

# LAB 3: MODULATION AND DETECTION

## I. OVERVIEW

The objective of this laboratory session is to introduce the basics of transmitter and receiver design. At the transmitter, we focus on modulation; while at the receiver, we focus on demodulation and detection. Modulation is the variation of parameters of a sinusoidal carrier according to the data. Parameters of a sinusoidal carrier are amplitude, frequency and phase. In a digital communication system, these parameters take on discrete values. In the first part of this lab, we build a modulation virtual instrument (VI) that is capable of mapping bits into digital symbols, and converting those into analog waveforms based on an appropriate modulation scheme. In the second part, we build a demodulator for the same modulation scheme to detect the received symbols and decode their bit values.

A general block diagram of a transmitter is given in Fig. 1 below:

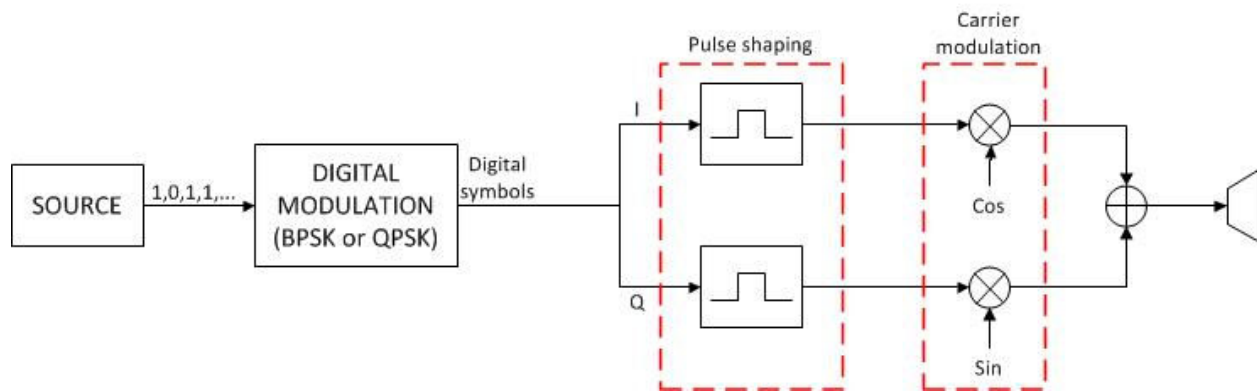


Fig. 1 – Transmitter block diagram

A general block diagram of a receiver is given in Fig. 2 below:

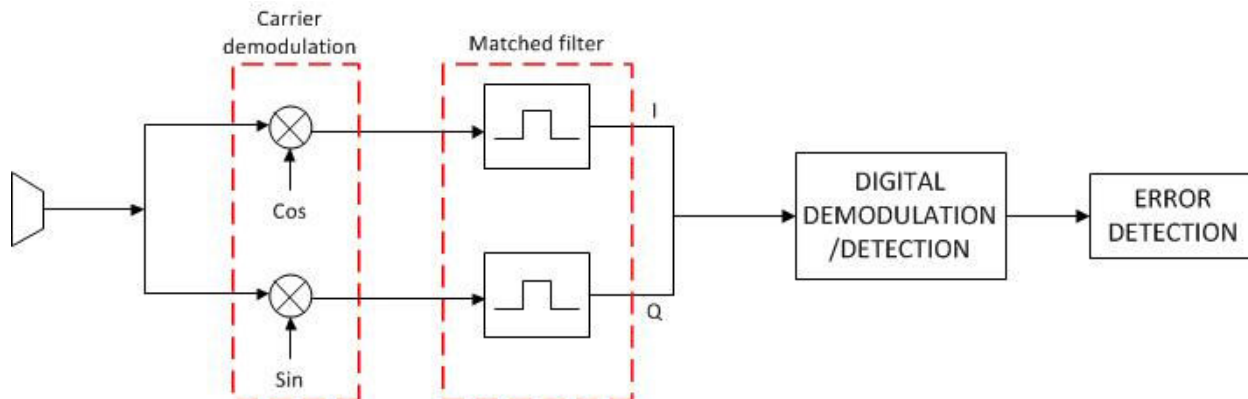


Fig. 2 – Receiver block diagram

In this lab session we implement the Digital Modulation block at the transmitter and the Digital Demodulation/Detection block at the receiver.

### PART 1: DIGITAL MODULATION

In communications, modulation is the process of varying parameters of a carrier waveform (amplitude, frequency, phase) according to an information signal (analog modulation) or information bits (digital modulation). Modulation of both amplitude and phase is implemented by varying the amplitude of two carriers, one sine and the other cosine.

In our modulation scheme, we introduce a bit stream as the input data. This bit stream may represent any data format (text, image, voice, video, etc). Then we map the input bit stream to complex numbers representing the amplitude and phase of a carrier signal at a higher frequency. These complex numbers, referred to as digital symbols, represent the amplitude and phase of a radio frequency (RF) carrier waveform. The RF signal is suitable for transmission. A representation of this process is shown in Fig. 3 below.

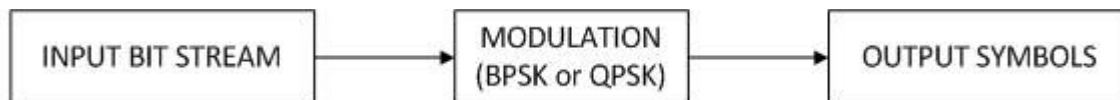


Fig. 3 – A representation of the modulation process

There are mainly two types of modulation: (i) Analog and (ii) Digital.

- (i) **Analog Modulation:** In analog modulation, both input and output signals are analog. Common analog modulation techniques are:

- a) **Amplitude Modulation (AM):** Only the amplitude is modulated. Examples of amplitude modulations are double sideband modulation (DSB), single sideband modulation (SSB), and vestigial sideband modulation (VSB).
  - b) **Angle Modulation (PM):** Only the angle (frequency or phase) is modulated, while the amplitude remains fixed (in other words, the modulated signal has constant envelope). There are two types of PM: frequency modulation (FM) and phase modulation (PM).
- (ii) **Digital Modulation:** In digital modulation, cosine and sine carriers are modulated by a discrete signal. Simple relations exist between the amplitude and phase of the modulated digital symbol and the amplitudes of the two carriers. Common digital modulations are:
- a) **Frequency-Shift Keying (FSK):** A finite number of carrier frequencies are used for modulation.
  - b) **Amplitude-Shift Keying (ASK):** A finite number of carrier amplitudes are used for modulation.
  - c) **Quadrature Amplitude Modulation (QAM):** Discrete amplitude and phase modulation.
  - d) **Phase-Shift Keying (PSK):** A finite number of phases of the carrier are used for modulation. Examples of common PSK techniques include: Binary PSK (BPSK), quadrature PSK (QPSK), 8PSK, 16PSK, and differential PSK (DPSK).

In this lab, we work with two PSK modulation schemes: BPSK and QPSK.

- (i) **Binary Phase Shift Keying (BPSK):** BPSK is the simplest form of phase shift keying techniques. It has two symbols with  $180^\circ$  phase difference. In other words, symbols are purely real, distinguished by a sign difference. Set of possible outputs, then, can be written as follows:

$$A_{BPSK} = \{\sqrt{E}, -\sqrt{E}\} \quad (1.1)$$

where E is the symbol energy.

*Constellation diagram* is a tool used to represent symbols according to their in-phase (I) and quadrature (Q) coordinates. The constellation diagram of BPSK signals with symbol set (1.1) is depicted below in Fig. 4.

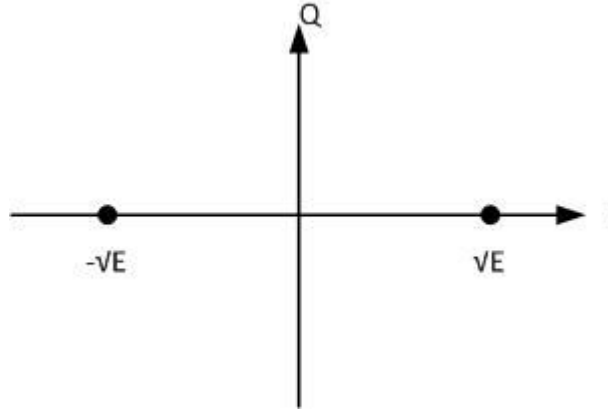


Fig. 4 – Constellation diagram for BPSK signal set given in (1.1)

Note that the distance between the constellation points is  $d = 2\sqrt{E}$ .

The BPSK probability of error is given by the expression:

$$P_e = Q\left(\sqrt{\frac{2E}{N_0}}\right) \quad (1.2)$$

where  $N_0$  is the noise power spectral density. Denoting  $d = 2\sqrt{E}$ , we can rewrite (1.2) in terms of the distance between constellation points:

$$P_e = Q\left(\sqrt{\frac{d^2}{2N_0}}\right) \quad (1.3)$$

- (ii) **Quadrature Phase Shift Keying (QPSK):** QPSK has four symbols spaced at  $90^\circ$  phase difference. The set of possible outputs, then, can be written as follows:

$$A_{QPSK} = \left\{ \left( \sqrt{\frac{E}{2}} + j\sqrt{\frac{E}{2}} \right), \left( -\sqrt{\frac{E}{2}} + j\sqrt{\frac{E}{2}} \right), \left( -\sqrt{\frac{E}{2}} - j\sqrt{\frac{E}{2}} \right), \left( \sqrt{\frac{E}{2}} - j\sqrt{\frac{E}{2}} \right) \right\} \quad (1.4)$$

The constellation diagram for BPSK signal with the symbol set (1.4) is depicted below in Fig. 5.

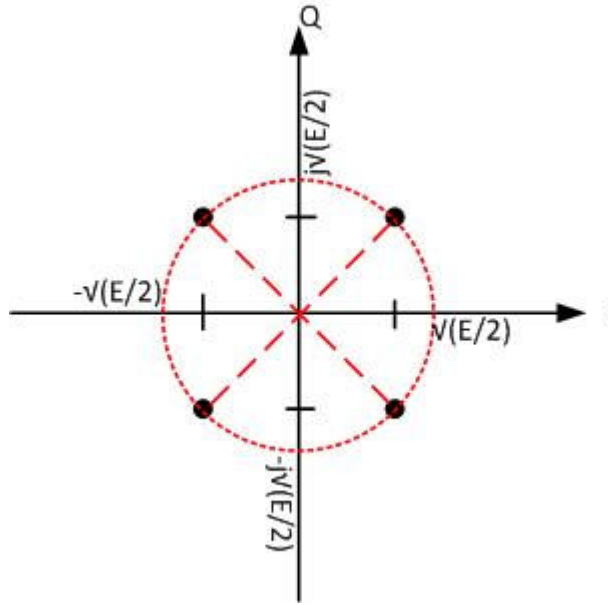


Fig. 5 – Constellation diagram for QPSK signal set given in (1.4)

Note that the minimum distance between two constellation points for QPSK is  $d = \sqrt{2E}$  (Fig. 6). Hence, the probability of error is given by:

$$P_e = Q\left(\sqrt{\frac{E}{N_0}}\right) \quad (1.5)$$

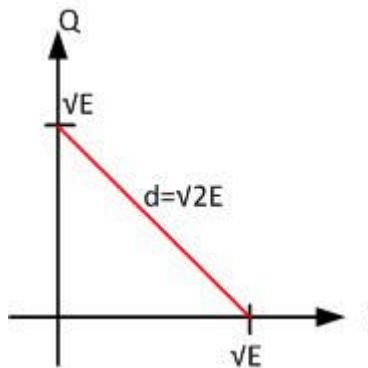


Fig. 6 – Minimum distance between two QPSK constellation points (45° phase shifted constellation is used here for simplicity)

The modulation is implemented via a LabVIEW virtual instrument (detailed in Section II of the lab instructions). The VI is designed such that it maps the input bit sequence to symbols according to the selected modulation type.

**The mapping procedure for BPSK:**

1. Take the input bit stream and divide it by 2.
2. Use the remainder of this division (either 0 or 1) as the index. Please refer to the example below:

Input Bit Stream									
1	0	1	1	0	1	0	0	1	0

From binary to decimal conversion:  $1011010010 = 1*2^1+1*2^4+1*2^6+1*2^7+1*2^9 = 722$

Remainder of  $(722/2) = 0$

**The mapping procedure for QPSK:**

1. Take the input bit stream and divide it into two sub-arrays: even and odd.
2. Multiply even array members by 2, and add the odd array.
3. Divide this sum by 4, and use the remainder (can be 0, 1, 2, or 3) as the index to pick the appropriate constellation points to use. Please refer to the example below:

Input Bit Stream									
1	0	1	1	0	1	0	0	1	0

Element 1 - even (of Decimate 1D array)					Element 2 - odd (of Decimate 1D array)				
1	1	0	0	1	0	1	1	0	0

From binary to decimal conversion:  $11001 = 1*2^0+0*2^1+0*2^2+1*2^3+1*2^4 = 1+8+16 = 25$  and  $01100 = 0*2^0+0*2^1+1*2^2+1*2^3+0*2^4 = 4+8 = 12$

Sum =  $2*(\text{Element 1}) + (\text{Element 2}) = 2*25+12 = 62$

Remainder of  $(62/4) = 2$

**PART 2: DIGITAL DEMODULATION/DETECTION**

Demodulation is the process of extracting the original information-bearing signal from a modulated carrier wave. A demodulator is an electronic circuit (or LabVIEW program in our software-defined radio system) used to recover the information content from the modulated carrier wave. The demodulation type should match the modulation type to successfully retrieve the information from the incoming radio wave.

Since the signal is received in the presence of noise, the discrete amplitude and phase values obtained from the demodulation, will generally not be exactly equal to any of the transmitted digital symbols. The process of deciding which symbol was transmitted based on the the demodulated value is called detection. In our detection scheme, we receive the modulated signal sent from the transmitter and obtain the input bit stream using a Maximum Likelihood (ML) detection algorithm. A representation of this process is given in Fig. 7 below.

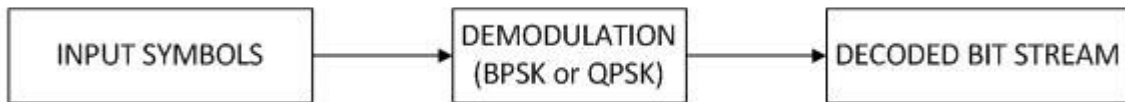


Fig. 7 – A representation of the demodulation process

### **Maximum Likelihood (ML) Detection**

ML is a commonly used detection algorithm. Let the discrete time signal model representing the received signal be

$$r = s_m + n$$

where  $s_m$ ,  $m = 1, \dots, M$  is a digital symbol in a set with  $M$  possible symbols, and  $n$  is noise. The ML is a mathematical approach that can be shown to result in a minimum distance decision rule, i.e., the symbol decision is in favor of the symbol  $s_{m_0}$  nearest to the received symbol  $r$ .

Mathematically, this is expressed

$$\hat{s} = \arg \min_{1 \leq m \leq M} \|r - s_m\|^2 \quad (1.6)$$

where  $\hat{s}$  is the estimated symbol. The ML decision rule is illustrated in Fig. 8.

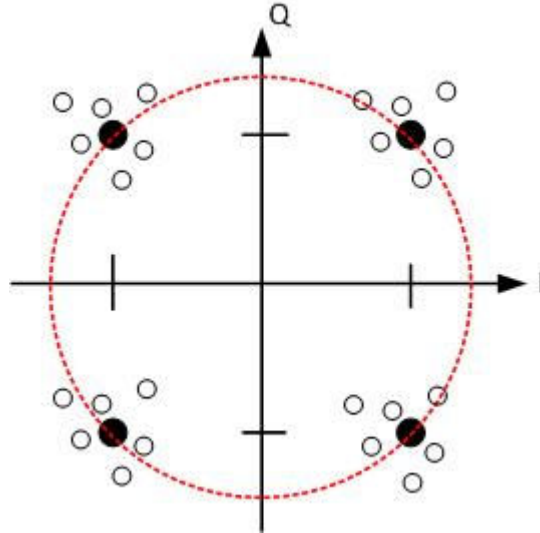


Fig. 8 – Illustration of the estimated symbols (clear points) around the real symbol (black points) on a QPSK constellation diagram.

Detected bit stream will be observed in two ways: (i) constellation diagram, (ii) eye diagram.

**Eye Diagram**

In digital communications, an eye diagram is used to visualize the effect of noise and signal distortion as a result of transmission over a channel. The eye diagram overlays a sequence of received pulses.

The eye diagram plots the signal levels on the vertical axis versus the normalized time on the horizontal axis. For example in a BPSK system there are four possible transition states: (i) from  $\{+1\}$  to  $\{+1\}$ , (ii) from  $\{+1\}$  to  $\{-1\}$ , (iii) from  $\{-1\}$  to  $\{+1\}$ , and (iv) from  $\{-1\}$  to  $\{-1\}$ . A visualization of these transitions is shown in Fig. 9.

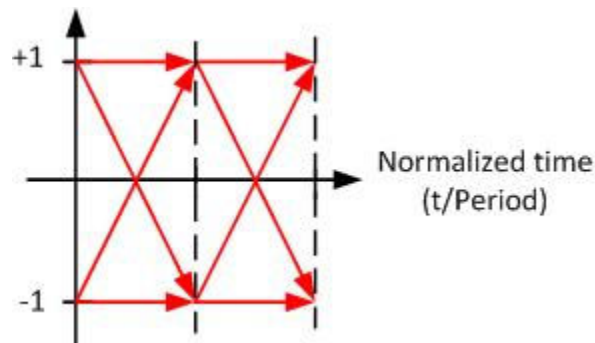


Fig. 9 – Visualization of transitions on an eye diagram

The eye diagram of a BPSK system is shown in Fig. 10(a) and the eye diagram of the same system with multipath interference is shown in Fig. 10(b) <sup>[1]</sup>.



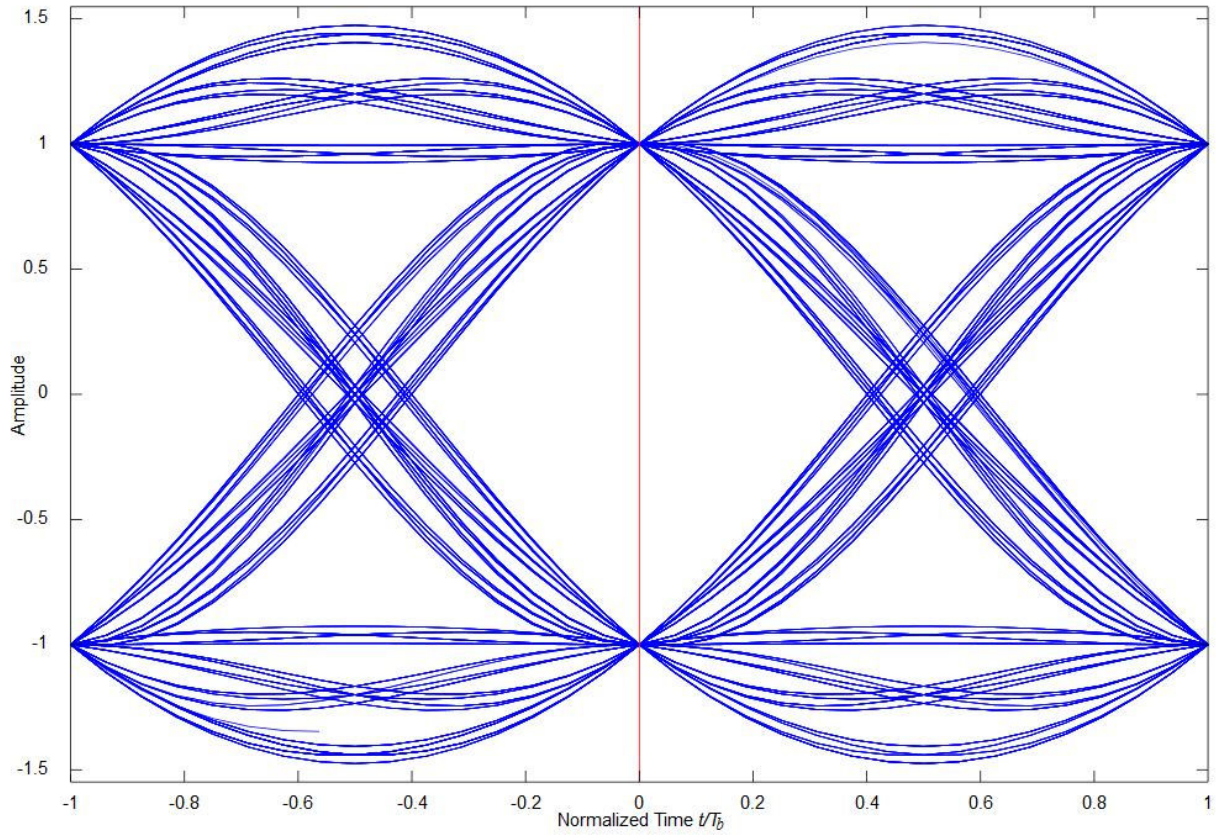


Fig. 10(a) - The eye diagram of a BPSK system

The opening in the middle is called “eye opening”, which measures the effect of additive noise on the signal. Namely, if there is more noise (or symbol interference), the opening will be narrower.

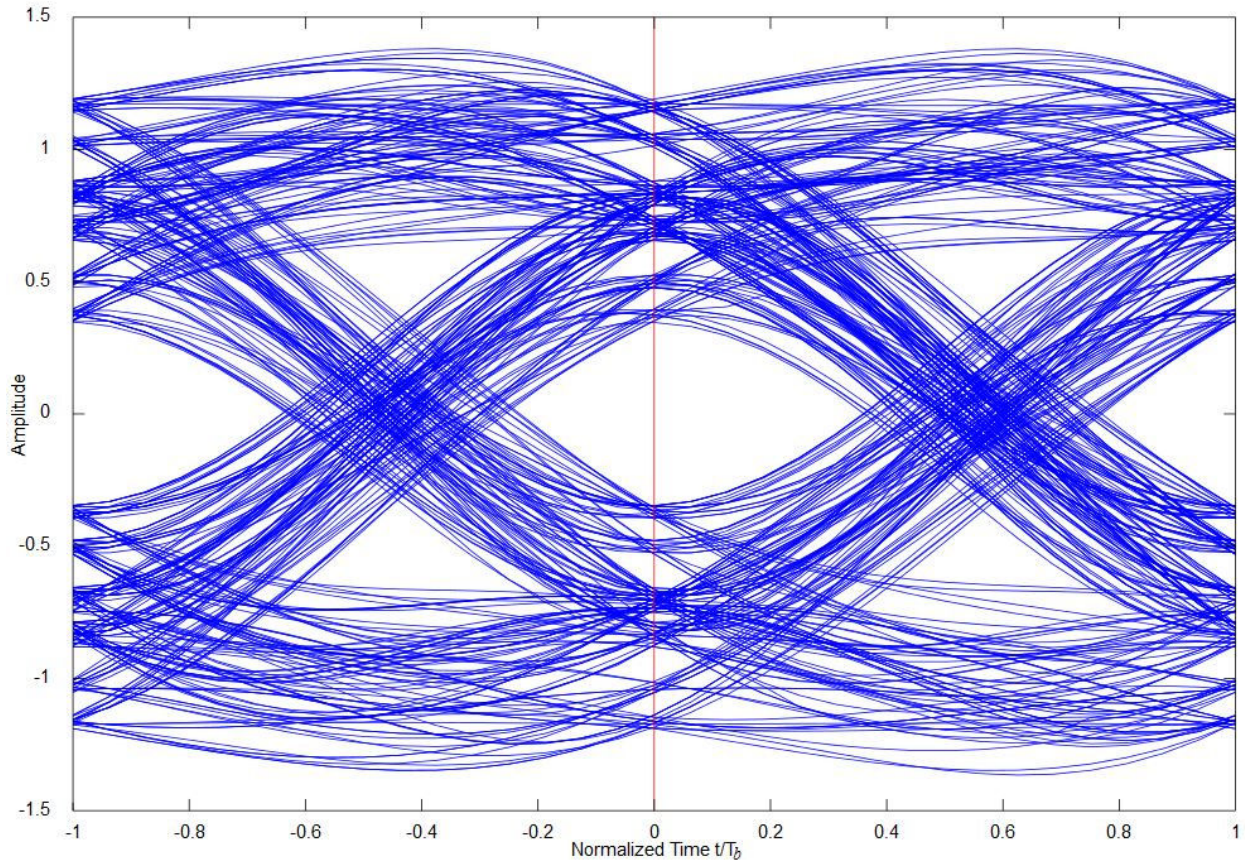


Fig. 10(b) - The eye diagram of the same system with multipath interference

As it can be seen on Fig. 10(b), multipath introduces delayed copies of the same symbol to the receiver. This causes a narrower eye opening.

AH The detection is implemented via a LabVIEW virtual instrument (which will be detailed in section II. Lab). The VI is designed such that it maps the input symbols to a detected bit stream using the results of maximum likelihood estimation algorithm and based on the selected modulation type. WHAT IS THIS PAR ABOUT?

### **Frequency Offset**

Mixers coupled with local oscillators are used to transform the modulated data from one frequency to another (i.e., from baseband to RF for transmitter, and from RF to baseband for receiver). See Fig. 11(a) and (b) for receiver and transmitter block diagrams.

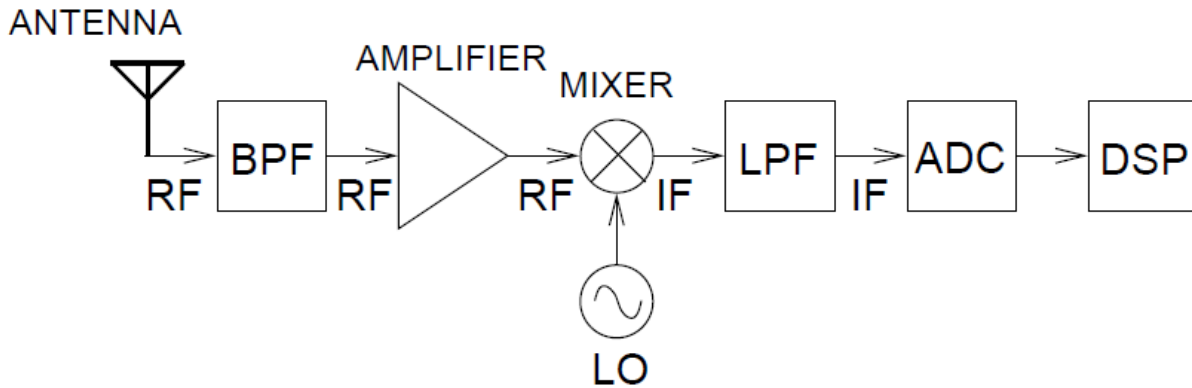


Fig. 11(a) – Generalized representation of a receiver with one mixer stage

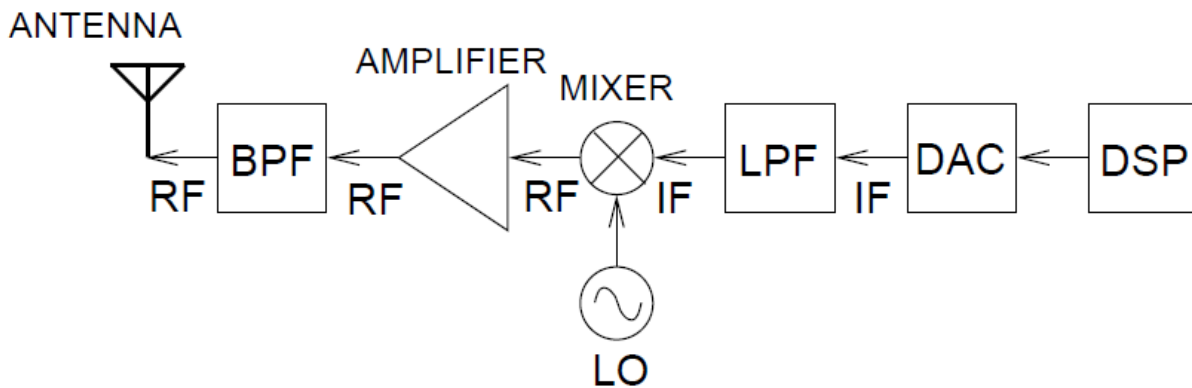


Fig. 11(b) – Generalized representation of a transmitter with one mixer stage

At the transmitter, a baseband signal, constituted by a sequence of pulses representing digital symbols, modulates an intermediate frequency (IF) carrier. The IF signal is up converted by a mixer to RF for transmission over the air.

At the receiver, the received RF signal is stepped down to IF using a mixer stage. Subsequently, the IF signal is demodulated to baseband. With the mixer driven by a large local oscillator (LO) signal, the output at the intermediate frequency (IF) is at the difference frequency of the RF and LO (see Fig. 12). Thus  $f_{IF} = |f_{RF} - f_{LO}|^{[2]}$ .

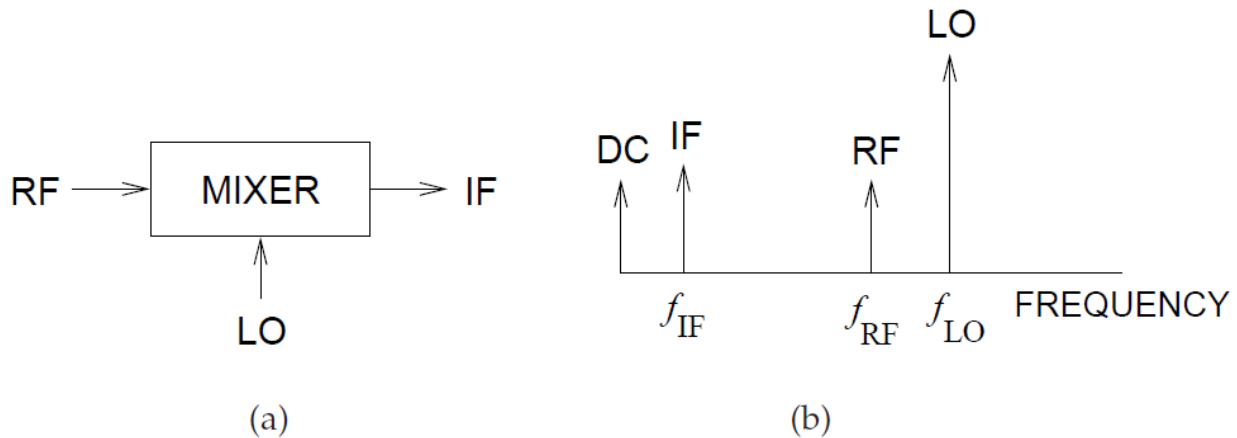


Fig. 12 – Simple mixer circuit: (a) block diagram and (b) spectrum

A frequency offset may be introduced by a mismatch between the carrier frequency of the received signal and the frequency of the LO. Let  $\Delta f$  be this frequency offset, then

$$\Delta f = |f_R - f_S| \quad (1.7)$$

Simply, the received bandpass signal is given as:

$$r(t) = \sqrt{2} \cdot \Re \left\{ \tilde{r}(t) e^{j2\pi f_R t} \right\} \quad (1.8)$$

where,

$$\tilde{r}(t) = \tilde{s}(t) e^{-j2\pi \Delta f t} \quad (1.9)$$

From the equation above it can be concluded that frequency offset is a time varying *rotation* of the transmitted complex baseband samples in baseband level.

Frequency offset correction process removes this time varying rotation by compensating the frequency offset between transmitter and receiver.

[1] Figure reference: [http://en.wikipedia.org/wiki/Eye\\_pattern](http://en.wikipedia.org/wiki/Eye_pattern) (Last accessed: January 2013).

[2] "Microwave and RF Design: A Systems Approach", Michael Steer, 1st Ed., 2010.