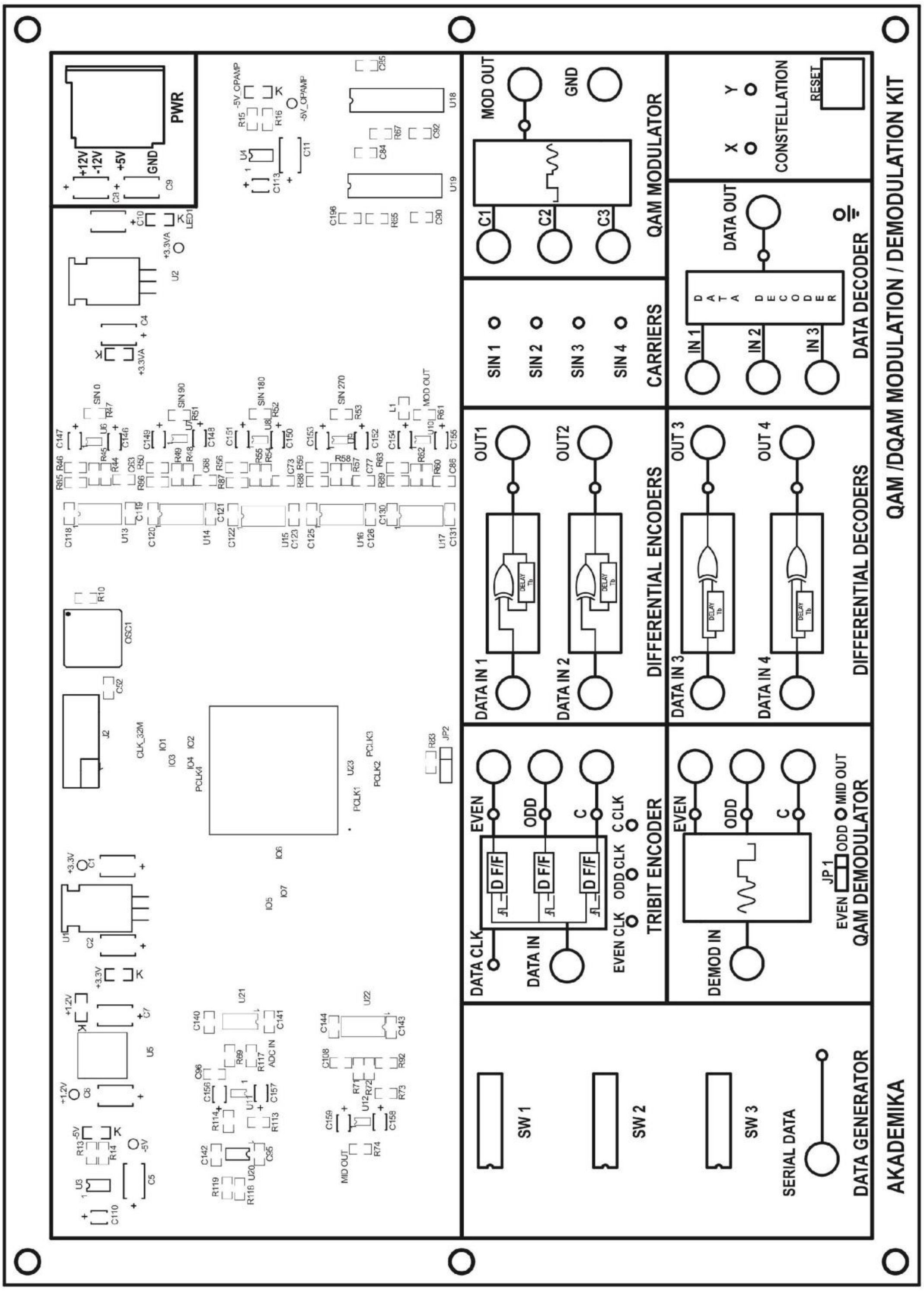
Experiment # 5

Study of 8-Quadrature Amplitude Modulation (8-QAM) and Demodulation.

FUNCTIONAL BLOCK DIAGRAM



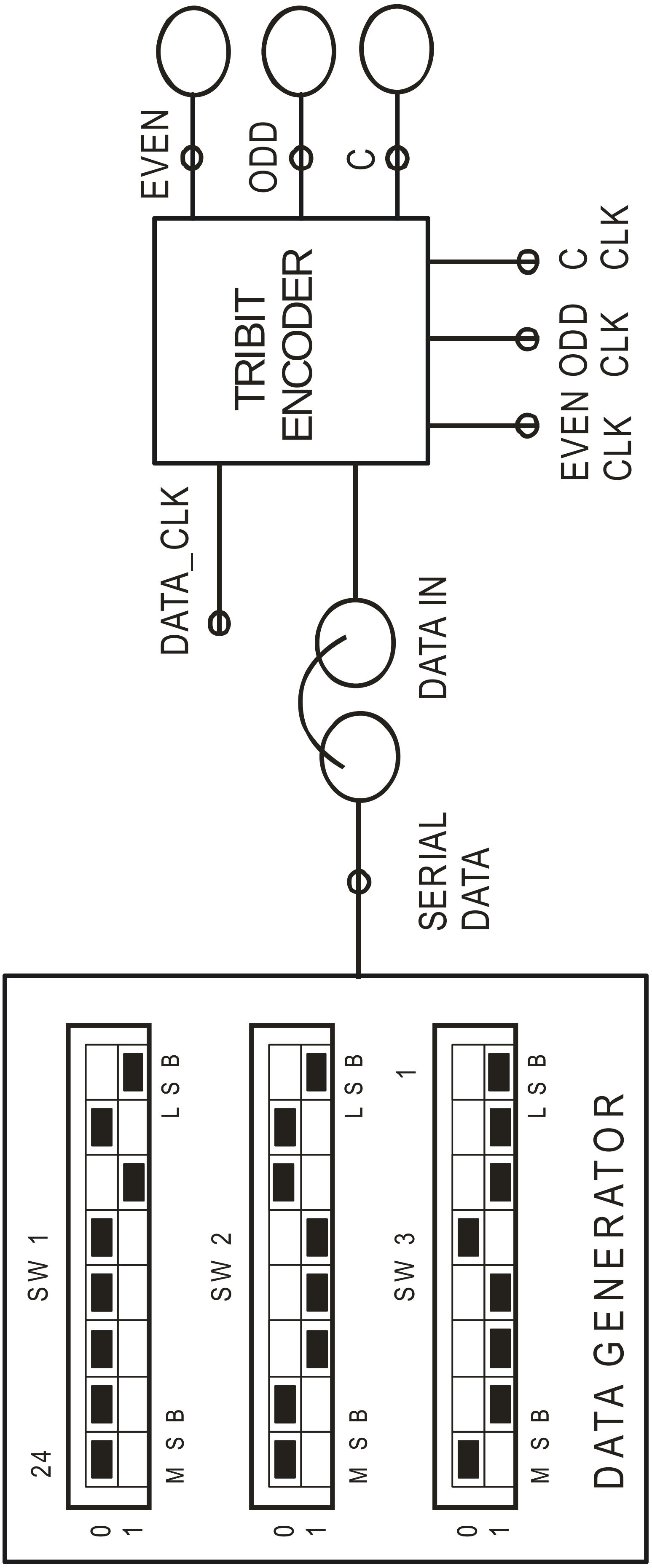


FIG 1.1 BLOCK DIAGRAM FOR TRIBIT ENCODING OF NRZ-L DATA

EXPERIMENT NO: 5

NAME:

TRIBIT DATA CODING TECHNIQUE OF NRZ-L DATA FORMAT

OBJECTIVE:

To study tribit coding techniques for Non-Return to Zero data format

THEORY:

NON - RETURN TO ZERO signal are the easiest formats that can be generated. These signals do not return to zero with the clock. The frequency component associated with these signals are half that of the clock frequency. Non-return to zero encoding is commonly used in slow speed communications interfaces for both synchronous and asynchronous transmission. Using NRZ, logic ‘1’ bit is sent as a high value and logic ‘0’ bit is sent as a low value.

The mechanism by which a bit stream b(t) generates a QAM signal for transmission is shown in fig. 1.2 and relevant waveforms are shown in fig.1.3. In these waveforms we have arbitrarily assumed that in every case the active edge of the clock waveform is the upward edge. The D flip-flop generates three clocks waveforms. These clocks have period 3Tb. The active edge of one of the clocks and the active edges of the other are separated by the bit time Tb. The bit stream b (t) is applied as the data input to type-D flip-flops, driven by the three different clock waveform. Each flip-flop registers bits during positive transition of its clock in the bit stream b (t) and holds each such registered bit for three bit intervals that is for the time 3Tb. In fig.1.3 we have numbered the bits in the stream b (t). Note that the bit stream EVEN bit (which is the output of the flip-flop driven by the EVEN clock)registers bit 1 and holds that bit for time 3Tb, then register bit 4 for time 3Tb, then bit 7 for 3Tb, etc. The next bit stream ODD bit holds, for times 3Tb each, the bits numbered 2, 5, 8, etc. similarly the C bit stream holds the data bit numbered 3, 6,9 for the bit interval 3Tb.

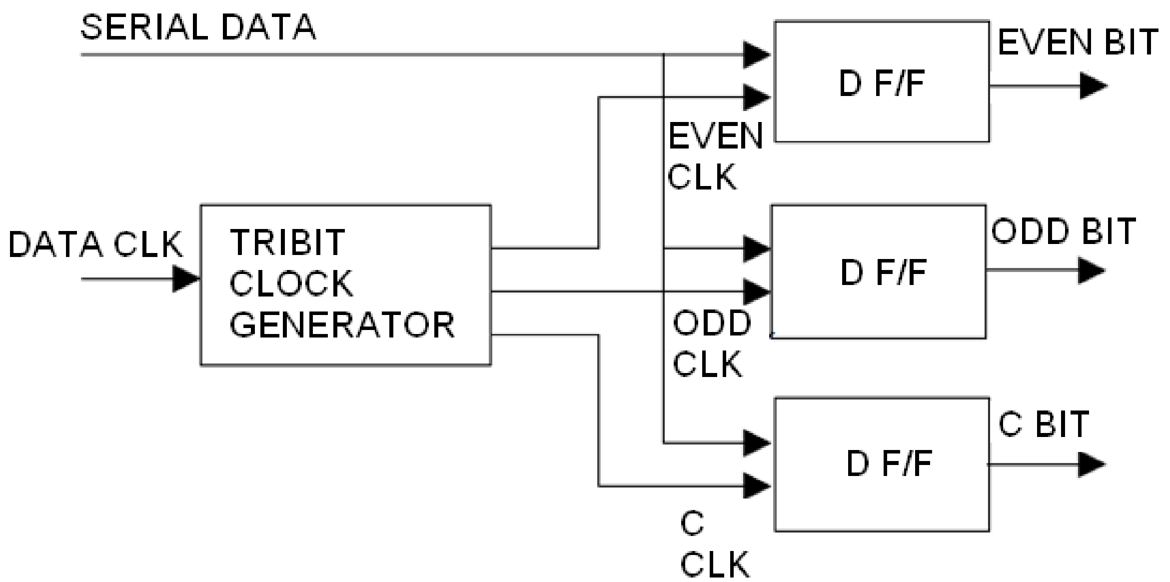
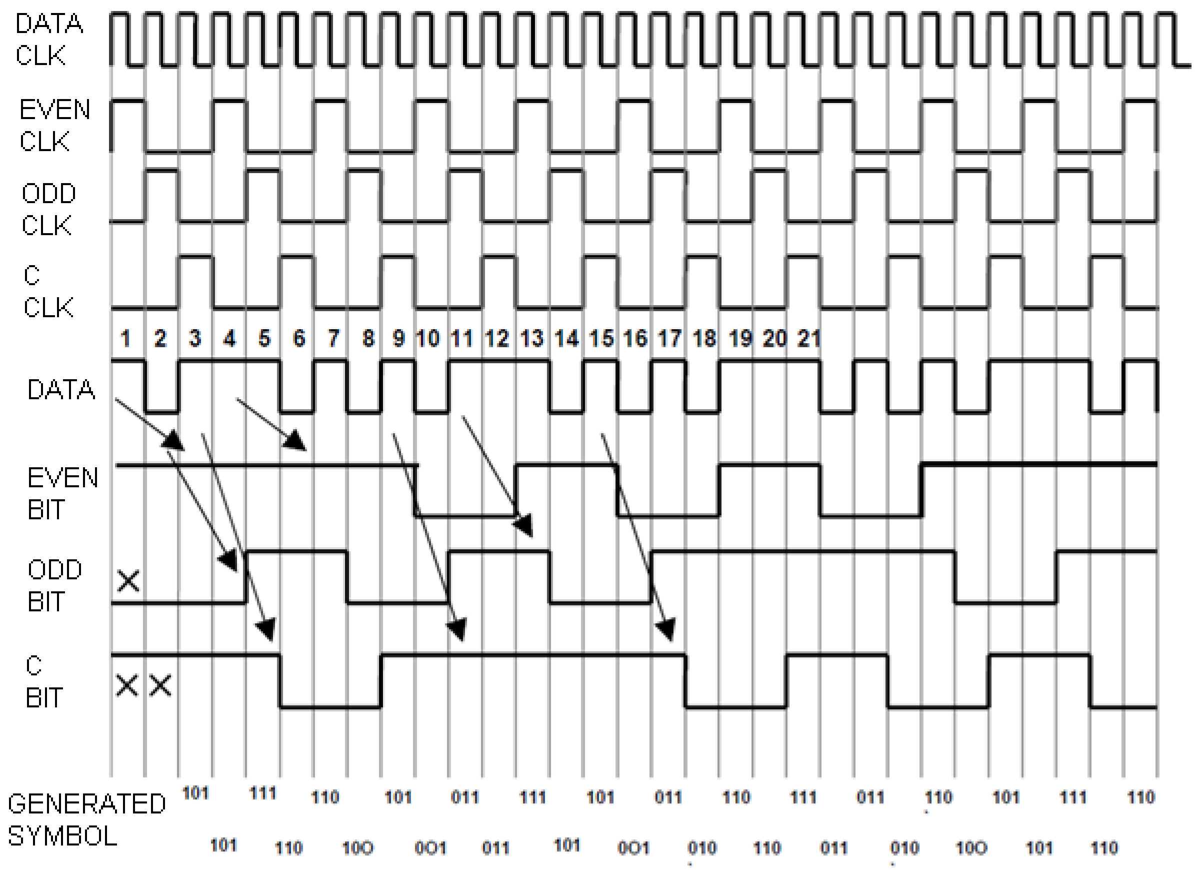


Fig. 1.2 TRIBIT CODING



EQUIPMENTS:

- Experimental Kit DCL-QAM
- Connecting Chords
- Power supply
- 20MHz Dual Trace Oscilloscope

PROCEDURE:

1. Refer to the block diagram (Fig.1.1) and carry out the following connections and switch settings.
2. Connect power supply in proper polarity to the kit **DCL-QAM** and switch it on.
3. Select Data pattern of simulated data using switch **SW1, SW2, SW3.**
4. Connect **SERIAL DATA** generated to **DATA IN** of **TRIBIT ENCODER**.
5. Observe the tribit clock generated at **EVEN CLK, ODD CLK** and **C CLK** on the oscilloscope with respect to **DATA_CLOCK.** (Fig.1.4).
6. Observe the coded signal **EVEN, ODD** and **C** data on the oscilloscope with respect to **SERIAL DATA.** (Fig.1.4).

OBSERVATION:

Observe the following waveforms on oscilloscope and plot it on the paper.

1. Transmitter clock **DATA_CLOCK** with respect to NRZ-L coded Data **SERIAL DATA.** (Fig1.4 (a))
2. **EVEN CLK** with respect to **ODD CLK.** (Fig1.4 (b))
3. **EVEN CLK** with respect to **C CLK.** (Fig1.4 (c))
4. **EVEN** data with respect to **EVEN CLK.** (Fig1.4 (d))
5. **ODD** data with respect to **ODDCLK.** (Fig1.4 (e))
6. **C** data with respect to **CCLK.** (Fig1.4 (f))

CAPTURED WAVEFORM:

CH 1: DATA CLK (256 KHz) & CH 2: SERIAL DATA (0000010100111001011110111)

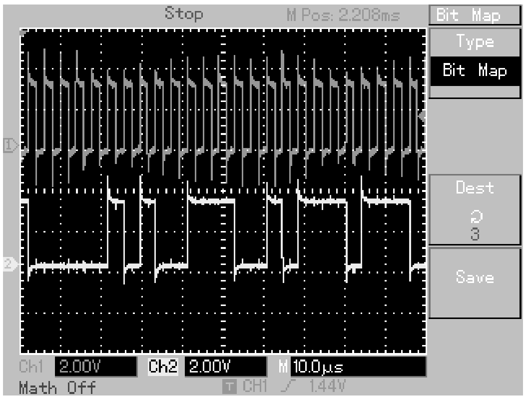


FIG. 1.4(a)

CH 1: EVEN CLK & CH 2: ODD CLK

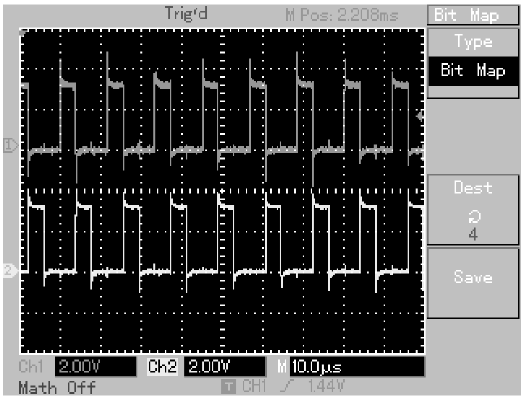


FIG. 1.4(b)

CH 1: EVEN CLK & CH 2: C CLK

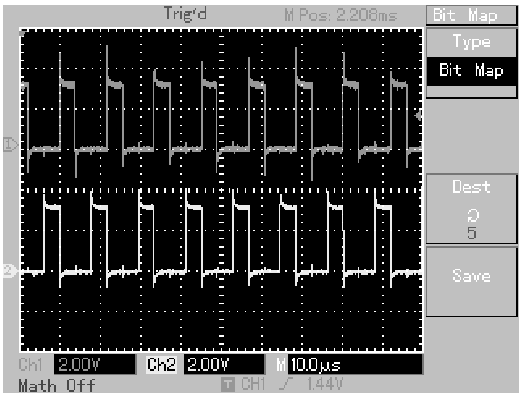


FIG. 1.4(c)

CH 1: EVEN CLK & CH 2: EVEN (TRIBIT ENCODER)

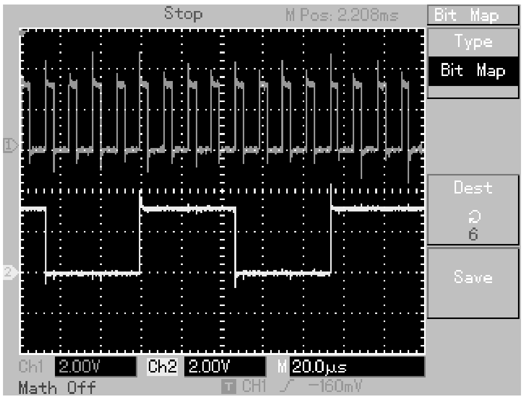


FIG. 1.4(d)

CH 1: ODD CLK & CH 2: ODD (TRIBIT ENCODER)

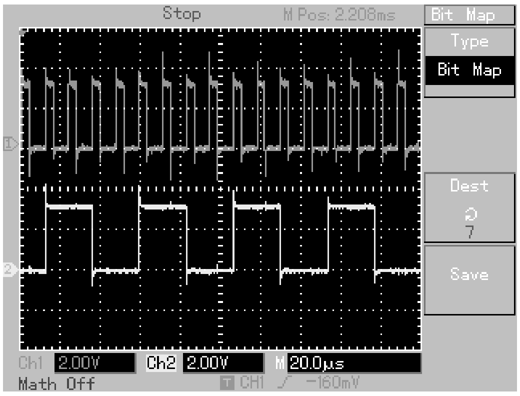


FIG. 1.4(e)

CH 1: C CLK & CH 2: C (TRIBIT ENCODER)

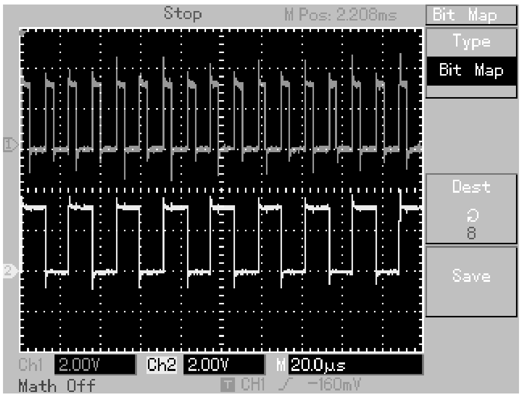


FIG. 1.4(f)

CONCLUSION:

The data are coded in Tribit, which generates, A data signal EVEN(in phase) consisting in voltage levels corresponding to the value of the first bit of the considered data, for a period equal to 3 bit intervals. A data signal ODD (in quadrature) consisting in voltage levels corresponding to the value of the second bit of the data, for duration equal to 3 bit intervals. A data signal C consisting in voltage levels corresponding to the value of the third bit of the data, for duration equal to 3 bit intervals.

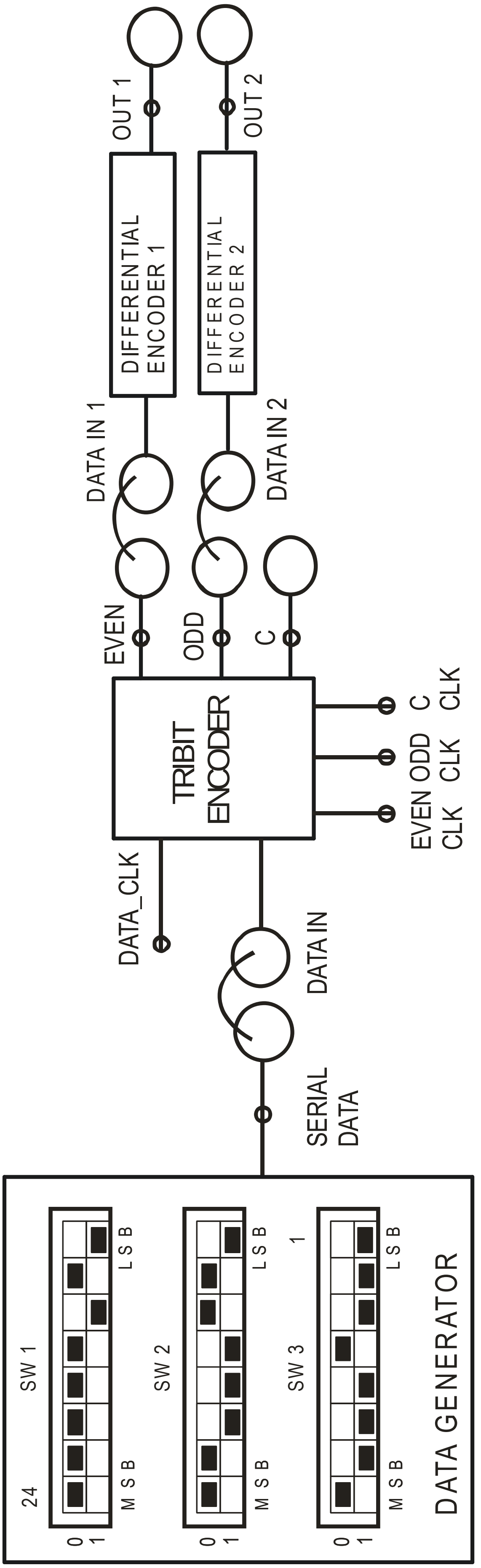


FIG 2.1 BLOCK DIAGRAM FOR DIFFERENTIAL ENCODING OF TRIBIT DATA

NAME:

DIFFERENTIAL ENCODING OF DATA

OBJECTIVE:

To study differential encoding techniques for data

THEORY:

Differential Encoding Logic:

A means of generating a differentially encoded data is shown in fig 2.2. The data stream to be transmitted, d (t), is applied to one input of an Ex-OR logic gate. The other input of gate is the output of the Ex-OR gate b (t) delayed by the time Tb allocated to one bit. This second input is then b(t-Tb).

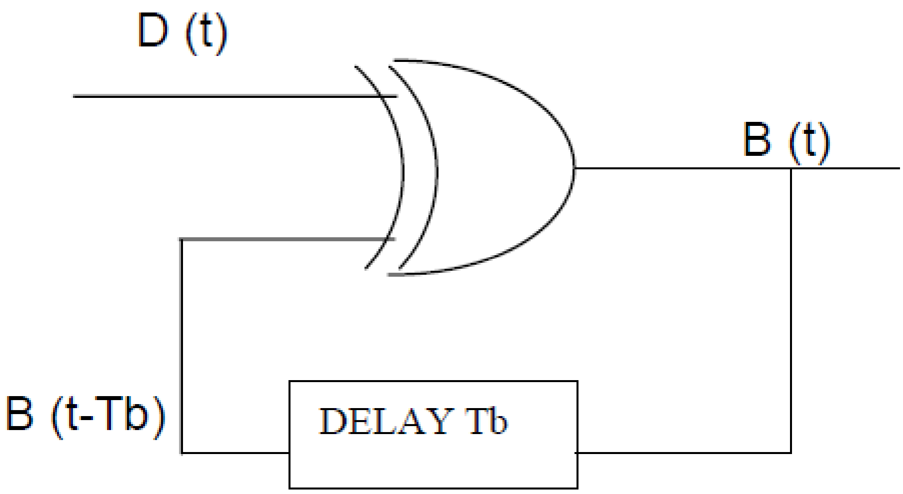


Fig 2.2 Differential Encoder

In fig 2.3 we have drawn the logic waveform to illustrate the response b(t) to an input d(t). The upper level of the waveform corresponds to logic 1,the lower level to logic 0. Because of the feedback involved in the system of fig 2.2 there is difficulty in determining the logic levels in the interval in which we start to draw the Waveform (interval 1 in fig 3.3) we cannot determine b (t) in this first interval of our waveform unless we know b(k=0). But we cannot determine b(0) unless we know both d(0) and b(-1), etc. thus; to justify any set of logic levels in an initial bit interval we need to know the logic levels in the preceding interval. But such a determination requires information about the interval two bit times earlier and so on. In the waveform of fig 3.3 we have circumvented the problem by arbitrarily assuming that in the first interval b(0) =0. It is shown below that, the data will be correctly determined regardless of our assumption concerning b(0).

We now observe that the response of b(t) to d(t) is that b(t) changes level at the beginning of each interval in which d(t) = 1 and b(t) does not changes level when d(t) = 0. Thus during interval 3, d(3) = 1, and correspondingly b(3) changes at the beginning at that interval. During interval 6 & 7, d(6) = d(7) =1 and there are changes in b (t) at the beginning of both intervals. During bits 10, 11, 12, and 13d(t) =1 and there are changes in b(t) at the beginnings of each of these intervals. This behavior is to be anticipated from the truth tables of the exclusive- OR gate. For we note that when d(t) =0, b(t)=b(t-Tb) so that, whatever the initial value of DELAY Tb b(t-Tb),it reproduces itself. On the other hand when d(t)=1 then b(t)=1/b(t-Tb). Thus, in each successive bit intervals b(t) changes from its value in the previous interval.

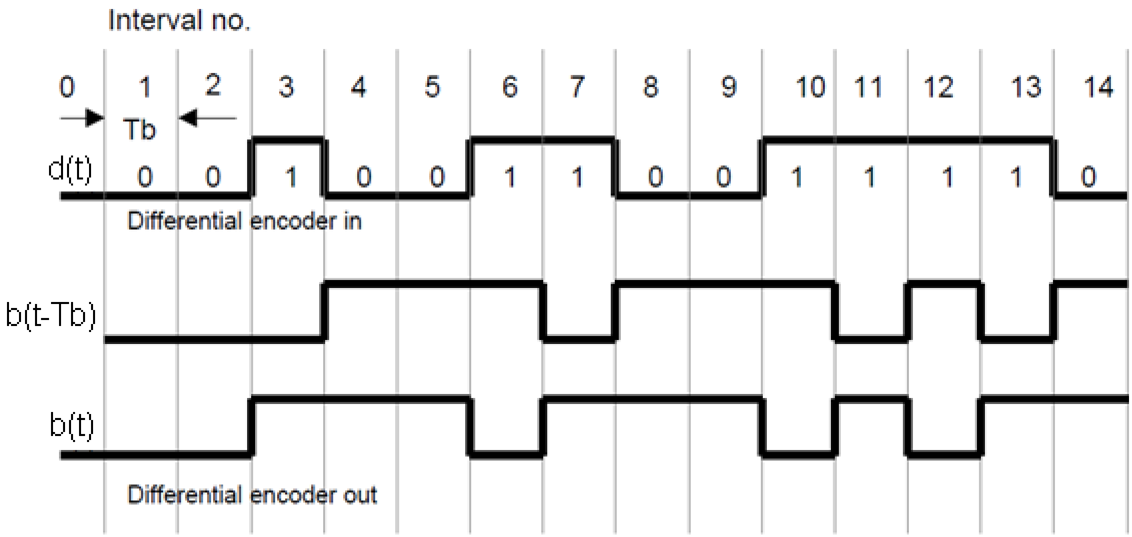


FIG 2.3 waveform of DIFFERENTIAL ENCODING of data

Note that in some intervals where d(t) = 0 we have b(t) =0 and in other intervals when d(t) =0 we have b(t)= 1. Similarly, when d(t) = 1 sometimes b(t) =1 and sometimes b(t) =0. Thus there is no correspondence between the levels of d(t) and b(t), and the only invariant feature of the system is that a change (some time up and sometime down) in b(t) occurs whenever d(t)=1, and that no change in b(t) will occur whenever d(t) =0.
Finally, we note that in waveform of fig 2.3 are drawn on the assumption that, in interval 1, b(0) =0. As is easily verified, if not intuitively apparent, if we had assumed b(0) = 1, the invariant feature by which we have characterized the system would continue to apply. Since b(0) must be either b(0) = 0 or b(0) = 1, there being no other possibilities, our result is valid quite generally. If, however, we had started with b(0) = 1 the levels b(1) and b(0) would have been inverted.

EQUIPMENTS:

- Experimental Kit **DCL-QAM**
- Connecting Chords.
- Power supply.
- 20MHz Dual Trace Oscilloscope.

PROCEDURE:

1. Refer to the block diagram (Fig 2.1) and carry out the following connections and switch settings.
2. Connect power supply in proper polarity to the kit **DCL-QAM** and switch it on.
3. Select Data pattern of simulated data using switch **SW1, SW2, SW3,**
4. Connect **SERIAL DATA** generated to **DATA IN** of **TRIBIT ENCODER**.
5. Connect generated **EVEN** and **ODD** data to **DATA IN1**and**DATA IN2** of **DIFFERENTIAL ENCODERS** respectively.
6. Observe the input data and the differentially encoded **EVEN**&**ODD** data at **OUT1 and OUT2**of **DIFFERENTIAL ENCODERS** respectively.

OBSERVATION:

ON KIT **DCL-QAM**
Observe the following waveforms on oscilloscope and plot it on the paper.

1. Differentially encoded data **OUT1** with respect to coded data **EVEN** (Fig.2.4(a))
2. Differentially encoded data **OUT2** with respect to coded data **ODD** (Fig.2.4(b))

CAPTURED WAVEFORM:

CH 1: EVEN(TRIBIT ENCODER) & CH 2: OUT1

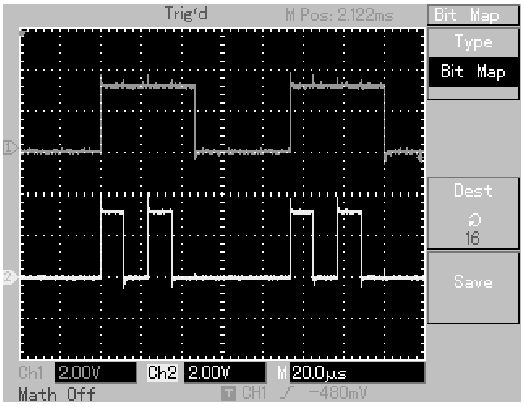


Fig.2.4 (a)

CH 1: ODD (TRIBIT ENCODER) & CH 2: OUT2

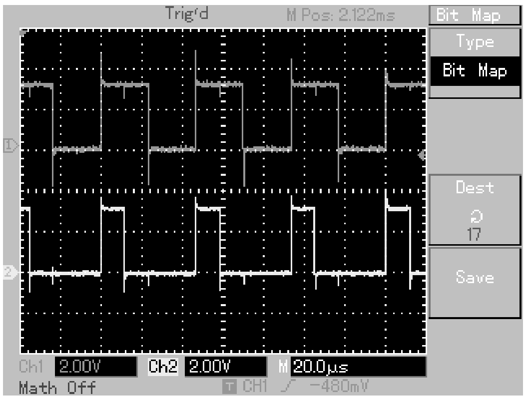


Fig.2.4 (b)

CONCLUSION:

It is observed that when input data to the differential encoder contains “1” the output of the differential encoder makes transition from its previous state. If input data contains “0” then output of differential encoder maintains the previous state.

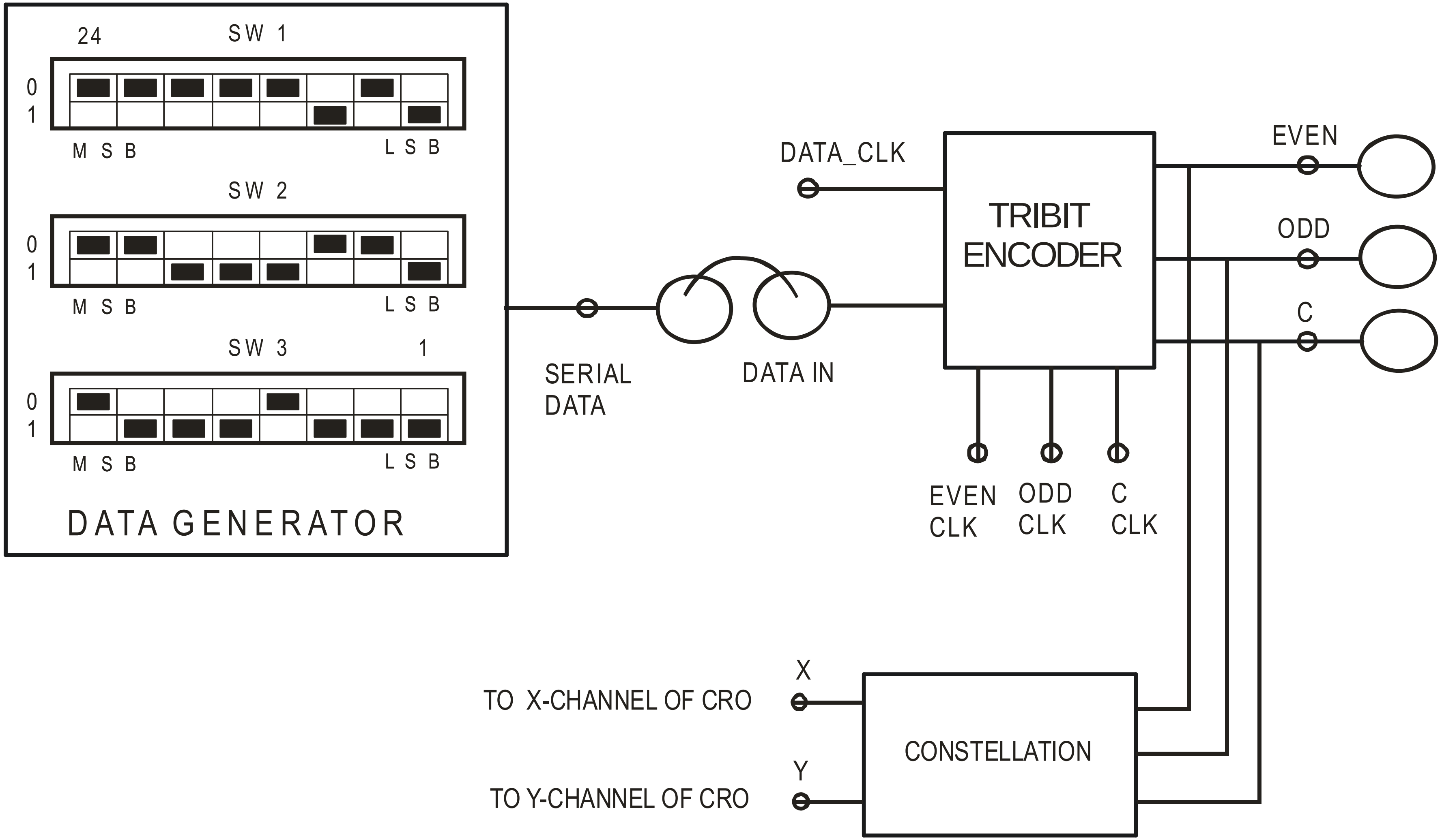


FIG 3.1 BLOCK DIAGRAM FOR OBSERVATION OF CONSTELLATION DIAGRAM

EXPERIMENT NO: 3

NAME:

OBSERVATION OF THE CONSTELLATION DIAGRAM FOR QAM AND STUDY OF BANDWIDTH EFFICIENCY OF QAM

OBJECTIVE:

(A) To study the constellation diagram of QAM.
(B) Study of bandwidth efficiency in Quadrature Amplitude Modulation techniques.

THEORY:

The constellation diagram or geometrical representation is as shown in fig 3.2 below. The point in signal space corresponding to each of the eight possible transmitted signals is indicated by dots. For each such signal we can recover three bits rather than one. The distance of a signal point from the origin is $\sqrt{(Es)}$which is the square root of the signal energy associated with the symbol, that is Es=Ps * Ts = Ps(2Tb). As we know the ability to determine a bit without error is measured by the distance in signal space between points corresponding to the different values of the bit. We note from fig. that points which differ in a single bit are separated by the distance d = $2\sqrt{Ps\ Tb} = 2\sqrt{Eb}$ where Eb is the energy contained in a bit transmitted for a time Tb. This distance for QPSK is the same as for BPSK. Hence, altogether, we have the important result that, in spite of the reduction by a factor of two in the bandwidth required by QPSK in comparison with BPSK, the noise immunity of the two systems are the same.

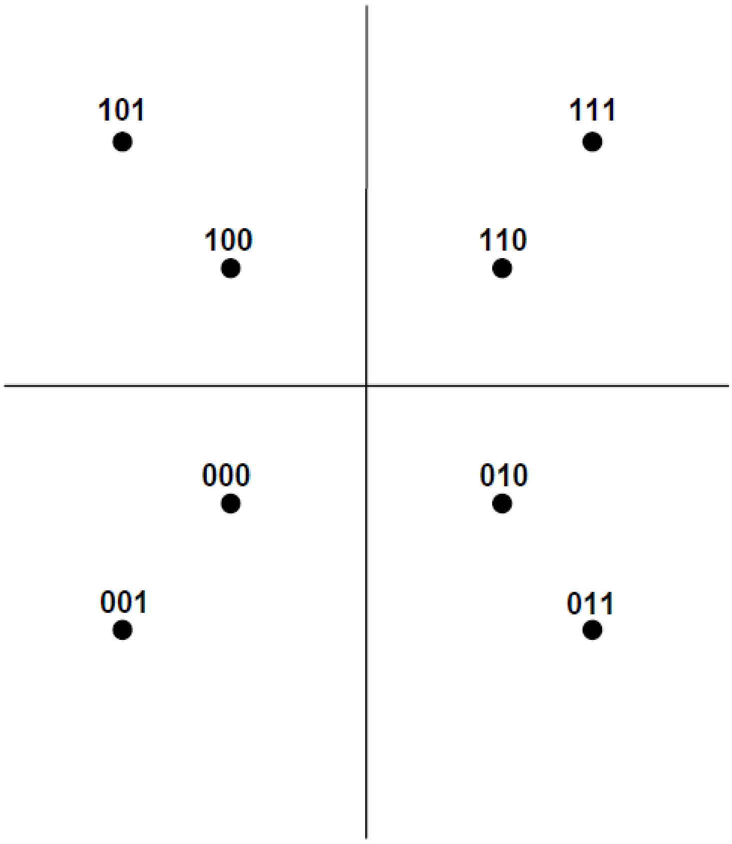


FIG 3.2 CONSTELLATION DIAGRAM

The number of dot points appearing in the constellation diagram depends on the number of symbol generated due to EVEN, ODD and C bit. The position of dot points in the quadrant of the constellation diagram is also depends on the symbol Generated due to the EVEN, ODD and C bit as shown above. The fig below shows examples of constellation diagram.

In fig 3.3 the data pattern used is 111001010011100101110000. If we plot the expected data pattern of EVEN, ODD and C bit as shown in fig, then there are 8symbols generated as 000, 001, 010, 011, 100, 101, 110, 111 thus there are 8dots appearing in the constellation diagram in all four quadrants.

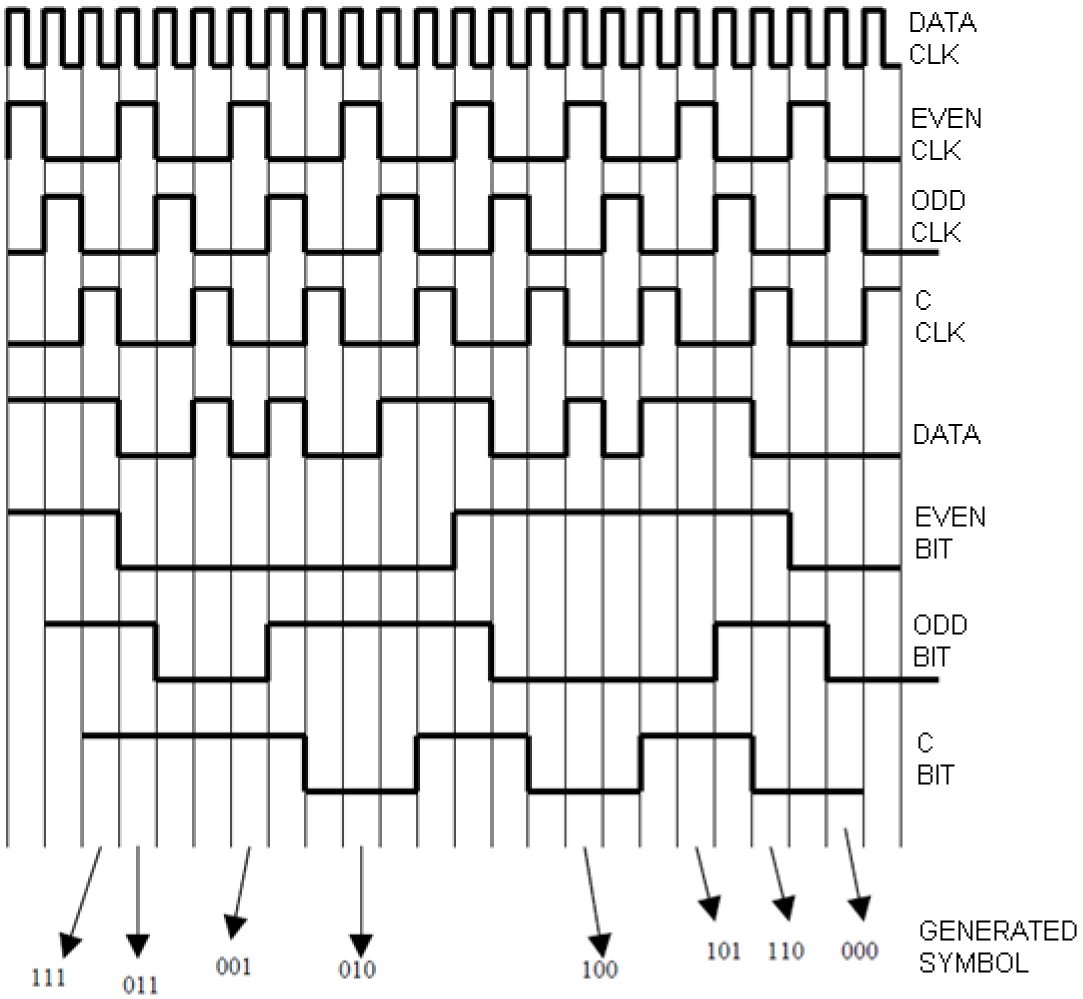


Fig 3.3

Bandwidth efficiency of QAM is defined by the ratio of bit transmission speed in QAM to Bandwidth of QAM signal. It is given by

Bandwidth Efficiency = Fb / Bw

Where Fb is Bit transmission speed and
Bw is the bandwidth of signal transmitted.

The more the bandwidth efficiency more is the data transfer within the same bandwidth of signal transmission.

EQUIPMENTS:

- Experimenter Kit DCL-QAM
- Connecting Chords.
- Power supply.
- 20MHz Dual Trace Oscilloscope.

PROCEDURE:

(A)Study of constellation diagram.

1. Refer to the block diagram (Fig 3.1) and carry out the following connections and switch settings.
2. Connect power supply in proper polarity to the kit **DCL-QAM** and switch it on.
3. Select Data pattern of simulated data using switch **SW1, SW2, SW3.**
4. Connect **SERIAL DATA** generated to **DATA IN** of the **TRIBIT ENCODER**.
5. Now connect **X & Y** port of **CONSTELLATION BLOCK** to X-channel and Y-channel of CRO respectively
6. Observe waveforms as mentioned below (Fig 3. 4.).

OBSERVATION:

Observe the following waveforms on oscilloscope and plot it on the paper.
ON KIT **DCL-QAM**

1. **SERIAL DATA** with respect to **DATA_CLK**. (Fig3.4 (a))
2. **EVEN** data with respect to **EVEN CLK.** (Fig3.4(b))
3. **ODD** data with respect to **ODDCLK.** (Fig3.4(c))
4. **C** data with respect to **CCLK.** (Fig3.4(d))
5. Constellation diagram on CRO for data pattern
6. “000001010011100101110111”. (Fig3.4 (e))
7. Constellation diagram on CRO for data pattern “101010101010101010101010”. (Fig3.4 (f))

CAPTURED WAVEFORM:

CH 1: DATA CLK (256 KHz) & CH 2: SERIAL DATA (000001010011100101110111)

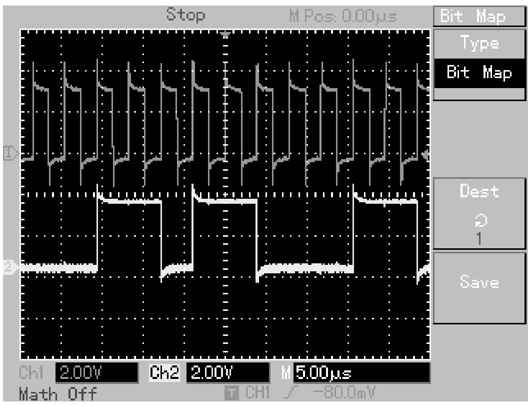


FIG. 3.4(a)

CH 1: EVEN CLK & CH 2: EVEN (TRIBIT ENCODER)

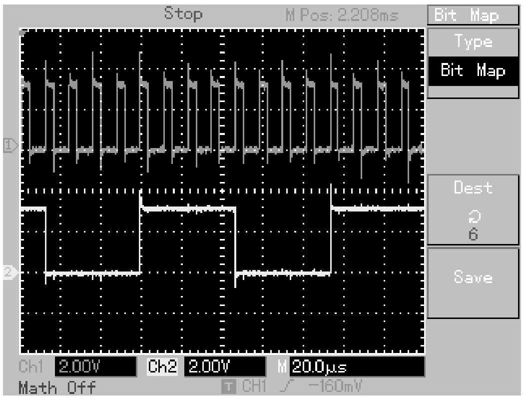


Fig.3.4(b)

CH 1: ODD CLK & CH 2: ODD (TRIBIT ENCODER)

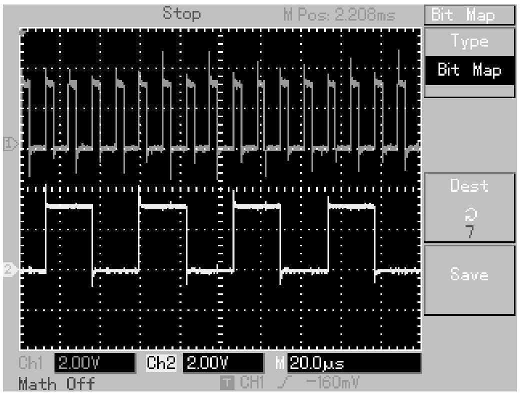


Fig.3.4(c)

CH 1: C CLK & CH 2: C (TRIBIT ENCODER)

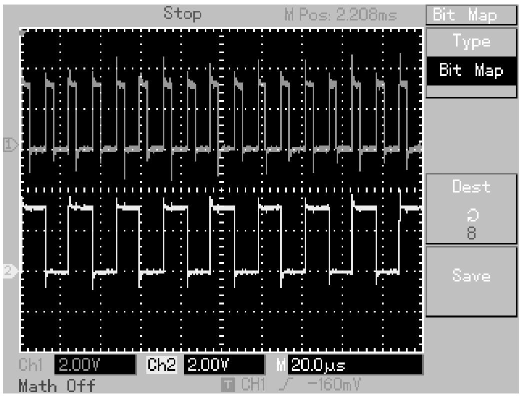


Fig.3.4(d)

SERIAL DATA: 000001010011100101110111
CH 1: X & CH 2: Y

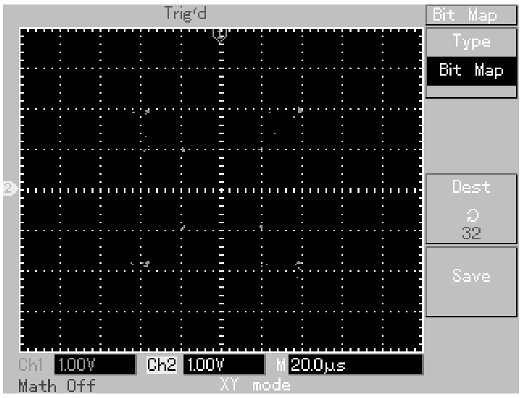


Fig. 3.4(e)

SERIAL DATA: 101010101010101010101010
CH 1: X & CH 2: Y

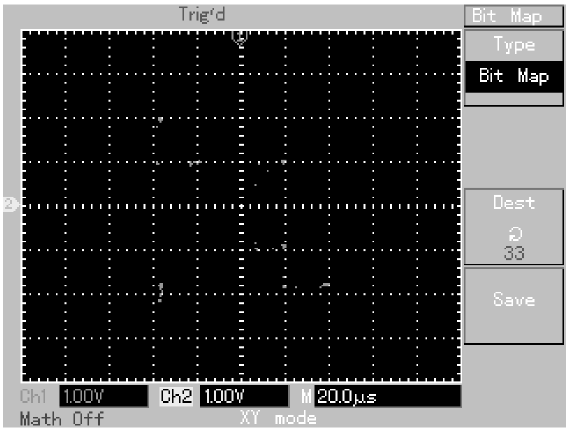


Fig. 3.4(f)

(B)Bandwidth efficiency of QAM technique.

1. Measure the transmission clock at **DATA_CLOCK** post i.e. **256KHz**
2. Divide this clock by the number of bits transmitted simultaneously, i.e.3 Bits in this case (EVEN, ODD& C Bits).
3. Transmission clock is the bit transmission speed (256KHz) and Bandwidth of modulator is clock divide by the number of bits transmitted (i.e. 256KHz/ 3 = 85.33 KHz).
4. From the above data, calculate bandwidth efficiency by substituting these values in the formula as follows;

Bandwidth Efficiency = Fb / Bw

i.e. = 256/85.33

= 3

CONCLUSION:

It is observed from the constellation diagram that, the symbol generated due to EVEN bit, ODD bit & C bit have eight possible values and lies in four quadrants. Also from the constellation diagram we can determine the distance between the two symbols. The transmitted signal, if it changes, changes phase by 90 deg. Rather than by 180 deg. as in BPSK.

Bandwidth Efficiency generally depends on the number of bits transmitted simultaneously

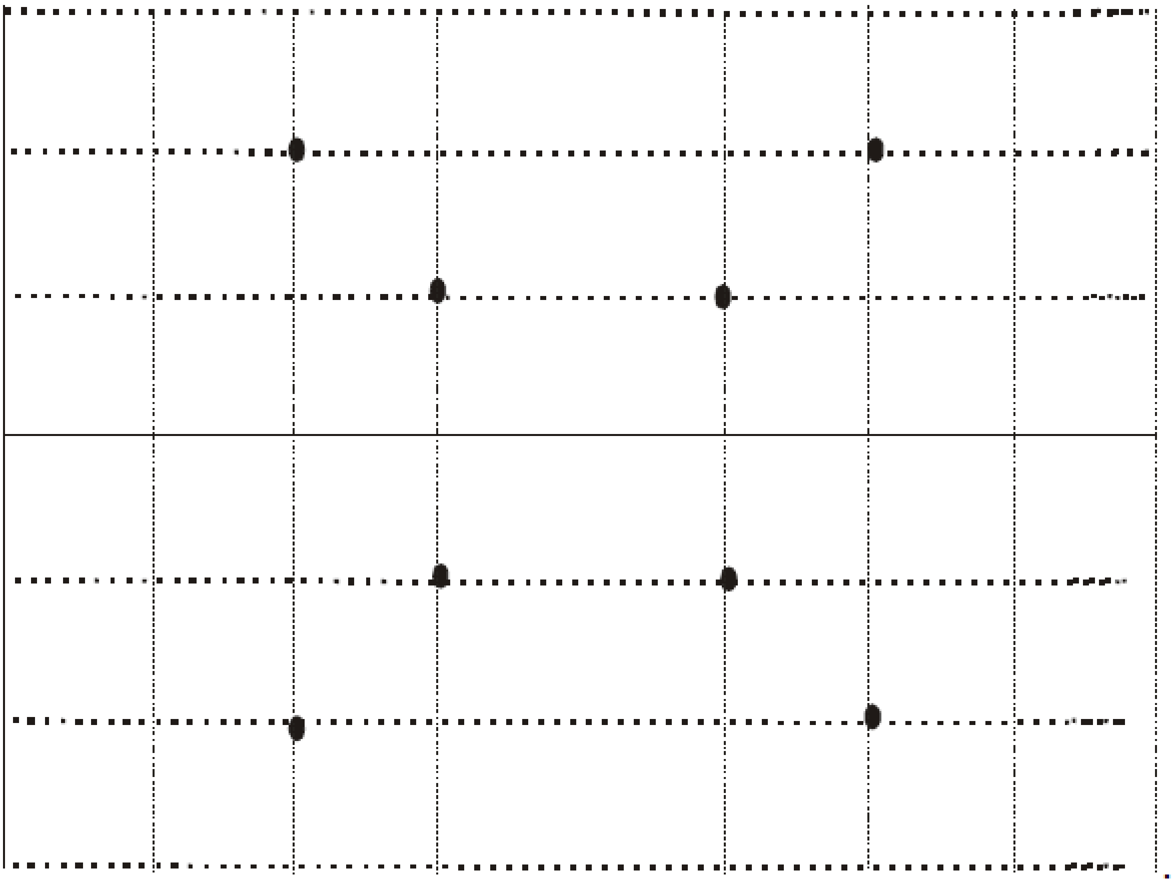


FIG. 3.4 CONSTELLATION DIAGRAM

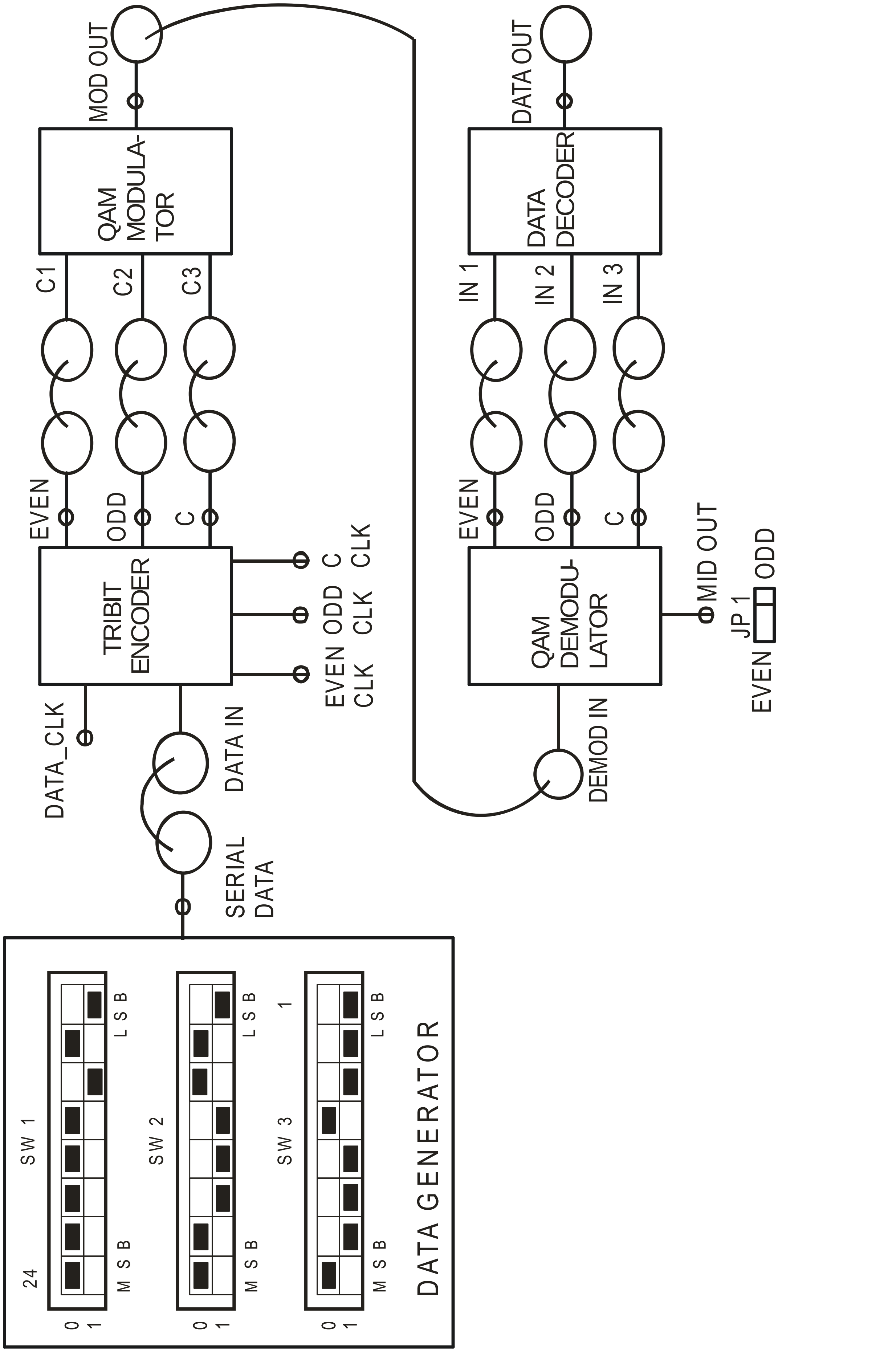


FIG 4.1 BLOCK DIAGRAM FOR QUADRATURE AMPLITUDE MODULATION AND DEMODULATION TECHNIQUE

NAME:

QUADRATURE AMPLITUDE MODULATION AND DEMODULATION TECHNIQUES

OBJECTIVE:

Study of Carrier Modulation and demodulation Techniques by Quadrature Amplitude method

THEORY:

The QAM is a digital modulation where the information is contained into the phase as well as the amplitude of the transmitted carrier. In the 8-QAM the data are divided into the group of 3 bits (tribit), one of which will varies the amplitude of the carrier, the other two the phase. The modulated signal can take 4different phases and 2 different amplitudes, for a total of 8 different states. Similarly in the 16-QAM the data are divided into group of 4 bits (quad bit). The16 possible combinations change amplitude and phase of the carrier, which can take 16 different states.

A generator of 8-QAM signals for 3-bit symbol is shown in fig 4.2. For 8 QAM the main data source is divided into 3 bits called EVEN bit, ODD bit and C bit.
These three bits are called TRIBIT. These tribit together forms a symbol. We have 24 bit input data which gives 8 possible symbols. Among the 3 bits EVEN&ODD bit is responsible for phase modulation and the last bit (C bit) performs the amplitude modulation. The effect of each symbol on the final QAM signal is shown in the table below.

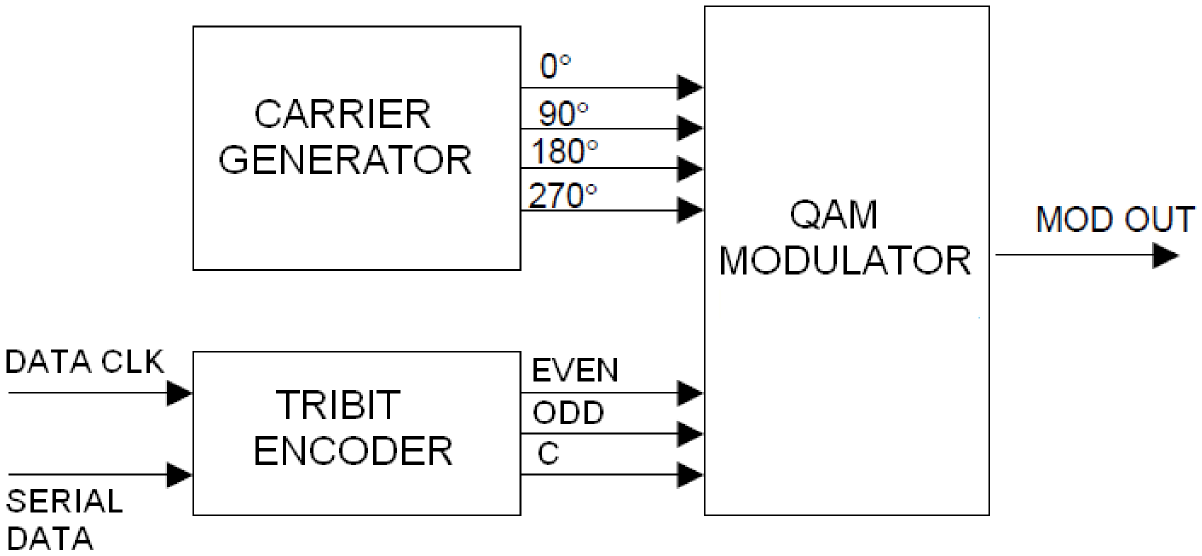


FIG 4.2 QAM MODULATOR

BINARY INPUT			QAM MOD OUT	
EVEN	ODD	C	AMPLITUDE	PHASE
0	0	0	1 V	180°
0	0	1	2 V	180°
0	1	0	1 V	90°
0	1	1	2 V	90°
1	0	0	1 V	270°
1	0	1	2 V	270°
1	1	0	1 V	0°
1	1	1	2 V	0°

The block diagram of the modulator used on the module is shown in the fig 4.1four 1MHz sine carriers, shifted between them of 90 deg, are applied to modulator. The data (signal EVEN, ODD and C) reach the modulator from the Tribit coder. The instantaneous value of EVEN, ODD and C data bit generates a symbol. Since EVEN, ODD and C can take either 0 or 1 value, maximum 8 possible symbols can be generated as shown in the above table. According to the symbol generated one of the four-sine carriers will be selected. The relation between the symbol generated and sine carrier is shown in table above.

A receiver for the QAM signal is shown in fig 4.1 Synchronous detection
is required and hence it is necessary to locally regenerate the carriers. The scheme for carrier regeneration is similar to BPSK. In that earlier case we used the multiplier and filter to recover the data.

The incoming signal is applied to the multipliers to remove the phase shift and to envelope detector for C bit recovery. The output of the multipliers can be seen at MID EVEN and MID OUT posts. The output of the multipliers is then given to filters, where we get the recovered EVEN and ODD data. These recovered EVEN&ODD bits having exactly same phase & frequency compared to transmitter EVEN&ODD bit. The C bit is recovered simply by passing the QAM modulated data through envelope detector. These recovered EVEN, ODD& C bits then applied to data decoder logic to recover the original NRZ-L data.

EQUIPMENTS:

- Experimental Kit **DCL-QAM**
- Connecting Chords.
- Power supply.
- 20MHz Dual Trace Oscilloscope.

PROCEDURE:

1. Refer to the block diagram (Fig 4.1) and carry out the following connections and switch settings.
2. Connect power supply in proper polarity to the kit **DCL-QAM** and switch it on.
3. Select Data pattern of simulated data using switch **SW1, SW2, SW3.**
4. Connect **SERIAL DATA** generated to **DATA IN** of the **TRIBIT ENCODER**.
5. Connect the tribit data **EVEN, ODD** &**C** to control input **C1, C2** and **C3** of **QAM MODULATOR** respectively.
6. Connect QAM modulated signal **MOD OUT** of the **QAM MODULATOR** to the **DEMOD IN** of the **QAM DEMODULATOR**.
7. Observe output of multipliers at **MID OUT** post of **QAM DEMODULATOR** by changing jumper (JP1) at **EVEN** and **ODD** position respectively.
8. Connect the demodulated data **EVEN, ODD**&**C of QAM DEMODULATOR** to IN1, IN2, and IN3of **DATA DECODER** respectively.
9. Observe the decoded data at **DATA OUT** post of **DATA DECODER**. Compare the decoded data with **SERIAL DATA**.
10. Observe various waveforms as mentioned below (Fig4.3).

OBSERVATION:

Observe the following waveforms on oscilloscope and plot it on the paper.
ON KIT **DCL-QAM**

1. Transmitter clock **DATA_CLK** with respect to NRZ-L coded data **SERIAL DATA** (Fig4.3(a))
2. **EVEN CLK** with respect to **ODD CLK.** (Fig4.3(b))
3. **EVEN CLK** with respect to **C CLK.** (Fig4.3(c))
4. **EVEN** data with respect to **EVEN CLK.** (Fig4.3(d))
5. **ODD** data with respect to **ODDCLK.** (Fig4.3(e))
6. **C** data with respect to **CCLK.** (Fig4.3(f))
7. Carrier signals **SIN 1,SIN 2, SIN 3**and **SIN 4.** (Fig4.3(g,h))
8. **QAM** modulated signal at **MOD OUT** of **QAMMODULATOR** with respect to **EVEN** of **TRIBITENCODER**. (Fig4.3(i))
9. **QAM** modulated signal at **MOD OUT** of **QAM MODULATOR** with respect to **C** of **TRIBIT ENCODER**. (Fig4.3(j))
10. Mid **EVEN** signal at **MID OUT** post of **QAM DEMODULATOR** with respect to **EVEN** of **TRIBITENCODER**. (Fig4.3(k))
11. Mid **ODD** signal at **MID OUT** post of **QAM DEMODULATOR** with respect to **ODD** of **TRIBIT ENCODER**. (Fig4.3(l))
12. **EVEN** of **QAM DEMODULATOR** with respect to **EVEN** of **TRIBIT ENCODER**. (Fig4.3(m))
13. **ODD** of **QAM DEMODULATOR** with respect to **ODD** of

TRIBIT ENCODER. (Fig4.3(n))

14. **C** of **QAM DEMODULATOR** with respect to **C** of **TRIBIT ENCODER**. (Fig4.3(o))
15. **DATA OUT** with respect to **SERIAL DATA.** (Fig4.3(p))

CAPTURED WAVEFORM:

CH 1: DATA CLK (256 KHz) & CH 2: SERIAL DATA (000001010011100101110111)

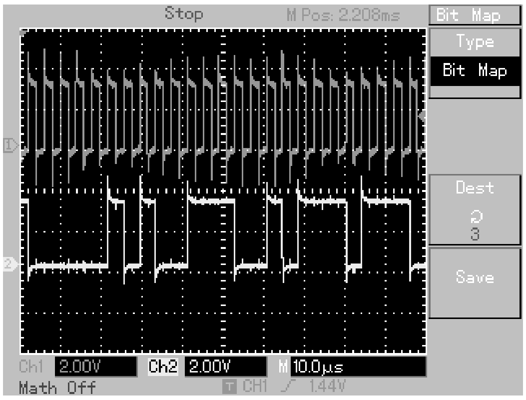


FIG. 4.3(a)

CH 1: EVEN CLK & CH 2: ODD CLK

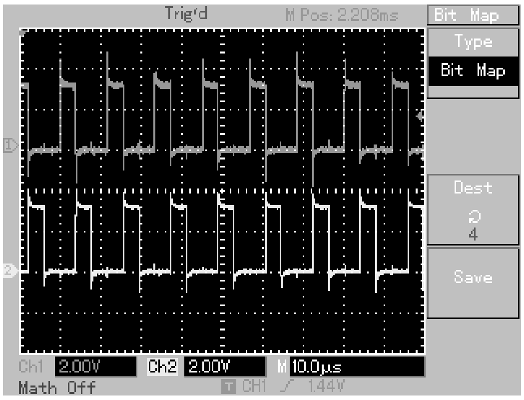


FIG. 4.3(b)

CH 1: EVEN CLK & CH 2: C CLK

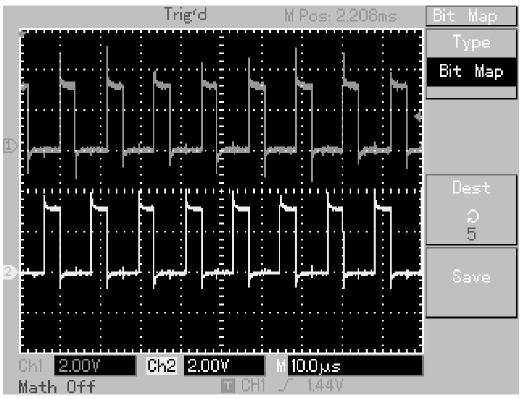


FIG. 4.3(c)

CH 1: EVEN CLK & CH 2: EVEN (TRIBIT ENCODER)

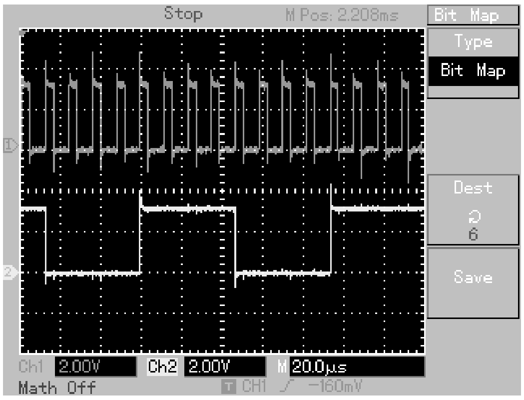


FIG. 4.3(d)

CH 1: ODD CLK & CH 2: ODD (TRIBIT ENCODER)

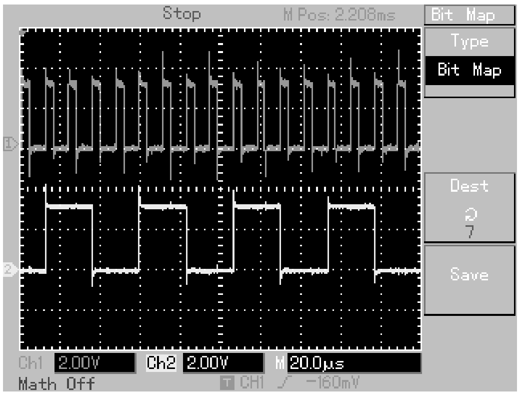


FIG. 4.3(e)

CH 1: C CLK & CH 2: C (TRIBIT ENCODER)

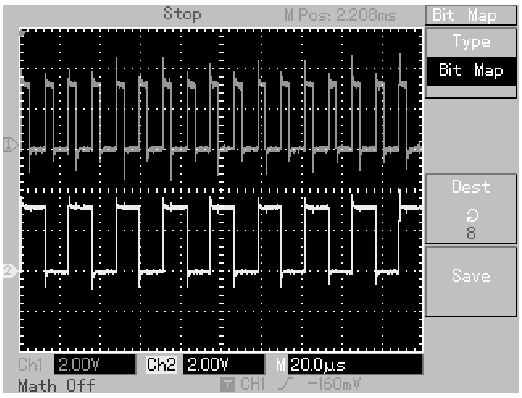


FIG. 4.3(f)

CH 1: SIN 1 (0º) & CH 2: SIN 2 (90º)

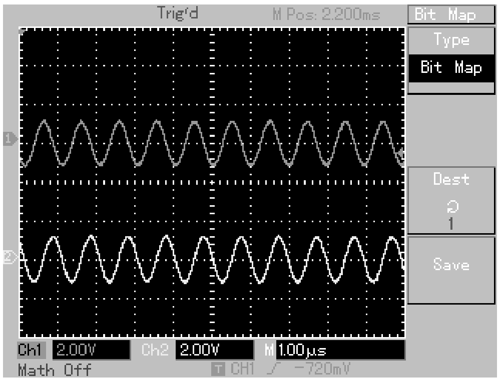


Fig.4.3 (g)

CH 1: SIN 3 (180º) & CH 2: SIN 4 (270º)

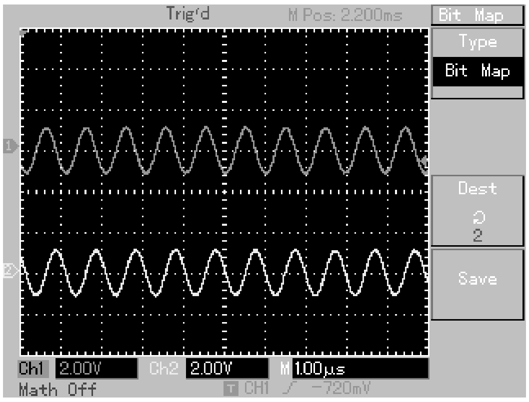


Fig.4.3 (h)

NOTE:

For **MOD OUT,** select a symbol using **EVEN** and **ODD** and then observe the **MOD OUT**. For waveform below a symbol is selected using **EVEN** and **ODD** and then **MOD OUT** is observed with respect to **EVEN.**

CH 1: EVEN (TRIBIT ENCODER) & CH 2: MOD OUT

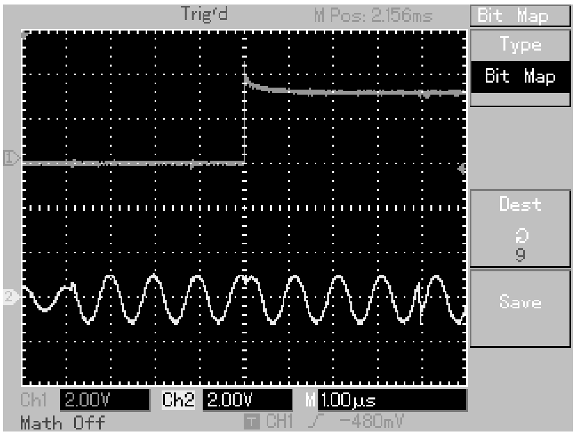


Fig.4.3(i)

CH 1: C(TRIBIT ENCODER) & CH 2: MOD OUT

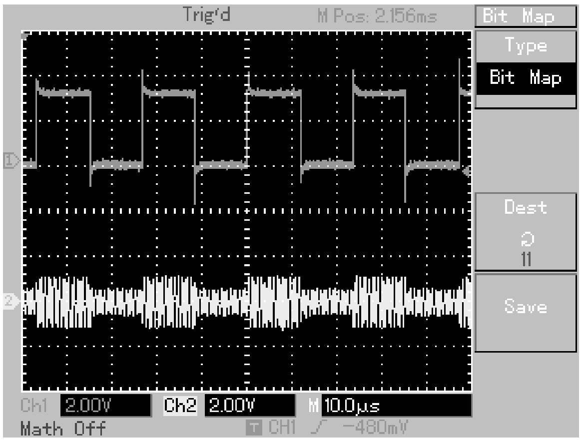


Fig.4.3(j)

CH 1: EVEN(TRIBIT ENCODER) & CH 2: MID OUT

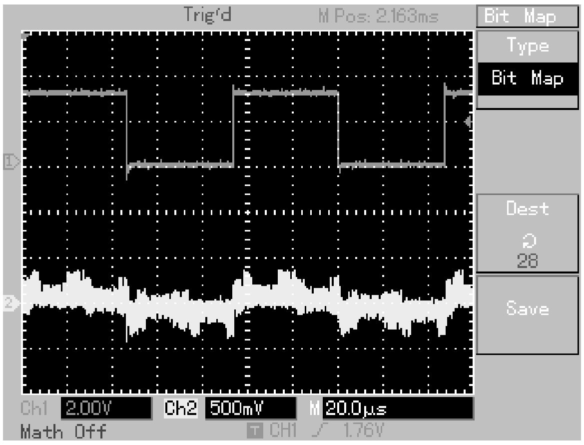


Fig.4.3(k)

CH 1: ODD (TRIBIT ENCODER) & CH 2: MID OUT

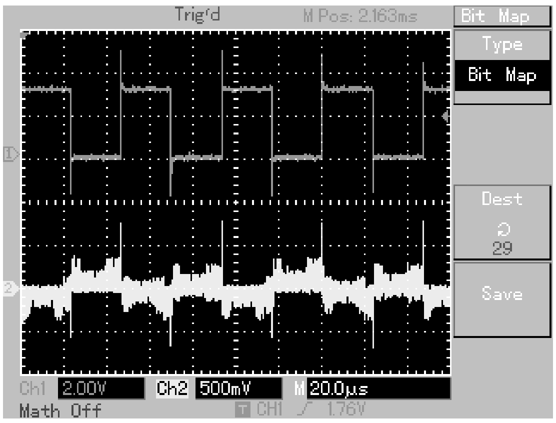


Fig.4.3(l)

CH 1: EVEN (TRIBIT ENCODER) & CH 2: EVEN(Demodulated)

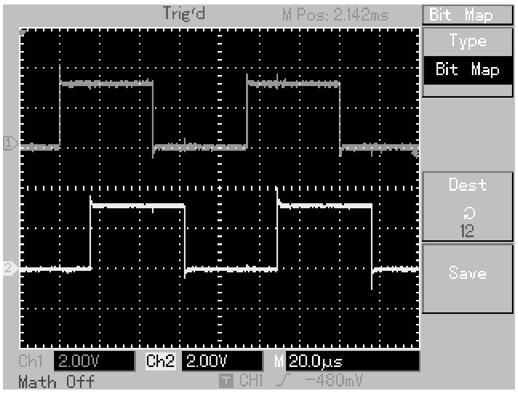


Fig.4.3(m)

CH 1: ODD(TRIBIT ENCODER) & CH 2: ODD(Demodulated)

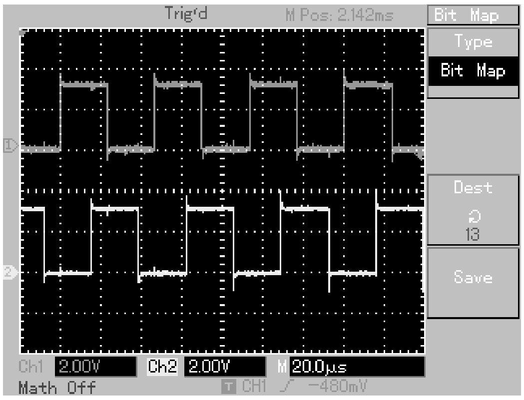


Fig.4.3(n)

CH 1: C(TRIBIT ENCODER) & CH 2: C(Demodulated)

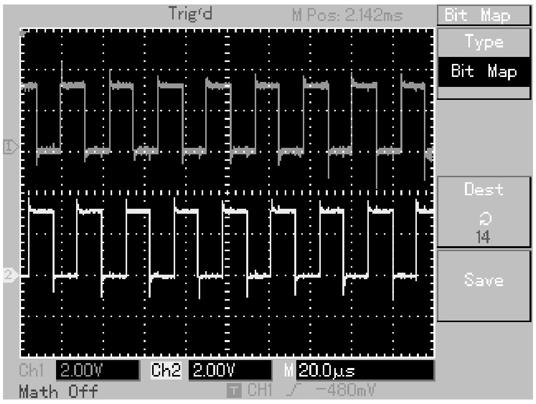


Fig.4.3(o)

CH 1: SERIAL DATA & CH 2: DATA OUT

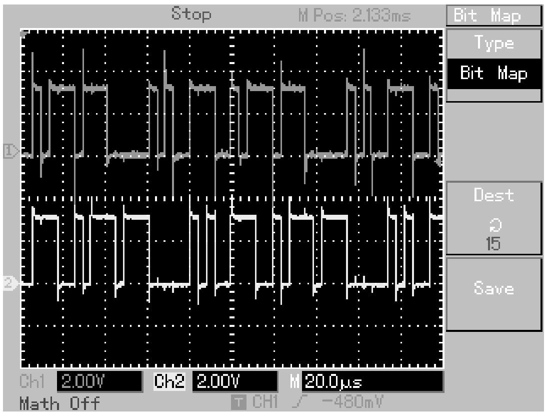


Fig.4.3(p)

CONCLUSION:

In BPSK we deal individually with each bit of duration Tb. In QAM we lump three bits together to form a SYMBOL. The symbol can have any one of eight possible values corresponding to three-bit sequence. We therefore arrange to make available for transmission eight distinct signals. At the receiver each signal represents one symbol and, correspondingly, three bits. When bits are transmitted, as in BPSK, the signal changes occur at the bit rate. When symbols are transmitted the changes occur at the symbol rate, which is one-third the bit rate. Thus the symbol time is Ts = 3Tb.