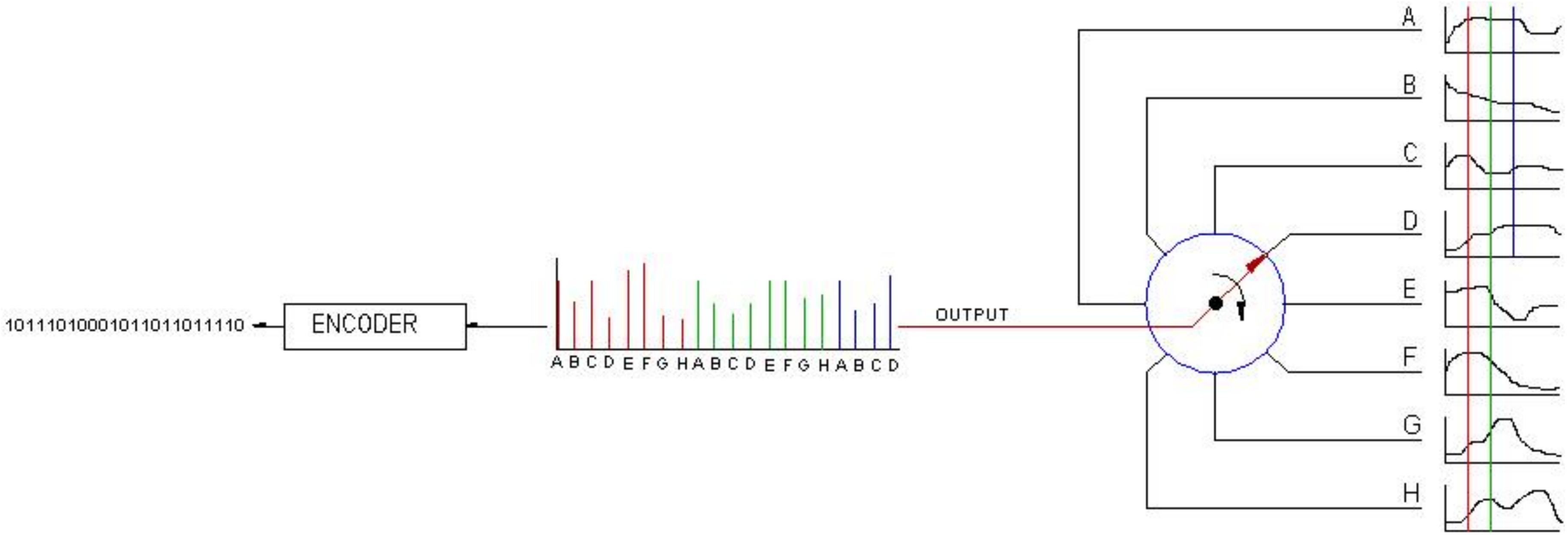
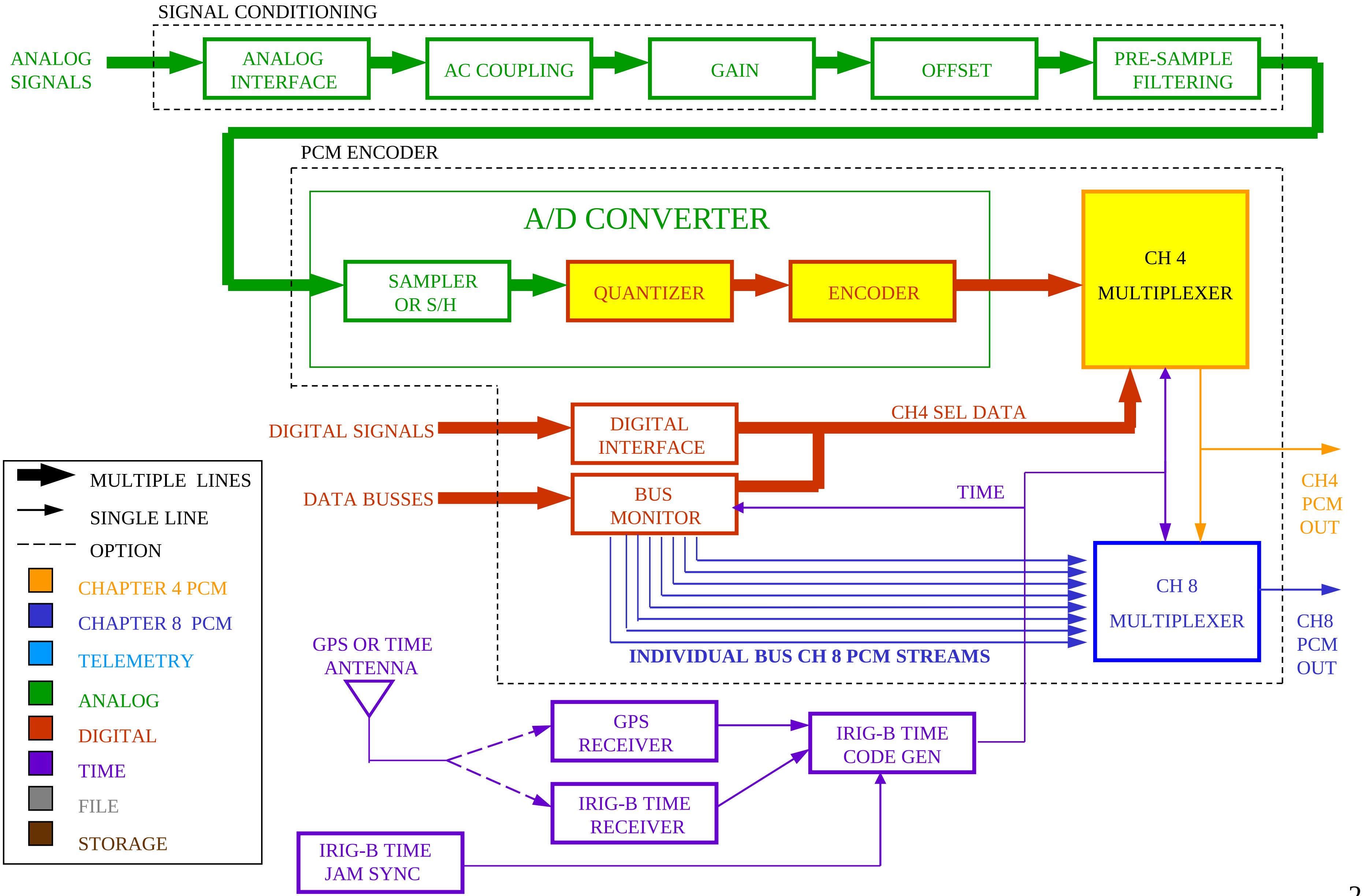
IRIG-106 Chapter 4: Pulse Code Modulation (PCM) Map and Structures



Data Acquisition System



The IRIG-106 Telemetry Standards

- IRIG stands for Inter-Range Instrumentation Group.
- The IRIG-106 Standard contains telemetry standards on transmitters, receivers, PCM formats, recorders, etc…
- The Telemetry Group of the Range Commanders Council prepared this document to foster compatibility between the test ranges.
- Everyone should have the latest copy of the IRIG-106 Telemetry Standards. It can be found at https://www.wsmr.army.mil/RCCsite/Documents/106-19_Telemetry_Standards/106-19_Telemetry_Standards.pdf

Introduction

The characteristics of a PCM stream are defined in Chapter 4 of the IRIG-106 Standard.

Two classes of PCM formats are discussed in Chapter 4. Class I is the basic simpler type, Class II is more complex, and usually involves more interaction with the ground station.

The PCM streams we utilize contain some of the Class II attributes.

What is PCM?

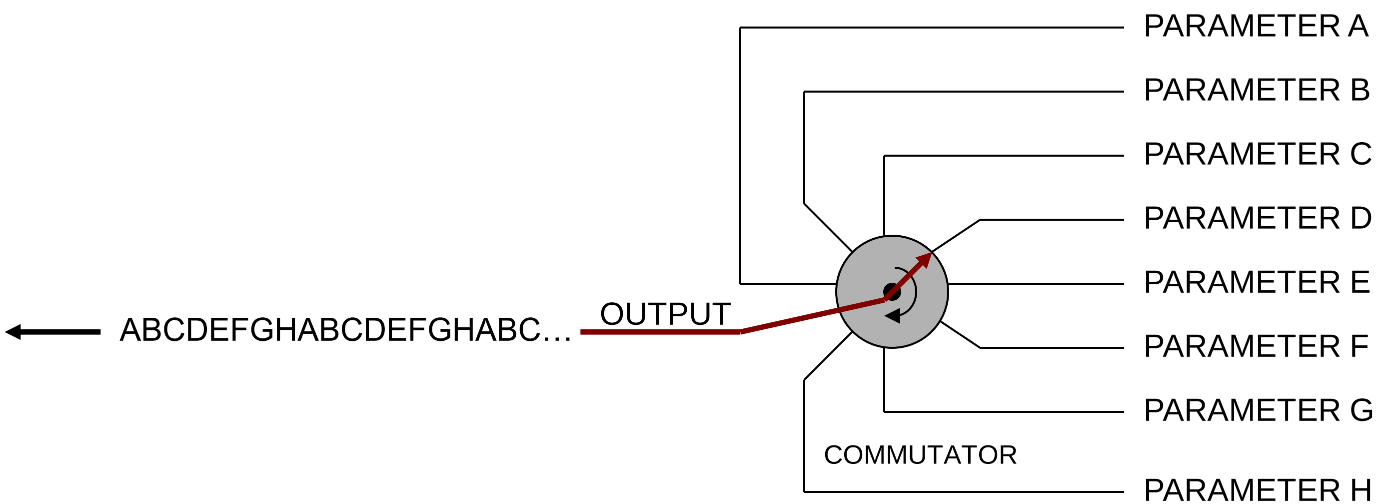
PCM stands for **P**ulse **C**ode **M**odulation, and it is a method of encoding analog parameters to a digital quantity.

Chapter 4 of the IRIG-106 Standard defines PCM as the serial bit stream of binary-coded time-division multiplexed words.

This definition will not have any meaning until we define some of the terminology and describe how this serial bit stream is created.

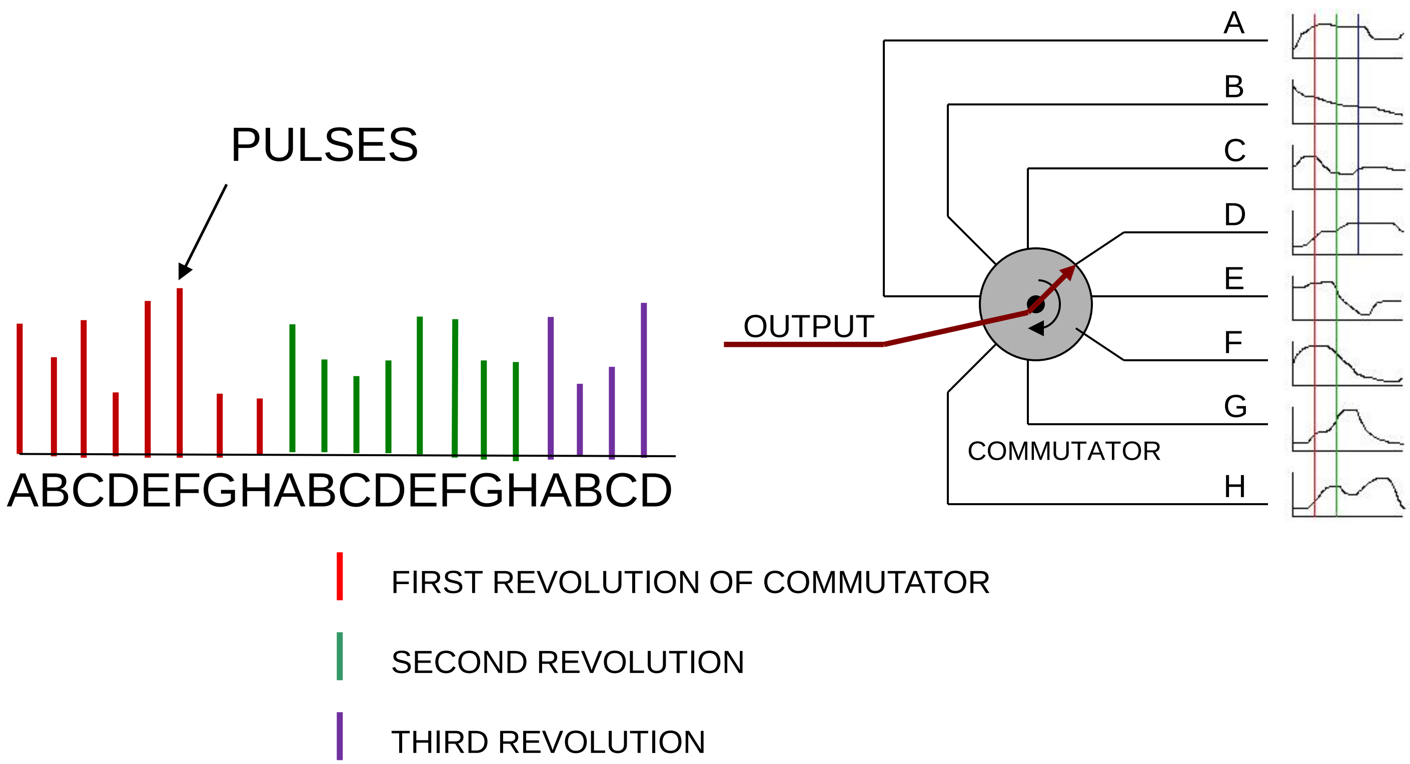
The Multiplexer/Sampler

A Multiplexer/Sampler can put several quantitative measurements over a single output line. The Commutator (shown below) is a mechanical model used to illustrate how a multiplexer/sampler works. As the arm rotates, each parameter is output within in a certain time period. This is known as Time Division Multiplexing (TDM).



The Multiplexer/Sampler

Each parameter is an analog signal. At the instant the analog signal is sampled, its amplitude is captured and is output from the multiplexer as a pulse with that same amplitude. This is the “Pulse” in Pulse Code Modulation.

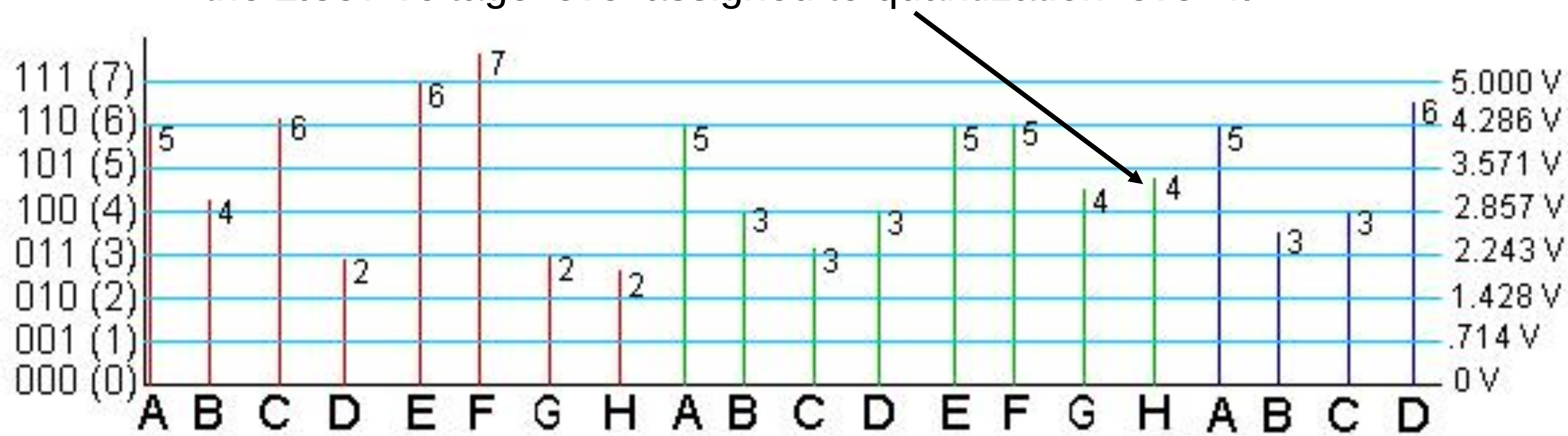


The Quantizer

The quantizer assigns a value corresponding to the amplitude of the individual pulses.

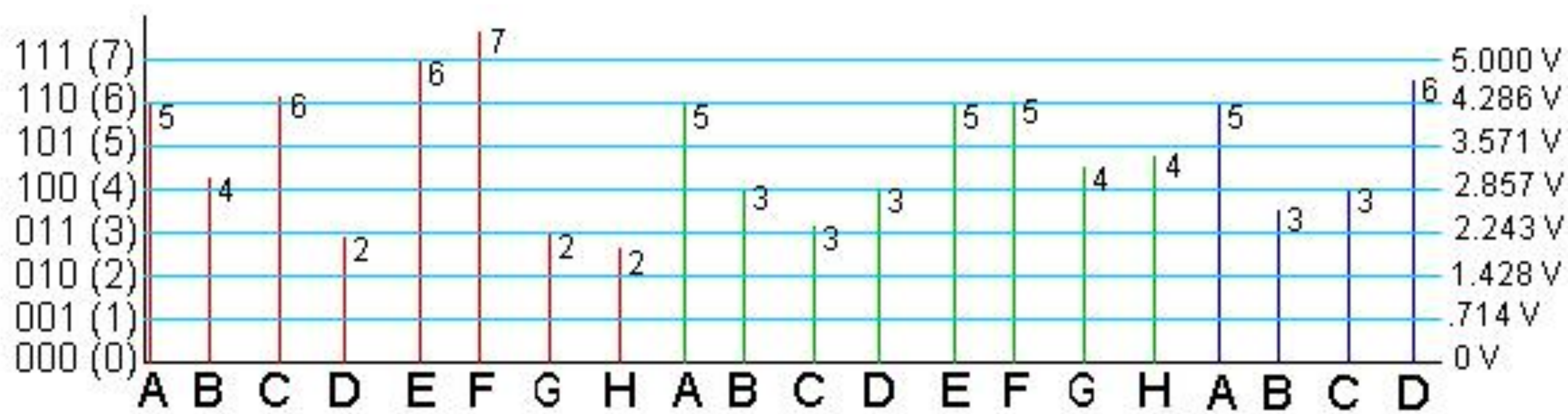
This example shows a 3-bit quantizer which can compare the amplitudes of the pulses to 8 different voltage levels (or quantization levels).

This pulse is assigned the number 4 because it exceeded the 2.857 voltage level assigned to quantization level 4.



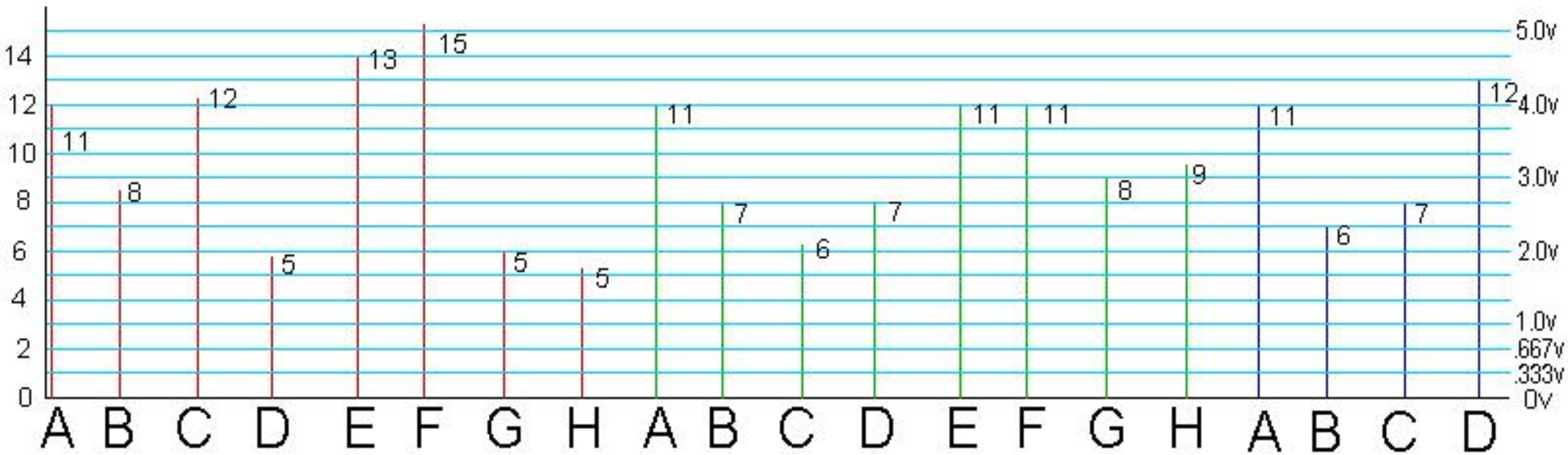
Resolution

The resolution of a measurement is the smallest quantity it can measure. For the 3-bit encoder, voltages between 0 volts and .7 volts will all be given the value of 0. The smallest voltage the encoder can detect is .714 volts, which would be assigned a value of 1. Higher voltages will be assigned the threshold values they exceed.



Resolution

To increase the resolution, you need to increase the number of bits in the encoder. Here we increased it to 4 bits, giving us 16 quantization levels and now we can detect voltages as low as .333 volts.



Calculating Resolution

The resolution for an *n*-bit encoder can easily be calculated by:

$$\text{Resolution} = \frac{Full\ Scale\ Voltage\ Range}{2^n}$$

So for our 12-bit systems that measure a full-scale voltage range of -5.12 to +5.12 volts, the resolution will be:

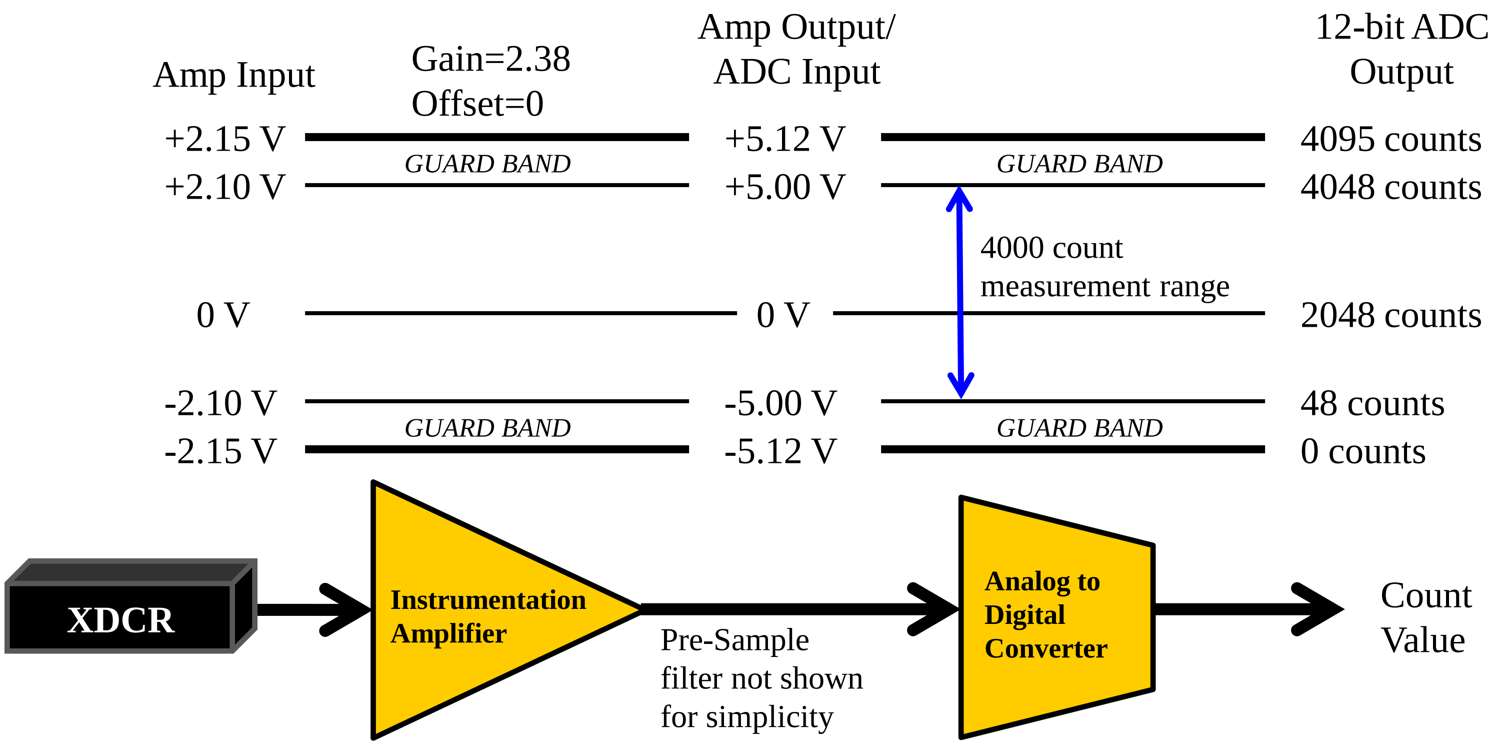
$$Resolution = \frac{[5.12 - (-5.12)]volts}{2^{12} counts} = \frac{[10.24]volts}{4096\ counts}$$

$$Resolution = 0.0025 \frac{volts}{count} = 2.5 \frac{mV}{count}$$

A Note on Calculating Resolution

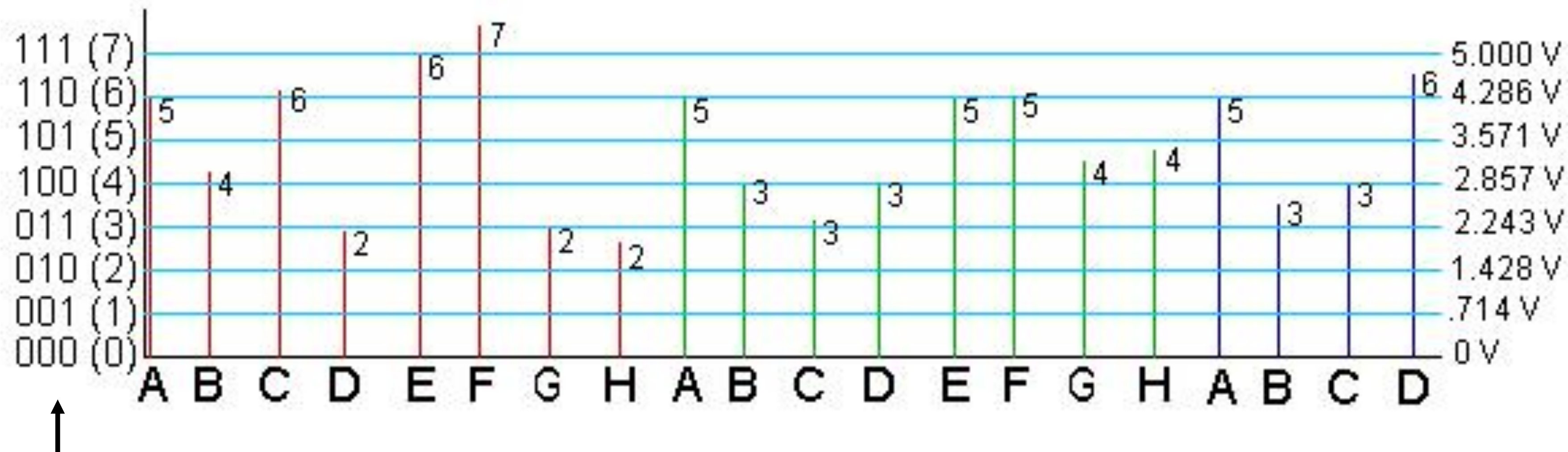
Most encoders allow some padding on each end of their full-scale range. When configuring data channels for a target voltage range of -5 to +5 volts (over a 4000-count range) it would look like the following:

The -5.12 to +5.12 volts allows some extra range should the signal overshoot your maximum range.



The Encoder

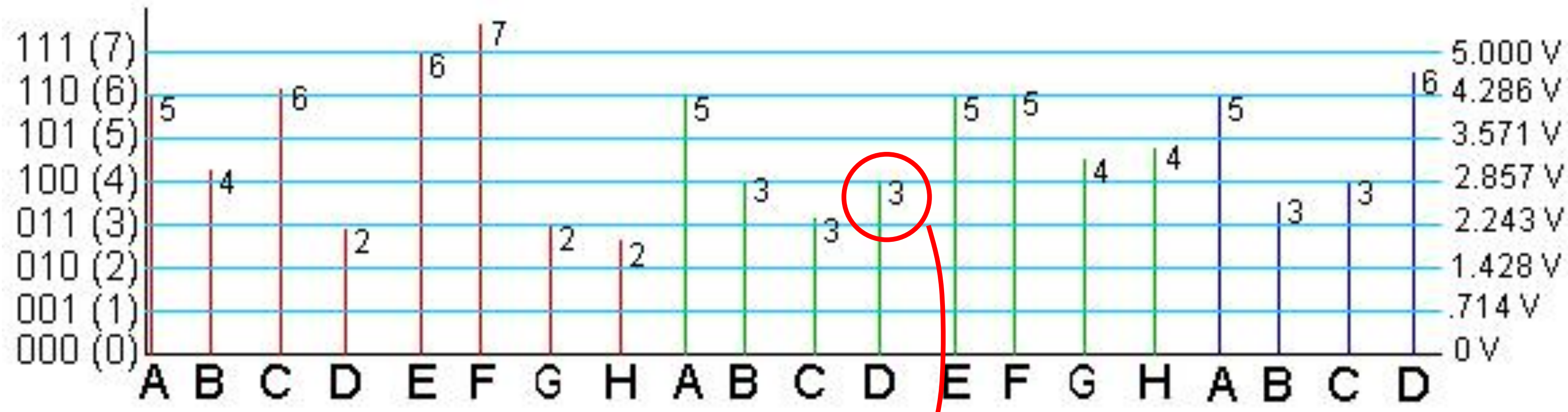
The Encoder takes the value from the quantizer and encodes it using some numbering representation. This example shows binary encoding, but you can also have 2's complement encoding as well. The SCD suite of cards for TTC's CDAU allows for both types of encoding. This step is the "Code" in Pulse Code Modulation.



Binary equivalents of quantization levels

The Encoder

The output from the encoder will be a string of bits consisting of the binary encoded values of the pulse amplitudes.



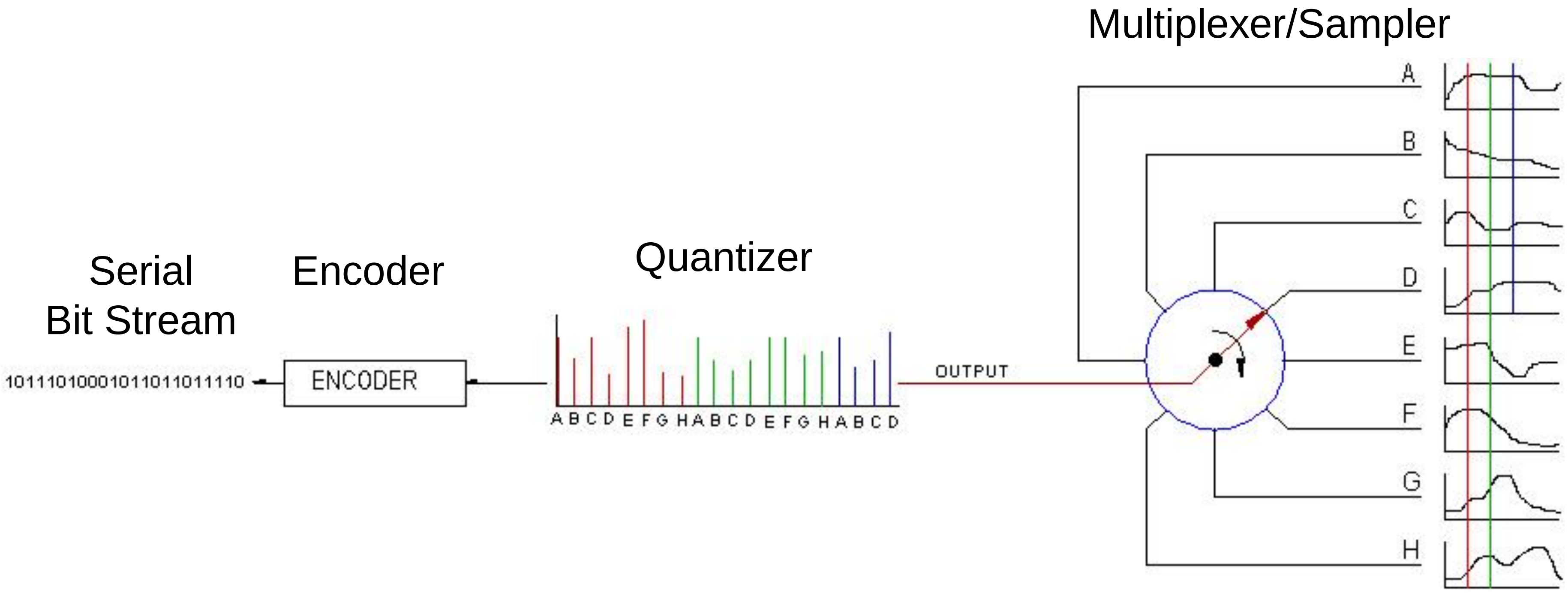
A B C D E F G H A B C D E F G H A B C D

101 100 110 010 110 111 010 010 101 011 011 011 101 101 100 100 101 011 011 110

The quantizer assigned the value of 3 to the sampled amplitude of D, the encoder coded that value as the 3-bit binary number 011 and placed it into the serial bit stream .

The Entire System

This diagram shows each of the components as a system. The multiplexer/sampler samples each of the signals, the quantizer assigns values to the amplitude of the pulses, and the encoder converts the amplitude value to a binary number, all which are output as a serial bit stream.



Class I PCM Stream

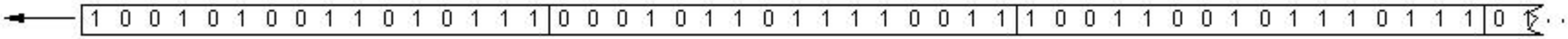
A PCM stream is defined as the serial bit stream of binary-coded time-division multiplexed words (or parameters).

This definition should make more sense now that the process of creating the PCM stream has been explained.

Serial Bit Stream

← 001101100110 011101010110 111001110100 011001001110

Bit Rate



The Bit Rate is the rate at which bits of the PCM stream are output within a second. Its units are bits/sec or bps.

For a Class I PCM Stream, the bit rate must be a minimum of 10 bps and maximum of 10 Mbps.

So a PCM stream with a bit rate of 2 Mbps outputs two million bits within a second.

PCM Words

When this serial stream of bits is divided into bit-groups called words, they convey information. Each word is the encoded sample of the parameters.

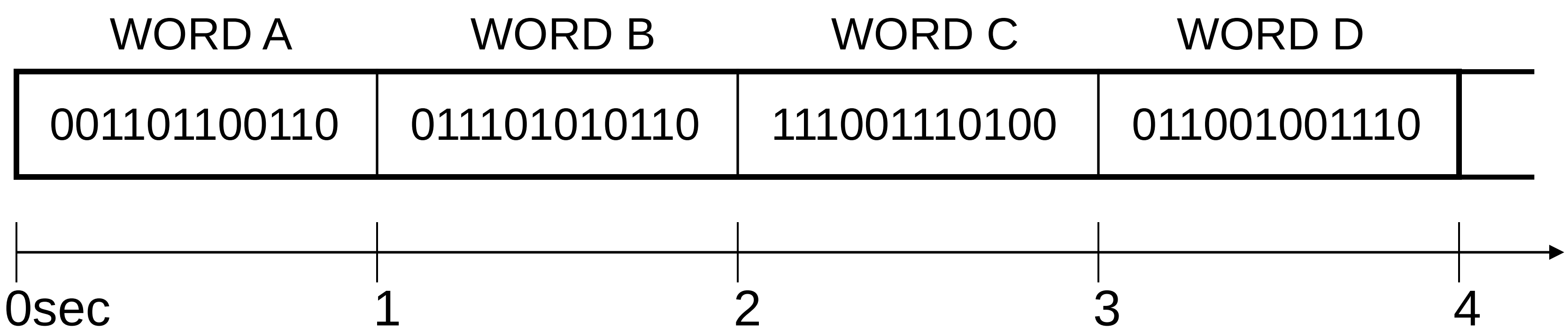
001101100110	011101010110	111001110100	011001001110

PCM Word (12-bits)

Time Division Multiplex (TDM)

in Reference to the PCM Stream

As shown earlier, only one word in the PCM stream is output at a time. For example, the information from Word B is output in the time period of 1 to 2 seconds and the information from Word C is output in the time period of 2 to 3 seconds. This is known as time division multiplexing as the parameters are output one at a time, not simultaneously.



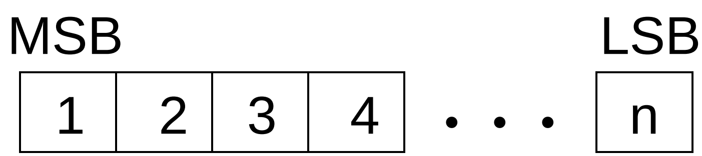
Word Length

The Word Length is defined as the number of bits per word (bpw).

For a Class I PCM Stream, this can vary from 4 to 32 bits.

Bit Numbering Within a Word

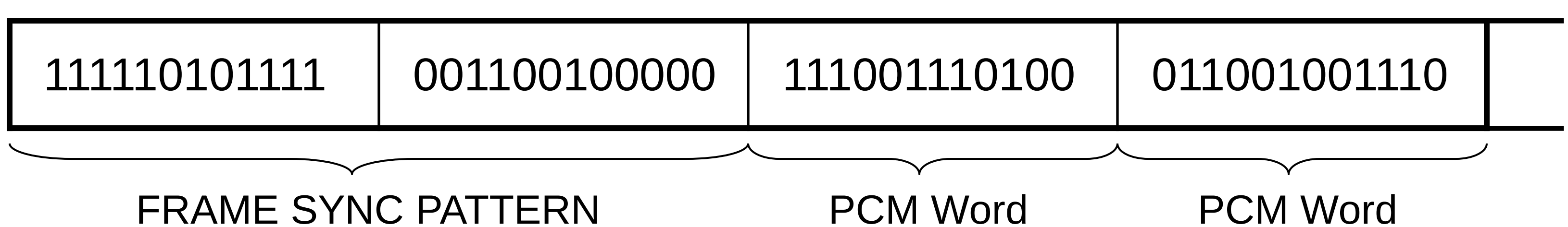
The most significant bit of a PCM word is bit position 1. Subsequent bits are numbered consecutively.



Be aware that when monitoring other systems and placing their data in a Chapter 4 PCM Stream, the bit numbering may not be the same. You will have to make a conversion chart which maps their numbering to Chapter 4's numbering. Not properly doing so will cause you to monitor the wrong bits.

Frame Synchronization Patterns

- Frame Synchronization (or Frame Sync) patterns are used to define the *beginning* of the PCM frame.
- Without a sync pattern, there is no reference to locate the beginning or end of a PCM stream. It just looks like an unending stream of 1’s and 0’s.
- The frame sync pattern length may vary from 16 to 33 bits. In practice, sync words are usually two PCM words in length in order to achieve frame sync patterns greater than 16 bits.



Frame Synchronization Patterns

- Frame sync patterns must be unique, such that two consecutive data words in your PCM stream don’t look like the assigned frame sync pattern.
- defined patterns of 1’s and 0’s called Barker Codes are used within frame sync patterns to get various lengths.
- Barker codes come in lengths of 2, 3, 4, 5, 7, 11, and 13 bits.
- Barker Codes were chosen because they are statistically less likely to appear as consecutive data words within the PCM stream.

Codes Assigned as Frame Sync Patterns

Table A-1. Optimum Frame Synchronization Patterns for PCM Telemetry

Pattern Length	Patterns									
16	111	010	111	001	000	0				
17	111	100	110	101	000	00				
18	111	100	110	101	000	000				
19	111	110	011	001	010	000	0			
20	111	011	011	110	001	000	00			
21	111	011	101	001	011	000	000			
22	111	100	110	110	101	000	000	0		
23	111	101	011	100	110	100	000	00		
24	111	110	101	111	001	100	100	000		
25	111	110	010	110	111	000	100	000	0	
26	111	110	100	110	101	100	110	000	00	
27	111	110	101	101	001	100	110	000	000	
28	111	101	011	110	010	110	011	000	000	0
29	111	101	011	110	011	001	101	000	000	00
30	111	110	101	111	001	100	110	100	000	000
31	111	111	100	110	111	110	101	000	010	000	0
32	111	111	100	110	101	100	101	000	010	000	00
33	111	110	111	010	011	101	001	010	010	011	000

Table A-1 of Appendix 4-A of the IRIG-106 Standard

Common Frame Sync Patterns

Word Lengths	Bit Pattern	Hex Equivalents
12 BITS/WD	1111 1010 1111 0011 0010 0000	FAF 320
16 BITS/WD	1111 1110 0110 1011 0010 1000 0100 0000	FE6B 2840

Because our data acquisition systems only use 12 and 16 bits, these are the codes we most commonly use.
Chapter 8, which has 24-bit words, utilizes FAF 320.

PCM Map

The PCM Map graphically shows the layout of the words within the PCM stream. It is laid out in a grid as shown below. Each block is a PCM word sample.

Minor Frame

A Minor Frame is the row of words from the beginning of a minor frame sync pattern to the beginning of the next minor frame sync pattern. This particular PCM map has 4 minor frames.

FRAME SYNC 1	FRAME SYNC 2						
FRAME SYNC 1	FRAME SYNC 2						
FRAME SYNC 1	FRAME SYNC 2						
FRAME SYNC 1	FRAME SYNC 2						

Each row is a minor frame in the PCM map.

Major Frame

A Major Frame contains the number of minor frames required to include one occurrence of every word in the format.

FRAME SYNC 1	FRAME SYNC 2						
FRAME SYNC 1	FRAME SYNC 2						
FRAME SYNC 1	FRAME SYNC 2						
FRAME SYNC 1	FRAME SYNC 2						

No Minor Frames?

Some PCM streams have a single minor frame. Therefore the major frame and the minor frame is the same. Although usually it is described as a PCM map that does not have any minor frames.

FRAME SYNC 1	FRAME SYNC 2						

Minor Frame Numbering

The first minor frame in a major frame shall be identified as minor frame 1. The remaining minor frames are numbered sequentially within the major frame.

For a Class I PCM stream, there are at most 256 minor frames in a major frame.

1	FRAME SYNC 1	FRAME SYNC 2						
2	FRAME SYNC 1	FRAME SYNC 2						
3	FRAME SYNC 1	FRAME SYNC 2						
4	FRAME SYNC 1	FRAME SYNC 2						

Subframe Identification

To identify between each of the minor frames within the major frame, a sub frame ID counter is used. It is usually the first word after the frame sync pattern. Depending on the system, this counter can start counting from 0 or 1.

1	FRAME SYNC 1	FRAME SYNC 2	SFID = 0					
2	FRAME SYNC 1	FRAME SYNC 2	SFID = 1					
3	FRAME SYNC 1	FRAME SYNC 2	SFID = 2					
4	FRAME SYNC 1	FRAME SYNC 2	SFID = 3					

A sub frame will be described later in this training.

Word Position Identification

The first word after the frame sync pattern shall be word number one. Each minor frame has the same word numbering with each individual word identified by its minor frame location (ex: word 4, minor frame 3). Do not get confused by identifying the location by the sub frame ID counter.

			1	2	3	4	5	6
1	FRAME SYNC 1	FRAME SYNC 2	SFID = 0					
2	FRAME SYNC 1	FRAME SYNC 2	SFID = 1					
3	FRAME SYNC 1	FRAME SYNC 2	SFID = 2			X		
4	FRAME SYNC 1	FRAME SYNC 2	SFID = 3					

Word Numbering

Because the first word after the frame sync pattern is designated as word 1, the PCM map is normally shown in this form in data acquisition software. This makes it easier for the person programming the hardware and creating the PCM map.

	1	2	3	4	5	6	7	8
1	SFID = 0						FRAME SYNC 1	FRAME SYNC 2
2	SFID = 1						FRAME SYNC 1	FRAME SYNC 2
3	SFID = 2						FRAME SYNC 1	FRAME SYNC 2
4	SFID = 3						FRAME SYNC 1	FRAME SYNC 2

This is a PCM map represented from the hardware point of view.

Word Numbering in TTCWare

This is how the PCM map is represented in TTCWare. Notice that the alternate method of placing the frame sync pattern at the end of each minor frame is used.

	Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8
Frame 1	SFID						SYNC	SYNC
Frame 2	SFID						SYNC	SYNC
Frame 3	SFID						SYNC	SYNC
Frame 4	SFID						SYNC	SYNC

Minor Frame Length

Minor Frame Length is defined as the number of words (including the frame sync pattern) within each minor frame.

For a Class I PCM Stream, the minor frame can be no longer than 8192 bits. For a 12-bit system that is 682 words, and for a 16-bit system that is 512 words. Additionally, no minor frame shall exceed 1024 words.

For our example, the minor frame length is 8 words/minor frame .

	1	2	3	4	5	6	7	8
1	SFID = 0						FRAME SYNC 1	FRAME SYNC 2
2	SFID = 1						FRAME SYNC 1	FRAME SYNC 2
3	SFID = 2						FRAME SYNC 1	FRAME SYNC 2
4	SFID = 3						FRAME SYNC 1	FRAME SYNC 2

Major Frame Length

Major Frame Length is defined as the minor frame length multiplied by the number of minor frames in the major frame.

In our example, the major frame length is

8 words/minor frame x 4 minor frames/major frame or

32 words/major frame.

	1	2	3	4	5	6	7	8
1	SFID = 0						FRAME SYNC 1	FRAME SYNC 2
2	SFID = 1						FRAME SYNC 1	FRAME SYNC 2
3	SFID = 2						FRAME SYNC 1	FRAME SYNC 2
4	SFID = 3						FRAME SYNC 1	FRAME SYNC 2

Minor Frame Word

A Minor Frame Word is one which is present only *once* in each minor frame.

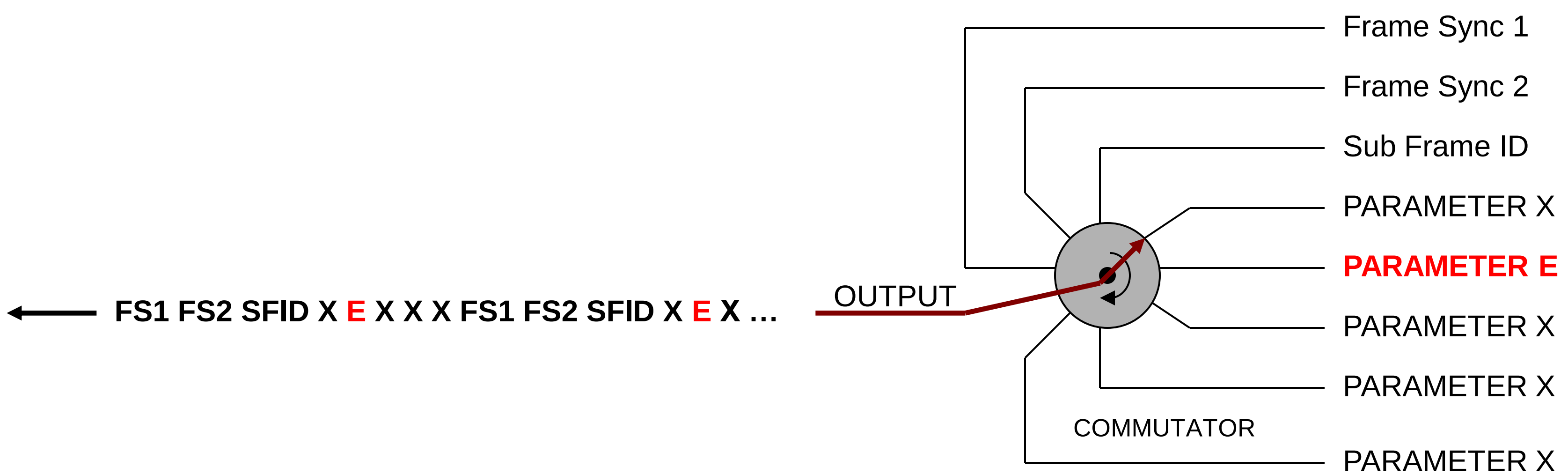
The word **E** in the PCM map below is a minor frame word.

	1	2	3	4	5	6	7	8
1	SFID = 0	X	E	X	X	X	FRAME SYNC 1	FRAME SYNC 2
2	SFID = 1	X	E	X	X	X	FRAME SYNC 1	FRAME SYNC 2
3	SFID = 2	X	E	X	X	X	FRAME SYNC 1	FRAME SYNC 2
4	SFID = 3	X	E	X	X	X	FRAME SYNC 1	FRAME SYNC 2

X designates spare word positions

Minor Frame Word

Going back to the commutator model, the minor frame is one revolution of the commutator. The parameter E only shows up once per revolution of the commutator, therefore it is a minor frame word.



Super Commutation

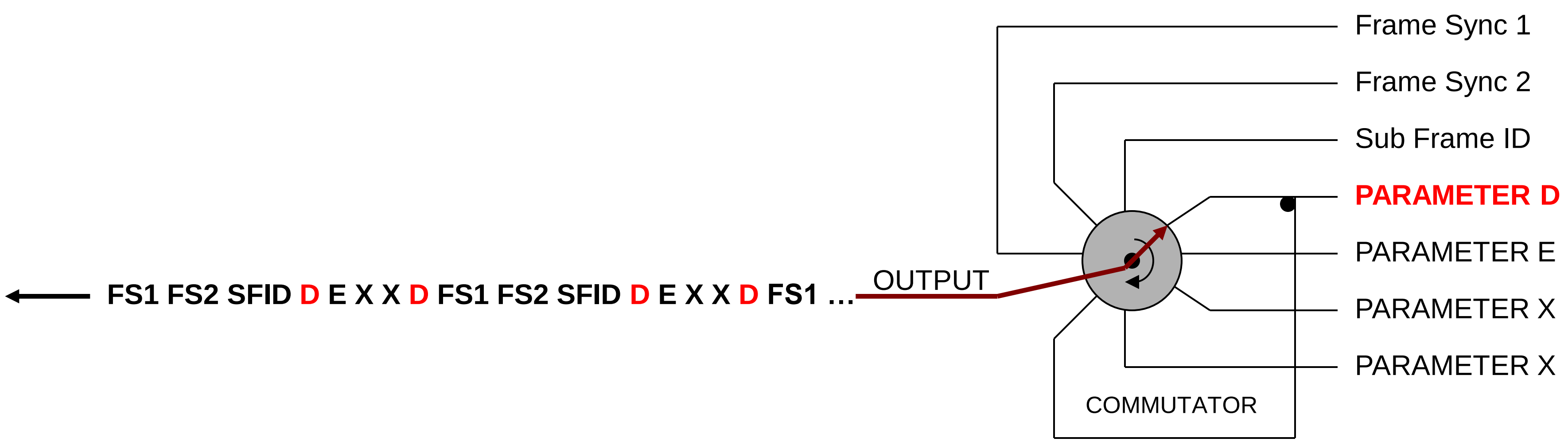
A super commutated word is one which appears more than once in a minor frame. This word *must appear in even word intervals*. Word D is a super commutated word appearing twice per minor frame in even intervals of 4 word positions.

	1	2	3	4	5	6	7	8
1	SFID = 0	D	E	X	X	D	FRAME SYNC 1	FRAME SYNC 2
2	SFID = 1	D	E	X	X	D	FRAME SYNC 1	FRAME SYNC 2
3	SFID = 2	D	E	X	X	D	FRAME SYNC 1	FRAME SYNC 2
4	SFID = 3	D	E	X	X	D	FRAME SYNC 1	FRAME SYNC 2

4 1 2 3 4 1 2 3

Super Commutation

Going back to the commutator model, The minor frame is one revolution of the commutator. The parameter D shows up more than once (two times) per revolution of the commutator, therefore it is a super commutated parameter.



Sub Frame

A Sub Frame is defined as a group of words in a column which occupy the same minor frame word in each of the minor frames. In this example, the sub frame occupies word 4.

	1	2	3	4	5	6	7	8
1	SFID = 0	D	E	X	X	D	FRAME SYNC 1	FRAME SYNC 2
2	SFID = 1	D	E	X	X	D	FRAME SYNC 1	FRAME SYNC 2
3	SFID = 2	D	E	X	X	D	FRAME SYNC 1	FRAME SYNC 2
4	SFID = 3	D	E	X	X	D	FRAME SYNC 1	FRAME SYNC 2

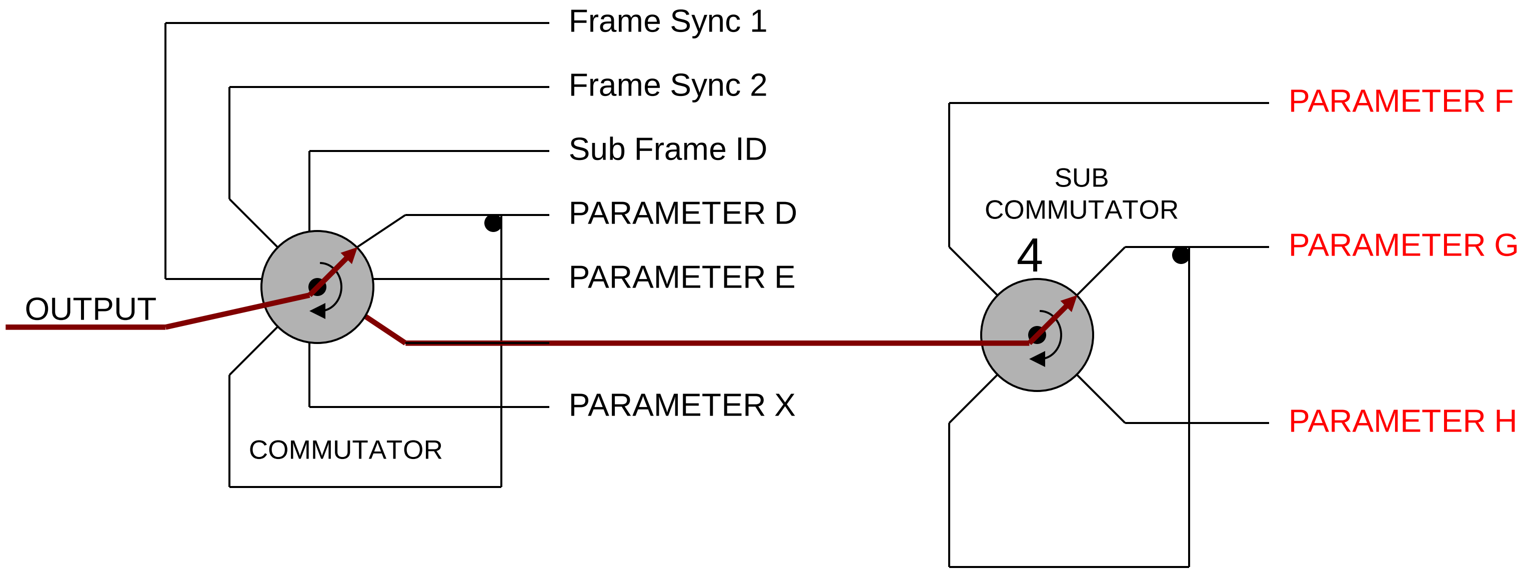
Sub Commutation

A Sub Commutated word is one which is sampled at evenly spaced sub multiple rates of the minor frame rate.   Parameters F and H are sampled ¼ of the minor frame rate and G is sampled ½ the minor frame rate. A parameter appearing 4 times would be a minor frame word (parameter E).

	1	2	3	4	5	6	7	8
1	SFID = 0	D	E	F		D	FRAME SYNC 1	FRAME SYNC 2
2	SFID = 1	D	E	G		D	FRAME SYNC 1	FRAME SYNC 2
3	SFID = 2	D	E	H		D	FRAME SYNC 1	FRAME SYNC 2
4	SFID = 3	D	E	G		D	FRAME SYNC 1	FRAME SYNC 2

Sub Commutation

Parameters F, G and H are each sub commutated words within the PCM Frame.



The commutator on the left is spinning 4 times faster than the sub commutator on the right.

Super Sub Commutation

This is a term used in TMATS (Chapter 9) but is not defined in Chapter 4.

A Super Sub Commutated word is one which appears multiple times within a sub frame. The word must be sampled at even intervals (in this case 16-word intervals) within the sub frame.

Word **G** is a super sub commutated word appearing twice within the sub frame 4.

	1	2	3	4	5	6	7	8
1	SFID = 0	D	E	F	X	D	FRAME SYNC 1	FRAME SYNC 2
2	SFID = 1	D	E	G	X	D	FRAME SYNC 1	FRAME SYNC 2
3	SFID = 2	D	E	H	X	D	FRAME SYNC 1	FRAME SYNC 2
4	SFID = 3	D	E	G	X	D	FRAME SYNC 1	FRAME SYNC 2

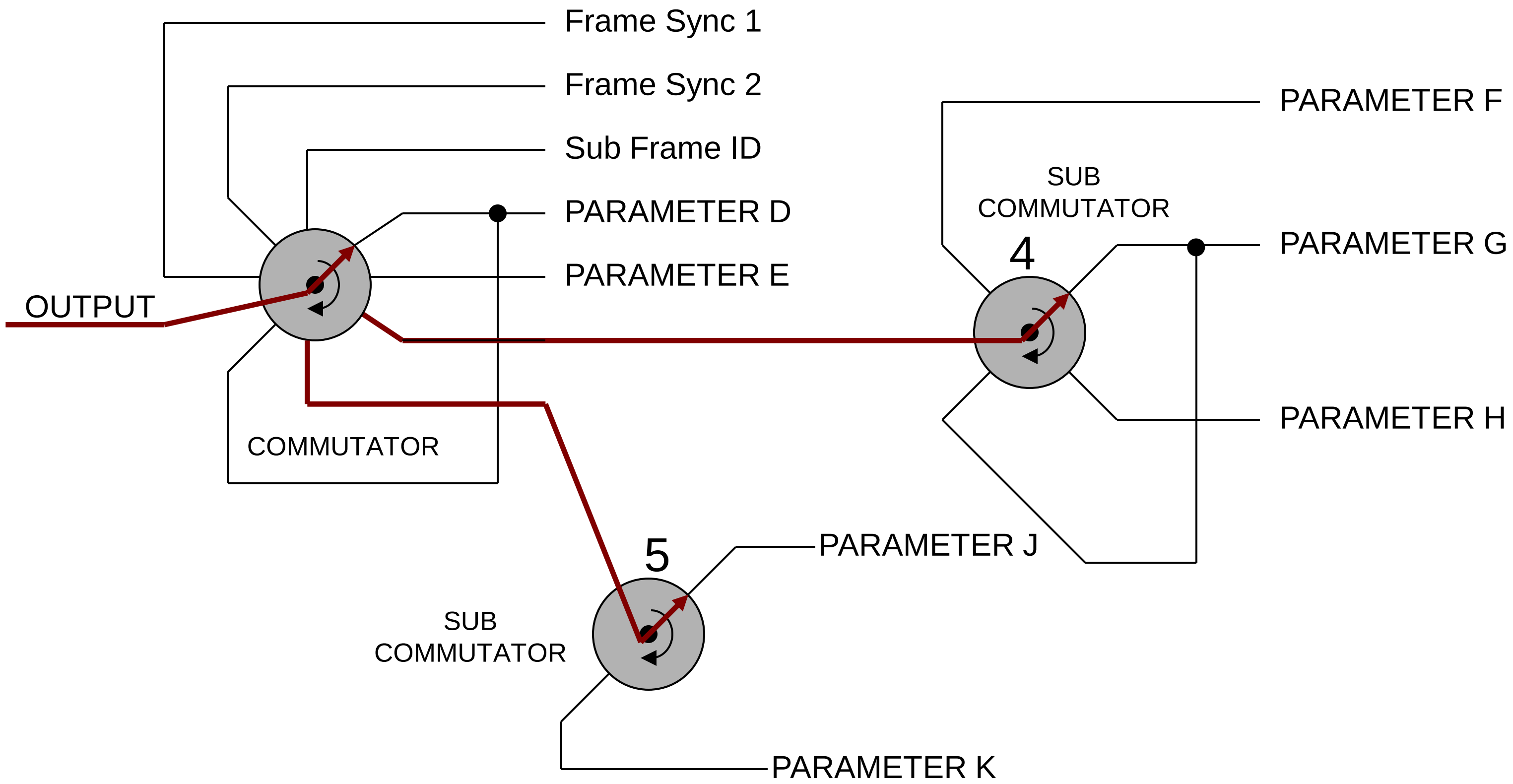
Sub Frame Depth

This can be somewhat confusing. Sub frame 4 and 5 both seem to have the same depth. However, sub frame depth is defined to be the number of minor frames needed until all parameters are sampled at least once, but not multiple times. Using this definition, sub frame 4 has a depth of 4 and sub frame 5 has a depth of 2.

	1	2	3	4	5	6	7	8
1	SFID = 0	D	E	F	J	D	FRAME SYNC 1	FRAME SYNC 2
2	SFID = 1	D	E	G	K	D	FRAME SYNC 1	FRAME SYNC 2
3	SFID = 2	D	E	H	J	D	FRAME SYNC 1	FRAME SYNC 2
4	SFID = 3	D	E	G	K	D	FRAME SYNC 1	FRAME SYNC 2

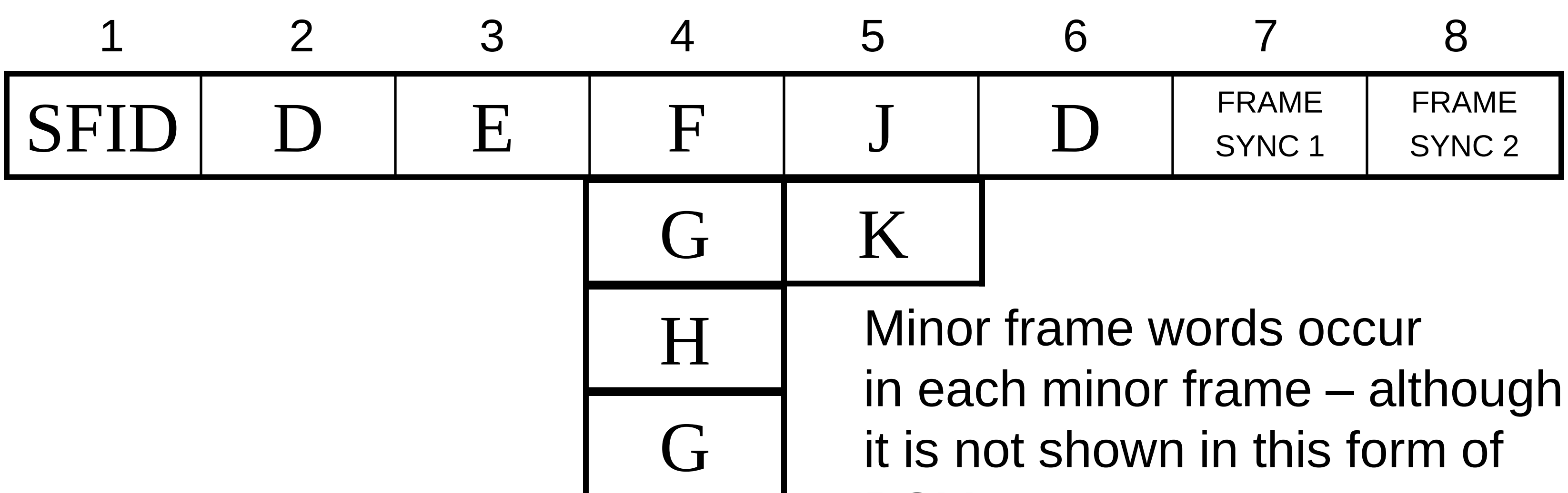
The Commutator Model of the PCM Map

In the commutator model, sub commutator 5 has a depth of 2 and therefore only has two inputs. Sub commutator 4 has a depth of four and has two inputs.



Alternate Method of Depicting a PCM Map

Sometimes PCM Maps are depicted in the following way. This simplifies the map by showing each word a minimal amount of times, but still conveys all the information needed to describe the PCM map. This makes the sub frames more obvious than in the previous maps shown and reflects the commutator model in the previous slide.



Minor frame words occur in each minor frame – although it is not shown in this form of PCM map.

Mixing Super and Sub Commutation Is Not Allowed

You cannot have a sub commutated word in multiple sub frames. This is not allowed because D is not evenly spaced within the map.

	1	2	3	4	5	6	7	8
1	SFID = 0	D	E			D	FRAME SYNC 1	FRAME SYNC 2
2	SFID = 1		E				FRAME SYNC 1	FRAME SYNC 2
3	SFID = 2	D	E			D	FRAME SYNC 1	FRAME SYNC 2
4	SFID = 3		E				FRAME SYNC 1	FRAME SYNC 2

4 WORDS

12 WORDS

If you need the parameter in the map four times, you must place all instances of that word in the same word position, like parameter E.

Class II PCM Stream Differences

- Bits Rate higher than 10 Mbits/sec
- Word Lengths greater than 32 bits, but less than 64 bits.
- Fragmented words
- More than 8,192, but less than 16,384 bits/minor frame
- Unevenly spaced super commutation
- Cyclic Redundancy Checks (CRC)
- Format changes
- Asynchronous embedded formats
- Tagged data formats
- Asynchronous data merging

Why Make This So Complex?

This is done so you can have multiple sampling rates to most efficiently utilize the PCM Frame and keep the Bit Rate as low as possible. Vibration measurements require high sample rates, temperature measurements require low sample rates.

- Super Commutation - for high sample rates
- Minor Frame words - for upper medium sample rates
- Super Sub Commutation - for lower medium sample rates
- Sub Commutation - for lower sample rates

Calculating the Sample Rate

- When a PCM Frame is built, the goal is to make sure that the words are being sampled above the minimum sampling rate.
- This minimum sampling rate is calculated from the filter's cutoff frequency for the parameter assigned to that word location.
- Taking the sampling rates of our parameters, we can fit them into the PCM map like a puzzle to obtain the minimum sampling rate.

Calculating Major Frame Length

The Major Frame Length is the minor frame length times the number of minor frames in a major frame.

$$Major\ Frame\ Length = Minor\ Frame\ Length \times \frac{Number\ of\ Minor\ Frames}{Major\ Frame}$$

$$Major\ Frame\ Length = \frac{words}{\cancel{minor\ frame}} \times \frac{\cancel{minor\ frames}}{major\ frame}$$

$$Major\ Frame\ Length = \frac{words}{major\ frame}$$

Calculating Major Frame Length

For our example,

The Minor Frame Length is 8 words/minor frame

The number of Minor Frames in a Major Frame = 4

The major frame length is calculated as:

$$Major\ Frame\ Length = Minor\ Frame\ Length \times \frac{Number\ of\ Minor\ Frames}{Major\ Frame}$$

$$Major\ Frame\ Length = \frac{8\ words}{minor\ frame} \times \frac{4\ minor\ frames}{major\ frame}$$

$$Major\ Frame\ Length = 32\ \frac{words}{major\ frame}$$

Calculating Major Frame Rate

The major frame rate is defined as the number of major frames occurring per second.

The Major Frame Rate is calculated by:

$$\boxed{Major\ Frame\ Rate = \frac{Bit\ Rate}{Word\ Length \times Major\ Frame\ Length}}$$

$$Major\ Frame\ Rate = \frac{\frac{bits}{sec}}{\frac{bits}{word} \times \frac{words}{major\ frame}}$$

$$Major\ Frame\ Rate = \frac{\cancel{bits}}{sec} \times \frac{\cancel{word}}{\cancel{bits}} \times \frac{major\ frames}{\cancel{word}}$$

$$Major\ Frame\ Rate = \frac{major\ frames}{sec}$$

Major Frame Rate

For our example,

The Bit Rate = 250K bits/sec

The Word Length = 12 bits/word

The Major Frame Length = 32 words/major frame

The major frame rate is calculated as:

$$Major\ Frame\ Rate = \frac{Bit\ Rate}{Word\ Length \times Major\ Frame\ Length}$$

$$Major\ Frame\ Rate = \frac{250K\ \frac{bits}{sec}}{12\frac{bits}{word} \times 32\frac{words}{major\ frame}}$$

$$Major\ Frame\ Rate = 651.04\ \frac{major\ frames}{sec}$$

Sampling Within the PCM Stream

	1	2	3	4	5	6	7	8
1	SFID = 0	D	E	F	J	D	FRAME SYNC 1	FRAME SYNC 2
2	SFID = 1	D	E	G	K	D	FRAME SYNC 1	FRAME SYNC 2
3	SFID = 2	D	E	H	J	D	FRAME SYNC 1	FRAME SYNC 2
4	SFID = 3	D	E	G	K	D	FRAME SYNC 1	FRAME SYNC 2

Sampling of a measurement occurs in the same interval as it appears in the PCM Stream. Word order for our example would then be:

START

FS1 FS2 0 D E F J D FS1 FS2 1 D E G K D

FS1 FS2 2 D E H J D FS1 FS2 3 D E G K D

This will occur 651.04 times every second (the major frame rate).

Calculating Parameter Sample Rate

The sample rate of a parameter is the number of times the parameter word appears in the major frame times the major frame rate.

$$\boxed{Parameter\ Sample\ Rate = \frac{Parameter\ Samples}{Major\ Frame} \times Major\ Frame\ Rate}$$

$$Parameter\ Sample\ Rate = \frac{samples}{\cancel{major\ frame}} \times \frac{\cancel{major\ frames}}{sec}$$

$$Parameter\ Sample\ Rate = \frac{samples}{sec}$$

Calculating Parameter Sample Rate

$$Parameter\ Sample\ Rate = \frac{Samples}{Major\ Frame} \times Major\ Frame\ Rate$$

	1	2	3	4	5	6	7	8
1	SFID = 0	D	E	F	J	D	FRAME SYNC 1	FRAME SYNC 2
2	SFID = 1	D	E	G	K	D	FRAME SYNC 1	FRAME SYNC 2
3	SFID = 2	D	E	H	J	D	FRAME SYNC 1	FRAME SYNC 2
4	SFID = 3	D	E	G	K	D	FRAME SYNC 1	FRAME SYNC 2

D: 8 samples/major frame

E: 4 samples/major frame

F and H: 1 sample/major frame

G, J and K : 2 sample/major frame

Calculating Parameter Sample Rate

$$Parameter\ Sample\ Rate = \frac{Samples}{Major\ Frame} \times Major\ Frame\ Rate$$

	1	2	3	4	5	6	7	8
1	SFID = 0	D	E	F	J	D	FRAME SYNC 1	FRAME SYNC 2
2	SFID = 1	D	E	G	K	D	FRAME SYNC 1	FRAME SYNC 2
3	SFID = 2	D	E	H	J	D	FRAME SYNC 1	FRAME SYNC 2
4	SFID = 3	D	E	G	K	D	FRAME SYNC 1	FRAME SYNC 2

Sample rate D = 8 X 651.04 = 5,208.33 sps

Sample rate E = 4 X 651.04 = 2,604.17 sps

Sample rate F and H = 1 X 651.04 = 651.04 sps

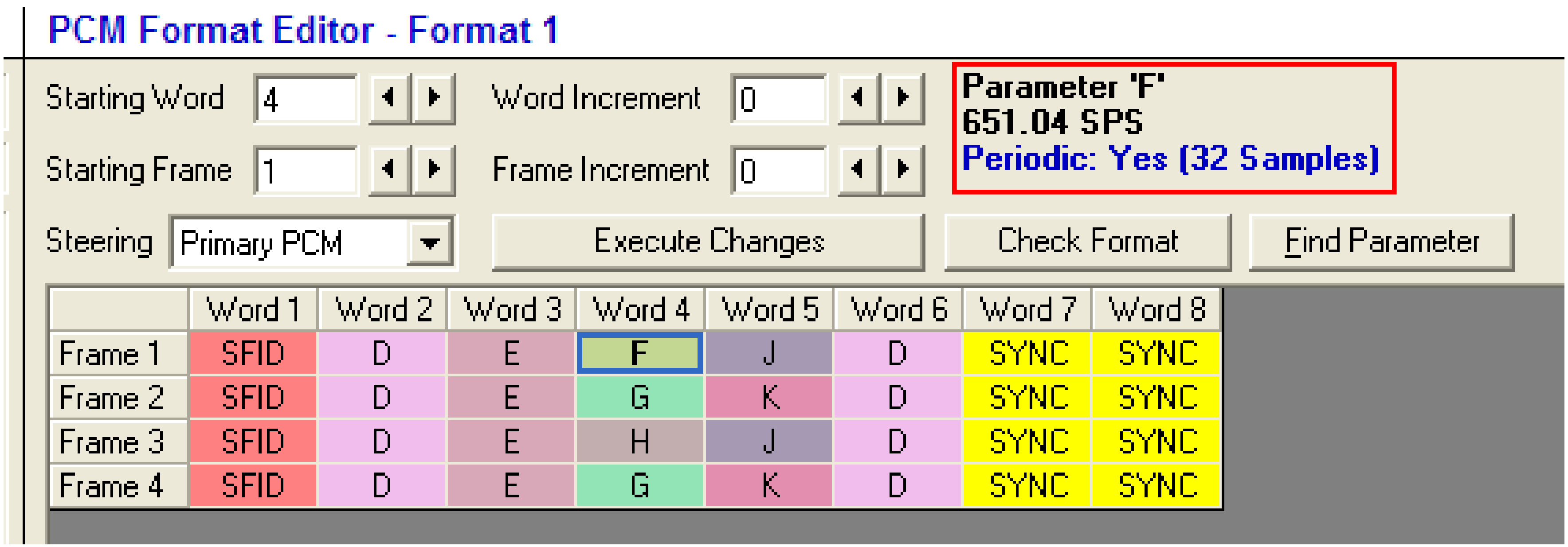
Sample rate G, J and K = 2 X 651.04 = 1,302.08 sps

Parameter Sample Rate

From the example you can see that we were able to get four sample rates ranging from 651.04 sps to 5,208.33 sps. The lowest sample rate will always be the major frame rate (651.04 major frames/sec).

Viewing the Parameter Sample Rate

The parameter sample rate can be seen in TTCWare by clicking on the parameter. F has a sample rate of 651.04 sps and is sampled periodically every 32 words.



	Word 1	Word 2	Word 3	Word 4	Word 5	Word 6	Word 7	Word 8
Frame 1	SFID	D	E	F	J	D	SYNC	SYNC
Frame 2	SFID	D	E	G	K	D	SYNC	SYNC
Frame 3	SFID	D	E	H	J	D	SYNC	SYNC
Frame 4	SFID	D	E	G	K	D	SYNC	SYNC

Wisely Selecting the Number of Minor Frames

- When building a PCM map, the number of minor frames and words per minor frame you choose effects the number of sample rates you can obtain.
- Normally, prime numbers like 5 or 11 are undesirable and odd numbers are not used because you can not evenly space super sub commutated words very easily.
- Numbers that can be divided evenly by several numbers are the best to use.

Wisely Selecting the Number of Minor Frames

Numbers that can be divided by several numbers are usually good choices. For example:

- 8 can be divided by 1, 2, 4, & 8 evenly
- 12 can be divided by 1, 2, 3, 4, 6, &12 evenly
- 24 can be divided by 1, 2, 3, 4, 6, 8, 12, & 24 evenly

Each number you can evenly divide into the number of minor frames, gives you more options on most efficiently generating your sampling rates.

Wisely Selecting the Number of Minor Frames

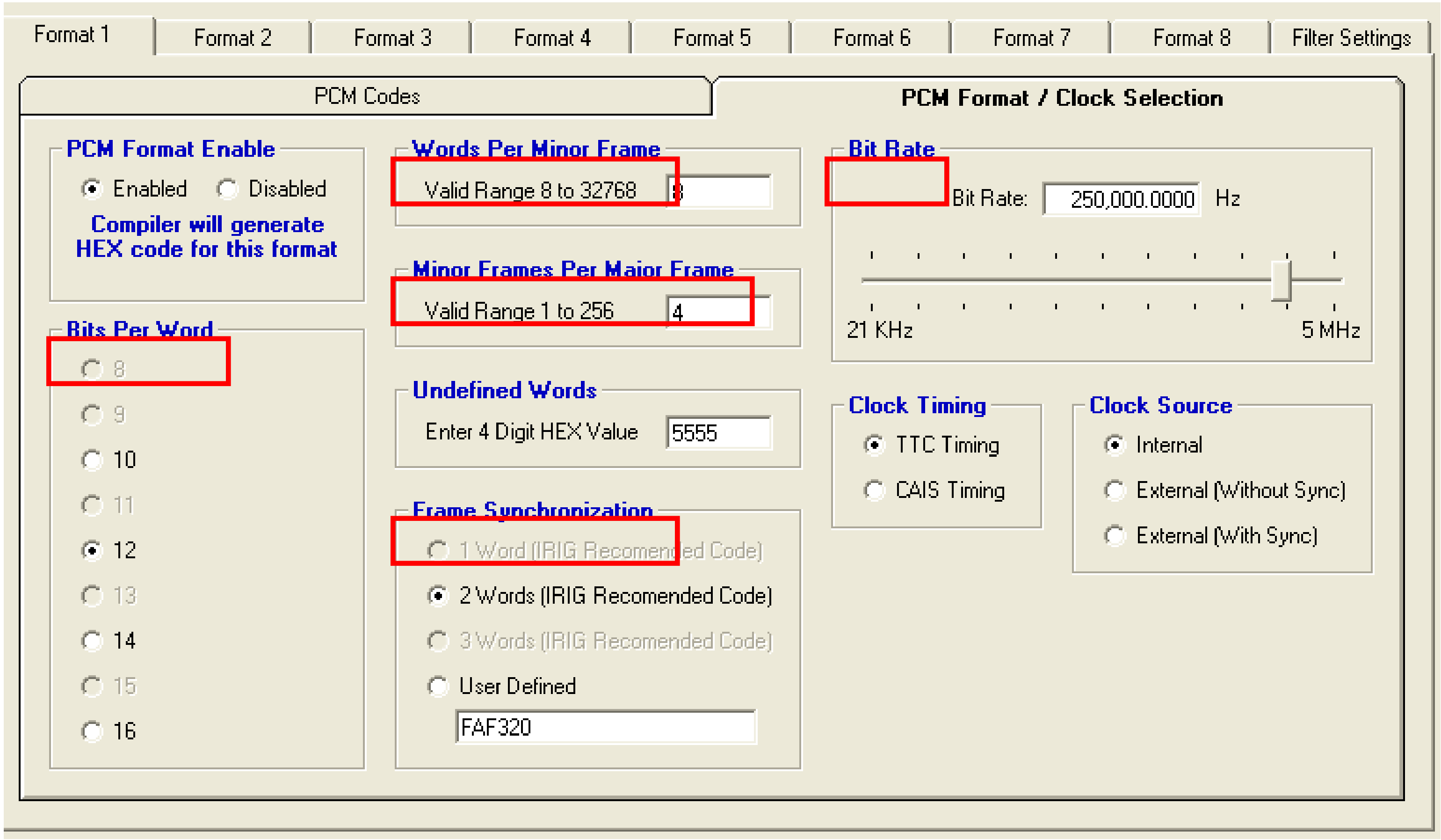
For example, if we have a major frame rate of 100 frames per second, and we have 24 minor frames within the major frame, we can have the following word sample rates:

100 x 1 = 100	100 x 6 = 600
100 x 2 = 200	100 x 8 = 800
100 x 3 = 300	100 x 12 = 1200
100 x 4 = 400	100 x 24 = 2400

and even higher sample rates are attainable through super commutation.

Entering PCM Map Format Information

The PCM map is generated in the multiplex portion of the data system. TTCWare supports multiple formats.



Creating a PCM Map From Scratch

- Creating a PCM Map from scratch can be a challenge because the attributes of the PCM stream (bit rate, bits/word, frame lengths, number of minor frames per major frame) all directly effect the sample rate of your parameters.
- Two people laying out the same list of parameters will not produce the same PCM map. But if all constraints (minimum sample rates) are adhered to, neither is more correct than the other.
- The only difference would be that one is more efficient at sampling than the other which would conserve bandwidth or solid state memory.

Creating a PCM Map From Scratch

Say you have a project where the following parameters have the requested frequency response ranges:

- 15 Position Measurements (f_d = 14 Hz)
- 10 Strain Gages (f_d = 20 Hz)
- 3 Accelerometers (f_d = 650 Hz)
- 3 Pressures (f_d = 100 Hz)
- 1 Voice Word (CVSD – 1,600 sps)

Note that the Voice Word is in samples per second since it has already been digitized.

What Cutoff Frequency to Use?

$$\boxed{A = \frac{1}{\sqrt{1+\left(f_d / f_c\right)^{2n}}}}$$

Solve the equation for f_c to get:

$$\boxed{f_c = \frac{f_d}{\sqrt[2n]{\left(1/A^2\right)-1}}}$$

f_c is the cutoff frequency
f_d is the max frequency of interest
A is the maximum attenuation allowed at f
n is the number of poles

Creating a PCM Map From Scratch

Using the cutoff frequency equation for a 6-pole Butterworth Filter

$$\boxed{f_c = 1.3837 f_d}$$

we get the following results:

- 15 Position Measurements (f_c = 20 Hz)
- 10 Strain Gages (f_c = 28 Hz)
- 3 Accelerometers (f_c = 900 Hz)
- 3 Pressures (f_c = 140 Hz)
- 1 Voice Word (CVSD – 1,600 sps)

Fc = .

Creating a PCM Map From Scratch

The *minimum* required sampling rate for each parameter will be 5 times the cutoff frequency for a 6-pole Butterworth filter and a 12-bit analog-to-digital converter.

- 15 Position Measurements (100 sps)
- 10 Strain Gages (140 sps)
- 3 Accelerometers (4,500 sps)
- 3 Pressures (700 sps)
- 1 Voice Word (1,600 sps)

See the *Sampling Theory* training for details on determining a parameter's sample rate.

Creating a PCM Map From Scratch

The total amount of data samples per second within the major frame will be.

- Position Measurements (15 x 100 sps = 1,500 sps)
- Strain Gages (10 x 140 sps = 1,400 sps)
- Accelerometers (3 x 4500 sps = 13,500 sps)
- Pressures (3 x 700 sps = 2,100 sps)
- 1 Voice Word (1,600 sps)

Total samples/second in the major frame = 20,100 sps

Creating a PCM Map From Scratch

A 20,100 sps/major frame aggregate sample rate is needed to adequately sample all of the parameters.

Taking the lowest sample rate, 100 sps (position measurements) and dividing it into the aggregate rate, you get the <u>minimum number of data words</u> needed in your major frame.

$$\frac{20{,}100\,\frac{samples/_{sec}}{major\ frame}}{100\,\frac{samples/_{sec}}{word}} = 201\,\frac{words}{major\ frame}$$

Creating a PCM Map From Scratch

If we decide to have 12 minor frames in the major frame, then each minor frame will have

$$\frac{201^{words}/_{major\ frame}}{12^{minor\ frames}/_{major\ frame}} = 16.75\,\frac{words}{minor\ frame} \approx 17\,\frac{words}{minor\ frame}$$

Creating a PCM Map From Scratch

Don’t forget the overhead words in each minor frame:

2 for the frame sync pattern

1 for the sub frame ID counter

Now we need 17 + 3 or 20 words/minor frame

Time words should be included as overhead words, but in order to see the entire PCM map on one slide, they are not included in this example.

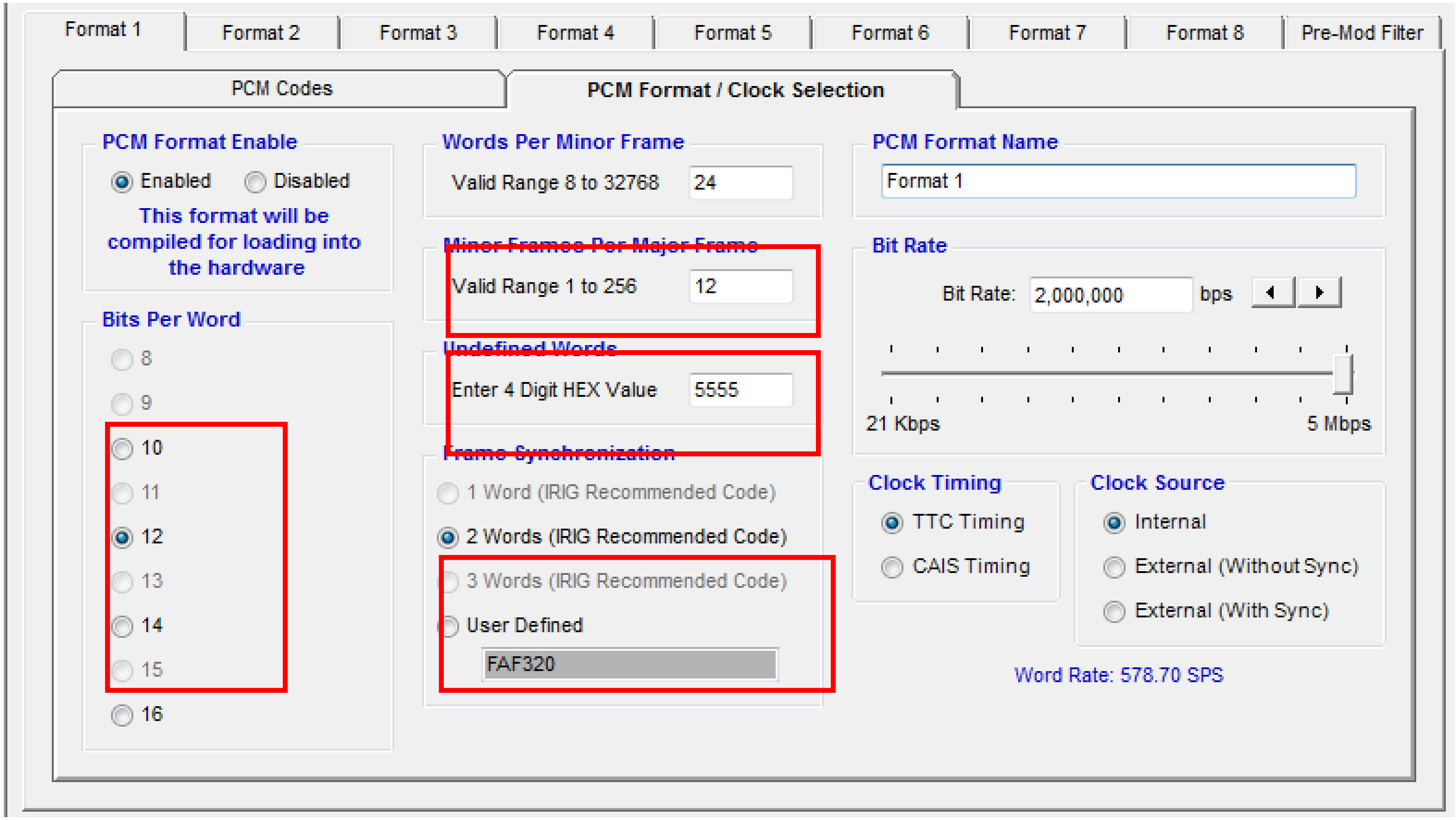
Creating a PCM Map From Scratch

To make the number of words per minor frame evenly divisible by several numbers, we will add 4 spare words giving us 24 words/minor frame.

This allows us to super commutate evenly and gives us some extra samples because we will not be able to achieve the exact minimum sample rates.

Creating a PCM Map From Scratch

In this example, we will use 12 bits per word. The structure of our PCM map is entered into the MCI-105 card within TTCWare.



Creating a PCM Map From Scratch

Now that we have our frame structure, we can now start placing the words into the PCM Map. Remember we are defining that each word location in the major frame is sampled at 100 sps (the major frame rate). This can be increased if necessary by increasing the bit rate.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1																								
2																								
3																								
4																								
5																								
6																								
7																								
8																								
9																								
10																								
11																								
12																								

Creating a PCM Map From Scratch

The two frame sync words (FS1 and FS2), automatically get placed in the last two word positions. The overhead words such as the sub frame ID counter (SFID) and time words (not in this example) would be placed into the map now.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	SFID																						FS1	FS2
2	SFID																						FS1	FS2
3	SFID																						FS1	FS2
4	SFID																						FS1	FS2
5	SFID																						FS1	FS2
6	SFID																						FS1	FS2
7	SFID																						FS1	FS2
8	SFID																						FS1	FS2
9	SFID																						FS1	FS2
10	SFID																						FS1	FS2
11	SFID																						FS1	FS2
12	SFID																						FS1	FS2

Creating a PCM Map From Scratch

To begin placing the parameters in the map, start with the ones that have the highest sample rate. In this case, each of the three accelerometers need a sample rate of 4500 samples a second.

We need to know how many accelerometer samples need to appear in the major frame. This can be calculated by dividing the accelerometer sample rate by the major frame rate:

$$\frac{4500\,{}^{accel\ samples}/_{sec}}{100\,{}^{major\ frames}/_{sec}} = 45\ \frac{accel\ samples}{major\ frame}$$

We cannot fit 45 samples in a minor frame word because a sub frame is only 12 samples deep. The accelerometer measurements will have to be super commutated.

Creating a PCM Map From Scratch

To determine the number of accelerometer samples in each minor frame, divide the number of accelerometer samples needed by the number of minor frames in the major frame:

$$\frac{45^{accel\ samples}/_{major\ frame}}{12^{minor\ frames}/_{major\ frame}} = 3.75\,\frac{accel\ samples}{minor\ frame} \approx 4\,\frac{accel\ samples}{minor\ frame}$$

So the accelerometers have to be evenly spaced 4 times within the minor frames.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	SFID	A1	A2	A3				A1	A2	A3				A1	A2	A3				A1	A2	A3	FS1	FS2
2	SFID	A1	A2	A3				A1	A2	A3				A1	A2	A3				A1	A2	A3	FS1	FS2
3	SFID	A1	A2	A3				A1	A2	A3				A1	A2	A3				A1	A2	A3	FS1	FS2
4	SFID	A1	A2	A3				A1	A2	A3				A1	A2	A3				A1	A2	A3	FS1	FS2
5	SFID	A1	A2	A3				A1	A2	A3				A1	A2	A3				A1	A2	A3	FS1	FS2
6	SFID	A1	A2	A3				A1	A2	A3				A1	A2	A3				A1	A2	A3	FS1	FS2
7	SFID	A1	A2	A3				A1	A2	A3				A1	A2	A3				A1	A2	A3	FS1	FS2
8	SFID	A1	A2	A3				A1	A2	A3				A1	A2	A3				A1	A2	A3	FS1	FS2
9	SFID	A1	A2	A3				A1	A2	A3				A1	A2	A3				A1	A2	A3	FS1	FS2
10	SFID	A1	A2	A3				A1	A2	A3				A1	A2	A3				A1	A2	A3	FS1	FS2
11	SFID	A1	A2	A3				A1	A2	A3				A1	A2	A3				A1	A2	A3	FS1	FS2
12	SFID	A1	A2	A3				A1	A2	A3				A1	A2	A3				A1	A2	A3	FS1	FS2

Creating a PCM Map From Scratch

The parameter with the next highest sample rate is the CVSD Voice word at 1600 sps.

$$\frac{1600\,{}^{audio\ samples}/_{sec}}{100\,{}^{major\ frames}/_{sec}} = 16\ \frac{audio\ samples}{major\ frame}$$

This number is greater than 12, so it will have to be super commutated also.

$$\frac{16^{audio\ samples}/_{major\ frame}}{12^{minor\ frames}/_{major\ frame}} = 1.33\,\frac{audio\ samples}{minor\ frame} \approx 2\ \frac{audio\ samples}{minor\ frame}$$

So the CVSD Voice would have to be evenly spaced twice in each minor frame.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	SFID	A1	A2	A3	V			A1	A2	A3				A1	A2	A3	V			A1	A2	A3	FS1	FS2
2	SFID	A1	A2	A3	V			A1	A2	A3				A1	A2	A3	V			A1	A2	A3	FS1	FS2
3	SFID	A1	A2	A3	V			A1	A2	A3				A1	A2	A3	V			A1	A2	A3	FS1	FS2
4	SFID	A1	A2	A3	V			A1	A2	A3				A1	A2	A3	V			A1	A2	A3	FS1	FS2
5	SFID	A1	A2	A3	V			A1	A2	A3				A1	A2	A3	V			A1	A2	A3	FS1	FS2
6	SFID	A1	A2	A3	V			A1	A2	A3				A1	A2	A3	V			A1	A2	A3	FS1	FS2
7	SFID	A1	A2	A3	V			A1	A2	A3				A1	A2	A3	V			A1	A2	A3	FS1	FS2
8	SFID	A1	A2	A3	V			A1	A2	A3				A1	A2	A3	V			A1	A2	A3	FS1	FS2
9	SFID	A1	A2	A3	V			A1	A2	A3				A1	A2	A3	V			A1	A2	A3	FS1	FS2
10	SFID	A1	A2	A3	V			A1	A2	A3				A1	A2	A3	V			A1	A2	A3	FS1	FS2
11	SFID	A1	A2	A3	V			A1	A2	A3				A1	A2	A3	V			A1	A2	A3	FS1	FS2
12	SFID	A1	A2	A3	V			A1	A2	A3				A1	A2	A3	V			A1	A2	A3	FS1	FS2

Creating a PCM Map From Scratch

The parameter with the next highest sample rate are the three pressure parameters at 700 sps.

$$\frac{700\,{}^{press\ samples}/_{sec}}{100\,{}^{major\ frames}/_{sec}} = 7\ \frac{press\ samples}{major\ frame}$$

Seven words will fit within a sub frame, but not evenly. So the pressure parameters will have to be placed as a minor frame word, 12 times within the major frame. This illustrates some of the inefficiencies you will get when building a map. This is why you add spare words at the start.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
2	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
3	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
4	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
5	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
6	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
7	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
8	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
9	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
10	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
11	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
12	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2

Creating a PCM Map From Scratch

The parameter with the next highest sample rate are the ten strains at 140 sps each.

$$\frac{140\,{}^{gage\ samples}/_{sec}}{100\,{}^{major\ frames}/_{sec}} = 1.4\,\frac{gage\ samples}{major\ frame} \approx 2\,\frac{gage\ samples}{major\ fame}$$

We can evenly sub commutate 2 words (super sub commutation) within the 12-word deep sub frame. Each strain measurement will be spaced 6 minor frames apart.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	SFID	A1	A2	A3	V	S1	S2	A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
2	SFID	A1	A2	A3	V	S3	S4	A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
3	SFID	A1	A2	A3	V	S5	S6	A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
4	SFID	A1	A2	A3	V	S7	S8	A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
5	SFID	A1	A2	A3	V	S9	S10	A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
6	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
7	SFID	A1	A2	A3	V	S1	S2	A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
8	SFID	A1	A2	A3	V	S3	S4	A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
9	SFID	A1	A2	A3	V	S5	S6	A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
10	SFID	A1	A2	A3	V	S7	S8	A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
11	SFID	A1	A2	A3	V	S9	S10	A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
12	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2

Creating a PCM Map From Scratch

The remaining parameters are the position measurements with a required sample rate of 100 sps.

Because we designed the major frame rate to be 100 major frames/sec, these words only need to be placed in the major frame once.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	SFID	A1	A2	A3	V	S1	S2	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	PM1	PM2	A1	A2	A3	FS1	FS2
2	SFID	A1	A2	A3	V	S3	S4	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	PM3	PM4	A1	A2	A3	FS1	FS2
3	SFID	A1	A2	A3	V	S5	S6	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	PM5	PM6	A1	A2	A3	FS1	FS2
4	SFID	A1	A2	A3	V	S7	S8	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	PM7	PM8	A1	A2	A3	FS1	FS2
5	SFID	A1	A2	A3	V	S9	S10	A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
6	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
7	SFID	A1	A2	A3	V	S1	S2	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	PM9	PM10	A1	A2	A3	FS1	FS2
8	SFID	A1	A2	A3	V	S3	S4	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	PM11	PM12	A1	A2	A3	FS1	FS2
9	SFID	A1	A2	A3	V	S5	S6	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	PM13	PM14	A1	A2	A3	FS1	FS2
10	SFID	A1	A2	A3	V	S7	S8	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	PM15		A1	A2	A3	FS1	FS2
11	SFID	A1	A2	A3	V	S9	S10	A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2
12	SFID	A1	A2	A3	V			A1	A2	A3	P1	P2	P3	A1	A2	A3	V			A1	A2	A3	FS1	FS2

Alternate form of the PCM Map

This would be the alternate form of the map showing the different sub frame lengths.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
SFID	A1	A2	A3	V	S1	S2	A1	A2	A3	P1	P2	P3	A1	A2	A3	V	PM1	PM2	A1	A2	A3	FS1	FS2
					S3	S4											PM3	PM4					
					S5	S6											PM5	PM6					
					S7	S8											PM7	PM8					
					S9	S10											SP	SP					
					SP	SP											SP	SP					
																	PM9	PM10					
																	PM11	PM12					
																	PM13	PM14					
																	PM15	SP					
																	SP	SP					
																	SP	SP					

How Do We Choose the Proper Bit Rate?

To select the bit rate, we will use the same equations as before, but work backwards using algebra to get the bit rate.

Calculating Bit Rate

Our major frame length would be:

$$Major\ Frame\ Length = Minor\ Frame\ Length \times \frac{Number\ of\ Minor\ Frames}{Major\ Frame}$$

$$Major\ Frame\ Length = 24\,\frac{words}{minor\ frame} \times 12\,\frac{minor\ frames}{major\ frame}$$

$$Major\ Frame\ Length = 288\,\frac{words}{major\ frame}$$

Calculating Bit Rate

The Bit Rate will be calculated from the Major Frame Rate equation using some algebra:

$$Major\ Frame\ Rate = \frac{Bit\ Rate}{Word\ Length \times Major\ Frame\ Length}$$

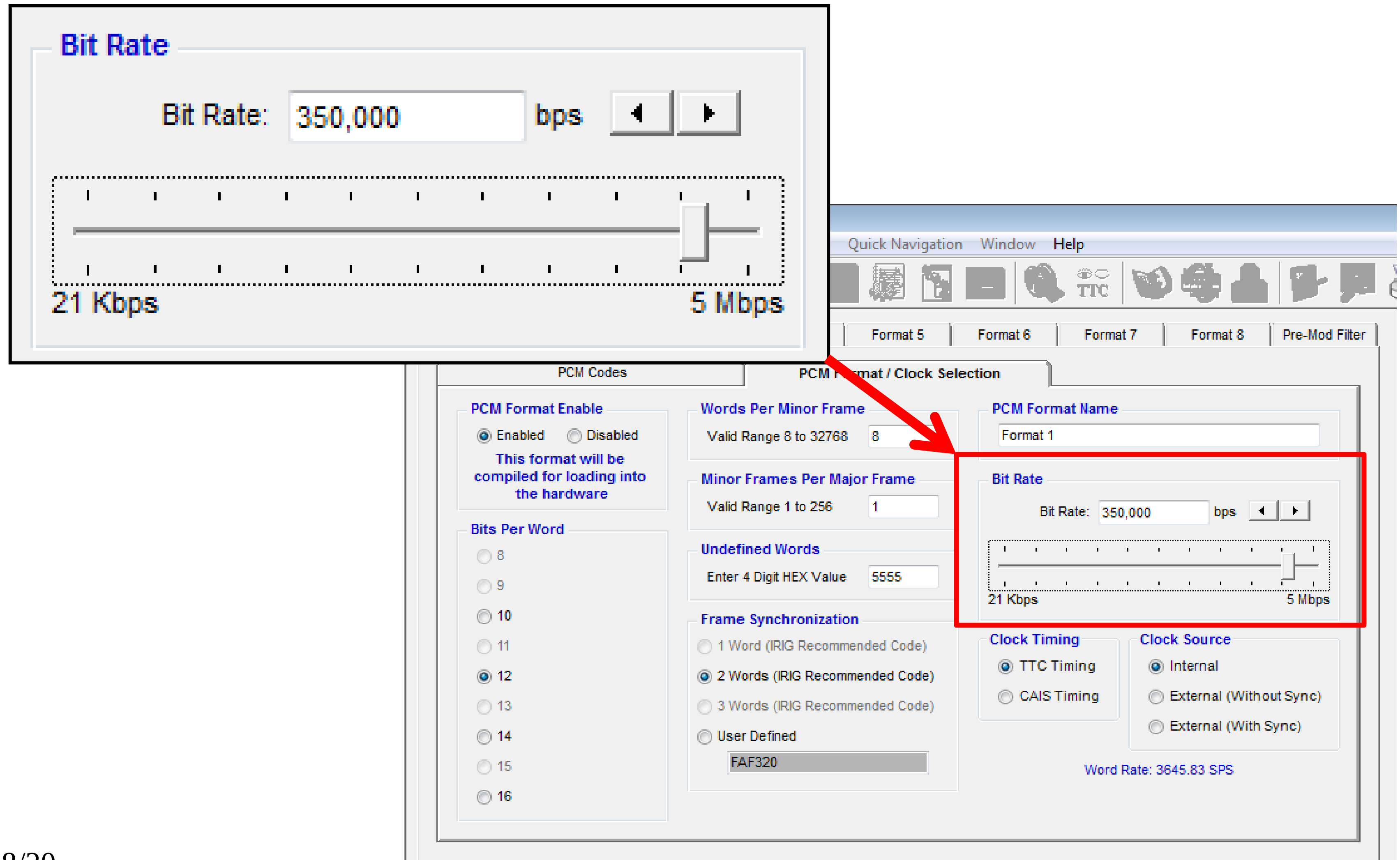
$$Bit\ Rate = Major\ Frame\ Rate \times Word\ Length \times Major\ Frame\ Length$$

$$Bit\ Rate = 100\,\frac{major\ frames}{sec} \times 12\,\frac{bits}{word} \times 288\,\frac{words}{major\ \ frame}$$

$$Bit\ Rate = 345{,}600\,\frac{bits}{sec}$$

The next highest bit rate greater than 345,600 that is easy to remember in TTCWare is 350 Kbps.

Calculating Bit Rate



Actual Sample Rates

Since our chosen bit rate of 350 Kbps is not exactly what we have calculated, we must figure out what our actual sample rate is of all the parameters.

$$Major\ Frame\ Rate = \frac{Bit\ Rate}{Word\ Length \times Major\ Frame\ Length}$$

$$Major\ Frame\ Rate = \frac{350K\,\frac{bits}{sec}}{12\,\frac{bits}{word} \times 288\,\frac{words}{major\ frame}}$$

$$Major\ Frame\ Rate = 101.3\,\frac{major\ frames}{sec}$$

Actual Sample Rates

Now take each parameter and multiply the major frame rate by how many times it appears in the major frame.

Measurement	Actual sps	Minimum sps
Positions: 1 x 101.3	101.3 sps	100 sps
Strains: 2 x 101.3	202.6 sps	140 sps
Pressures: 12 x 101.3	1215.6 sps	700 sps
Accelerometers: 48 x 101.3	4862.4 sps	4500 sps
CVSD Voice: 24 x 101.3	2431.2 sps	1600 sps

Summary

- It is important to maintain the minimum sample rate for each parameter
- Changing bit rate, bits/word, frame lengths, number of minor frames per major frame will effect the sample rate
- Equations used when constructing a PCM map:

$$\boxed{Major\ Frame\ Length = Minor\ Frame\ Length \times \frac{Number\ of\ Minor\ Frames}{Major\ Frame}}$$

$$\boxed{Major\ Frame\ Rate = \frac{Bit\ Rate}{Word\ Length \times Major\ Frame\ Length}}$$

$$\boxed{Parameter\ Sample\ Rate = \frac{Parameter\ Samples}{Major\ Frame} \times Major\ Frame\ Rate}$$

References

- IRIG-106, Chapter 4, Pulse Code Modulation