Sampling Process

Stating the sampling theorem for band-limited signals of finite energy, into two equivalent parts, as applied to the transmitter and receiver of a pulse-modulation system:

1. A band-limited signal of finite energy, which has no frequency components higher than B hertz, is completely described by specifying the values of the signal at instants of time separated by 1/2B seconds.
2. A band-limited signal of finite energy, which has no frequency components higher than B hertz, may be completely recovered from a knowledge of its samples taken at the rate of 2B samples per second.

The sampling rate of 2W samples/second, for a signal bandwidth of B hertz, is called ***Nyquist rate***; its reciprocal 1/2W (measured in seconds) is called ***Nyquist interval***.

Aliasing – refers to the phenomenon of a high frequency component in the spectrum of a signal seemingly taking on the identity of a lower frequency in the spectrum of its sampled version (undersampled version of the message signal)

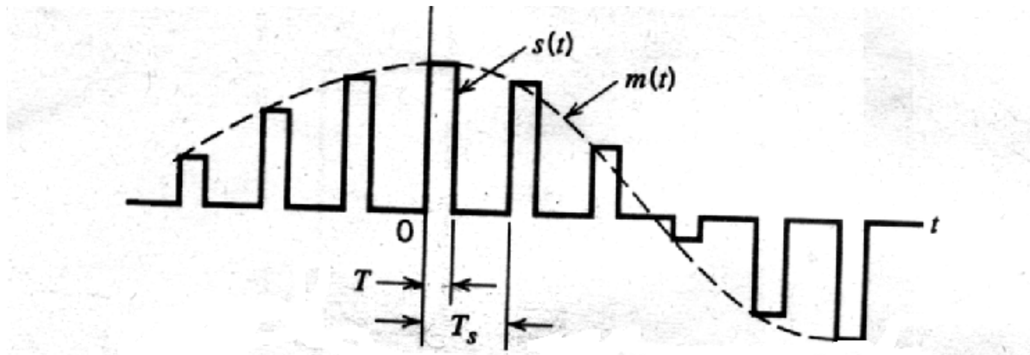
Corrective measures for aliasing effects

1. Prior to sampling, a low-pass anti-aliasing filter is used to attenuate those high-frequency components of the signal that are not essential to the information being conveyed by the signal.
2. The filtered signal is sampled at a rate higher than the Nyquist rate.

Pulse-Amplitude Modulation (PAM)

- the simplest and most basic form of analog pulse modulation.

- In PAM, the amplitudes of regularly spaced pulses are varied in proportion to the corresponding sample values of a continuous message signal; the pulses can be of a rectangular form or some other appropriate shape.



Flat-top samples, representing an analog signal.

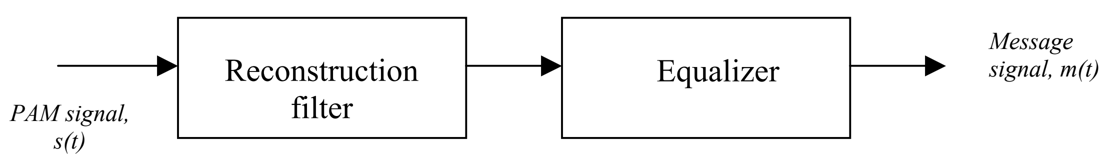
Dashed curve depicts the waveform of the message signal ***m(t)*** and the sequence of amplitude-modulated rectangular pulses represent the corresponding PAM signal, ***s(t)***.

PAM Generation

1. ***Instantaneous sampling*** of the message signal m(t) every T_s seconds, where the sampling rate $f_s = 1/T_s$ is chosen in accordance with the sampling theorem.
2. ***Lengthening*** the duration of each sample so obtained to some constant value T.

Note: In digital circuit technology, these two operations are jointly called **"sample and hold."**

Recovering the message signal from the PAM signal



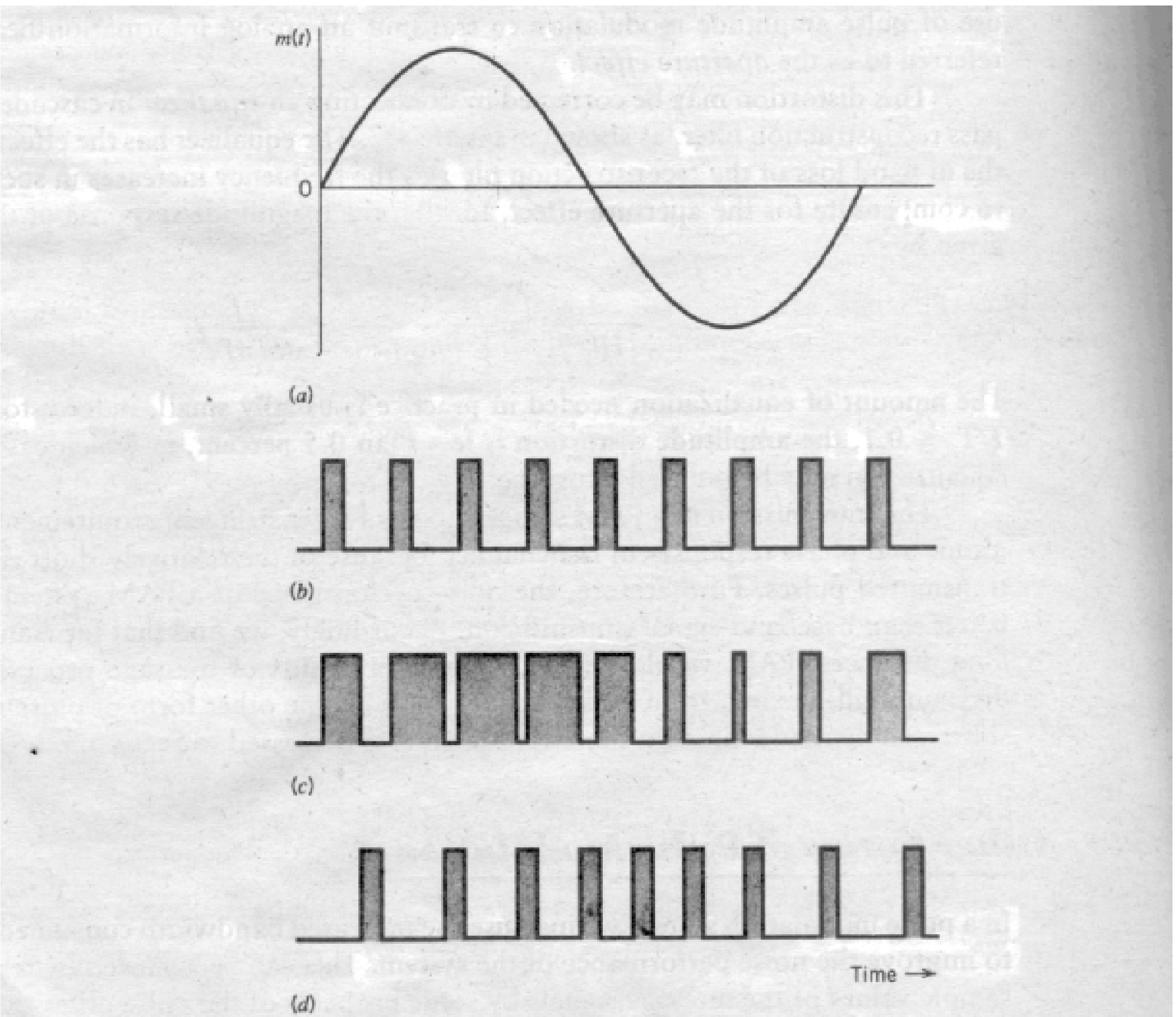
Assumption: The message signal is limited to bandwidth B and the sampling rate f_s is larger than the Nyquist rate.

By using flat-top samples to generate a PAM signal, amplitude distortion is introduced.

Aperture effect – the distortion caused by the use of PAM to transmit an analog-information bearing signal

Other Forms of Pulse Modulation

1. **Pulse-duration modulation (PDM),** also referred to as *pulse-width modulation (PWM,* where samples of the message signal are used to vary the duration of the individual pulses in the carrier.
2. **Pulse-position modulation (PPM)**, where the position of a pulse relative to its unmodulated time of occurrence is varied in accordance with the message signal.



Illustrating two different forms of pulse-time modulation for the case of a sinusoidal modulating wave. (*a*) Modulating wave. (*b*) Pulse carrier. (*c*) PDM wave. (*d*) PPM wave.

Notes:

- In PDM, long pulses expend considerable power while bearing no additional information.
- Accordingly, PPM is a more efficient form of pulse modulation than PDM.

Digital Pulse Modulation (Pulse-code modulation)

- a form of digital pulse modulation where a message signal is represented in discrete form in both time and amplitude. This form of signal representation permits the transmission of the message signal as a sequence of ***coded binary pulses***.
- PCM is essentially analog-to-digital conversion of a special type where the information contained in the instantaneous samples of an analog signal is represented by digital words in a serial bit stream. Hence, if we assume that each of the digital words has n binary digits, there are $M = 2^n$ unique code words that are possible.
- Two fundamental processes are involved in the generation of a binary PCM wave: ***sampling and quantization***.

Advantages of PCM:

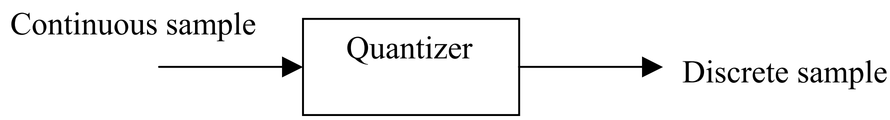
1. Relativrly inexpensive digital circuitry may be used extensively in the system.
2. PCM signals derived from all types of analog sources (audio, video, etc.) may be merged with data signals (like from digital computers) and transmitted over a common high-speed digital communication system.
3. In long-distance digital telephone systems requiring repeaters, a clean PCM waveform can be regenerated at the output of each repeater, where the input consists of a noisy PCM waveform.
4. The noise performance of a digital system can be superior to that of an analog system.

Main disadvantage: a much wider bandwidth than that of the corresponding analog signal

Quantization

- It is not necessary to transmit the exact amplitude of the samples. The receiver (like the human ear) can detect only finite intensity differences. This means that the original continuous signal may be *approximated* by a signal constructed of discrete amplitudes detected on a minimum error basis from an available set. ***The existence of a finite number discrete amplitude levels is a basic condition of PCM.***

Amplitude quantization – the process of transforming the sample amplitude of a message signal at a time into a discrete amplitude taken from a finite set of possible values.



Description of a memoryless quantizer

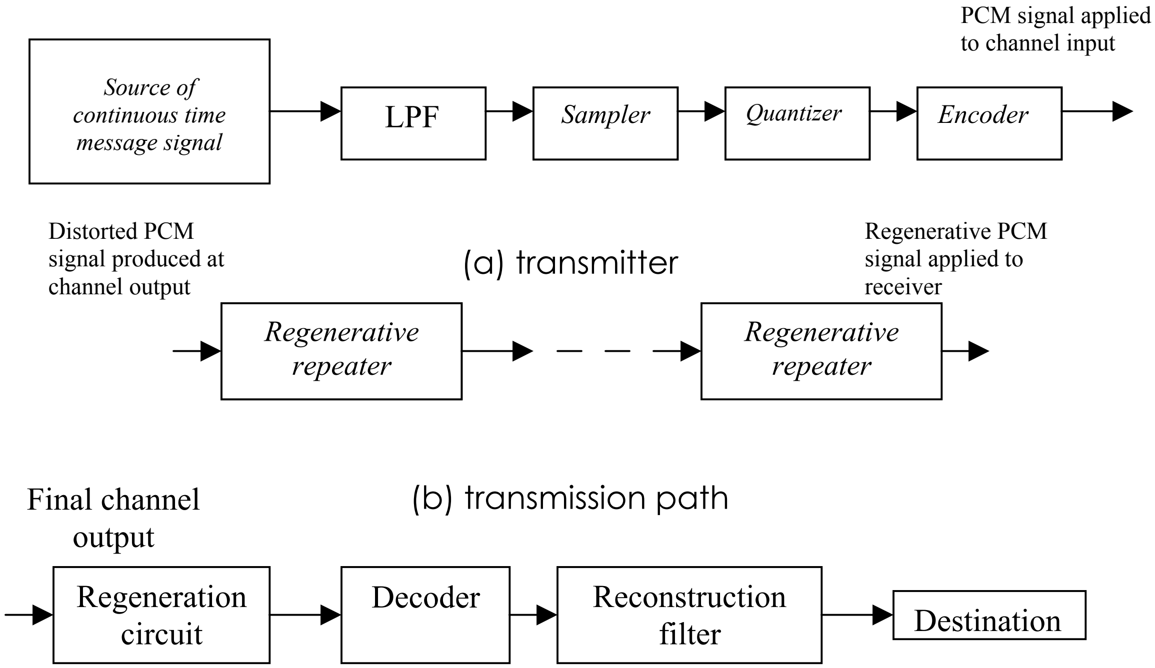
decision levels (or decision thresholds) – discrete amplitudes at the quantizer input.
representation levels or reconstruction levels – discrete amplitudes at the quantizer output.
quantum or step size – spacing between two adjacent representation levels.

- Quantizers can be of a uniform or nonuniform type. In a uniform quantizer, the representation levels are uniformly spaced; otherwise the quantizer is nonuniform.

quantization noise – an error defined as the difference between the input signal and the output signal.

Elements of a PCM system

- Basic operations performed in the transmitter: sampling, quantizing, encoding
- LPF prior to sampling is included to prevent aliasing of the message signal; the quantizing and encoding operations are usually performed by a circuit known as ***analog-to-digital converter***..
- Basic operations in the receiver are regeneration of impaired signals, decoding and reconstruction of the train of quantized pulses. Regeneration also occurs at intermediate points along the transmission path as necessary



(c) Receiver

Basic elements of a PCM system

Transmitter:

Low –pass aliasing filter – used at the front-end of the sampler to exclude frequencies greater than B before sampling.

Sampler – permits the reduction of the continuously varying message signal (of some finite duration) to a limited number of discrete values per second.

Quantizer – provides a new representation of the signal that is discrete in both time and amplitude.

In telephonic communication, it is preferable to use a variable separation between separation levels.

The use of a nonuniform quantizer is equivalent to passing the baseband signal through a ***compressor*** and then applying the compressed signal to a uniform quantizer.

Forms of compression laws:

1. **μ-law** – a signal compression law used in the United States, Canada and Japan. The μ-law is defined by

$$|v| = \frac{\ln(1+\mu|m|)}{\ln(1+\mu)}$$

where m and v are the normalized input and output voltages and μ is a positive constant.

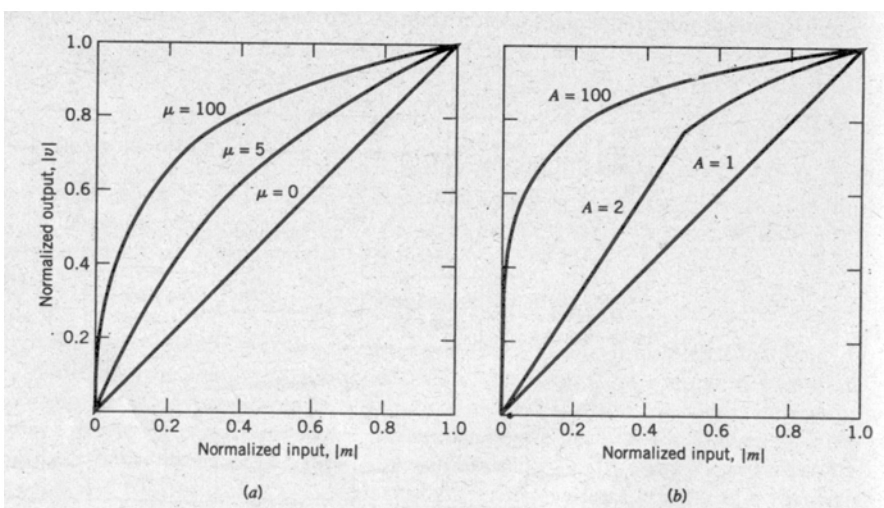
2. A-law – signal compression used in Europe; described by

$$|v| = \frac{A|m|}{1+\log A}, 0 \le |m| \le \frac{1}{A}$$

$$= \frac{1+\log(A|m|)}{1+\log A}, \frac{1}{A} \le |m| \le 1$$

To restore the signals sampled to their correct relative level, a device in the receiver complements the work of the compressor. This is called an ***expander.*** The combination of a compressor and an expander is called ***compander***.

SNR for low-level signals increases at the expense of the SNR for high-level signals. As a compromise, values of μ and A are adopted in practice. Typical values are μ = 255 and A = 87.6



Compression laws. (*a*) μ-law. (*b*) A-law.

Encoding

To exploit the advantages of sampling and quantizing for the purpose of making the transmitted signal more robust to noise and interference, we require the use of ***encoding*** to translate the discrete set of sample values to a more appropriate form of signal.

code – any plan for representing each of the discrete set of values as a particular arrangement of discrete events
code element or symbol – one of the discrete events in a code.
code word or character – a particular arrangement of symbols used in a code to represent a single value.

Using a code word of R bits, we may represent a total of 2^R distinct numbers.

The maximum advantage over the effects of noise in a transmission medium is obtained by using a binary code, because a binary symbol withstands relatively high level of noise and is easy to generate.

Binary Line Codes – used to electrically represent a binary data stream.
Categories:
1. ***Return-to-zero (RZ)*** – the waveform returns a zero-volt level for a portion (usually one-half) of the bit interval.
2. ***Nonreturn-to-zero***

A. Unipolar nonreturn-to-zero (NRZ) signaling

In this line code, symbol 1is represented by transmitting a pulse of amplitude A for the duration of the symbol, and the symbol 0 is represented by switching off the pulse. This code is also called ***on-off signaling***.
Advantage: uses circuits that that require only one power supply (e.g. +5V power supply for TTL circuits)
Disadvantage: waste of power due to the transmitted dc level.

B. Polar nonreturn-to-zero (NRZ) signaling

Binary 1's and 0's are represented by equal positive and negative levels.
Advantage: easy to generate, since this code doesn't require a dc-coupled channel
Disadvantage: circuitry requires a positive-voltage and negative-voltage power supply

C. Unipolar return-to-zero (RZ) signaling

In this line code, symbol 1 is represented by a rectangular pulse of amplitude A and half-symbol width, and symbol 0 is represented by transmitting no pulse.

Advantage: the presence of delta functions at f=o, $\pm 1/T_b$, in the power spectrum of the transmitted signal, which can be used for timing recovery in the receiver.

Disadvantage: requires 3 dB more power than the unipolar non return-to-zero signaling for the same probability of symbol error.

D. Bipolar return-to-zero (BRZ) signaling

This line code uses 3 amplitude levels. Specifically, positive and negative pulses of equal amplitude (+A and –A) are used alternately for symbol 1, with each symbol having half-width; no pulse is always used for symbol 0. This line code is also called **alternate mark inversion (AMI) signaling.**

Advantage: power spectrum of transmitted dc signal has no dc component and relatively low-frequency components for the case when 1 and 0 occur with equal probability.

E. Split-phase (Manchester code)

A symbol 1 is represented by a positive pulse of amplitude A followed by a negative pulse of amplitude –A, with both pulses being half-symbol wide.

For symbol 0, the polarities of the two pulses are reversed.

Advantage: Always has a 0 dc value, regardless of data sequence.

Disadvantage: twice the bandwidth of the unipolar NRZ or polar NRZ codes because the pulses are half the width.

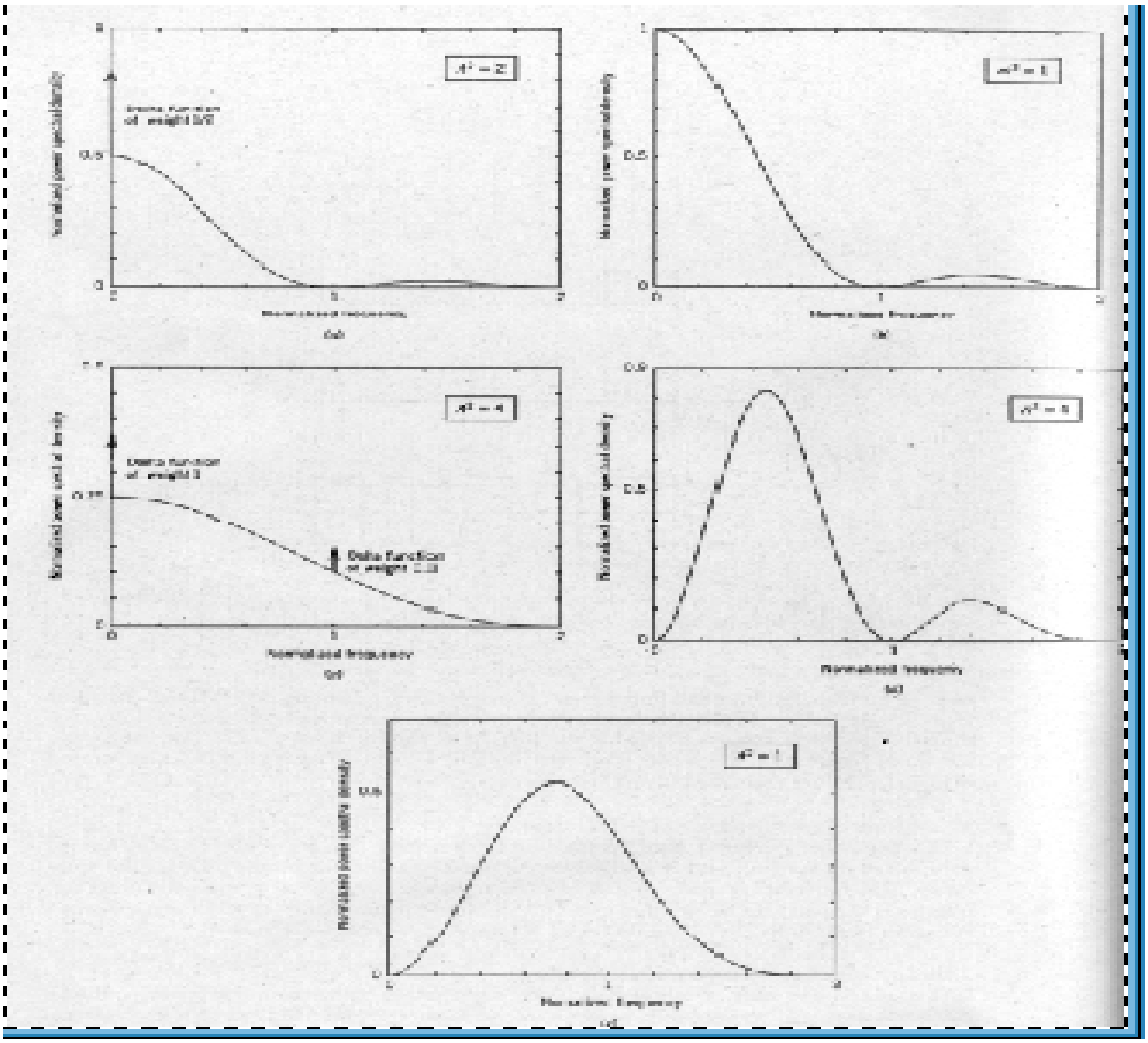
Problem: Given a binary data stream of 01101001. Show the line codes as electrical representation of the data.

Desirable properties of line codes

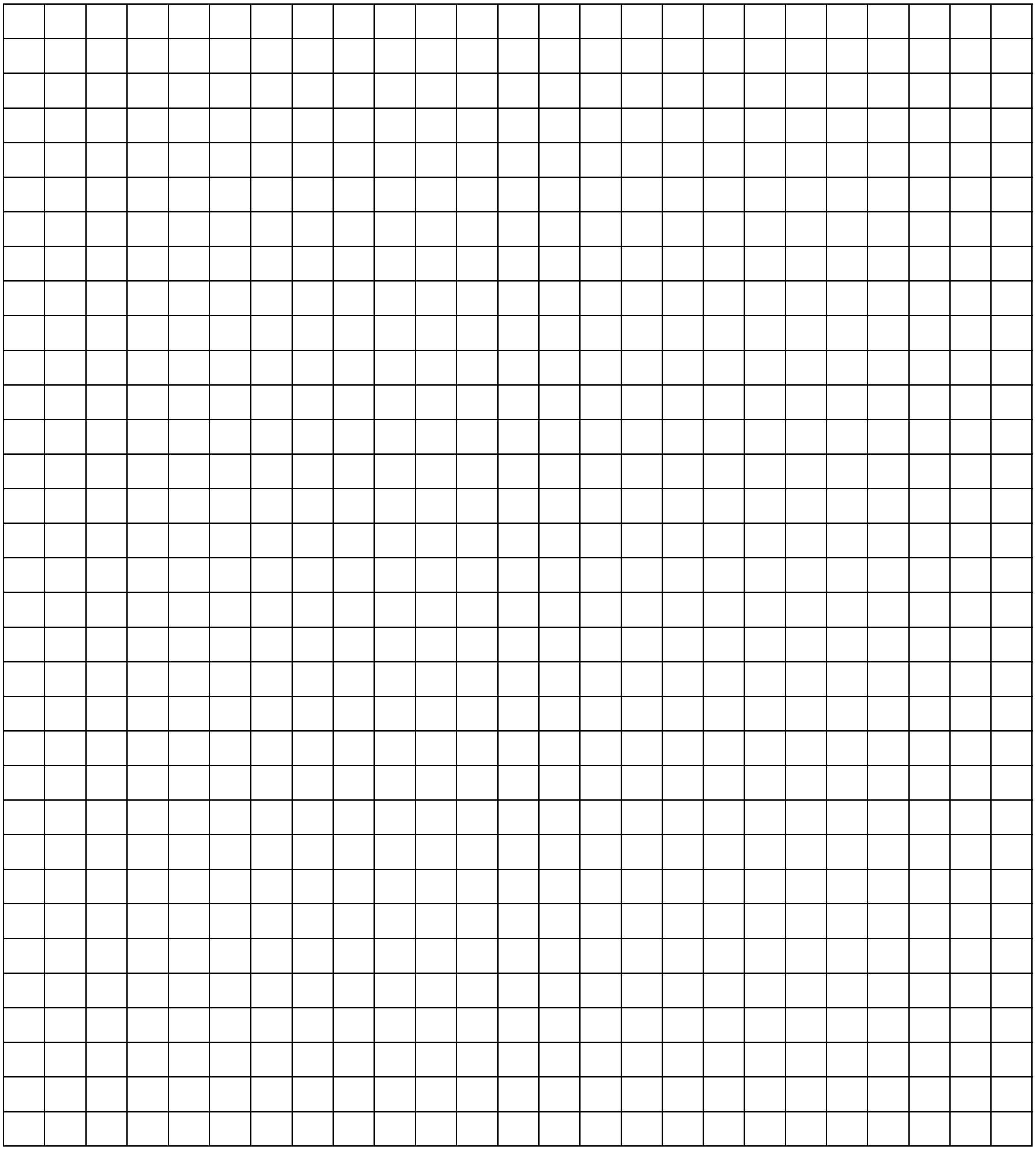
Self synchronization- There is enough timing information built into the code so that bit synchronizers can be designed to extract the timing or clock signal. A long series of 1s and 0s should not cause a problem in time recovery.

Low probability of bit error – receivers can be designed that will recover the binary data with a low probability of bit error when the input data is corrupted by noise.

A spectrum that is suitable for the channel – If the channel is ac coupled, the PSD of the line code signal should be negligible at frequencies near zero.
Transmission bandwidth – It should be as small as possible.
Error detection capability – It should be possible to implement this feature easily by the addition of channel encoders and decoders or it should be incorporated in the code.
Transparency – The data protocol and line code are designed so that every possible sequence of data is faithfully and transparently received.



Power spectra of line codes: (a) Unipolar NRZ; (b) Polar NRZ; (c) Unipolar RZ; (d) bipolar RZ; (e) Manchester encoding



Differential encoding

This method is used to encode information in terms of **signal transitions.** In particular, a transition is used to designate symbol 0 in the incoming data stream, while no transition is used to designate the symbol 1.

The original binary information is recovered by simply comparing the polarity of adjacent binary symbols to establish whether a transition has occurred or not.

Note that the differential encoding requires the use of a reference bit before initiating the encoding process.

Problem: Show the waveform of a differentially encoded data using unipolar NRZ signaling assuming a reference bit of 1. The original binary data is 01101001.

Regeneration

The most important feature of PCM systems lies in the ability to control the effects of distortion and noise produced by transmitting a PCM signal through a channel.

This capability is achieved by reconstructing the PCM signal by means of a chain of **regenerative repeaters**.

Decoding

The first operation in the receiver is to regenerate (reshape and cleanup) the received pulses one last time. These clean pulses are regrouped into code words and decoded (mapped back) into a quantized PAM signal.

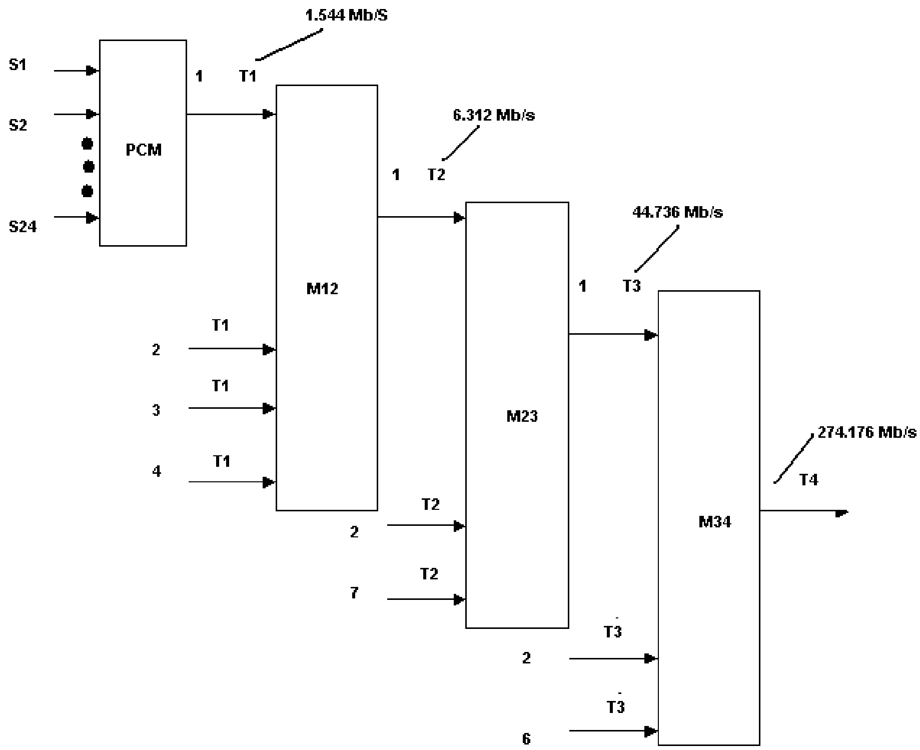
Filtering

The final operation in the receiver is to recover the message by passing the decoder output through a low-pass reconstruction filter whose cut-off frequency is equal to the message bandwidth.

Noise Considerations in PCM Systems

The performance of a PCM system is influenced by two major sources of noise:

1. ***Channel noise,*** introduced anywhere from between transmitter output and receiver input. Channel noise is always present, once the equipment is switched on.
2. ***Quantization noise,*** which is introduced in the transmitter and is carried all the way to receiver output. Unlike channel noise quantization noise is signal-dependent in the sense that it disappears when the message signal is switched off.



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S1
S2
S24
PCM
1
T1
6.312 Mb/s
1
T2
M12
T1
2
T1
3
T1
4
44.736 Mb/s
1
T3
M23
T2
2
T2
7
274.176 Mb/s
T4
M34
T3
2
T3
6