PULSE CODE MODULATION (PCM)

1. PCM quantization Techniques
2. PCM Transmission Bandwidth
3. PCM Coding Techniques
4. PCM Integrated Circuits
5. Advantages of PCM

EEEN 464 – DIGITAL COMMUNICATION

Friday, 13 February 2026

SYLLABUS

Course Purpose:
To enable students understand the fundamental principles of digital transmission systems as used in fixed and mobile telephony, wired and wireless computer networks, data storage and digital broadcasting.

Expected Learning Outcomes:
At the end of the course, students will be able to:

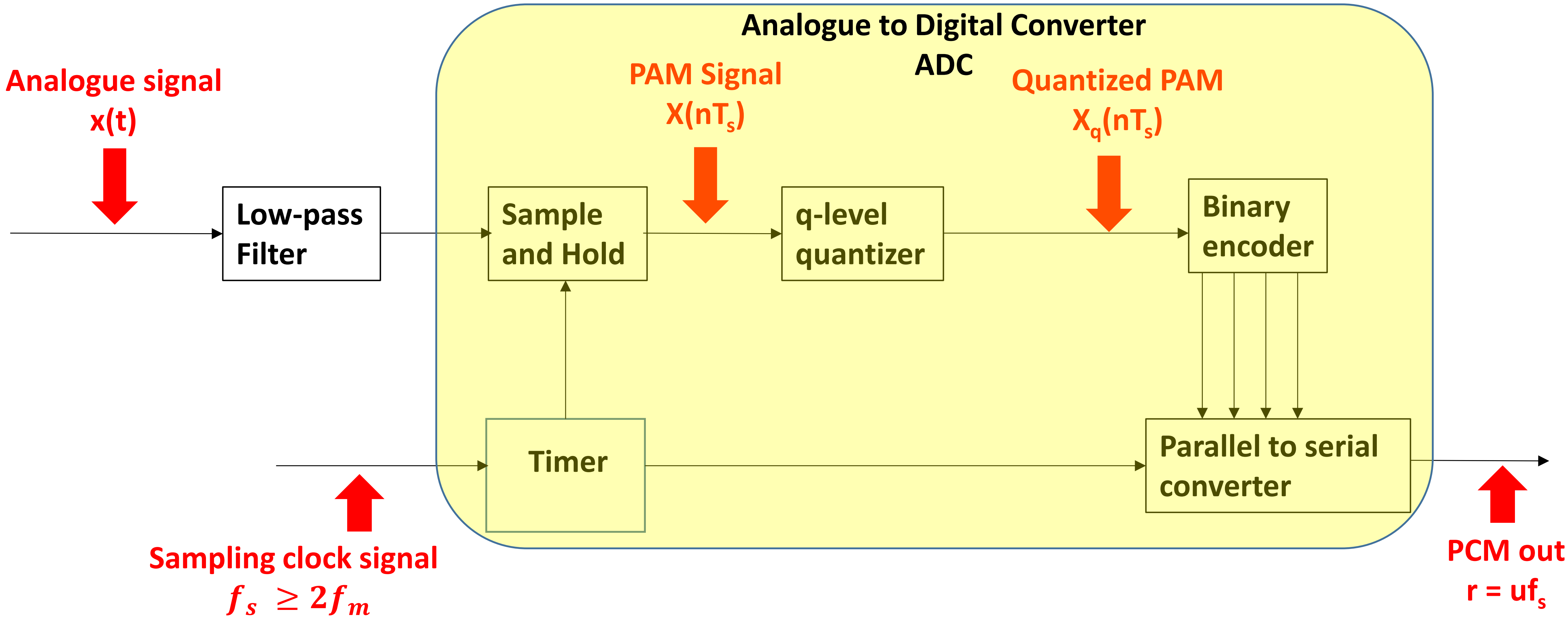
(i) describe binary and duo binary pulse Amplitude Modulation (PAM);
(ii) design digital coding schemes;
(iii) derive error performance equations for digital modulation schemes(ASK,FSK,PSK,DPSK);
(iv) state strengths and weaknesses of M-ary PSK with QAM signaling schemes;
(v) design a basic digital communication systems.

Course Content:
Signal digitization: Pulse Amplitude Modulation (PAM), sampling theorems and sampling circuits, Pulse code modulation (PCM). Quantization and signal conditioning: Uniform and non-uniform quantization; companding methods; vocoders; signal-to- quantization noise ratio. Waveform coding: Pulse transmission, PCM, Pulse-shaping; Delta modulation; adaptive delta modulation; Differential Pulse Code Modulation (DPCM), M-ary encoding. Digital Modulation: Amplitude shift keying (ASK), Frequency Shift Keying (FSK), Phase Shift Keying (PSK), Quadrature Amplitude Modulation (QAM) and Differential Phase Shift Keying (DPSK). Signal recovery in ASK, FSK and PSK; Gaussian Minimum Shift Keying (GMSK); Performance comparison. Information theory: information sources, entropy, channel capacity; Source Coding; entropy coding. Error control: Error control coding techniques; Transmission errors; Error detection methods; intersymbol interference and the eye pattern; Linear block codes; Cyclic codes; convolution codes. Multiplexing: Frequency division multiplex (FDM), Time Division Multiplexing (TDM), plesiochronous digital hierarchy (PDH). Spread spectrum communication: Direct sequence and frequency hopping methods; synchronization, spreading codes and their generation. Data transmission: Local data transmission protocals (Ethernet, token ring); Modems; high Asymmetric Digital subscriber line (ADSL); Very–high Speed Digital subscriber line (VDSL), integrated services digital network (ISDN).

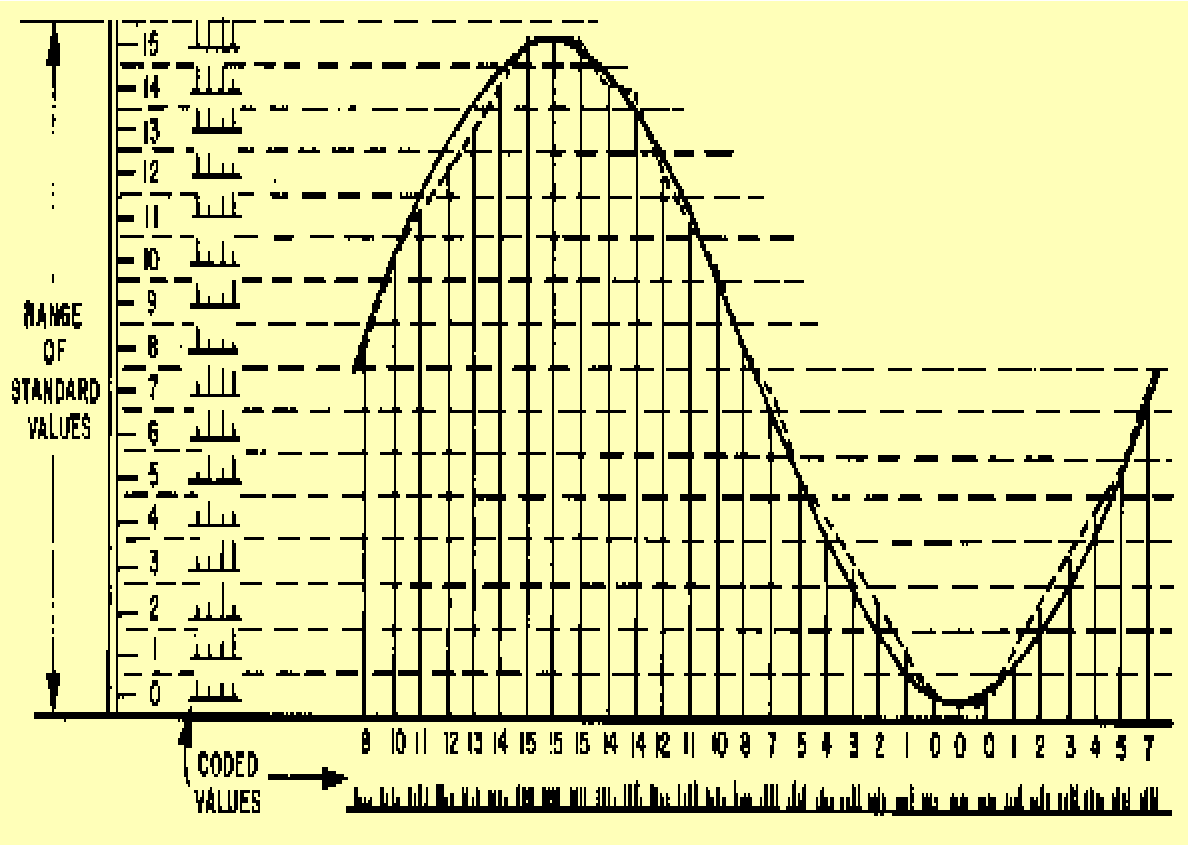
KEY POINTS ABOUT PCM

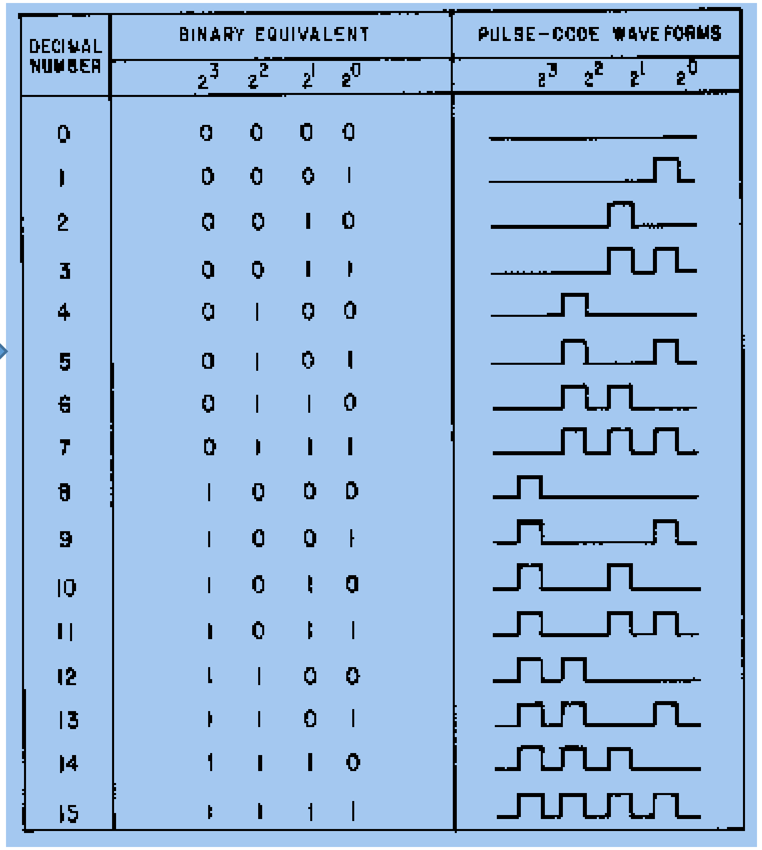
1. While PCM is a pulse modulation technique much like PWM, PAM or PPM.
2. PCM is digital while the others are either analogue in time or amplitude, i.e PCM pulses are discrete in time and amplitude unlike PAM, PWM or PPM.
3. Essential aspects of a PCM transmitter are sampling, quantizing and encoding.
4. PCM is not a modulation in the conventional sense because it does not rely on varying a characteristic of a carrier (amplitude, frequency or phase).

PCM TRANSMITTER



BINARY EQUIVALENTS AND PULSE CODE WAVEFORMS

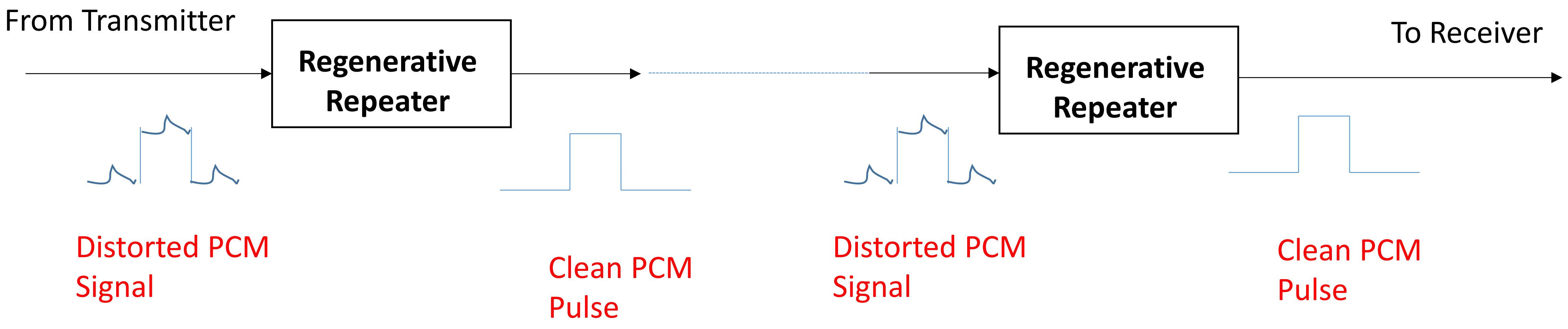




DECIMAL NUMBER	BINARY EQUIVALENT 2^3	2^2	2^1	2^0	PULSE-CODE WAVEFORMS 2^3 2^2 2^1 2^0
0	0	0	0	0	
1	0	0	0	1	
2	0	0	1	0	
3	0	0	1	1	
4	0	1	0	0	
5	0	1	0	1	
6	0	1	1	0	
7	0	1	1	1	
8	1	0	0	0	
9	1	0	0	1	
10	1	0	1	0	
11	1	0	1	1	
12	1	1	0	0	
13	1	1	0	1	
14	1	1	1	0	
15	1	1	1	1	

PCM TRANSMISSION PATH

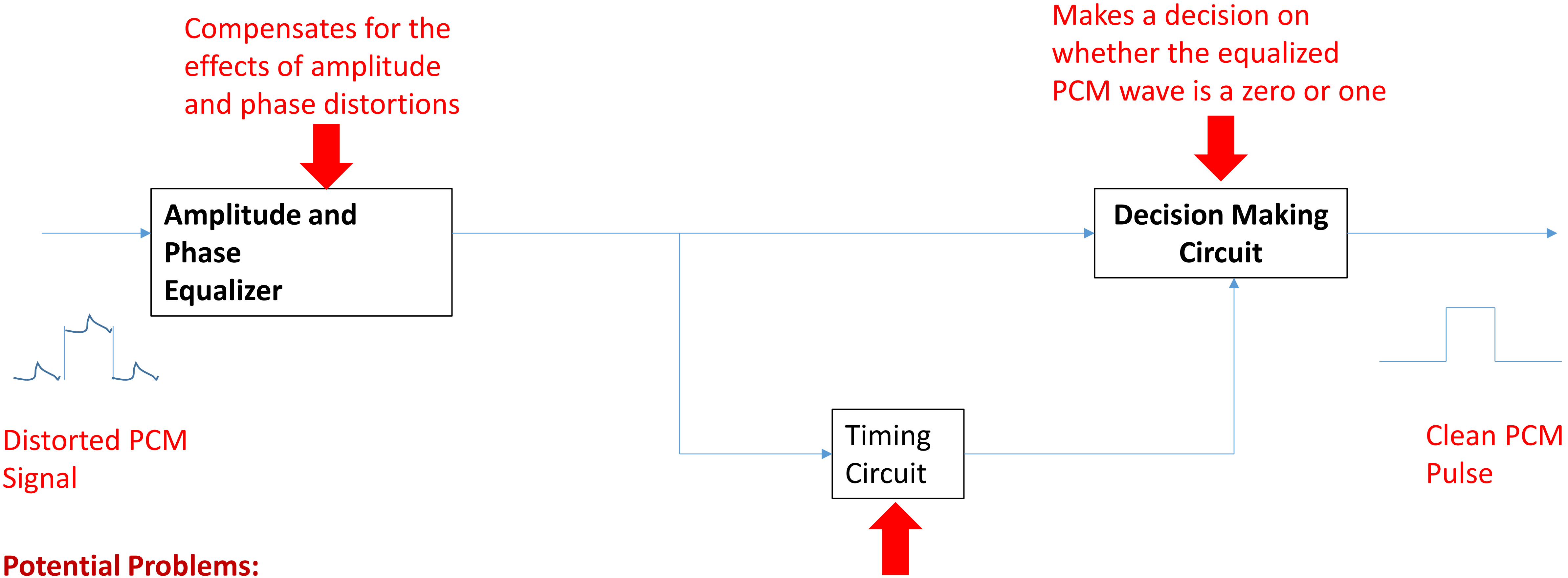
- **PCM transmission path** refers to the path the the signal travels between the transmitter and the receiver.



HOW A PCM REPEATER WORKS

1. **A PCM repeater does the follows:**
   a) **Receives a PCM signal**
   b) Regenerates the signal by cleaning up noise and distortion
   c) Retransmitting a fresh, reshaped signal matching the original signal quality
2. The use of repeaters enables long-distance transmission without significant signal degradation by periodically amplifying and reshaping the signal at repeater stations along the transmission path.

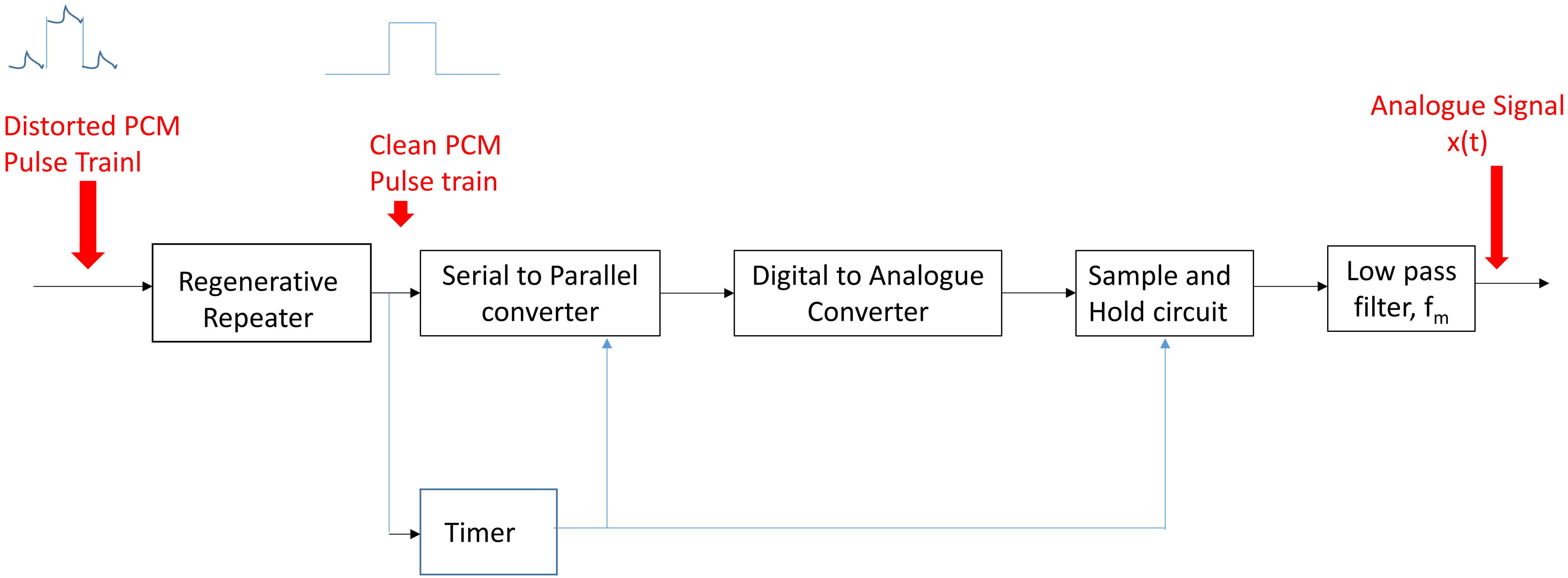
HOW A PCM REPEATER WORKS



Potential Problems:

1. SNR too low for compensation
2. Signal contains too many zeroes for the clock recovery circuit to work well

PCM RECEIVER

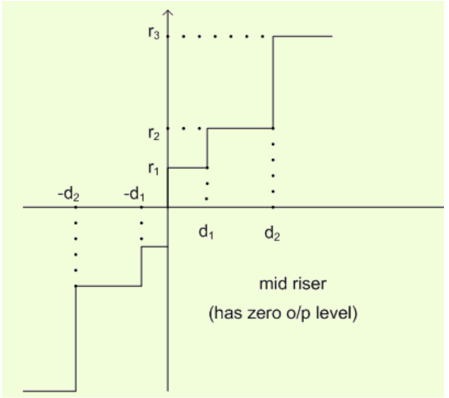


TYPES OF QUANTIZERS

Quantization

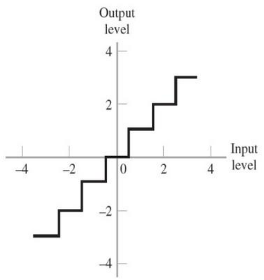
Uniform Quantization

Non-Uniform Quantization



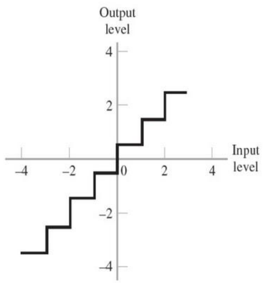
Step size varies according the input signal values

Midtread Quantization



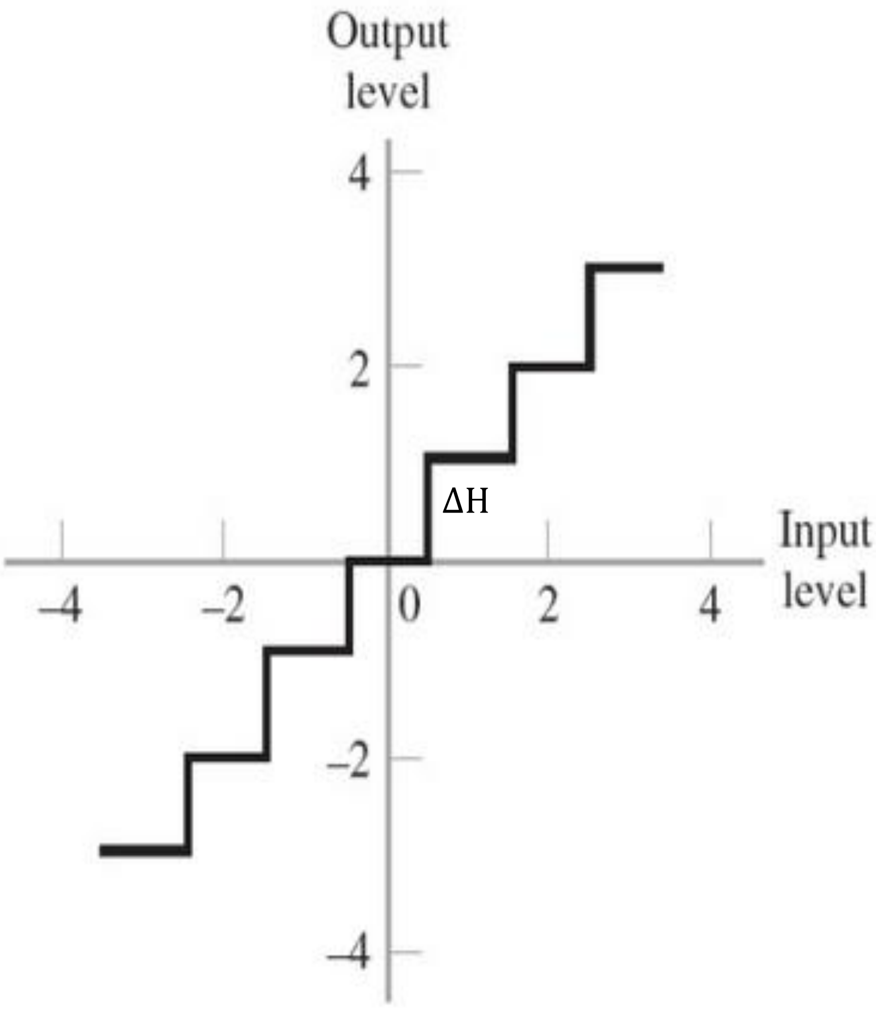
Step size is the same throughout the input signal range

Midrise Quantization



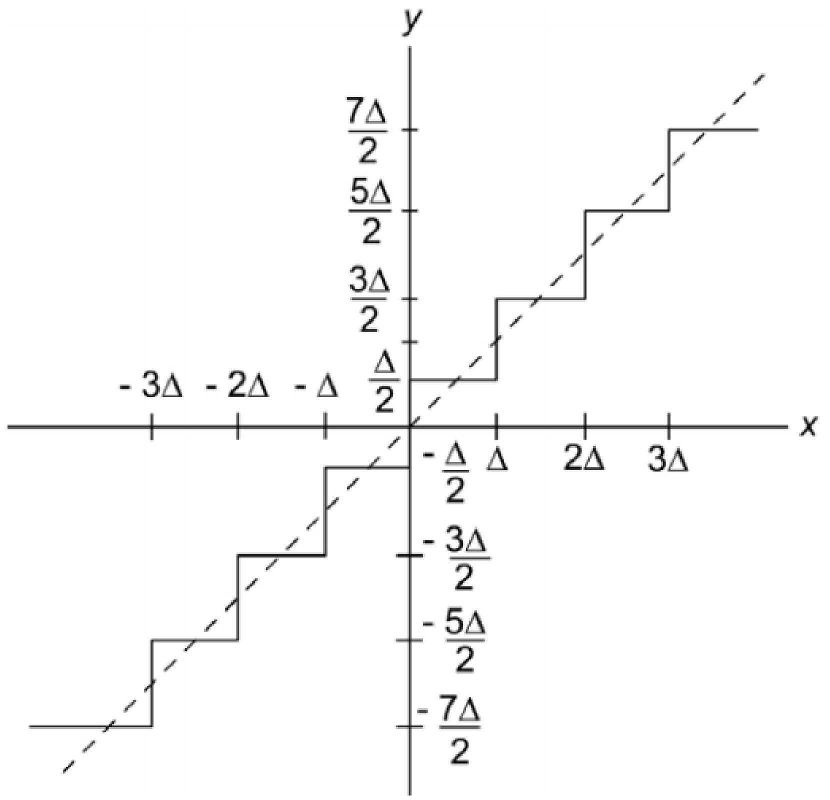
MIDTREAD QUANTIZER

1. **A midtread quantizer** assumes values of the form ΔH_i ·where Δ is the step size and $H_i = 0, \pm1, \pm2, \pm3, \ldots$
2. It is called **mid-tread** because the origin lies in the middle of a tread of a staircase-like graph.



MIDRISER QUANTIZER

1. A **mid-riser quantizer** has output levels are given by $\frac{\Delta}{2}H_i$, where Δ is the step size and H_i = ±1, ±2, ±3, ...
2. The origin lies in the middle of the rising part of the staircase-like characteristic graph.



PCM TRANSMISSION BANDWIDTH

1. Assume the a PCM encoder has q levels which are encoded to υ bits.
2. We can infer

$$q = 2^{\upsilon}$$

3. The number of bits per second can be expressed as:

$$f_{pcm} = \upsilon f_s \quad \text{where } f_s \geq 2f_m \text{ (Nyquist criterion)}$$

4. It therefore follows that the bandwidth, BW of a PCM channel is bounded by:

$$BW_{pcm} \geq 2\upsilon f_m$$

EXAMPLE 1

1. A TV signal with a bandwidth of 4.2 MHz is transmitted using binary PCM system using 512 quantization levels. Determine

   (a) Code word-length

   (b) The PCM bandwidth/bit rate

SOLUTION

(a) $f_m = 4.2\ MHz$

$q = 2^v = 512$

$v = log_2 512$ = 9 bits

(b) Bandwidth, BW $= v(2f_m)$ = 2 x9 $\times$ 4.2 = 75.6 Mb/s

WHY IT IS NECESSARY TO HAVE NON-UNIFORM QUANTIZATION?

1. Using linear quantization, the quantization error is given by:

$$\epsilon = \frac{\Delta}{2}$$

2. If q quantization levels of a bipolar signal are used, we can write:

$$\Delta = \frac{2x_{max}}{q}$$

3. Consider a PCM system with $\upsilon = 4$ bits and $x_{max} = 1$ Volt, then:

$$q = 2^4 = 16$$

$$\Delta = \frac{2\times1}{q} = \frac{2}{16} = \frac{1}{8}$$

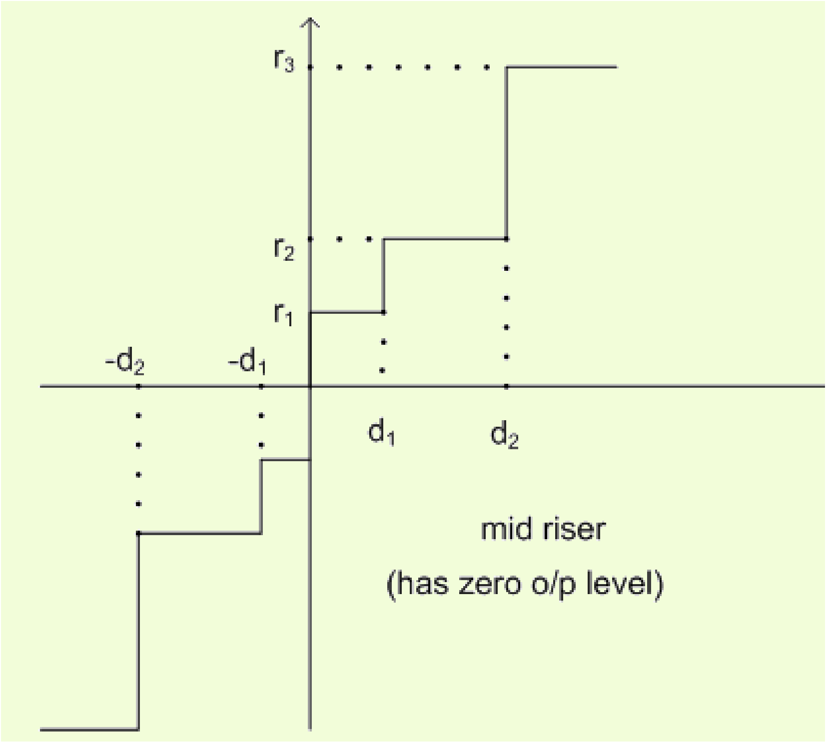
The maximum quantization error is therefore

$$\varepsilon_{max} = \left|\frac{\Delta}{2}\right| = \frac{1}{16}$$

4. At maximum, the relative error is 1 volt out of 16 volts or 6.25%

5. At lower levels, e.g. 2 volts, the relative error is 1 volt out of 2 volts or 50%.

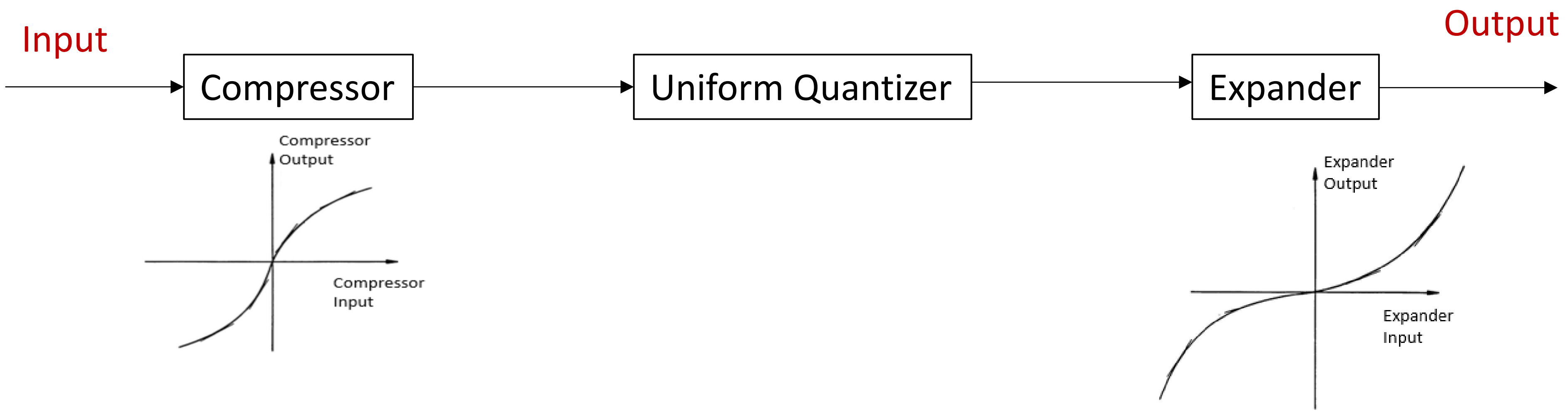
6. To reduce this high relative error at low levels, PCM systems use non-uniform quantization .



COMPANDING

1. **In uniform sampling**, the quantization step is fixed thus resulting in uniform quantization noise power.
2. However signal power is not constant, it is proportional to the square of the signal amplitude. This means Quantization Noise is very significant at low amplitudes.
3. To reduce quantization noise at lower amplitudes, we use commanding:

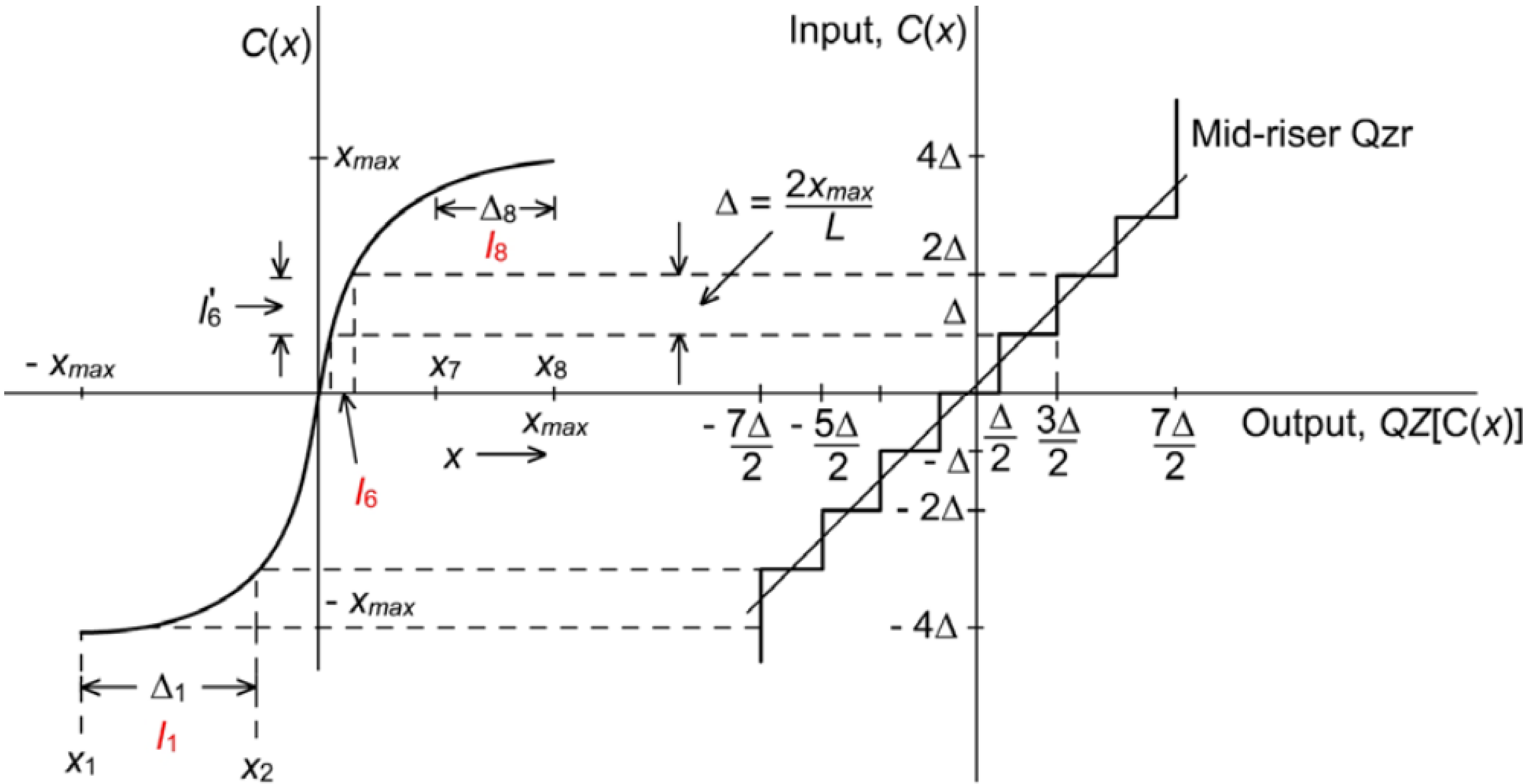
Companding = **Compr**essing + Ex**panding**



Provides High Gain to Weak Signals and Low Gain to strong Signals

Provides Low Gain to Weak Signals and High Gain to strong Signals

COMPRESSING WITH MIDRIZER QUANTIZER



WHY WE USE COMPANDING IN COMMUNICATION SYSTEMS

1. **Companding is a technique for reducing the data rate of audio signals by making the quantization levels unequal.**
2. The loudest sound that can be tolerated **(120 dB SPL)** is about one-million times the amplitude of the weakest sound that we can hear **(0 dB SPL).**
3. **If the quantization levels are equally spaced (uniform quantization), 12 bits** must be used to obtain telephone quality speech.
4. **However, only 8 bits are required if the quantization levels are made unequal (companding)** to match the characteristics of human hearing.

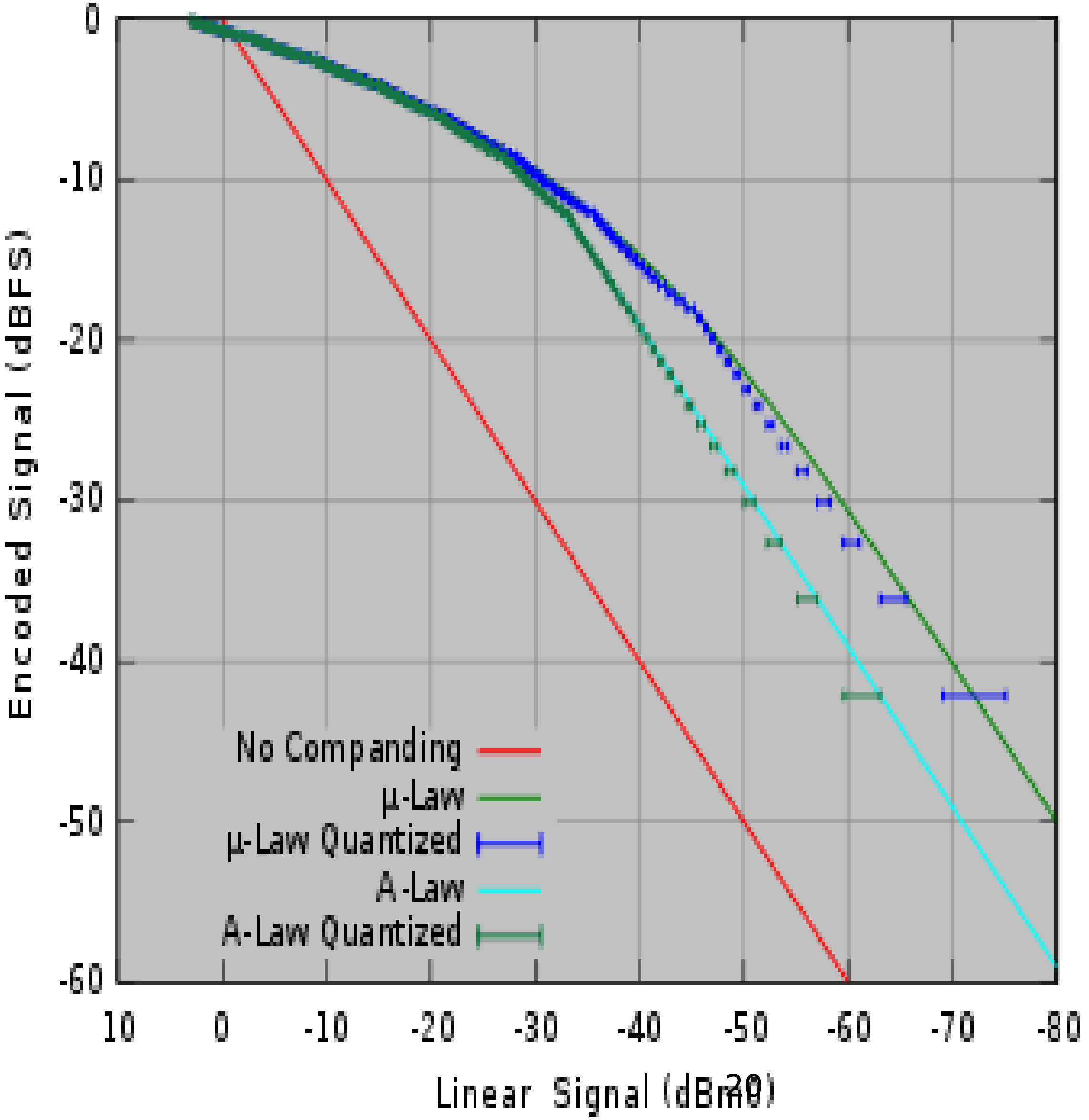
THREE METHODS OF REALIZING COMPANDING IN COMMUNICATION SYSTEMS

1. Three methods of companding in communication systems are:
   a) Run the analog signal through a nonlinear circuit before reaching a linear 8 bit ADC,
   b) Use an 8-bit ADC that internally has unequally spaced steps, or
   c) Use a linear 12-bit ADC followed by a digital look-up table (12 bits in, 8 bits out).
2. Each of these three options requires the same nonlinearity, just in a different place, i.e at analog circuit, in the ADC, or a digital circuit after the ADC.

COMPANDING STANDARDS

(1) µ255 law used in North America

(2) "A" law, used in Europe.



"A" LAW COMPANDING

$$F(x) = \operatorname{sgn}(x) \begin{cases} \frac{A|x|}{1+\ln(A)}, & |x| < \frac{1}{A} \\ \frac{1+\ln(A|x|)}{1+\ln(A)}, & \frac{1}{A} \leq |x| \leq 1, \end{cases}$$

Where A is the compression parameter

$$F^{-1}(y) = \operatorname{sgn}(y) \begin{cases} \frac{|y|(1+\ln(A))}{A}, & |y| < \frac{1}{1+\ln(A)} \\ \frac{\exp(|y|(1+\ln(A))-1)}{A}, & \frac{1}{1+\ln(A)} \leq |y| < 1. \end{cases}$$

μ-LAW COMPANDING

$$F(x) = \mathrm{sgn}(x)\frac{\ln(1+\mu|x|)}{\ln(1+\mu)} \qquad -1 \leq x \leq 1.$$

where μ is 255 for 8 bits.

$$F^{-1}(y) = \mathrm{sgn}(y)(1/\mu)((1+\mu)^{|y|}-1) \qquad -1 \leq y \leq 1$$

CODING TECHNIQUES

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BINARY ENCODING

1. **Encoding** converts the quantized samples into a form that is more convenient for the purpose of transmission.

2. **Encoding** is a one-to-one mapping of the quantized samples by using code elements or symbols of the required length per sample.

1	2				3				4				5				
Decimal Level No.	Natural Binary code				Folded Binary code				Inverted folded binary				Gray code				Comments
	b_4	b_3	b_2	b_1									g_4	g_3	g_2	g_1	
15	1	1	1	1	1	1	1	1	1	0	0	0	1	0	0	0	Levels assigned to positive message samples
14	1	1	1	0	1	1	1	0	1	0	0	1	1	0	0	1	
13	1	1	0	1	1	1	0	1	1	0	1	0	1	0	1	1	
12	1	1	0	0	1	1	0	0	1	0	1	1	1	0	1	0	
11	1	0	1	1	1	0	1	1	1	1	0	0	1	1	1	0	
10	1	0	1	0	1	0	1	0	1	1	0	1	1	1	1	1	
9	1	0	0	1	1	0	0	1	1	1	1	0	1	1	0	1	
8	1	0	0	0	1	0	0	0	1	1	1	1	1	1	0	0	
7	0	1	1	1	0	0	0	0	0	1	1	1	0	1	0	0	Levels assigned to negative message samples
6	0	1	1	0	0	0	0	1	0	1	1	0	0	1	0	1	
5	0	1	0	1	0	0	1	0	0	1	0	1	0	1	1	1	
4	0	1	0	0	0	0	1	1	0	1	0	0	0	1	1	0	
3	0	0	1	1	0	1	0	0	0	0	1	1	0	0	1	0	
2	0	0	1	0	0	1	0	1	0	0	1	0	0	0	1	1	
1	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	1	
0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	

FOLDED BINARY CODE

- **Folded binary code** (also called the sign-magnitude representation) assigns the first (left most) digit to the sign and the remaining digits are used to code the magnitude.
- **The main advantage of folded-binary code** is its ability to efficiently represent both positive and negative numbers within a limited bit range, particularly when dealing with small amplitude signals where **a higher density of '1' bits is beneficial, like in voice communication.**

1	2				3				4				5				
Decimal Level No.	Natural Binary code				Folded Binary code				Inverted folded binary				Gray code				Comments
	b_4	b_3	b_2	b_1									g_4	g_3	g_2	g_1	
15	1	1	1	1	1	1	1	1	1	0	0	0	1	0	0	0	Levels assigned to positive message samples
14	1	1	1	0	1	1	1	0	1	0	0	1	1	0	0	1	
13	1	1	0	1	1	1	0	1	1	0	1	0	1	0	1	1	
12	1	1	0	0	1	1	0	0	1	0	1	1	1	0	1	0	
11	1	0	1	1	1	0	1	1	1	1	0	0	1	1	1	0	
10	1	0	1	0	1	0	1	0	1	1	0	1	1	1	1	1	
9	1	0	0	1	1	0	0	1	1	1	1	0	1	1	0	1	
8	1	0	0	0	1	0	0	0	1	1	1	1	1	1	0	0	
7	0	1	1	1	0	0	0	0	0	1	1	1	0	1	0	0	Levels assigned to negative message samples
6	0	1	1	0	0	0	0	1	0	1	1	0	0	1	0	1	
5	0	1	0	1	0	0	1	0	0	1	0	1	0	1	1	1	
4	0	1	0	0	0	0	1	1	0	1	0	0	0	1	1	0	
3	0	0	1	1	0	1	0	0	0	0	1	1	0	0	1	0	
2	0	0	1	0	0	1	0	1	0	0	1	0	0	0	1	1	
1	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	1	
0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	

INVERTED FOLDED BINARY CODE

1. If only the amplitude digits of a folded binary code are complemented (1's changed to 0's and 0's to 1's), an inverted folded binary code results.
2. This code has the advantage of higher density of 1's for small amplitude signals, which are most probable for voice messages.
3. The higher density of 1's also relieves some system timing errors.

1	2				3				4				5				
Decimal Level No.	Natural Binary code				Folded Binary code				Inverted folded binary				Gray code				Comments
	b_4	b_3	b_2	b_1									g_4	g_3	g_2	g_1	
15	1	1	1	1	1	1	1	1	1	0	0	0	1	0	0	0	Levels assigned to positive message samples
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13	1	1	0	1	1	1	0	1	1	0	1	0	1	0	1	1	
12	1	1	0	0	1	1	0	0	1	0	1	1	1	0	1	0	
11	1	0	1	1	1	0	1	1	1	1	0	0	1	1	1	0	
10	1	0	1	0	1	0	1	0	1	1	0	1	1	1	1	1	
9	1	0	0	1	1	0	0	1	1	1	1	0	1	1	0	1	
8	1	0	0	0	1	0	0	0	1	1	1	1	1	1	0	0	
7	0	1	1	1	0	0	0	0	0	1	1	1	0	1	0	0	Levels assigned to negative message samples
6	0	1	1	0	0	0	0	1	0	1	1	0	0	1	0	1	
5	0	1	0	1	0	0	1	0	0	1	0	1	0	1	1	1	
4	0	1	0	0	0	0	1	1	0	1	0	0	0	1	1	0	
3	0	0	1	1	0	1	0	0	0	0	1	1	0	0	1	0	
2	0	0	1	0	0	1	0	1	0	0	1	0	0	0	1	1	
1	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	1	
0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	

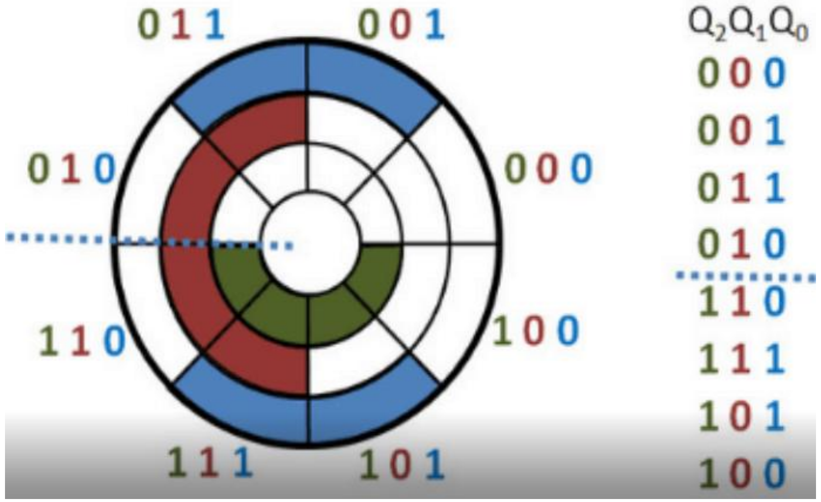
GRAY CODE

1. With natural binary encoding, a number of codeword digits can change even when a change of only one quantization level occurs. For example, a change from level 7 to 8 entails every bit changing in the 4-bit code illustrated.
2. In some applications, this behavior is undesirable and a code is desired for which only one digit changes when any transition occurs between adjacent levels.
3. The Gray Code has this property

1	2				3				4				5				
Decimal Level No.	Natural Binary code				Folded Binary code				Inverted folded binary				Gray code				Comments
	b_4	b_3	b_2	b_1									g_4	g_3	g_2	g_1	
15	1	1	1	1	1	1	1	1	1	0	0	0	1	0	0	0	Levels assigned to positive message samples
14	1	1	1	0	1	1	1	0	1	0	0	1	1	0	0	1	
13	1	1	0	1	1	1	0	1	1	0	1	0	1	0	1	1	
12	1	1	0	0	1	1	0	0	1	0	1	1	1	0	1	0	
11	1	0	1	1	1	0	1	1	1	1	0	0	1	1	1	0	
10	1	0	1	0	1	0	1	0	1	1	0	1	1	1	1	1	
9	1	0	0	1	1	0	0	1	1	1	1	0	1	1	0	1	
8	1	0	0	0	1	0	0	0	1	1	1	1	1	1	0	0	
7	0	1	1	1	0	0	0	0	0	1	1	1	0	1	0	0	Levels assigned to negative message samples
6	0	1	1	0	0	0	0	1	0	1	1	0	0	1	0	1	
5	0	1	0	1	0	0	1	0	0	1	0	1	0	1	1	1	
4	0	1	0	0	0	0	1	1	0	1	0	0	0	1	1	0	
3	0	0	1	1	0	1	0	0	0	0	1	1	0	0	1	0	
2	0	0	1	0	0	1	0	1	0	0	1	0	0	0	1	1	
1	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	1	
0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	

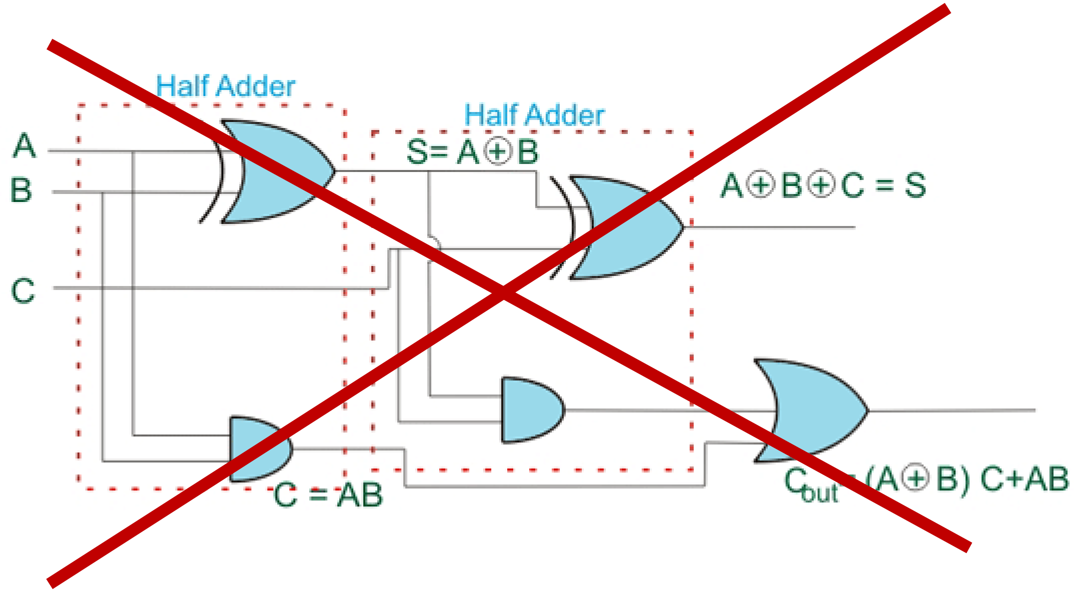
ADVANTAGES OF GREY CODE

1. **Error reduction:** Due to the single bit change property, Gray code minimizes the chance of spurious outputs or glitches during state transitions.
2. **Reliable in electromechanical systems:** Gray code is widely used in devices like rotary encoders as only one bit changes at a time, preventing misinterpretations.
3. **Simplified logic design:** The predictable nature of Gray code simplifies the **design of circuits that need to interpret positional data**, as only one bit needs to be monitored for changes.

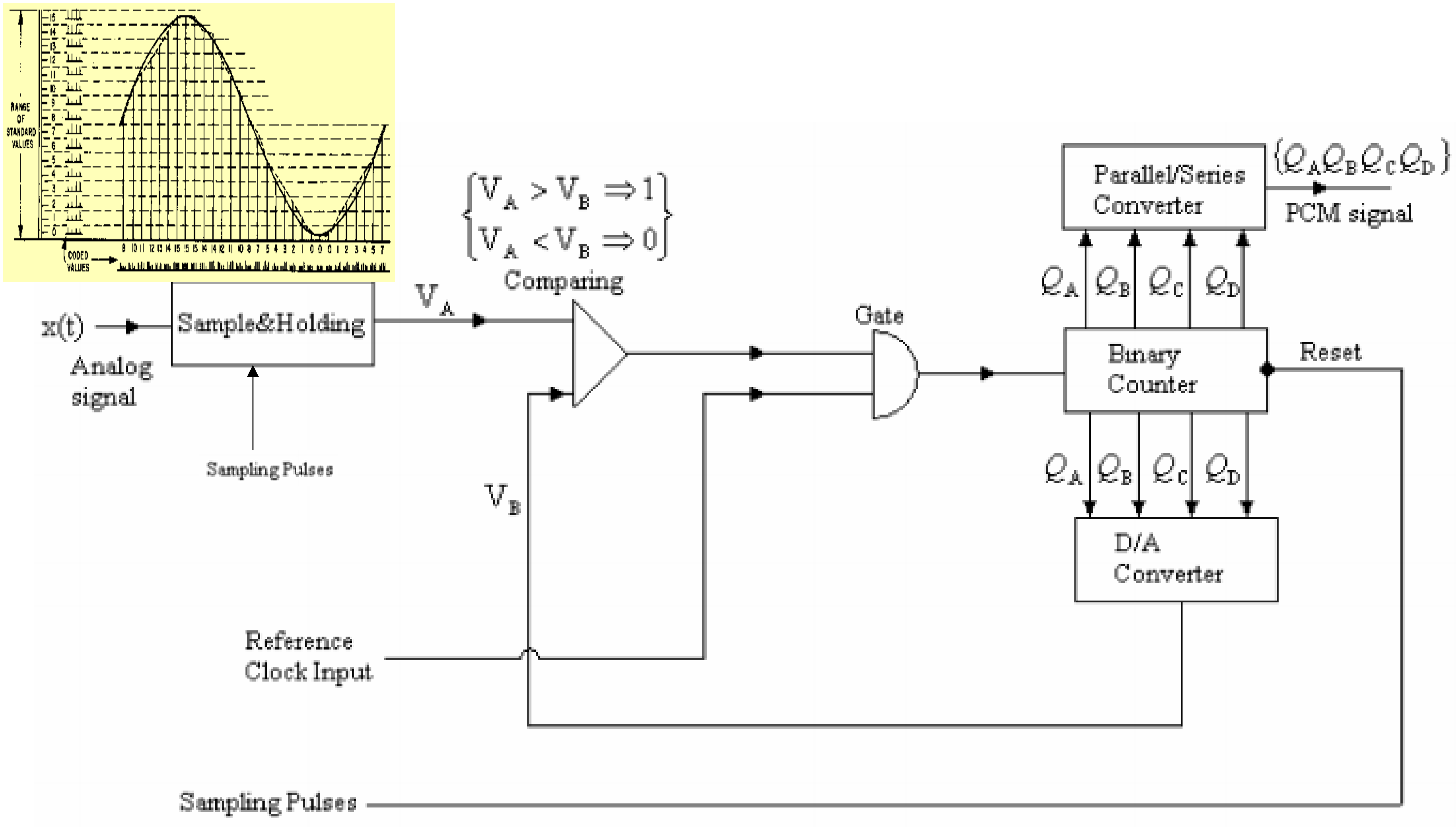


DISADVANTAGES OF GREY CODE

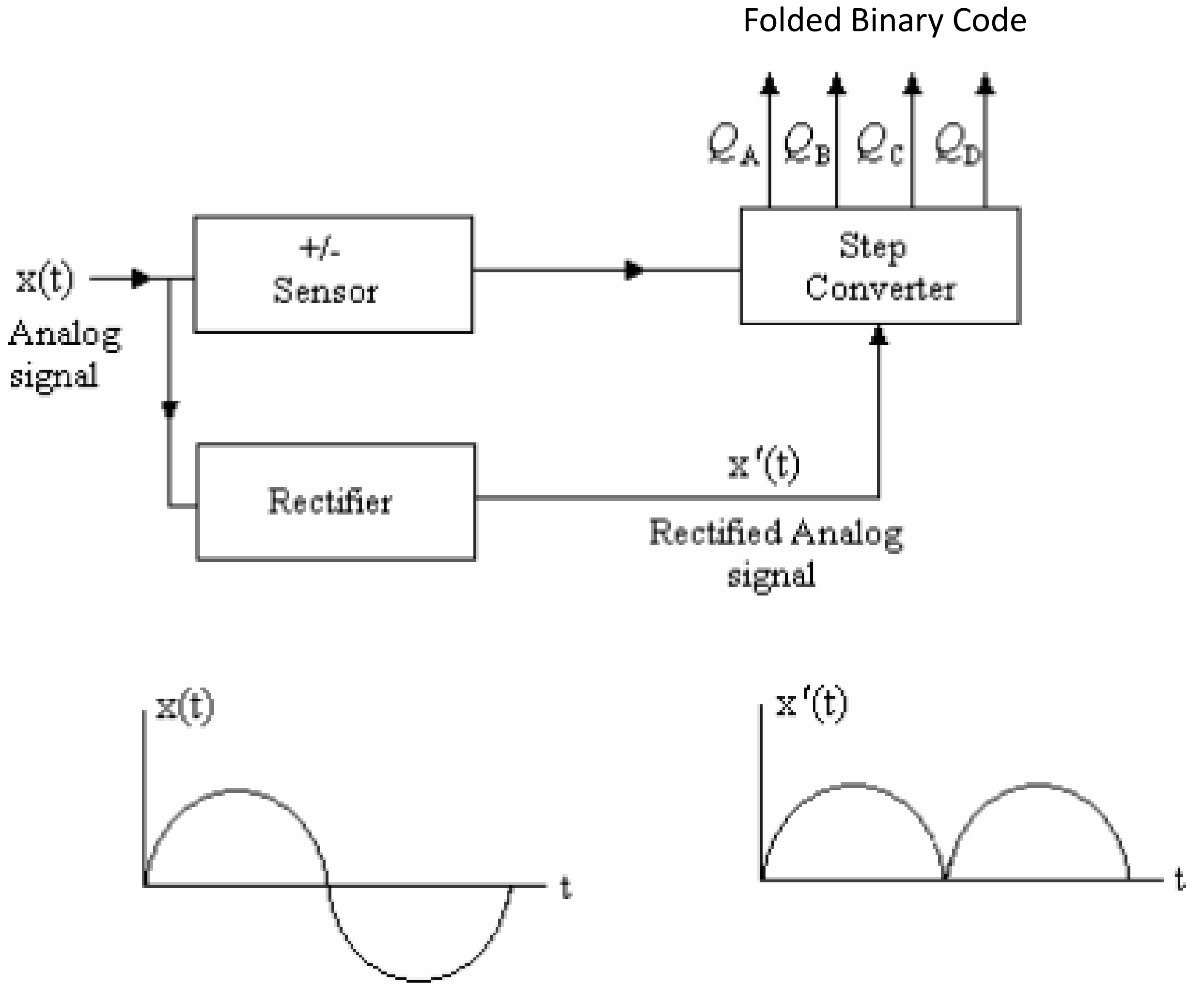
The main disadvantage of grey code is that performing arithmetic operations like addition or subtraction directly on Gray code numbers is complex and not readily achievable, and conversion to binary must be done for calculations.



4-BIT PCM TRANSMITTER - CIRCUIT SCHEMATIC



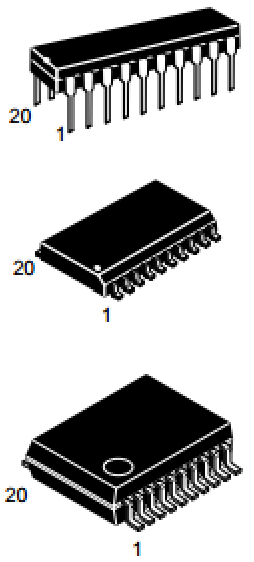
PCM FOR BI-POLAR SIGNALS



PCM INTEGRATED CIRCUITS - MC14LC5480

1. The MC14LC5480 is a general purpose per channel PCM Codec–Filter with pin selectable µ–Law or A–Law companding, and is offered in 20–pin DIP, SOG, and SSOP packages.
2. MC14LC5480 performs voice digitization and reconstruction as well as the band limiting and smoothing required for PCM systems.
3. MC14LC5480 designed to operate in both synchronous and asynchronous applications and contains an on–chip precision reference voltage.

MC14LC5480



P SUFFIX
PLASTIC DIP
CASE 738

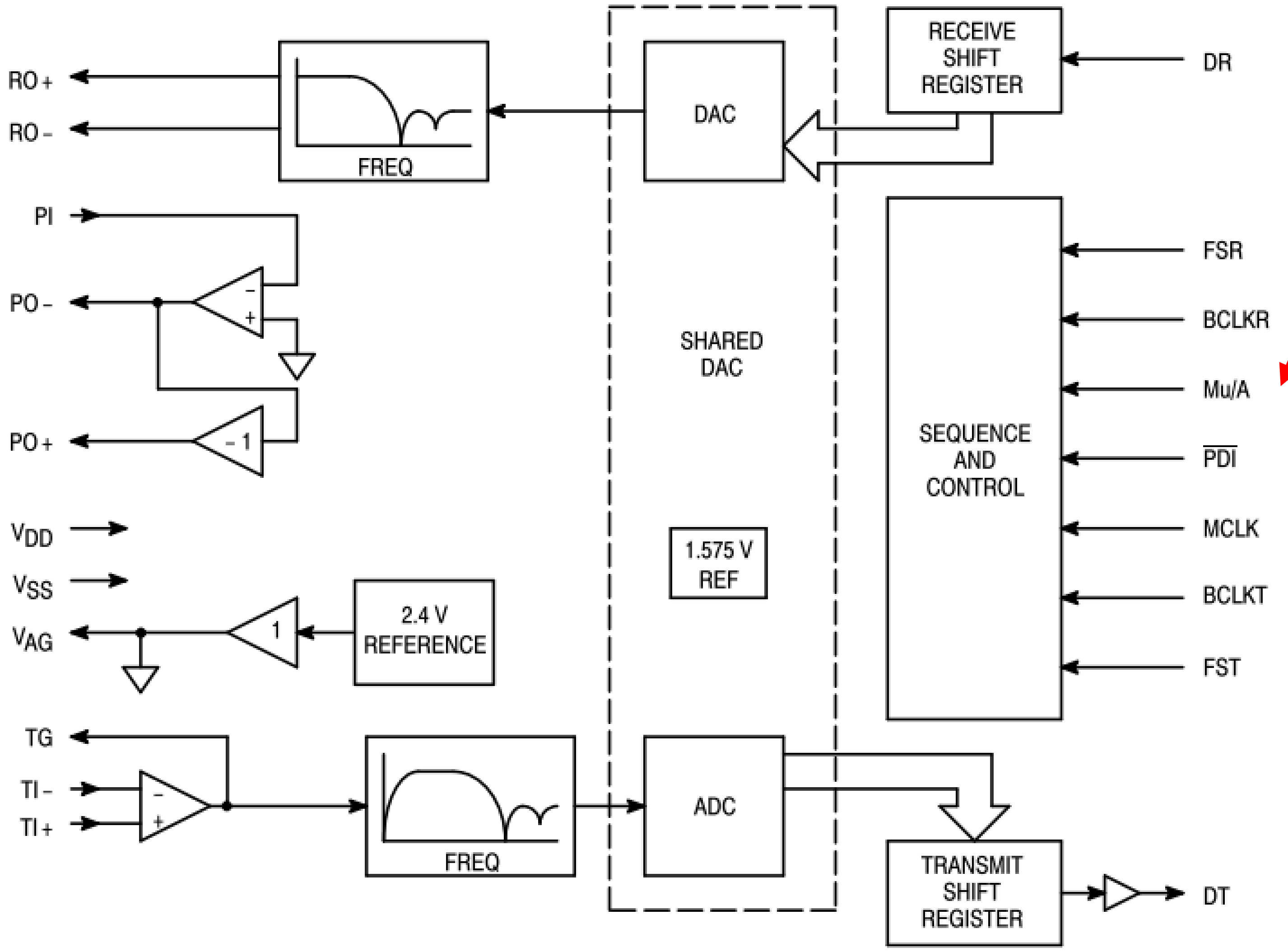
DW SUFFIX
SOG PACKAGE
CASE 751D

SD SUFFIX
SSOP
CASE 940C

ORDERING INFORMATION

MC14LC5480P	Plastic DIP
MC14LC5480DW	SOG Package
MC14LC5480SD	SSOP

MC14LC5480 - BLOCK DIAGRAM



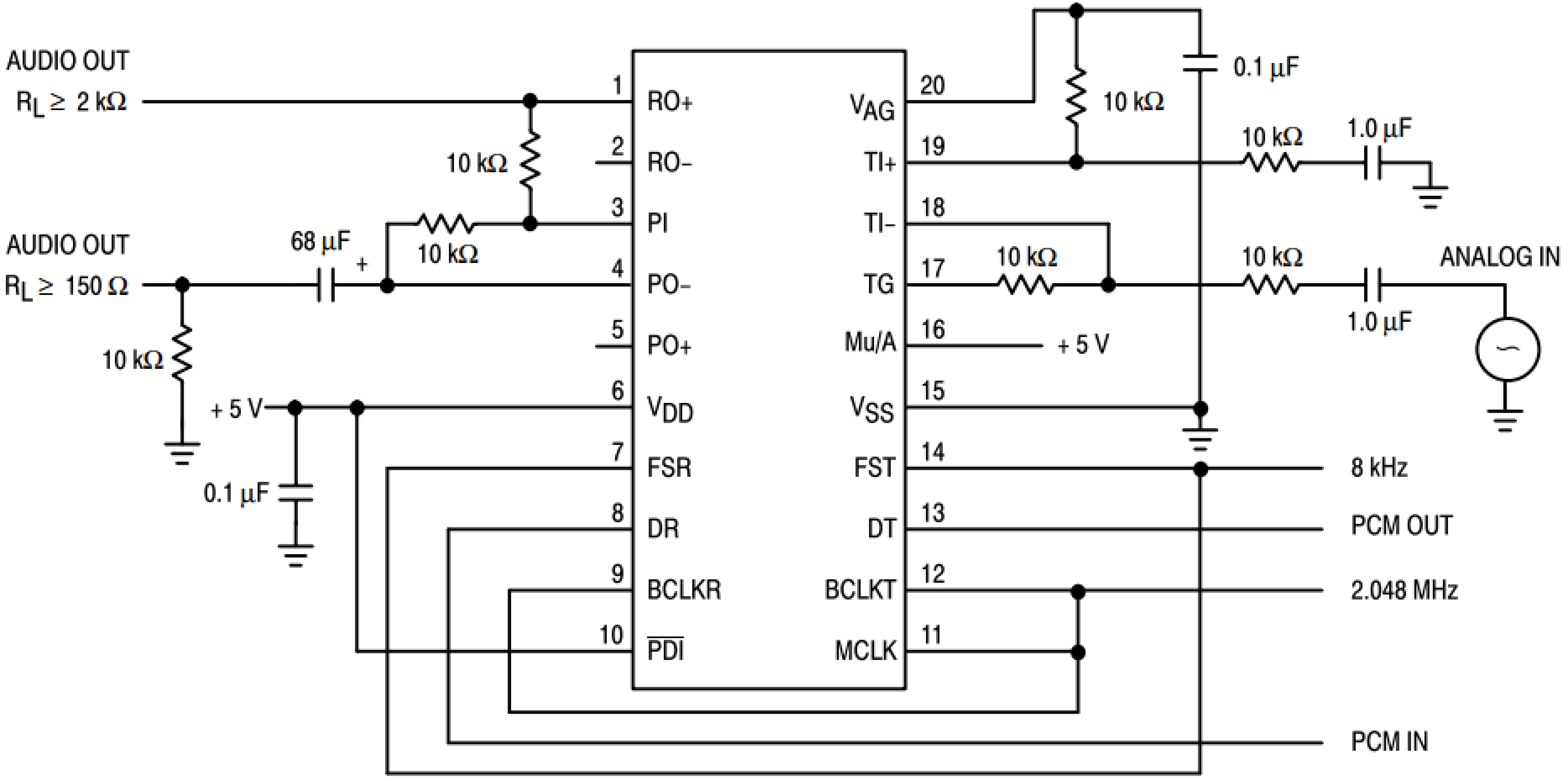
μ/A Law Select (Pin 16)

This pin controls the compression for the encoder and the expansion for the decoder.

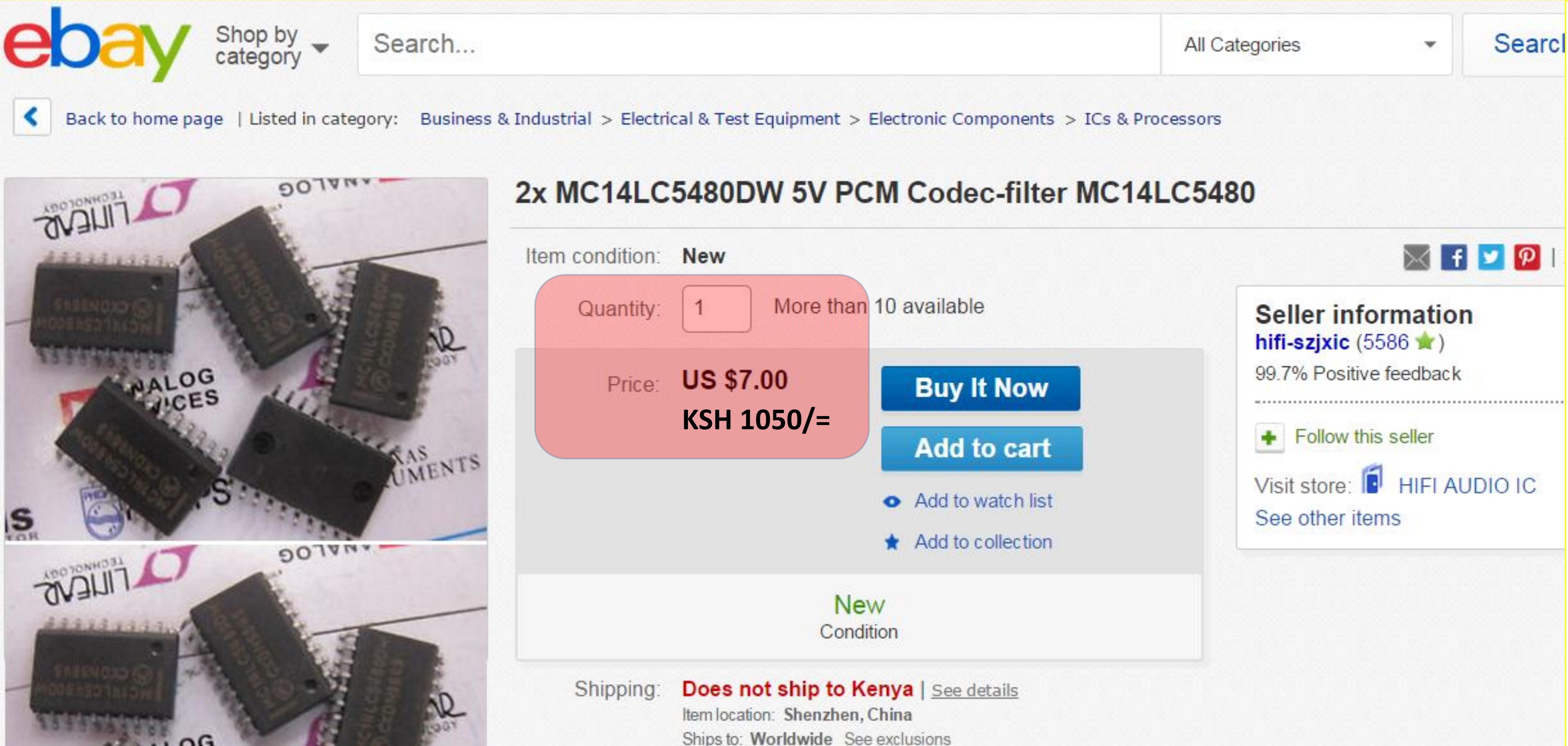
Mu–Law companding is selected when this pin is connected to VDD

A–Law companding is selected when this pin is connected to VSS.

MC14LC5480 - TYPICAL CONNECTION



MC14LC5480 - COST



RECAP: ADVANTAGES OF PCM

1. PCM provides high noise immunity

2. Allows regeneration of clean signal by using repeaters placed between the transmitter and the receiver.

3. PCM signals can be stored for later use or retransmission with high fidelity

4. PCM signals can be encrypted more easily and to very high standards.

RECAP: DISADVANTAGES OF PCM

1. PCM requires complex circuitry to sample, quantize, code and decode.

2. PCM requires large bandwidth compared with that of the original analog signal, i.e
   $BW_{pcm} \geq 2v f_m$