Telecommunications
Communications Technologies

Quadrature Amplitude Modulation (QAM/DQAM)

Instructor Guide

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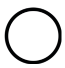
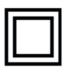
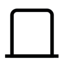
Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger
	Caution, lifting hazard
	Caution, hand entanglement hazard
	Notice, non-ionizing radiation
⎓	Direct current
∼	Alternating current
≂	Both direct and alternating current
3∼	Three-phase alternating current
⏚	Earth (ground) terminal

Safety and Common Symbols

Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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Preface

Digital communication offers so many advantages over analog communication that the majority of today's communications systems are digital.

Unlike analog communication systems, digital systems do not require accurate recovery of the transmitted waveform at the receiver end. Instead, the receiver periodically detects which waveform is being transmitted, among a limited number of possible waveforms, and maps the detected waveform back to the data it represents. This allows extremely low error rates, even when the signal has been corrupted by noise.

The digital circuits are often implemented using application specific integrated circuits (ASIC) and field-programmable gate arrays (FPGA). Although this "system-on-a-chip" approach is very effective for commercial and military applications, the resulting systems do not allow access to internal signals and data and are therefore poorly suited for educational use. It is for this reason that we designed the Communications Technologies Training System.

The Communications Technologies Training System, Model 8087, is a state-of-the-art communications training system. Specially designed for hands-on training, it facilitates the study of many different types of digital modulation/demodulation technologies such as PAM, PWM, PPM, PCM, Delta Modulation, ASK, FSK, and BPSK as well as spectrally efficient technologies such as QPSK, QAM, and ADSL. The system also enables the study of direct-sequence and frequency-hopping spread spectrum (DSSS and FHSS), two key technologies used in modern wireless communication systems (CDMA cellular-telephony networks, Global Positioning System, Bluetooth interface for wireless connectivity, etc.) to implement code-division multiple access (CDMA), improve interference rejection, minimize interference with other systems, etc. The system is designed to reflect the standards commonly used in modern communications systems.

Unlike conventional, hardware-based training systems that use a variety of physical modules to implement different technologies and instruments, the Communications Technologies Training System is based on a Reconfigurable Training Module (RTM) and the Communications Technologies (LVCT) software, providing tremendous flexibility at a reduced cost.

Each of the communications technologies to be studied is provided as an application that can be selected from a menu. Once loaded into the LVCT software, the selected application configures the RTM to implement the communications technology, and provides a specially designed user interface for the student.

The LVCT software provides settings for full user control over the operating parameters of each communications technology application. Functional block diagrams for the circuits involved are shown on screen. The digital or analog signals at various points in the circuits can be viewed and analyzed using the virtual instruments included in the software. In addition, some of these signals are made available at physical connectors on the RTM and can be displayed and measured using conventional instruments.

The courseware for the Communications Technologies Training System consists of a series of student manuals covering the different technologies as well as instructor guides that provide the answers to procedure step questions and to review questions. The Communications Technologies Training System and the accompanying courseware provide a complete study program for these key information-age technologies.

We invite readers of this manual to send us their tips, feedback, and suggestions for improving the book.

Please send these to did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

Acknowledgements

We thank the following people for their participation in the development of the Communications Technologies Training System: Richard Tervo, Ph.D., P.Eng. from the University of New Brunswick, and John Ahern, M.Sc.A. and Marcel Pelletier, Ph.D. from Comlab Telecommunications Inc.

About This Manual

Manual Objective

When you have completed this manual, you will be familiar with the principles of QAM modulation and demodulation. You will be familiar with the use of differential QAM (DQAM), which uses V.22 *bis* encoding to overcome phase ambiguity, and with the use of data scrambling to ensure frequent transitions in the modulated signal. You will also be able to troubleshoot instructor-inserted faults in the QAM/DQAM application.

Description

This Student Manual begins with an Introduction presenting important background information. Following this are a number of exercises designed to present the subject matter in convenient instructional segments. In each exercise, principles and concepts are presented first followed by a step-by-step, hands-on procedure to complete the learning process.

Each exercise contains:

- A clearly defined Exercise Objective
- A Discussion Outline listing the main points presented in the Discussion
- A Discussion of the theory involved
- A Procedure Outline listing the main sections in the Procedure
- A step-by-step Procedure in which the student observes and measures the important phenomena, including questions to help in understanding the important principles.
- A Conclusion
- Review Questions

In this manual, all New Terms are defined at the end of the Introduction. In addition, an Index of New Terms is provided at the end of this manual.

Because the theory of QAM is similar to that of QPSK, some parts of the Discussions in this manual are similar to the Discussions in the student manual Quadrature Phase Shift Keying (QPSK/DQPSK)*, part number 39865-10*.

Preparation

Before beginning this manual, it is preferable to be familiar with the following topics:

- Pseudorandom binary sequences (PRBSs), also called pseudorandom bit sequences, n-sequences or maximum-length sequences — their time-domain and frequency-domain characteristics.
- Quadrature phase shift keying (QPSK) — the generation and demodulation of QPSK signals and their time-domain and frequency-domain characteristics.

About This Manual

Safety considerations

Safety symbols that may be used in this manual and on the equipment are listed in the Safety Symbols table at the beginning of the manual.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

Systems of units

Units are expressed using the International System of Units (SI) followed by units expressed in the U.S. customary system of units (between parentheses).

Conventions Used in This Manual

Special character formats

Colored sidebars contain complementary information that will be of interest to the reader.

New terms are shown in **bold colored characters** the first time they appear.

Important terms are shown in **bold colored characters** the first time they appear.

Notes provide details that should be noted by the reader.

Tips provide information on effectively using the system. These are particularly helpful for inexperienced users.

This symbol refers you to another manual or document.

Software commands and dialog box names are shown in color. "Choose *File* ▶ *Print*" means choose the *Print* command in the *File* menu.

Probe connections

Instrument probe connections to test points are usually presented in tables showing the type of probe to use, the test point (TP) to connect it to, and the signal present at that test point:

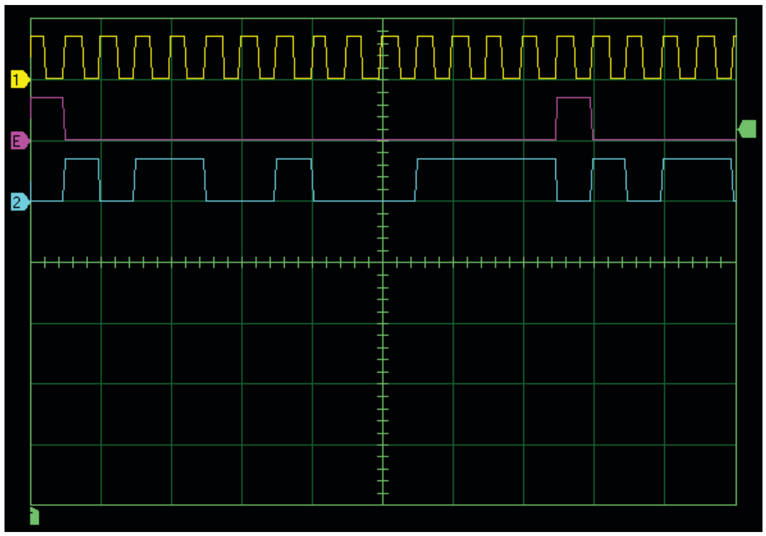
Oscilloscope probe	Connect to	Signal
1	TP1	DATA INPUT
2	TP2	CLOCK INPUT
E	TP3	BSG SYNC. OUTPUT

System and instrument settings

Unless you are instructed to make specific settings, you can use any system and instrument settings that will allow you to observe the phenomena of interest. As a guide, important settings that were used to produce a figure may be shown beside the figure.

Generator Settings:
Bit Rate .... 2000 bit/s
n 4

Oscilloscope Settings:
Channel 1................................. 5 V/div
Channel 2................................. 5 V/div
Channel E .... 5 V/div
Time Base............................. 1 ms/div
Trigger: Slope .... Rising
Trigger: Level .... 1 V
Trigger: Source .... Ext



List of Equipment Required

The following equipment is required to perform the procedures in this manual:

QTY	DESCRIPTION	MODEL
1	Power Supply	9408
1	Reconfigurable Training Module	9431
1	Data Acquisition Interface	9466
1	Analog/Digital Output Interface	9467
1	LVCT Software	9432-0
1	QPSK / QAM / ADSL Applications	9432-4
1	Cables and Accessories	9483

Additional Equipment

The LVCT software requires a current model computer running Windows® operating system. An Ethernet (100 Mb/s or better) network interface adapter is also required. A dual-output video adapter and two monitors are recommended to allow viewing the diagrams and the virtual instruments simultaneously.

The Communications Technologies Host Computer, Model 9695-A0, meets or exceeds these requirements.

Optional Equipment

You may wish to use a conventional oscilloscope (Model 797-20 or equivalent) and/or spectrum analyzer to observe the signals available at the BNC connectors and test points on the RTM (refer to the RTM Connections tab of the software to identify these outputs).

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this manual should be considered as a guide. Students who correctly performed the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Sample Exercise
Extracted from
the Student Manual
and the Instructor Guide

QAM Modulation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with QAM modulation, with the characteristics of QAM signals and with the QAM signal constellation. You will also be familiar with the LVCT software and the use of the virtual instruments.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- The QAM waveform
- QAM constellations
- A typical QAM modulator
- Symbol rate and bandwidth

DISCUSSION

The QAM waveform

Quadrature Amplitude Modulation or QAM (pronounced “kwam”) is a digital modulation technique that uses the data to be transmitted to vary both the amplitude and the phase of a sinusoidal waveform, while keeping its frequency constant. QAM is a natural extension of binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK), both of which vary only the phase of the waveform.

QAM is a type of *M*-ary signaling with *M* equal to the number of different symbols.

The number of different waveforms (unique combinations of amplitude and phase) used in QAM depends on the modem and may vary with the quality of the channel. With 16-QAM, for example, 16 different waveforms are available. 64-QAM and 256-QAM are also common. 16,384-QAM is possible in ADSL modems. In all cases, each different waveform, or amplitude-phase combination, is a **modulation symbol** that represents a specific group of bits.

With 16-QAM, there are sixteen different symbols (quadbits):

```
0000 0001 0010 0011
0100 0101 0110 0111
1000 1001 1010 1011
1100 1101 1110 1111
```

Each quadbit is represented by different modulation symbol (combination of phase and amplitude).

The LVCT Quadrature Amplitude Modulation (QAM/DQAM) application uses 16-QAM. In the modulator, consecutive data bits are grouped together four at a time to form **quadbits** and each quadbit is represented by a different modulation symbol. In the demodulator, each different modulation symbol in the received signal is interpreted as a unique pattern of 4 bits.

Figure 4 shows all 16 QAM modulation symbols superposed on the same axes. Four different colors are used in the figure and each color is used for four different waveforms. Each waveform has a different combination of phase and amplitude.

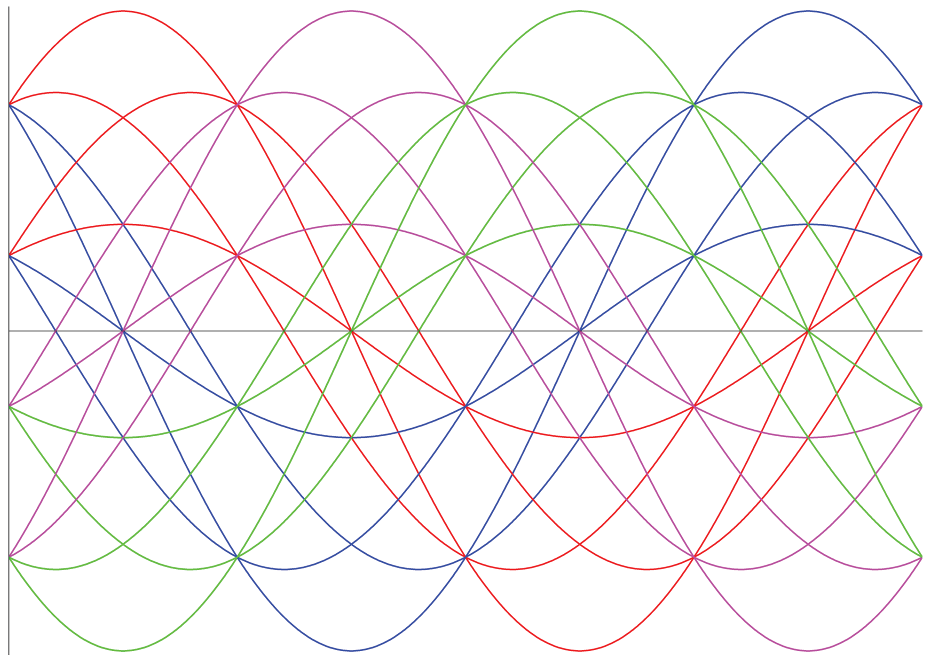


Figure 4. All QAM modulation symbols for 16-QAM.

QAM constellations

Figure 5 shows the constellation diagram for 16-QAM. The constellation diagram is a pictorial representation showing all possible modulation symbols (or signal states) as a set of constellation points. The position of each point in the diagram shows the amplitude and the phase of the corresponding symbol. Each constellation point corresponds (is mapped to) to a different quadbit.

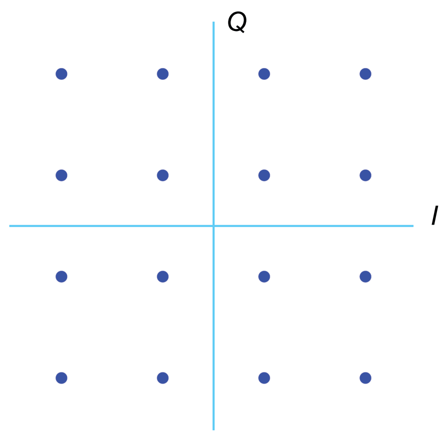


Figure 5. 16-QAM constellation (4-bits per modulation symbol).

The Gray code was designed by Bell Labs researcher Frank Gray and patented in 1953. Gray codes are widely used in digital communications.

Although any mapping between quadbits and constellation points would work under ideal conditions, the mapping usually uses a Gray code to ensure that the quadbits corresponding to adjacent constellation points differ only by one bit. This facilitates error correction since a small displacement of a constellation point due to noise will likely cause only one bit of the demodulated quadbit to be erroneous.

A typical QAM modulator

A QAM signal can be generated by independently amplitude-modulating two carriers in quadrature (cos ωt and sin ωt), as shown in Figure 6.

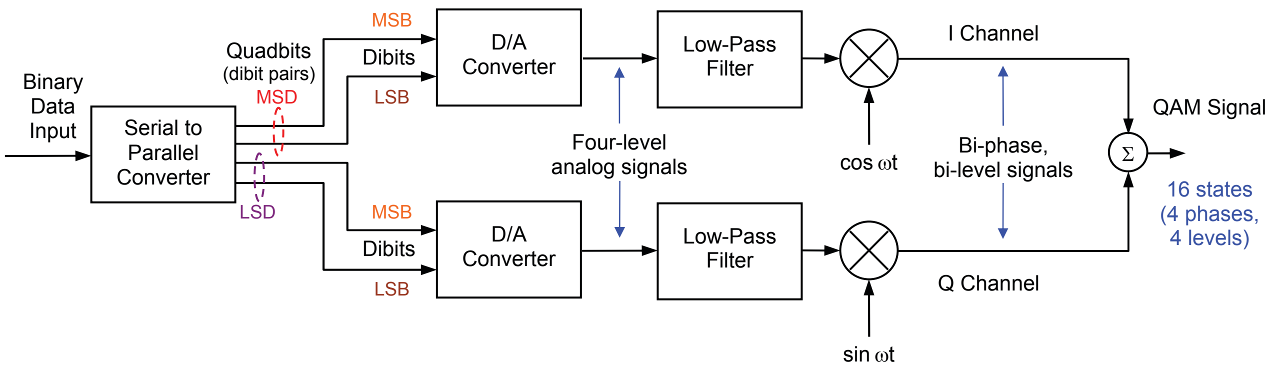


Figure 6. Simplified block diagram of a QAM modulator.

The Serial to Parallel Converter groups the incoming data into quadbits. Each time four bits have been clocked serially into its buffer, the Serial to Parallel Converter outputs one quadbit in parallel at its four outputs.

Colors (red, green, blue, and violet) are used in the data bit stream to help distinguish the individual bits.

The starting point for grouping bits into quadbits is *completely arbitrary*. Figure 7 shows an example using the repeating 12-bit binary sequence 1000 0000 0000. In this figure, the grouping initially starts at the beginning of the sequence (Condition A). The first quadbit at the output is 1000 followed by two all-zero quadbits 0000. Then the quadbit pattern repeats.

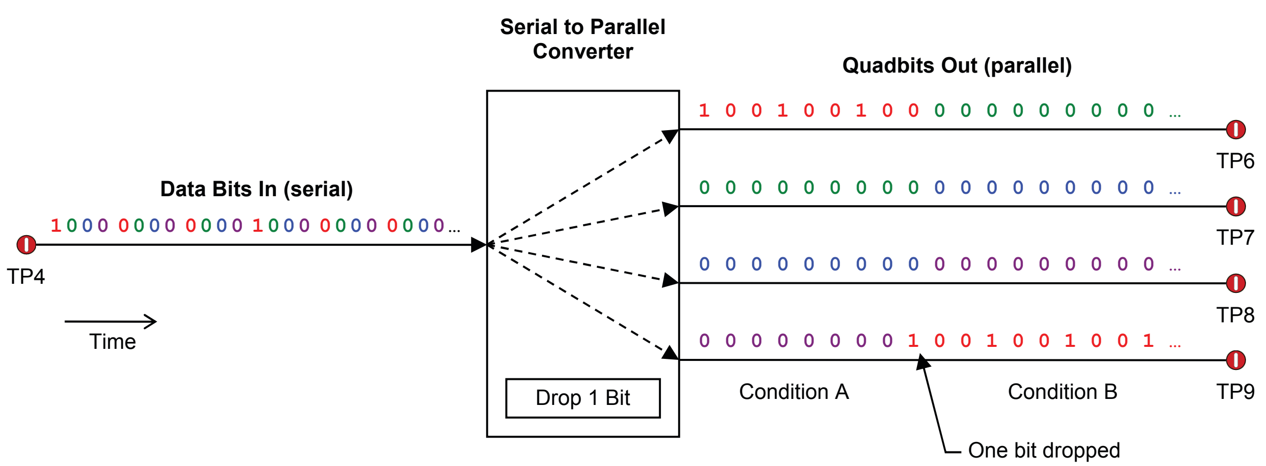


Figure 7. Serial to Parallel Converter operation with repeating sequence 1000 0000 0000.

In the QAM/DQAM application, the **Drop 1 Bit** button is included in the Serial to Parallel Converter for educational purposes. Clicking this button causes the Serial to Parallel Converter to ignore one bit in the data sequence. This changes the grouping of all subsequent data bits into quadbits (see Condition B in Figure 7).

Each quadbit consists of a pair of dibits, which can be called the most significant dibit (MSD) and the least significant dibit (LSD). The MSD is sent to the I-channel of the modulator; the LSD is sent to the Q-channel of the modulator. Each channel of the modulator works independently to processes the data it receives.

In the QAM/DQAM application, the MSB input of the D/A Converter determines the sign of the output voltage and the LSB input determines the magnitude of the output voltage.

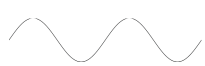
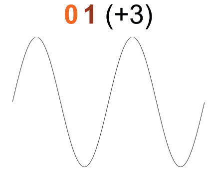
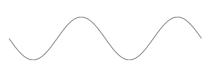
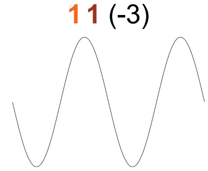
The D/A Converter in each channel converts the dibit stream into a (baseband) four-level pulse stream that can be applied to one input of the mixer. Each of the four levels represents a specific dibit. The four levels used are proportional to -3, -1, +1, and +3. This makes the distribution of the constellation points uniform.

To restrict the bandwidth of the QAM signal, a low-pass filter is usually used before the mixer in each channel of the modulator in order to provide the desired spectral shaping. In addition, a bandpass filter (not shown in Figure 6) may be used to filter the QAM signal before transmission.

Each mixer performs modulation by multiplying the sinusoidal carrier by the four-level data signal. Multiplying the carrier by ±1 causes a 180° phase shifts in the mixer output signal and is equivalent to BPSK modulation. Multiplying by +3 causes a three-fold increase in peak amplitude and is essentially a type of ASK modulation. Multiplying the carrier by -3 causes a 180° phase shift and a three-fold increase in peak amplitude. The mixer output signal is therefore a bi-phase, bi-level sinusoidal signal. The effect of the mixer is to shift the frequency spectrum of the baseband signal up to the frequency of the carrier.

Table 2 shows the mapping used in the QAM/DQAM application from dibit to relative pulse level (shown in brackets) and the resulting waveforms. In this mapping, the first bit (**MSB**) of each dibit determines the phase of the mixer output signal and the second bit (**LSB**) determines the amplitude.

Table 2. Mapping of dibit to pulse level to waveform in one channel of the modulator.

Dibit, (Relative Pulse Level), and Waveform	
0 0 (+1) 	**0 1** (+3) 
1 0 (-1) 	**1 1** (-3) 

Orthogonal signals can be summed, transmitted in a channel and (theoretically) perfectly separated in the demodulator without any mutual interference.

The two bi-phase, bi-level signals are summed to produce the QAM signal. Because these two bi-phase, bi-level signals are generated using orthogonal carriers (in phase quadrature), the signals themselves are **orthogonal**, and the QAM demodulator will be able to demodulate them separately.

By convention, the amplitude levels used in the pulse streams $d_I(t)$ and $d_Q(t)$ are proportional to ±1, ±3, ±5, ..., up to the number of different levels required for the type of QAM used. This makes the distribution of the constellation points uniform and ensures optimal error performance in the presence of noise.

The output signal of the modulator is a sinusoidal carrier with 16 possible states, each of which represents a four-bit symbol (quadbit). This signal can be represented by Equation (3).

$$s(t) = d_I(t)\cos(\omega t) + d_Q(t)\sin(\omega t) \quad (3)$$

where $s(t)$ is the QAM signal waveform
$d_I(t)$ is the I-channel four-level pulse stream d_0, d_2, d_4 …
$d_Q(t)$ is the Q-channel four-level pulse stream d_1, d_3, d_5 …
ω is the angular frequency

Symbol rate and bandwidth

With 16-QAM, each symbol represents four bits. Therefore the rate that the symbols occur in the QAM signal (the symbol rate) is one quarter the bit rate. Table 3 compares the symbol rates (and bandwidths) for BPSK, QPSK, and QAM.

Table 3. Symbol rates and bandwidths.

Modulation	Bits per symbol	Symbol rate vs. Bit rate	First-nulls bandwidth
BPSK	1	$R_s = R_b$	$2R_b$
QPSK	2	$R_s = \frac{R_b}{2}$	R_b
QAM	4	$R_s = \frac{R_b}{4}$	$\frac{R_b}{2}$

The bandwidth of a modulated signal depends on the rate of change in the signal (i.e. the symbol rate) and not on the magnitude of each change. For this reason, QAM requires one-half as much bandwidth as QPSK and one-quarter as much as BPSK for a given bit rate. This is illustrated in Figure 8, where f_c is the carrier frequency. Alternatively, using QAM instead of QPSK or BPSK can double or quadruple the bit rate for a given signal bandwidth.

Figure 8 shows that, for the same bit rate, the first-nulls bandwidth of a QAM signal is one-half that of a QPSK signal, and one quarter that of a BPSK. Of the three modulation techniques, QAM has the highest bandwidth efficiency.

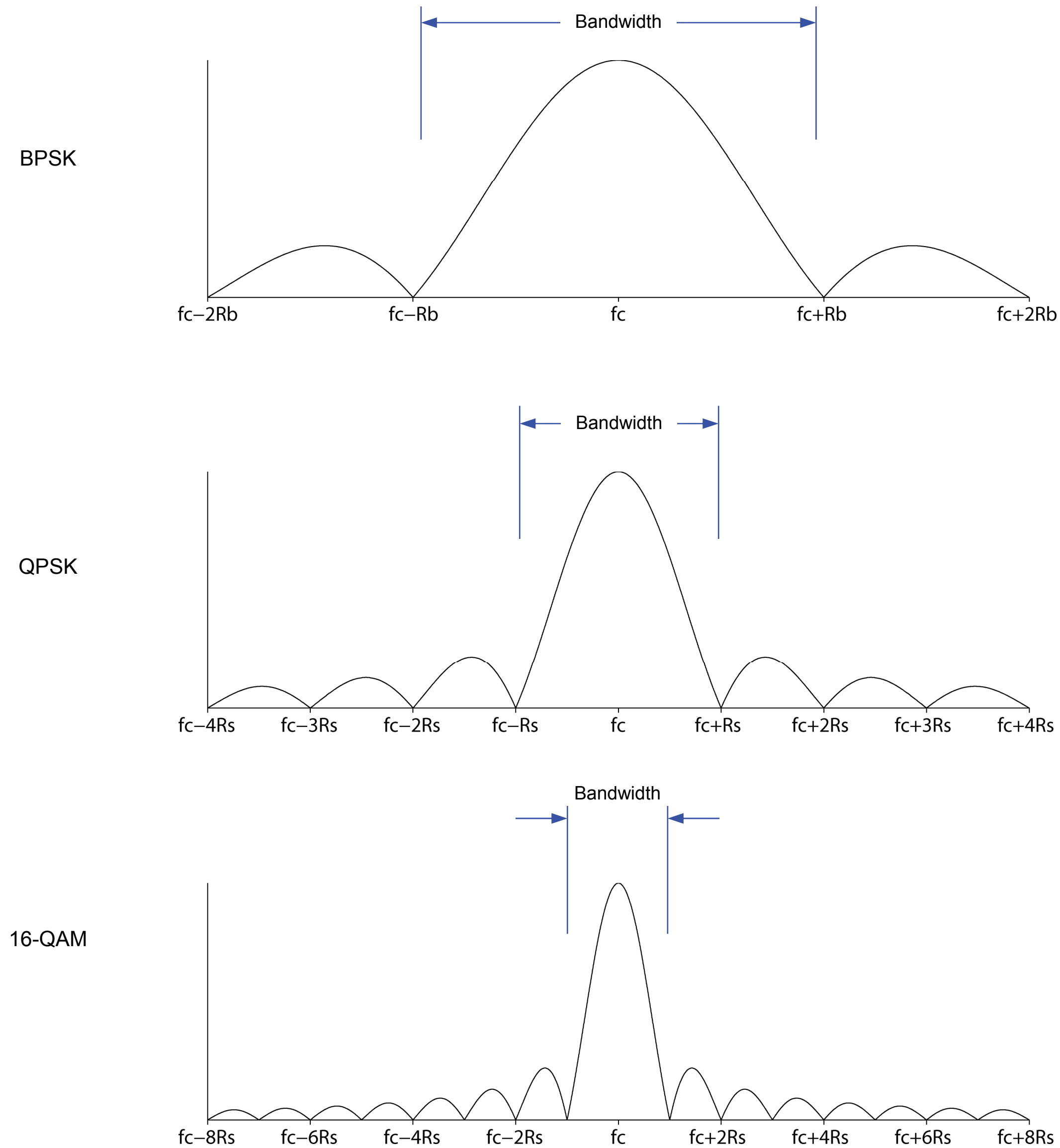


Figure 8. BPSK, QPSK, and 16-QAM magnitude spectrum (for equal bit rates).

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set-up and connections
- Observing binary sequences using the virtual instruments
- The Serial to Parallel Converter
- D/A Converter
- The Filters and mixers
- The summer
- Signal constellations

PROCEDURE

Set-up and connections

1. Turn on the RTM Power Supply and the RTM and make sure the RTM power LED is lit.

File ▶ Restore Default Settings *returns all settings to their default values, but does not deactivate activated faults.*

2. Start the LVCT software. In the Application Selection box, choose *QAM/DQAM* and click OK. This begins a new session with all settings set to their default values and with all faults deactivated.

   If the software is already running, choose *Exit* in the *File* menu and restart LVCT to begin a new session with all faults deactivated.

3. Make the Default external connections shown on the System Diagram tab of the software. For details of connections to the Reconfigurable Training Module, refer to the RTM Connections tab of the software.

   Click the **Default** button to show the required external connections.

4. As an option, connect a conventional oscilloscope to the BSG CLOCK OUTPUT and the BSG DATA OUTPUT, using BNC T-connectors. Use the BSG SYNC./4 OUTPUT as an external trigger.

   On-line help is accessible from the *Help* menu of the software and the *Help* menu of each instrument.

   You can print out the screen of any instrument by choosing *File* ▶ *Print* in that instrument.

Observing binary sequences using the virtual instruments

5. Make the following Generator settings:

   Generation Mode .... Pseudo-Random
   n 4
   Bit Rate .... 2000 bit/s

Settings

This application has tables of settings that allow you to change various software parameters in order to configure the system. Two Settings tables are provided – QAM Settings and Generator Settings. By default, these tables are located at the right side of the main window and only one of these tables is visible at a time. Two tabs at the bottom allow you to select which table is visible and the name of the visible table is displayed at the top. (Refer to on-line help for more information.)

Settings tables have two columns. The name of each setting is shown in the left column and the current value of each setting is shown in the right column. The column separator can be moved using the mouse, and the entire table can be resized as desired.

Some settings have a drop-down list of possible values. To change this type of setting, click the setting and then click the down arrow to display the drop-down list and select a new value. You can also click the setting and then roll the mouse wheel to change the value or repeatedly double-click the setting to cycle through the available values.

To change an editable numerical setting, simply select or delete the current value in the settings table, type a new value and press Enter or Tab. You can also click the setting and roll the mouse wheel. When fine adjustments are possible, holding down the Ctrl key on the keyboard while rolling the mouse wheel will change the value by small increments.

When you change the value of a numerical setting, the focus remains on that setting until you click elsewhere in the software. To immediately change the setting to another value, you can simply type the new value and press Enter.

6. Click the QAM Modulator tab in order to display the QAM Modulator diagram.

   Show the Probes bar (click in the toolbar or choose *View* ▶ *Probes Bar*). Connect the probes as follows:

Oscilloscope probe	Connect to	Signal
1	TP2	CLOCK INPUT
2	TP1	DATA INPUT
E	TP3	BSG SYNC. OUTPUT

Logic Analyzer probe	Connect to	Signal
C	TP2	CLOCK INPUT
1	TP3	BSG SYNC. OUTPUT
2	TP1	DATA INPUT

Other probes	Connect to	Signal
Spectrum Analyzer	TP1	DATA INPUT

To move a probe from the Probes bar to a test point, click the probe, move the mouse until the tip of the probe is over the test point, and click the mouse button to connect the probe.

To move a probe from one test point to another, move the mouse pointer over the probe until the pointer changes into a grasping hand. Then, click the probe and, *without releasing* the mouse button, drag the probe to another test point. Release the mouse button.

7. Show the Oscilloscope (click in the toolbar or choose *Instruments* ▶ *Oscilloscope*). Figure 9 shows an example of settings and what you should observe.

Unless you are instructed to make specific settings, you can use any system and instrument settings that will allow you to observe the phenomena of interest. As a guide, important settings that were used to produce a figure may be shown beside the figure.

Generator Settings:
Generation Mode ...... Pseudo-Random
n 4
Bit Rate .... 2000 bit/s

Oscilloscope Settings:
Channel 1 .... 5 V/div
Channel 2 .... 5 V/div
Channel E .... 5 V/div
Time Base .... 1 ms/div
Trigger: Slope .... Rising
Trigger: Level .... 1 V
Trigger: Source .... Ext

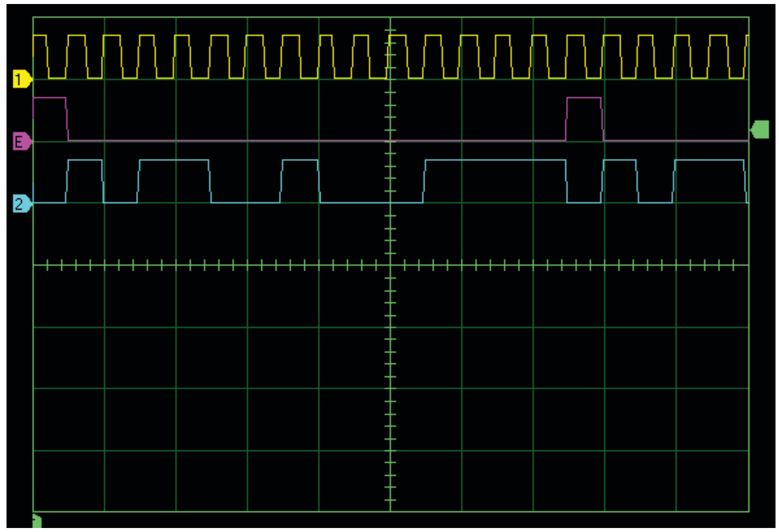


Figure 9. Clock, Sync. and PRBS data signals.

Some settings have a drop-down list of possible values. To change this type of setting, click the setting and then click the down arrow to display the drop-down list and select a new value. You can also click the setting and then roll the mouse wheel to change the value or repeatedly double-click the setting to cycle through the available values.

To display the trace of any channel on the Oscilloscope, you must set the Visible setting for that channel to On. (You can trigger the Oscilloscope on a channel even when Visible is set to Off.)

Channel 1 on the Oscilloscope shows the Clock signal. Channel E (External) shows the BSG SYNC. signal, which is used as the trigger source for the Oscilloscope. This signal goes high for one clock period at the beginning of each sequence period. Note that the level changes of the pulses in the other signals align with the *rising* edges of the clock signal.

Channel 2 shows a pseudo-random binary sequence (PRBS). With, n = 4 in the Generator Settings, the length $L = 2^4-1 = 15$. Count the number of clock cycles from one sync. pulse to the next to verify that this is the case. Note that the PRBS begins to repeat at the second sync. pulse.

To refresh and freeze the display, click the button in the instrument toolbar. This refreshes the display once and freezes it. You can also press F5 or choose *View* ▶ *Single Refresh*. Click , press F6 or choose *View* ▶ *Continuous Refresh* to resume normal operation.

8. Experiment with the Binary Sequence Generator by changing the value of n and the Bit Rate. Adjust the Time Base on the Oscilloscope as necessary.

In order for the Oscilloscope to trigger properly, the Time Base must be set so that at least one complete period of the Trigger Source signal is displayed on the screen.

Generator Settings:
Generation Mode ...... Pseudo-Random
n 4
Bit Rate .... 2000 bit/s

Logic Analyzer Settings:
Display Width .... 10 ms
Clock Grid .... Falling Edge
Source .... Ch 1
Source Edge .... Rising
Clock Edge .... Falling
S1 Data .... [ch1]
S2 Data .... [ch2]

9. Show the Logic Analyzer (click in the toolbar or choose *Instruments* ▶ *Logic Analyzer*).

   Click in the Logic Analyzer toolbar to record data. Figure 10 shows an example of settings and what you should observe. Compare the signals as displayed on the Logic Analyzer with the same signals as displayed on the Oscilloscope.

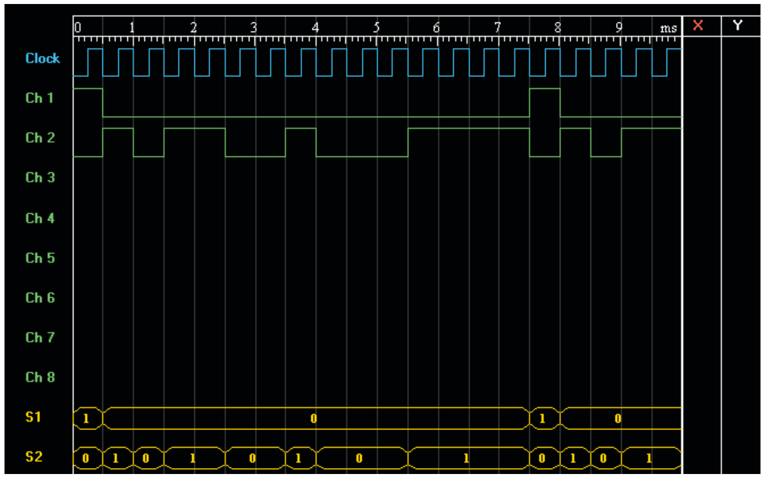


Figure 10. Clock, sync. and PRBS data on Logic Analyzer.

Note that the signals displayed on the Oscilloscope and on the Logic Analyzer are very similar. With the Logic Analyzer settings shown in Figure 10, however, the level changes of the pulses in the Sync. signal (Bit 0) and in the Data signal (Bit 1) align with the *falling* edges of the Clock signal.

Logic Analyzer operation

The Logic Analyzer does not display data in real time. Instead, after you click , it waits for the trigger and then begins recording data. When its memory is full, it stops recording and displays the recorded data.

The **Source** setting determines which signal is used to trigger the recording and the **Source Edge** setting determines whether the rising edge or the falling edge of this signal triggers the recording.

When recording data, the Logic Analyzer samples each channel *only once per clock period.* The display shows either a high level (1) or a low level (0) in the corresponding trace for each sample taken. The **Clock Edge** setting determines whether the sampling instants correspond to the rising edges or the falling edges of the clock signal. (For this reason, the Logic Analyzer cannot display the precise timing relationship between signals as does the Oscilloscope.)

The following sequence shows how the Logic Analyzer records data:

- The user clicks or presses F5 or selects *View* ▶ *Record*.
- The Logic Analyzer waits for the selected Source Edge (Rising or Falling) of the trigger Source signal.
- The Logic Analyzer takes one sample of each channel at each selected Clock Edge (Rising or Falling) until 256 samples of each channel have been recorded. It then updates the display.

The Oscilloscope shows that the transitions in the DATA INPUT signal occur on the *rising* edges of the clock signal. Therefore it is preferable to set Clock Edge to *Falling* as this ensures that the signal will be sampled in the middle of each bit, where the signal voltage is not changing. (Setting Clock Edge to Rising would cause the Logic Analyzer to sample the DATA INPUT signal exactly where the transitions occur, which could result in ambiguous values.)

To observe the output of a functional block that is *falling-edge triggered*, as indicated by the symbol at the clock input, it is preferable to set Clock Edge to *Rising*.

10. Show the Spectrum Analyzer (click in the toolbar or choose *Instruments* ▶ *Spectrum Analyzer*). Figure 11 shows an example of settings and what you should observe. In the Generator Settings, vary the value of n and the Bit Rate and observe the effect on the spectrum.

To reduce fluctuations in the displayed spectrum, set Averaging to the number of consecutive spectra to be averaged. The higher the setting, the lower the fluctuations, however, the spectrum will take longer to stabilize after a change.

Generator Settings:
Generation Mode ...... Pseudo-Random
n 3
Bit Rate .... 5000 bit/s

Spectrum Analyzer Settings:
Maximum Input .... 10 dBV
Scale Type .... Logarithmic
Scale .... 10 dBV/div
Averaging 4
Frequency Span .... 2 kHz/div
Reference Frequency 0
Cursors .... Vertical

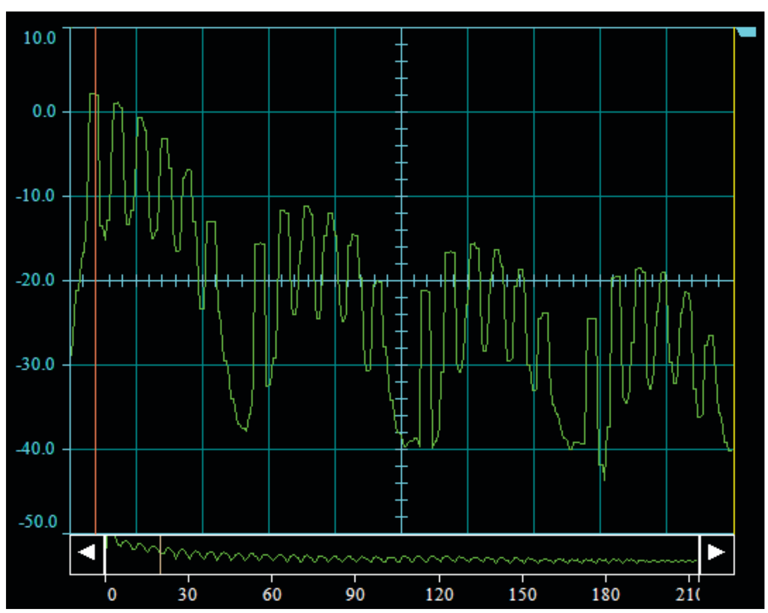


Figure 11. Spectrum of a PRBS.

Use a vertical cursor, as shown in the figure, to determine the approximate frequency of various spectral elements. You can position each cursor by dragging it with the mouse.

Theoretically, the spectral lines have an infinitesimal width. On a spectrum analyzer, however, they appear as bars or peaks. If the spectral lines are very close together, they are not resolved by the Spectrum Analyzer and the spectrum appears to be continuous.

Note that the spectrum of a PRBS consists of a series of lobes of decreasing magnitude with nulls at multiples of the Bit Rate R_b. This makes the first-null bandwidth equal to the bit rate.

Since the data signal is not truly random but consists of a sequence that repeats every $L = 2^n - 1$ bits, the spectrum is not continuous. Instead, it consists of spectral "lines" spaced at frequencies that are multiples of $\frac{1}{T} = \frac{R_b}{2^n - 1}$ where T is the period of the sequence in seconds.

11. In the generator Settings, set the Generation Mode to User Entry. Enter different binary sequences in the Binary Sequence setting and observe the result using the virtual instruments.

When the Generation Mode is set to User Entry, the Binary Sequence Generator generates a repeating binary sequence defined by the Binary Sequence setting. You can enter up to 32 binary digits (1s and 0s) in this setting. You can include spaces in this setting to make the pattern more legible (the software ignores spaces in this setting).

The Serial to Parallel Converter

12. Make the following Generator settings:

Generation Mode .... User Entry
Binary Sequence 1001 1000 1110 1110
Bit Rate .... 1000 bit/s

The Serial to Parallel Converter groups the input data stream into quadbits and sends the first dibit of each quadbit to the I Channel of the modulator and the other dibit to the Q Channel of the modulator. Since the Serial to Parallel Converter is not synchronized with the data, the grouping into quadbits can start at any bit. Because the number of bits in the Binary Sequence is a multiple of 4, there are four possible conditions:

A) The grouping starts with the *first* bit of the defined Binary Sequence, giving quadbits 1001 1000 1110 1110, as they appear in the Binary Sequence setting.

B) The grouping starts with the *second* bit of the sequence.

C) The grouping starts with the *third* bit of the sequence.

D) The grouping starts with the *fourth* bit of the sequence.

If the grouping starts with any other bit, the result is equivalent to one of the above conditions, since the sequence repeats indefinitely.

The first row of Table 4 shows the data bits from this Binary Sequence. After 16 bits, the sequence begins to repeat. A, B, C, and D in the table represent the four ways the data bits can be grouped into quadbits.

Complete the four **Quadbit** rows of this table, grouping the data bits into quadbits in four different ways.

Table 4. Serial to Parallel Converter inputs and outputs.

	Data Bits	1	0	0	1	1	0	0	0	1	1	1	0	1	1	1	0	1	0	0
A	**Quadbit**	1	0	0	1															
	Hex	9																		
B	**Quadbit**		0	0	1	1														
	Hex		3																	
C	**Quadbit**																			
	Hex																			
D	**Quadbit**																			
	Hex																			

Represent each of the quadbits in Table 4 as a hexadecimal Logic Analyzer symbol where, if the four digits of the quadbit are (b_3, b_2, b_1, b_0), the symbol value is equal to $2^3 \times b_3 + 2^2 \times b_2 + 2 \times b_1 + b_0$. This will help in interpreting the symbols displayed by the Logic Analyzer.

Logic Analyzer symbols are hexadecimal values derived from combinations of binary data in selected channels. They should not be confused with the symbols used in M*-aray signaling.*

In this manual, the channel selections for each Logic Analyzer symbol, and the hexadecimal symbol values, are shown in square brackets.

Channels and symbols

The Logic Analyzer display includes a **Clock** channel, eight data channels **Ch 1** to **Ch 8**, each of which displays the sampled binary data (1s and 0s) from one probe, as well as two "symbol" channels **S1** and **S2**. Each of these symbol channels displays a series of hexadecimal numbers that result from combining the binary data from selected data channels.

The data channels that contribute to each symbol channel are selected using the Symbol buttons near the bottom of the screen. By default, all Symbol buttons are up (no channels are selected). Each selected channel contributes one bit to the hexadecimal symbol value; the most significant bit (MSB) corresponding to the leftmost pressed-down button and the least significant bit (LSB) corresponding to the rightmost pressed-down button.

For example, if channels [ch1, ch3, ch6, ch7] are selected for Symbol 1, the hexadecimal values displayed in the S1 channel correspond to $2^3 \times \text{Ch 1} + 2^2 \times \text{Ch 3} + 2^1 \times \text{Ch 6} + 2^0 \times \text{Ch 7}$. In this case, since four data channels are combined into one symbol, the symbol values can range from [0] to [F] (0000_2 to 1111_2). If only two data channels are combined into one symbol, the symbol values can range from [0] to [3] (00_2 to 11_2).

Table 4. Serial to Parallel Converter inputs and outputs.

	Data Bits	1	0	0	1	1	0	0	0	1	1	1	0	1	1	1	0	1	0	0
A	**Quadbit**	1	0	0	1	1	0	0	0	1	1	1	0	1	1	1	0			
	Hex	9				8				E				E						
B	**Quadbit**		0	0	1	1	0	0	0	1	1	1	0	1	1	1	0	1		
	Hex		3				1				D				D					
C	**Quadbit**			0	1	1	0	0	0	1	1	1	0	1	1	1	0	1	0	
	Hex			6				3				B				A				
D	**Quadbit**				1	1	0	0	0	1	1	1	0	1	1	1	0	1	0	0
	Hex				C				7				7				4			

13. Connect the Logic Analyzer probes as follows:

Connect the probes exactly as shown so that the Logic Analyzer will display the symbols as shown in Table 4.

Logic Analyzer probe	Connect to	Signal
C	TP2	CLOCK INPUT
1	TP3	BSG SYNC. OUTPUT
2	TP4	Serial to Parallel Converter input
3	TP6	Serial to Parallel Converter output (MSB)
4	TP7	Serial to Parallel Converter output
5	TP8	Serial to Parallel Converter output
6	TP9	Serial to Parallel Converter output (LSB)

To make it easier to connect the probes, you may wish to zoom into this region of the diagram. To zoom in a diagram, right-click on the diagram and choose *Zoom* in the context-sensitive menu. This changes the mouse pointer to . Drag the mouse pointer up or down to zoom in or out. Another way to zoom is to click the diagram and roll the mouse wheel.

14. Record data with the Logic Analyzer and examine the data. Using the Symbol buttons, set Symbol 1 to [ch2] and Symbol 2 to [ch3, ch4, ch5, ch6].

Examine the data displayed by the Logic Analyzer. Figure 12 to Figure 15 show the four possible conditions, depending on how the Serial to Parallel Converter groups the data sequence into quadbits.

Click the Drop 1 Bit button *once only* in the modulator and perform another recording. Ch 2 and S1, the input data, will not change but the results in Ch 3 to Ch 6 and S2 should be different.

For each of Figure 12 to Figure 15, identify which of the four possible conditions (A, B, C, or D) from Table 4 the figure represents.

Because the Serial to Parallel Converter operates on four bits at a time, it introduces a slight delay in the output bit streams. The timing relationship changes slightly after clicking Drop 1 Bit.

Logic Analyzer Settings:

Display Width .... 38 ms
Clock Grid .... Falling Edge
Source .... Ch 1
Source Edge .... Rising
Clock Edge .... Falling
S1 Data .... [ch2]
S2 Data .... [ch3, ch4, ch5, ch6]

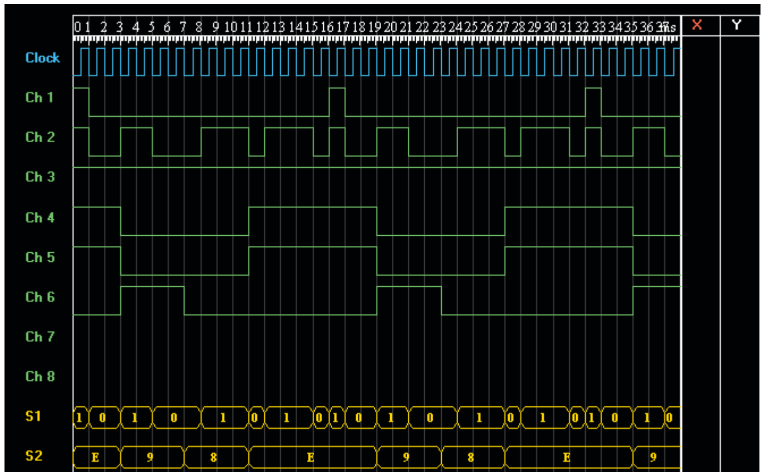


Figure 12. Serial to Parallel Converter input (Ch 2) and outputs (Ch 3 to Ch 6).

Figure 12 represents Condition: ☐ A ☐ B ☐ C ☐ D

Figure 12 represents Condition: ☑ A ☐ B ☐ C ☐ D

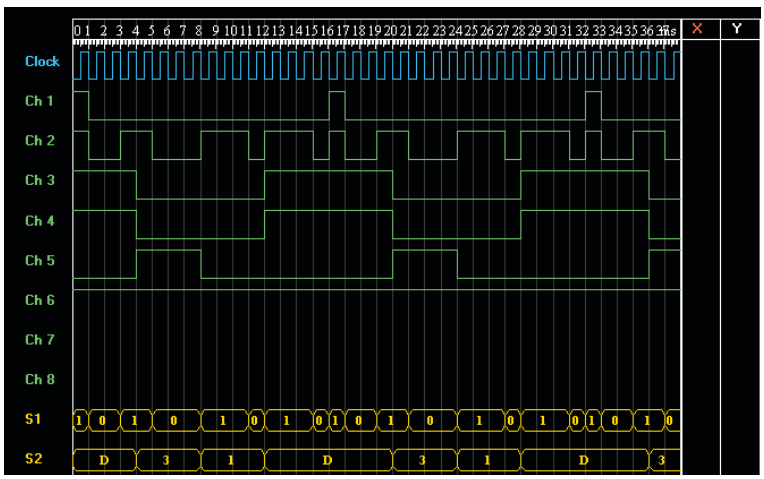


Figure 13. Serial to Parallel Converter input (Ch 2) and outputs (Ch 3 to Ch 6).

Figure 13 represents Condition: ☐ A ☐ B ☐ C ☐ D

Figure 13 represents Condition: ☐ A ☑ B ☐ C ☐ D

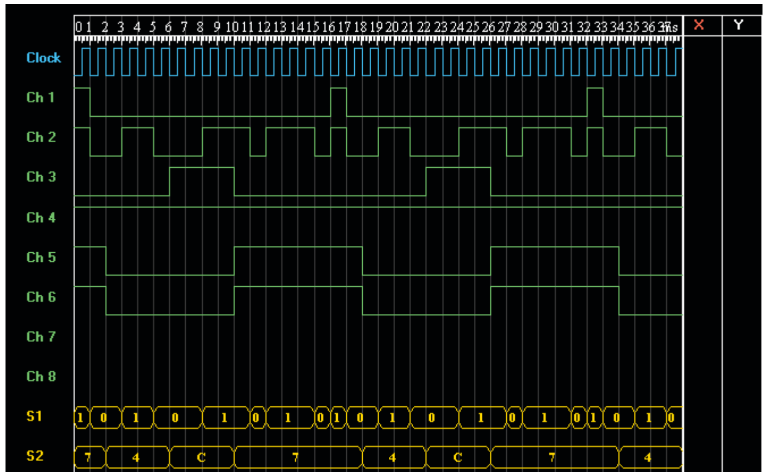


Figure 14. Serial to Parallel Converter input (Ch 2) and outputs (Ch 3 to Ch 6).

Figure 14 represents Condition: ☐ A ☐ B ☐ C ☐ D

Figure 14 represents Condition: ☐ A ☐ B ☐ C ☑ D

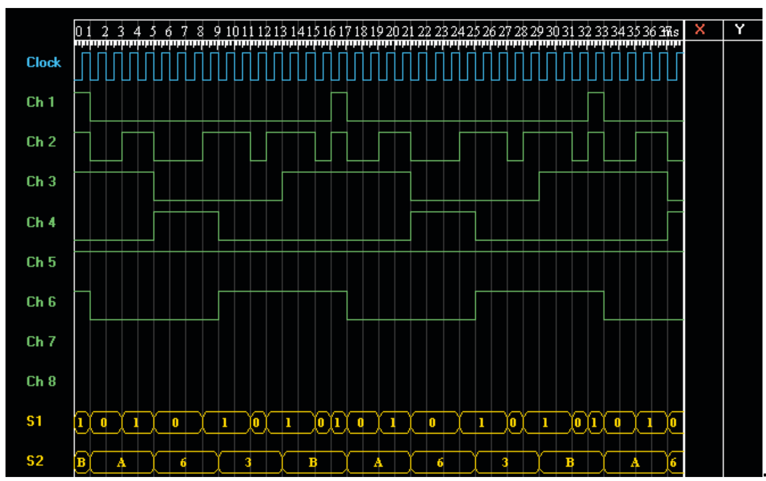


Figure 15. Serial to Parallel Converter input (Ch 2) and outputs (Ch 3 to Ch 6).

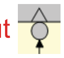
Figure 15 represents Condition: ☐ A ☐ B ☐ C ☐ D

Figure 15 represents Condition: ☐ A ☐ B ☑ C ☐ D

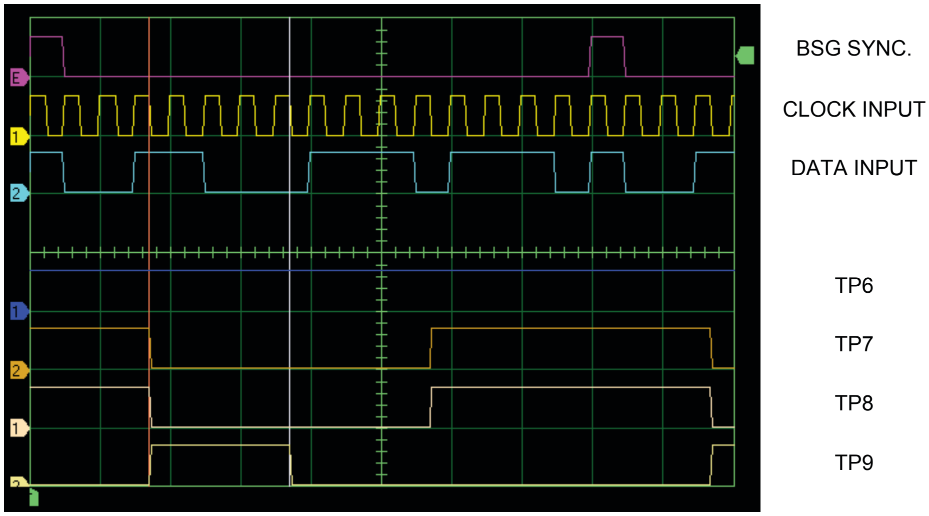
15. Use the oscilloscope to determine the exact timing relationship of the different signals. Since this requires observing several signals at a time, it will be helpful to use the memory of the Oscilloscope.

Click M1 or M2 in the instrument toolbar to store the current display in Memory 1 or Memory 2. Use the Memories setting to show the contents of Memory 1, Memory 2, or both.

Is the output of the Serial to Parallel Converter triggered by the rising edge or the falling edge of the clock signal? Does this correspond to the symbol used at the clock input of the Serial to Parallel Converter?

The Serial to Parallel Converter output is falling-edge triggered, as indicated by the symbol at the clock input  and in the following figure.

Oscilloscope Settings:
Channel 1 ....5 V/div
Channel 2 ....5 V/div
Channel E ....5 V/div
Memories .... Both
Time Base .... 2 ms/div
Trigger Slope .... Rising
Trigger Level .... 1.9 V
Trigger Source .... Ext
Cursors .... Vertical



Serial-to-Parallel Converter signal timing (Condition A).

D/A Converter

16. Connect the probes as follows:

Oscilloscope probe	Connect to	Signal
E	TP10	I-channel D/A Converter input (MSB)
1	TP11	I-channel D/A Converter input (LSB)
2	TP14	I-channel D/A Converter output

Logic Analyzer probe	Connect to	Signal
C	TP2	CLOCK INPUT
E	TP5	Frequency Divider output
1	TP6	Serial to Parallel Converter output (MSB)
2	TP7	Serial to Parallel Converter output
3	TP8	Serial to Parallel Converter output
4	TP9	Serial to Parallel Converter output (LSB)

To disconnect a probe and return it to the Probes bar, you can right-click the probe and choose *Disconnect Probe* in the context-sensitive menu. Alternatively, you can double-click the probe's place holder in the Probes bar.

The Frequency Divider divides the BSG SYNC. signal frequency in order to generate a signal that can be used as a trigger for the Oscilloscope or the Logic Analyzer. This is necessary when observing the Serial to Parallel Converter output with a binary sequence having an odd number of bits. (All pseudo-random sequences have an odd number of bits.)

Make the following Generator settings:

Generation Mode .... User Entry
Binary Sequence 0000 0100 1100 1000
Bit Rate .... 2000 bit/s

Record data on the Logic Analyzer and observe the signal states. Set Symbol 1 to [ch1, ch2] and Symbol 2 to [ch3, ch4].

The outputs of the Serial to Parallel Converter should be as shown in Figure 16, with Ch 1, Ch 2 and S1 changing state and Ch 3, Ch 4 and S2 always zero. This means that the first dibit in each quadbit of the defined Binary Sequence is sent to the I-channel of the modulator, and the second dibit (always 00) is sent to the Q-channel. If necessary, click the Drop 1 Bit button and observe the signals again until the signals are as shown in Figure 16.

Logic Analyzer Settings:
Display Width .... 20 ms
Clock Grid .... Falling Edge
Source .... Ext
Source Edge .... Rising
Clock Edge .... Falling
S1 Data .... [ch1, ch2]
S2 Data .... [ch3, ch4]

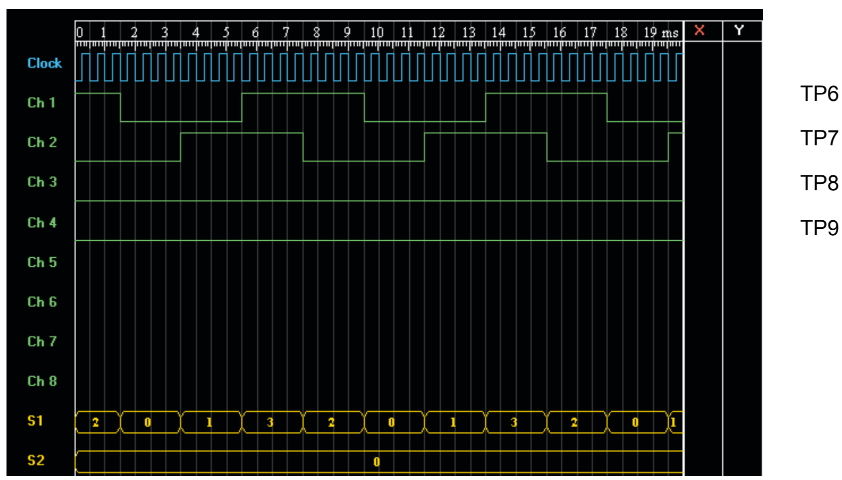


Figure 16. Desired Serial to Parallel Converter outputs.

Observe the D/A Converter inputs and output on the Oscilloscope. Figure 17 shows an example of what you should see.

Oscilloscope Settings:
Channel 1 ....5 V/div
Channel 2 ....2 V/div
Channel E ....5 V/div
Time Base .... 2 ms/div
Trigger: Slope ....Rising
Trigger: Level .... 0 V
Trigger: Source .... Ch 2

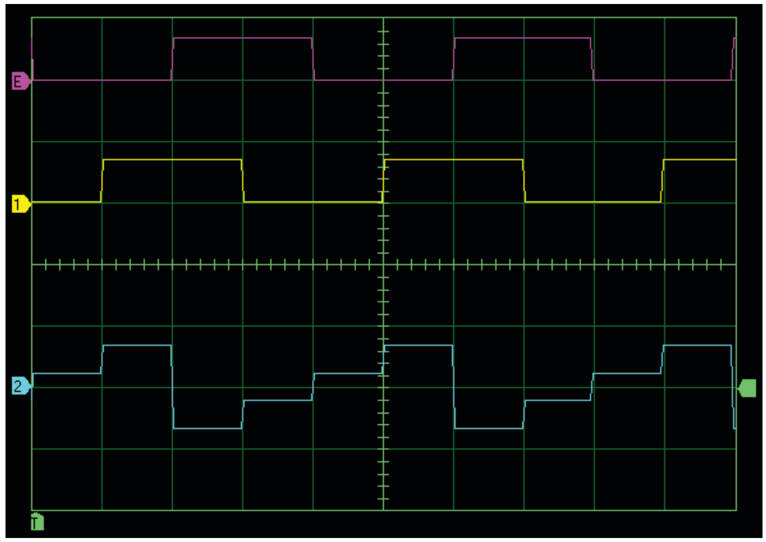


Figure 17. D/A Converter input and output signals.

You may wish to change the Channel 2 Scale setting to increase the precision of the measurements.

Use the cursors on the Oscilloscope to determine the different D/A Converter output voltage levels (TP14) for the different input states and enter these into Table 5. Divide each output level by the minimum positive output level to obtain the relative levels.

When the horizontal cursors are active, the voltage levels corresponding to the position of each cursor with respect to the Ch 1 and Ch 2 ground levels (as well as the voltage difference between the two cursors) are shown in the data below the graticule.

When the vertical cursors are active, the time position of each cursor (as well as the time difference between the two cursors) is shown in the data below the graticule. The voltage levels shown correspond to the levels at the intersections of the Ch 1 and Ch 2 traces with each cursor.

Table 5. D/A Converter input states and output levels.

Input Dibit (TP10, TP11)	Output Level (V)	Relative Level
00		
01		
11		
10		

Table 5. D/A Converter input states and output levels.

Input Dibit	Output Level (V)	Relative Level
00	0.45	+1
01	1.34	+3
11	-1.35	-3
10	-0.45	-1

Explain the operation of the D/A Converter.

The D/A Converter converts one dibit of digital data (b_1, b_0) signal into a four-level analog pulse signal whose voltage levels are proportional to -3, -1, +1 and +3.

What determines the sign and the amplitude of the D/A Converter output?

The first bit (MSB) of each dibit determines the sign and the second bit (LSB) determines the amplitude of the analog signal.

The Filters and mixers

17. Connect the Oscilloscope probes as follows.

Oscilloscope probe	Connect to	Signal
1	TP16	I-channel mixer input
E	TP17	I-channel carrier
2	TP20	I-channel mixer output

Turn the Low-Pass Filters Off. Figure 18 shows an example of what you may observe. Then turn the Low-Pass Filters On (see Figure 19).

QAM Settings:
Carrier Frequency .... 2000 Hz
Low-Pass Filters .... Off

Oscilloscope Settings:
Channel 1 .... 2 V/div
Channel 2 .... 1 V/div
Channel E .... 1 V/div
Time Base .... 1 ms/div
Trigger: Slope .... Rising
Trigger: Level .... 0 V
Trigger: Source .... Ch 1

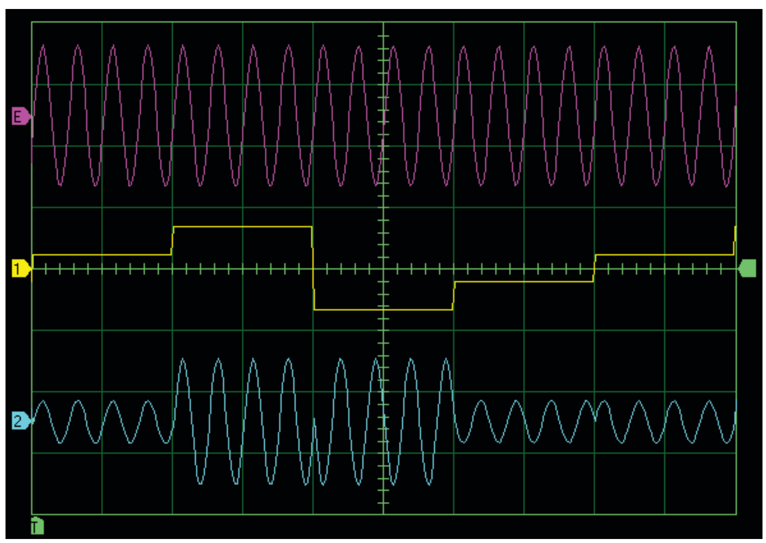


Figure 18. I-channel carrier, four-level data and mixer output signal (Low-Pass Filters Off).

QAM Settings:
Carrier Frequency.................. 2000 Hz
Low-Pass Filters .... On

Oscilloscope Settings:
Channel 1.................................2 V/div
Channel 2.................................1 V/div
Channel E ....1 V/div
Time Base............................. 1 ms/div
Trigger: Slope ....Rising
Trigger: Level................................ 0 V
Trigger: Source .... Ch 1

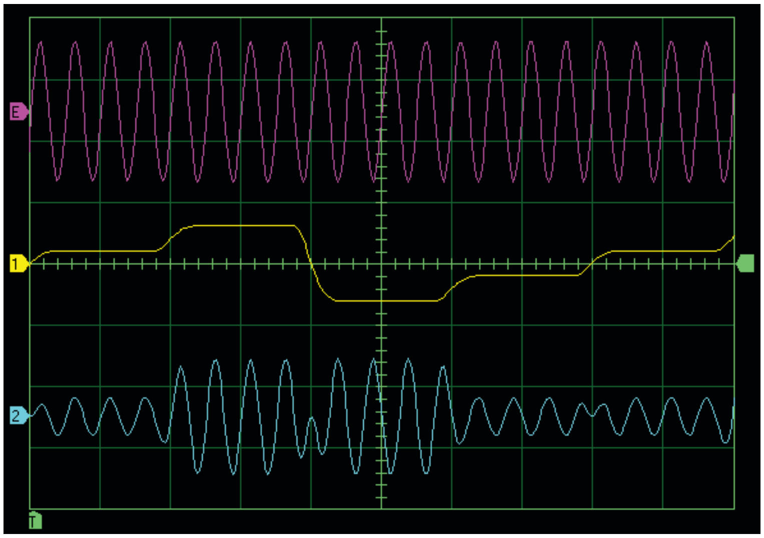


Figure 19. I-channel carrier, four-level data and mixer output signal (Low-Pass Filters On).

Describe the relationship between the amplitude and polarity of the four-level analog data signal and the amplitude and phase of the mixer output signal.

Because the mixer multiplies the carrier by the four-level analog signal, the amplitude of the mixer output signal is proportional to the absolute value of the amplitude of the four-level data signal, and the phase of the mixer output signal depends on the sign of the four-level analog signal.

What is the effect of the low-pass filter on the four-level data signal and on the mixer output signal? What is the advantage of filtering the data signal before modulation?

The low-pass filter smoothes the transitions in the four-level data signal. Since rapid changes lead to undesirable frequency components in the modulated signal, filtering reduces the bandwidth of the modulated signal.

18. Use the oscilloscope to observe the I- and Q-channel carrier signals. How are these signals related?

The I- and Q-channel carrier signals are in quadrature (out of phase by 90°). If the I-channel carrier is considered to be a cosine wave, the Q-channel carrier corresponds to a sine wave.

19. Use the Spectrum Analyzer to observe the frequency spectrum of the carrier, the baseband four-level data signal, and the mixer output signal (see Figure 20). Explain the relationship between the frequency spectra of these signals.

Click M1 or M2 in the instrument toolbar to store the current display in Memory 1 or Memory 2. Use the Memories setting to show the contents of Memory 1, Memory 2, or both.

QAM Settings:
Carrier Frequency .... 10 000 Hz
Low-Pass Filters .... On

Generator Settings:
Generation Mode ......Pseudo-Random
n 7
Bit Rate .... 5000 bit/s

Spectrum Analyzer Settings:
Maximum Input .... 20 dBV
Scale Type .... Logarithmic
Scale .... 10 dBV/div
Averaging..16
Frequency Span .... 2 kHz/div
Reference Frequency ....0 kHz
Memories .... Both

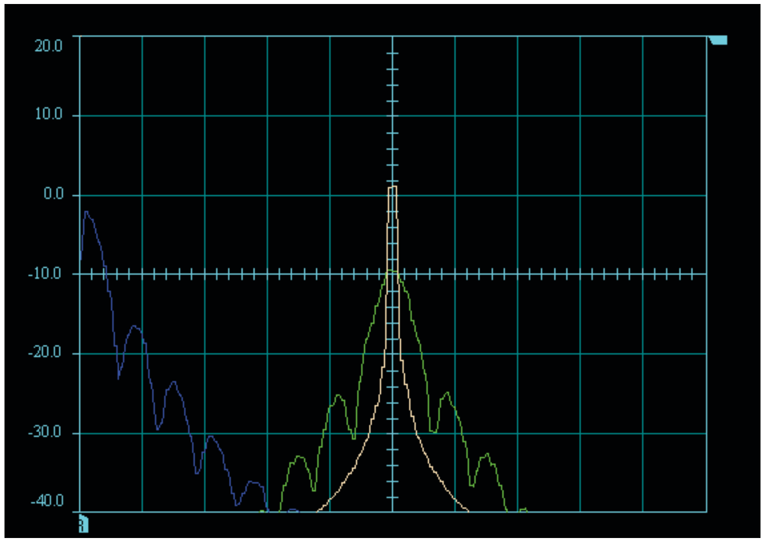


Figure 20. Frequency spectrum of four-level data signal, carrier and mixer output signal.

The spectrum of the modulated signal resembles the spectrum of the baseband data signal but is double-sided and is shifted up to (and centered on) the frequency of the carrier.

The summer

20. Use the Oscilloscope to observe the signals at the input and output of the summer (TP20, TP21, and TP22). Figure 21 shows an example.

As an option, use a conventional oscilloscope to observe the signal at the QAM Modulator OUTPUT (refer to the RTM Connections tab of the software).

QAM Settings:
Carrier Frequency .... 2000 Hz
Low-Pass Filters .... On

Generator Settings:
Generation Mode ......Pseudo-Random
n 5
Bit Rate .... 2000 bit/s

Oscilloscope Settings:
Channel 1................................1 V/div
Channel 2................................1 V/div
Channel E ....1 V/div
Time Base............................ 2 ms/div
(Single Refresh)

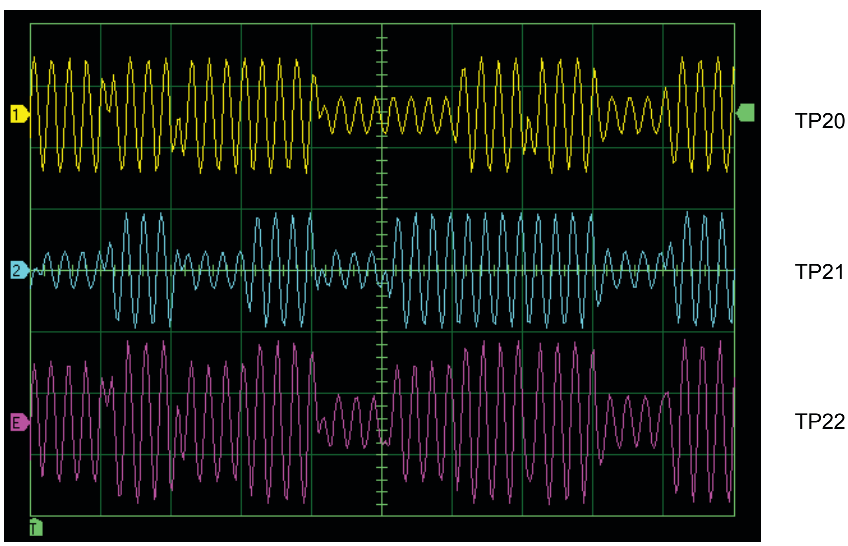


Figure 21. Summer input and output (QAM) signals.

Describe the operation of the summer.

The summer sums the I-channel and Q-channel bi-level, bi-phase signals to produce the QAM signal.

21. Use the Spectrum Analyzer to observe the spectrum of the QAM signal and compare this with the spectrum of the DATA INPUT signal (see Figure 22).

To reduce fluctuations in the displayed spectrum, set Averaging to the number of consecutive spectra to be averaged. The higher the setting, the lower the fluctuations, however, the spectrum will take longer to stabilize after a change.

QAM Settings:
Carrier Frequency.............. 10 000 Hz
Low-Pass Filters .... On

Generator Settings:
Bit Rate .... 4000 bit/s

Spectrum Analyzer Settings:
Maximum Input .... 20 dBV
Scale Type........................ Logarithmic
Scale .... 10 dBV/div
Averaging.. 16
Frequency Span .... 2 kHz/div
Reference Frequency ....0 kHz

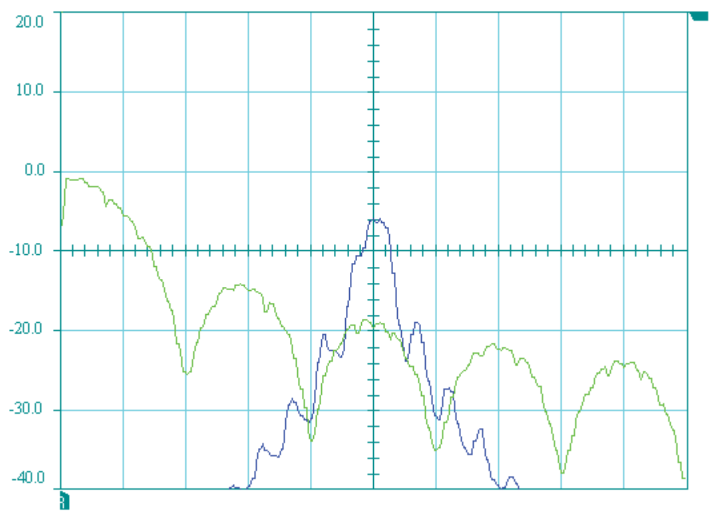


Figure 22. DATA INPUT signal and QAM signal spectrum.

In Figure 22, identify the features that correspond to the bit rate and the symbol rate. Express the bandwidth of the QAM signal in terms of the bit rate and the symbol rate.

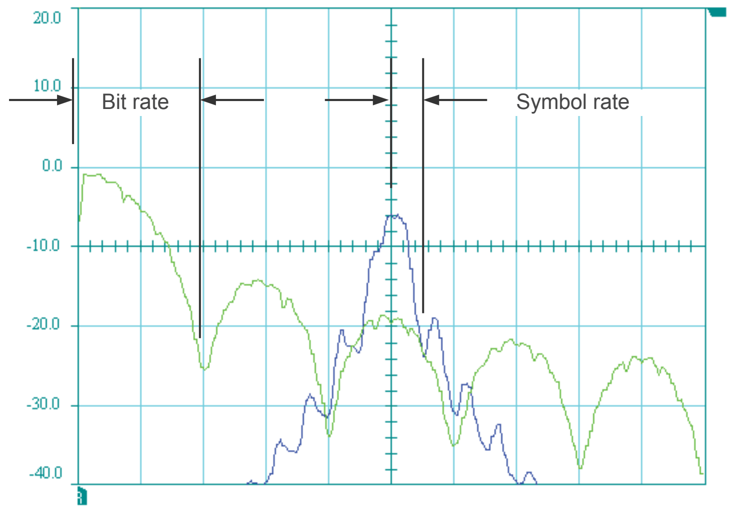


Figure 22. Four-level (baseband) signal and QAM signal spectrum.

The nulls in the QAM signal spectrum occur at multiples of the symbol rate R_s which is one-quarter the bit rate R_b. The first-nulls bandwidth of the QAM signal is therefore $2R_s = R_b/2$.

Explain why QAM is considered to be a bandwidth efficient modulation technique.

QAM is bandwidth efficient because it can transmit data at four times the bit rate over the same bandwidth as binary modulation techniques such as BPSK.

Signal constellations

22. Connect the Oscilloscope probes as follows:

Oscilloscope probe	Test point	Signal
1	TP14	I-channel D/A Converter output
2	TP15	Q-channel D/A Converter output
E	TP5	Frequency Divider output

As an option, connect a conventional oscilloscope to the QAM Demodulator I-CHANNEL OUTPUT and QAM Demodulator Q-CHANNEL OUTPUT (refer to the RTM Connections tab of the software). Use the conventional oscilloscope in the X-Y mode to observe the constellation. (The Low-Pass filters in the QAM Modulator must be set to On.)

Make the following Generator settings:

Generation Mode .... Pseudo-Random
n 3
Bit Rate .... 3000 bit/s

Figure 23 shows and example of what you should observe. The Oscilloscope will display the I- and Q-channel D/A Converter output signals. Each of these signals is a four-level analog signal that is used, after low-pass filtering, to modulate one of the sinusoidal carriers.

Oscilloscope Settings:
Channel 1 ....2 V/div
Channel 2 ....2 V/div
Time Base .... 2 ms/div
Trigger Slope ....Rising
Trigger Level .... 1 V
Trigger Source ....Ext

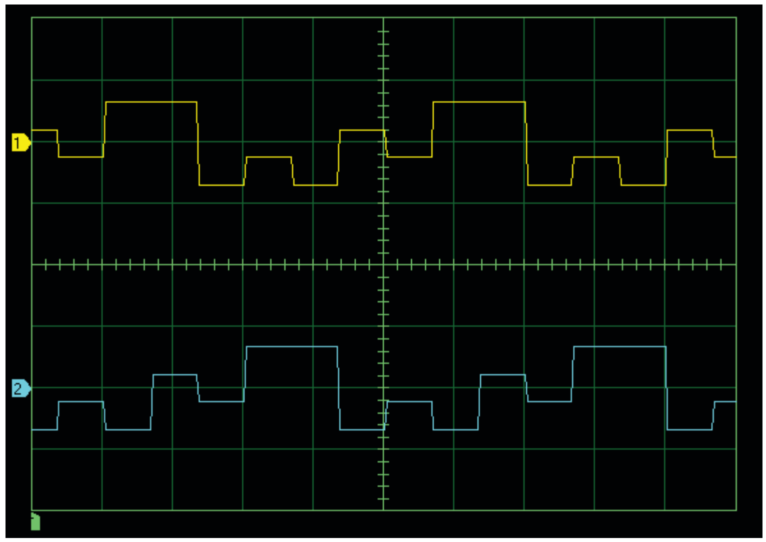


Figure 23. I- and Q-channel D/A Converter output signals.

23. Without moving the Oscilloscope probes, put the Oscilloscope in the X-Y mode. Figure 24 shows an example of what you should observe.

Oscilloscope Settings:
Channel 1 (X)...........................1 V/div
Channel 2 (Y)...........................1 V/div
Display Mode .... Dots
X-Y .... On
Sampling Window .... 100 ms

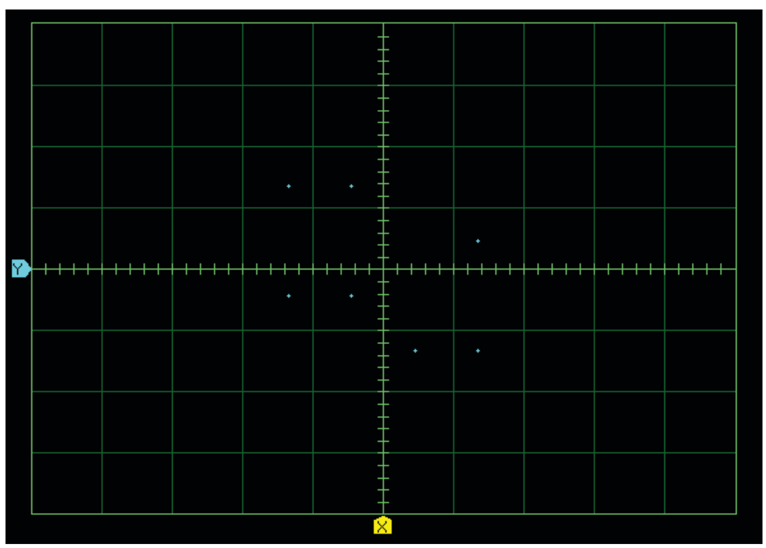


Figure 24. QAM constellation (7 points shown).

The Sampling Window setting determines the time during which the signals are sampled before each update of the display. In the present case, this should be 100 ms or greater so that all quadbits being generated appear each time the display is updated.

The Oscilloscope now displays a number of points in the signal constellation. What does each point in the constellation represent?

Each point displayed in the constellation corresponds to a one signal state, that is, to one combination of phase and amplitude. Each signal state corresponds to a different quadbit (pattern of four bits) in the input data stream.

With 16-QAM, the constellation should normally have 16 points. Why are only 7 points displayed?

With the Generator Setting n set to 3, only 7 of the 16 constellation points are used. This is due to the fact that the Pseudo-Random Binary Sequence is relatively short and therefore the number of *different* quadbits in the data is limited.

24. In the Generator Settings, set n to different values (2, 4, and 5, etc.) and observe the displayed constellation. What do you observe?

The longer the Pseudo-Random Binary Sequence, the greater the number of different quadbits in the data and the greater the number of constellation points displayed. When the Pseudo-Random Binary Sequence is long enough, all 16 constellation points are included.

25. Connect the Logic Analyzer probes as follows:

Logic Analyzer probe	Connect to	Signal
C	TP2	CLOCK INPUT
1	TP3	BSG SYNC. OUTPUT
2	TP4	Serial to Parallel Converter input
3	TP6	Serial to Parallel converter output (MSB)
4	TP7	Serial to Parallel converter output
5	TP8	Serial to Parallel converter output
6	TP9	Serial to Parallel converter output (LSB)

26. Set the Generation Mode to User-Entry. Set the Binary Sequence to the four-bit sequence (quadbit) 0000 and the Bit Rate to 2000 bit/s. Record data using the Logic Analyzer. Configure Symbol 2 of the Logic Analyzer to display the hexadecimal value of the quadbit, as shown in Figure 25.

Logic Analyzer Settings:
Display Width .... 10 ms
Clock Grid .... Falling Edge
Source... Ch 1
Source Edge .... Rising
Clock Edge .... Falling
S1 Data .... [ch2]
S2 Data .... [ch3, ch4, ch5, ch6]

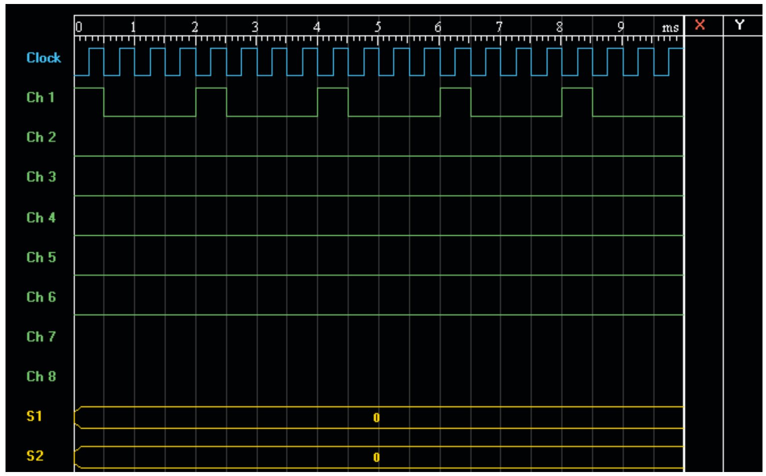


Figure 25. Logic Analyzer showing the quadbit 0000 in Ch 3 to Ch 6 and in S2.

With any four-bit Binary Sequence, the stream of quadbits at the output of the Serial to Parallel Converter is uniform over time – each quadbit is identical to the previous quadbit.

Observe the Oscilloscope display. Figure 26 shows the constellation point corresponding to the quadbit 0000. Note in Figure 27 that this constellation point has been identified with the quadbit it represents as well as the hexadecimal value of the quadbit in square brackets.

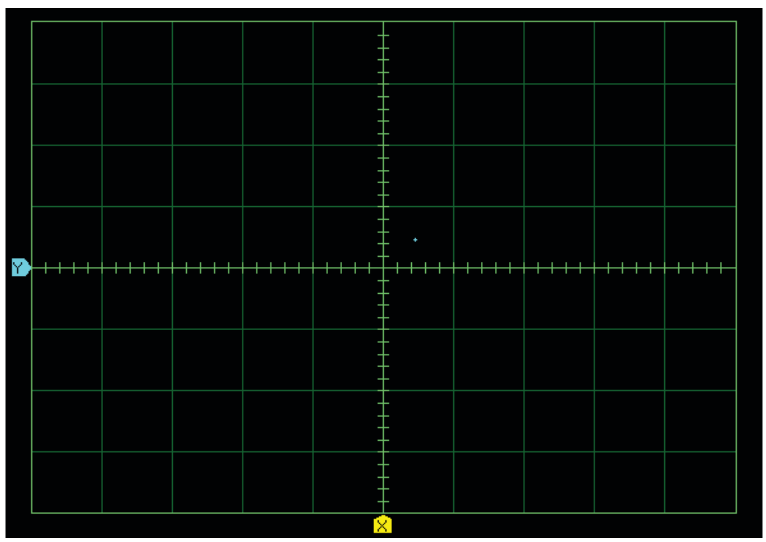


Figure 26. Oscilloscope showing the constellation point for the quadbit 0000.

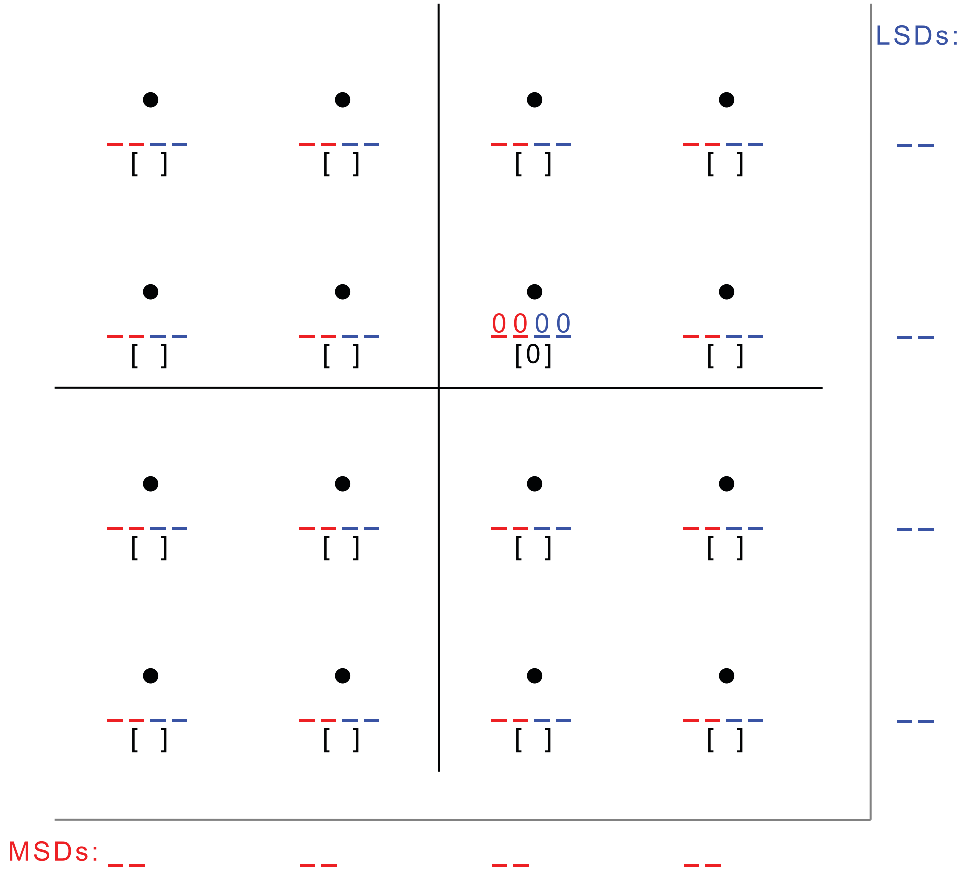


Figure 27. Quadbits [and HEX values] in the QAM constellation.

27. Set the Binary Sequence to 1111 and repeat the previous step. You have now identified two of the 16 points in the constellation. In the following steps, you will identify the remaining points.

Identifying constellation points

Identifying the constellation points that are mapped to 0000 and 1111 is straightforward because with each of these Binary Sequences, the four outputs of the Serial to Parallel Converter are identical. The bit at which the Serial to Parallel Converter begins to divide the DATA INPUT stream makes no difference.

With all other four-bit Binary Sequences, however, the bit at which the Serial to Parallel Converter begins *does* make a difference. For example, setting the Binary Sequence to 0001 will produce a uniform stream of one of the following quadbits: 0001, 0010, 0100, or 1000. There is no way to predict beforehand which of these quadbits you will obtain. Clicking the Drop 1 Bit button allows you to change the quadbit produced.

In the following steps, for each four-bit Binary Sequence you enter, you will use the Logic Analyzer to observe which quadbit is present at the output of the Serial to Parallel converter, and observe which constellation point is displayed on the Oscilloscope. Then you will use the Drop 1 Bit button to obtain all possible quadbit from that Binary Sequence.

28. Set the Binary Sequence to 0001. Record data on the Logic Analyzer and note which quadbit is present at the outputs of the Serial to Parallel Converter. Since TP6 represents the MSB, a 0 at TP6, TP7 and TP8 and a 1 at TP9 represents the quadbit 0001. Clicking the Drop 1 Bit button will change this quadbit to 0010.

Click the Drop 1 Bit button several times, each time observing the quadbit using the Logic Analyzer and observing the constellation point displayed on the Oscilloscope. Then write in Figure 27 the quadbits that correspond to these four constellation points.

By using different four-bit Binary Sequences and the Drop 1 Bit button, and by using the Logic Analyzer and the Oscilloscope, complete Figure 27 to show all 16 quadbits. Enter the hexadecimal value of each quadbit between the square brackets.

Each quadbit consists of two dibits – the most significant dibit (MSD) and the least significant dibit (LSD). Below the horizontal axis of Figure 27, write the MSDs that correspond to each of the columns. To the right of the vertical axis, write the LSDs that correspond to each of the rows.

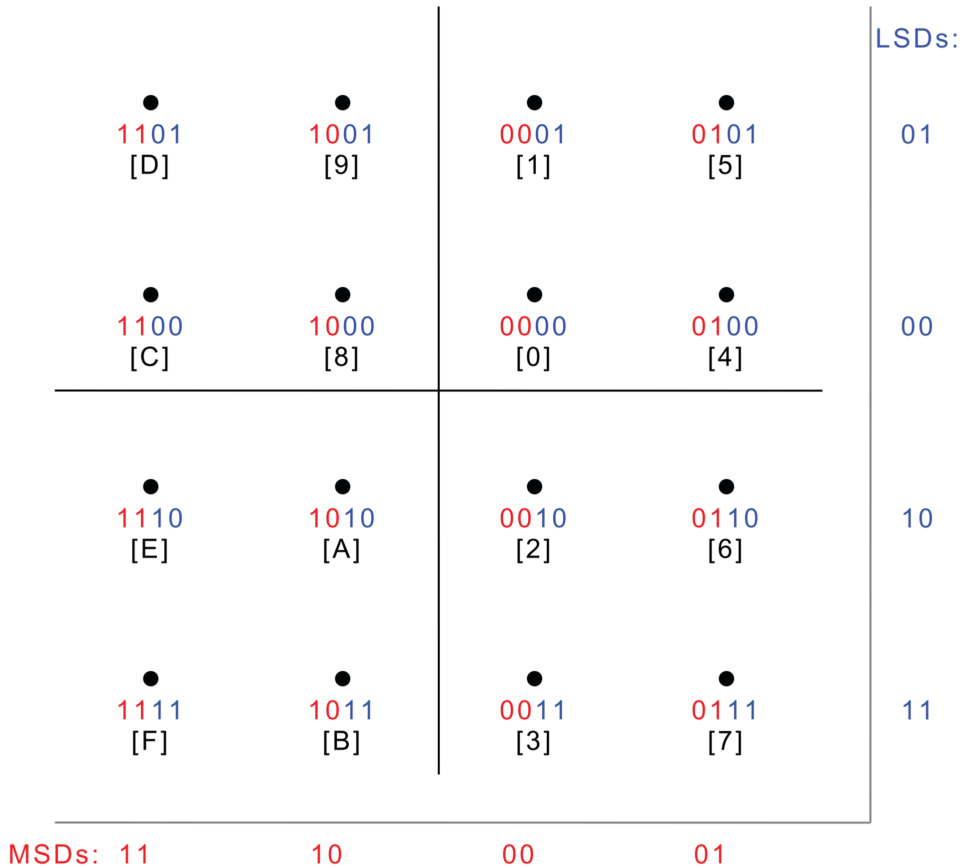


Figure 27. Quadbits [and HEX values] in the QAM constellation.

Note the order of the MSDs and the LSDs. Are they arranged consecutively?

The MSDs and LSDs are not arranged consecutively since 00 comes between 10 and 01.

The smallest distance between neighboring constellation points is the horizontal or vertical distance between consecutive points. Constellation points separated by this distance are considered to be adjacent. (The oblique distance between any two points is greater than this distance.) Note how the bits values of the quadbits change as you move from one point to any adjacent point.

Name the type of coding that is used here and explain the advantage of encoding the constellation points in this manner.

Moving from any constellation point to an adjacent point changes only one bit in the quadbit. This is an example of a Gray code, where two adjacent values differ in only one digit. The advantage of a Gray code is that when noise in the transmission channel causes a constellation point to deviate into the region of an adjacent point, only one bit is in error. When Gray coding is combined with an error correction mechanism capable of correcting single-bit errors, the transmission is less susceptible to noise.

29. Enter the three-bit Binary Sequence 111 and observe the constellation.

Change the binary Sequence to 101. Click the Drop 1 bit button several times and observe what happens.

Explain why this 3-bit sequence produces three constellation points, each of which represents four bits and why the drop 1 bit button seems to have no effect.

The number of bits in this sequence is not a multiple of four. Since the Serial to Parallel Converter groups bits four at a time, the sequence must pass four times before the system returns to its initial state (101 101 101 101). The quadbits sent to the modulator are therefore 1011 0110 and 1101. These three points appear in the constellation. Dropping one bit does not change the quadbits that this sequence produces.

30. When you have finished using the system, exit the LVCT software and turn off the equipment.

Conclusion

In this exercise, you became familiar with the LVCT software and studied the operation of the basic functional blocks of the QAM modulator. You observed that the Serial to Parallel Converter groups the input data stream into quadbits that are processed by two parallel channels, I and Q, and that the starting point of this grouping is arbitrary. You saw how the A/D Converters and the mixers generate two bi-phase, bi-level signals using two carriers in phase quadrature. You observed that summing these two signals produces the QAM signal. You also observed the signal constellations on the oscilloscope for various binary sequences.

Review Questions

1. Explain what is meant by bandwidth efficiency.

Bandwidth efficiency is a measure of how efficiently a modulation technique uses the available bandwidth. It is equal to the maximum theoretical number of bits per second that can be transmitted per unit bandwidth.

2. How does the bandwidth efficiency of QAM compare to that of other modulation techniques?

The bandwidth efficiency of QAM is twice that of QPSK and four times that of binary modulation techniques such as BPSK.

3. What does a constellation diagram represent?

The constellation diagram is a pictorial representation showing all possible signal states as a set of constellation points in the I-Q plane. Each constellation point corresponds to the head of a phasor and represents one of the symbols used by the modulation scheme. Its position in the diagram shows the amplitude and the phase of the corresponding waveform.

4. What is the role of the mixers in the QAM modulator?

Each mixer performs modulation by multiplying the sinusoidal carrier by the four-level baseband data signal. The effect of the mixer is to shift the frequency spectrum of the baseband signal up to the frequency of the carrier.

5. How are the signals at the outputs of the mixers combined to produce the QAM signal?

The I- and Q-channel mixer output signals are simply summed in order to produce the QAM signal.

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