling instant*.
4. each sample amplitude is compared with a finite set of amplitude levels. These are distributed (uniformly, for *linear* sampling) within the range ± 2.0 volts (the TIMS ANALOG REFERENCE LEVEL). These are the system *quantizing* levels.
5. each quantizing level is assigned a *number*, starting from zero for the lowest (most negative) level, with the highest number being (L-1), where L is the available number of levels.
6. each sample is *assigned* a digital (binary) code word representing the number associated with the quantizing level which is closest to the sample amplitude. The number of bits 'n' in the digital code word will depend upon the number of quantizing levels. In fact, $n = \log_2(L)$.
7. the code word is *assembled into a time frame* together with other bits as may be required (described below). In the TIMS PCM ENCODER (and many commercial systems) a single extra bit is added, in the least significant bit position. This is alternately a *one* or a *zero*. These bits are used by subsequent decoders for frame synchronization.
8. the *frames* are transmitted serially. They are transmitted at the same rate as the samples are taken (but see Tutorial Question 3). The serial bit stream appears at the output of the module.
9. also available from the module is a synchronizing signal FS ('frame synch'). This signals the *end* of each data frame.

¹ the *sample and hold* operation is examined separately in the experiment entitled *Sampling with SAMPLE & HOLD* in this Volume.

the PCM ENCODER module

front panel features

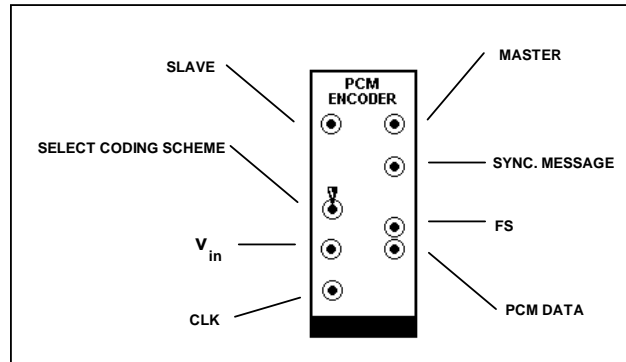


Figure 2: front panel layout of the PCM ENCODER

The front panel layout of the module is shown in Figure 2. Technical details are described in the *TIMS Advanced Modules User Manual*.

Note and understand the purpose of each of the input and output connections, and the three-position toggle switch. Counting from the top, these are:

- **SLAVE**: not used during this experiment. Do *not* connect anything to this input.
- **MASTER**: not used during this experiment. Do *not* connect anything to this output.
- **SYNC. MESSAGE**: periodic, ‘synchronized’, message. Either sinusoidal, or sinusoidal-like (‘sinuous’), its frequency being a sub-multiple of the MASTER CLOCK (being any one of four frequencies selected by an on-board switch SW2). A message synchronized to the system clock is convenient for obtaining stable oscilloscope displays. Having a recognisable shape (but being more complex than a simple sine wave) gives a qualitative idea of distortion during the decoding process (examined in a later experiment). See Table A-1 in the Appendix to this experiment for more details.
- **SELECT CODING SCHEME**: a three-position toggle switch which selects the 4-bit or 7-bit encoding scheme of the analog samples; or (together with an on-board jumper connection) the companding scheme.
- **FS**: frame synchronization, a signal which indicates the end of each data frame.
- **V_{in}**: the analog signal to be encoded.
- **PCM DATA**: the output data stream, the examination of which forms the major part of this experiment.
- **CLK**: this is a TTL (red) input, and serves as the MASTER CLOCK for the module. Clock rate must be 10 kHz or less. For this experiment you will use the 8.333 kHz TTL signal from the MASTER SIGNALS module.

the TIMS PCM time frame

Each binary word is located in a *time frame*. The time frame contains eight *slots* of equal length, and is eight clock periods long. The slots, from first to last, are numbered 7 through 0. These slots contain the bits of a binary word. The least significant bit (LSB) is contained in slot 0.

The LSB consists of alternating *ones* and *zeros*. These are placed ('embedded') in the frame by the encoder itself, and cannot be modified by the user. They are used by subsequent decoders to determine the location of each frame in the data stream, and its length. See the experiment entitled *PCM decoding* (in this Volume).

The remaining seven slots are available for the bits of the binary code word. Thus the system is capable of a resolution of seven-bits maximum. This resolution, for purposes of experiment, can be reduced to four bits (by front panel switch). The 4-bit mode uses only five of the available eight slots - one for the embedded frame synchronization bits, and the remaining four for the binary code word (in slots 4, 3, 2, and 1).

pre-calculations

You will be using an 8.333 kHz master clock. Answer Tutorial Question Q1 now, *before* commencing the experiment.

EXPERIMENT

The only module required for this experiment is a TIMS PCM ENCODER.

It is not necessary, for this experiment, to become involved with *how* the PCM ENCODER module achieves its purpose. What will be discovered is *what* it does under various conditions of operation.

The module is capable of being used in two modes: as a stand-alone PCM encoder, for one channel, or, with modifications to the data stream, as part of a two-channel time division multiplexed (TDM) PCM system.

Operation as a single channel PCM encoder is examined in this experiment.

Before plugging the module in:

T1 select the TIMS companding A_4 -law with the on-board COMP jumper (in preparation for a later part of the experiment).

T2 locate the on-board switch SW2. Put the LEFT HAND toggle DOWN and the RIGHT HAND toggle UP. This sets the frequency of a message from the module at SYNC. MESSAGE. This message is synchronized to a sub-multiple of the MASTER CLOCK frequency. For more detail see the Appendix to this experiment.

patching up

To determine some of the properties of the analog to digital conversion process it is best to start with a DC message. This ensures completely stable oscilloscope displays, and enables easy identification of the quantizing levels.

Selecting the 4-bit encoding scheme reduces the number of levels (2^4) to be examined.

T3 *insert the module into the TIMS frame. Switch the front panel toggle switch to 4-BIT LINEAR (ie., no companding).*

T4 *patch the 8.333 kHz TTL SAMPLE CLOCK from the MASTER SIGNALS module to the CLK input of the PCM ENCODER module.*

T5 *connect the V_{in} input socket to ground of the variable DC module.*

T6 *connect the frame synchronization signal FS to the oscilloscope ext. synchron. input.*

T7 *on CH1-A display the frame synchronization signal FS. Adjust the sweep speed to show three frame markers. These mark the **end** of each frame.*

T8 *on CH2-A display the CLK signal.*

T9 *record the number of clock periods per frame.*

Currently the analog input signal is zero volts (V_{in} is grounded). Before checking with the oscilloscope, consider what the PCM output signal might look like. Make a sketch of this signal, fully annotated. Then:

T10 *on CH2-B display the PCM DATA from the PCM DATA output socket.*

Except for the alternating pattern of '1' and '0' in the frame marker slot, you might have expected nothing else in the frame (all zeros), because the input analog signal is at zero volts. But you do not know the coding scheme.

There *is* an analog *input* signal to the encoder. It is of zero volts. This will have been coded into a 4-bit binary *output* number, which will appear in *each* frame. It need not be '0000'. The *same* number appears in *each* frame because the analog input is *constant*.

Your display should be similar to that of Figure 3 below, except that this shows five frames (too many frames on the oscilloscope display makes bit identification more difficult).

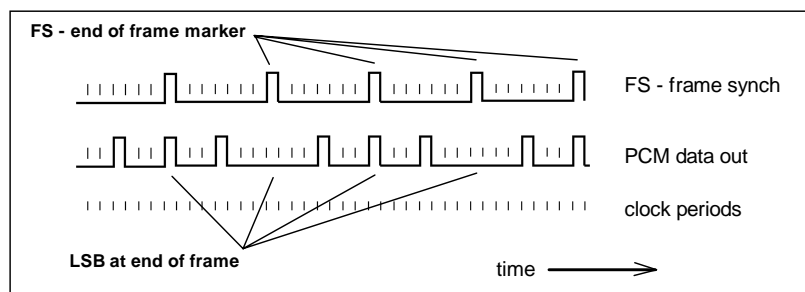


Figure 3: 5 frames of 4-bit PCM output for zero amplitude input

Knowing:

1. the number of slots per frame is 8
2. the location of the least significant bit is coincident with the end of the frame
3. the binary word length is four bits
4. the first three slots are 'empty' (in fact filled with zeros, but these remain unchanged under all conditions of the 4-bit coding scheme)

then:

T11 identify the binary word in slots 4, 3, 2, and 1.

quantizing levels for 4-bit linear encoding

You will now proceed to determine the quantizing/encoding scheme for the 4-bit linear case.

T12 remove the ground connection, and connect the output of the VARIABLE DC module to V_{in} . Sweep the DC voltage slowly backwards and forwards over its complete range, and note how the data pattern changes in discrete jumps.

T13 if you have a WIDEBAND TRUE RMS METER module use this to monitor the DC amplitude at V_{in} - otherwise use the oscilloscope (CH1-B). Adjust V_{in} to its maximum negative value. Record the DC voltage and the pattern of the 4-bit binary number.

T14 slowly increase the amplitude of the DC input signal until there is a sudden change to the PCM output signal format. Record the format of the new digital word, and the input amplitude at which the change occurred.

T15 continue this process over the full range of the DC supply.

T16 draw a diagram showing the quantizing levels and their associated binary numbers.

4-bit data format

From measurements made so far you should be able to answer the questions:

- what is the sampling rate ?
- what is the frame width ?
- what is the width of a data bit ?
- what is the width of a data word ?
- how many quantizing levels are there ?
- are the quantizing levels uniformly (linearly) spaced ?

7-bit linear encoding

T17 change to 7-bit linear encoding by use of the front panel toggle switch.

It would take a long time to repeat all of the above Tasks for the 7-bit encoding scheme. Instead:

T18 make sufficient measurements so that you can answer all of the above questions in the section titled 4-bit data format above. Making one or two assumptions (such as ?) you should be able to deduce the coding scheme used.

companding

This module is to be used in conjunction with the PCM DECODER in a later experiment. As a pair they have a *companding* option. There is compression in the encoder, and expansion in the decoder. In the encoder this means the quantizing levels are closer together for small input amplitudes - that is, in effect, that the input amplitude peaks are compressed during encoding. At the decoder the 'reverse action' is introduced to restore an approximate linear input/output characteristic.

It can be shown that this sort of characteristic offers certain advantages, especially when the message has a high peak-to-average amplitude characteristic, as does speech, and where the signal-to-noise ratio is not high.

This improvement will not be checked in this experiment. But the existence of the non-linear quantization in the encoder will be confirmed.

In a later experiment, entitled *PCM decoding* (in this Volume), it will be possible to check the input/output linearity of the modules as a compatible pair.

T19 change to 4-bit companding by use of the front panel toggle switch.

T20 the TIMS A₄ companding law has already been selected (first Task). Make the necessary measurements to determine the nature of the law.

periodic messages

Although the experiment is substantially complete, you may have wondered why a periodic message was not chosen at any time. Try it.

T21 take a periodic message from the SYNC. MESSAGE socket. This was set as the second Task.

T22 adjust the oscilloscope to display the message. Record its frequency and shape. Check if these are compatible with the Nyquist criterion; adjust the amplitude if necessary with one of the BUFFER AMPLIFIERS.

T23 now look at the PCM DATA output. Synchronize the oscilloscope (as previously) to the frame (FS) signal. Display two or three frames on CH1-A, and the PCM DATA output on CH2-A.

You will see that the data signal reveals very little. It consists of many overlaid digital words, all different.

One would need more sophisticated equipment than is assumed here (a digital analyzer, a storage oscilloscope, ability to capture a single frame, and so on) to deduce the coding and quantizing scheme from such an input signal.

conclusions

What is the advantage of 7-bit over 4-bit encoding ? Of what use is companding ? From your measurements alone these questions cannot be answered.

These and other questions will be addressed in the experiment entitled *PCM decoding* (in this volume - but see the Tutorial Questions).

The findings of this experiment will be required in later PCM experiments. These will involve decoding of the data stream, an investigation of companding, and time multiplexing of the outputs from two PCM ENCODER modules.

TUTORIAL QUESTIONS

- Q1** from your knowledge of the PCM ENCODER module, obtained during preparation for the experiment, calculate the sampling rate of the analog input signal. Show that it is the same for both the 4-bit and the 7-bit coding schemes. What can you say about the bandwidth of an input analog signal to be encoded ?
- Q2** define what is meant by the data 'frame' in this experiment. Draw a diagram showing the composition of a frame for:
- a) the 4-bit coding scheme
 - b) the 7-bit coding scheme
- Q3** it is possible to transmit each frame at a much slower rate than it was produced (and, of course, recover the original message as well). Explain how this might be done. When might this be an advantage ?
- Q4** explain why a DC message gives a stable oscilloscope display of the PCM DATA output. Why is the display 'unstable' when a sine wave (for example) is the message ?
- Q5** for the 4-bit encoder draw a diagram showing the amplitude quantization levels and the corresponding binary numbers used to encode them. Describe how this information was obtained experimentally.
- Q6** two PCM signals can be combined to produce a time division multiplexed (PCM TDM) signal. With the measurements so far performed this does not seem (and indeed, is not) possible with two PCM ENCODER modules ! Why is this so ? Suggest what changes could be made to the module to implement PCM TDM ².
- Q7** if you have studied the principles of companding in your course, describe its advantages. Then, if not already done so, plot the shape of the TIMS compression law introduced by the companding operation you measured. Compare this with published information about the 'A' and 'μ' companding laws used respectively in Europe and the USA.

² in a later experiment it will be seen that suitable modifications to the data stream have been introduced so that a two-channel PCM TDM can be modelled.

APPENDIX

For a MASTER CLOCK of 8.333 kHz, Table A-1 below gives the frequencies of the synchronized message at the SYNC. MESSAGE output for the setting of the on-board switch SW2.

For other clock frequencies the message frequency can be calculated by using the 'divide by' entry in the Table.

These messages are periodic, but not necessarily sinusoidal in shape. The term 'sinuous' means sine-like.

<i>LH toggle</i>	<i>RH toggle</i>	<i>divide clock by</i>	<i>freq with 8.333kHz clock</i>	<i>approx. ampl. and waveform</i>
UP	UP	32	260.4 Hz	0.2 V_{pp} sine
DOWN	UP	64	130.2 Hz	2.0 V_{pp} sine
UP	DOWN	128	65.1 Hz	4.0 V_{pp} sinuous
DOWN	DOWN	256	32.6 Hz	4.0 V_{pp} sinuous

Table A-1

