CS 4457: IQ Sampling and Modulation Notes

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1 IQ Sampling and Modulation

1.1 Physical Layer

The physical layer is the first/lowest layer of the Open System Interconnection (OSI) model. It manages the transmission and reception of bits from one computer to another through "physical" means such as an Ethernet cable.

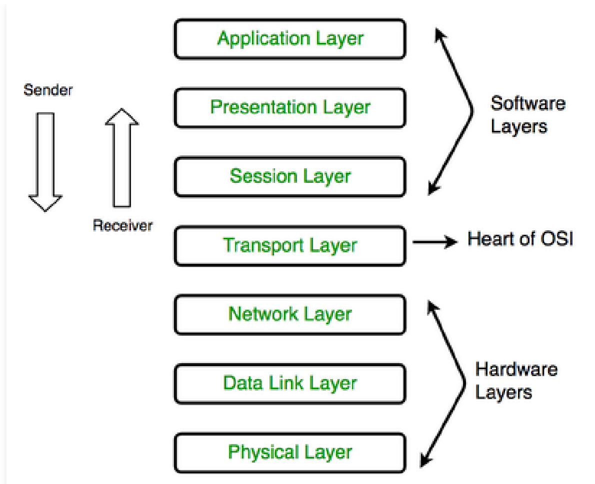

Figure 1: Layers of the OSI Model

1.2 Analog to Digital

In order to create a generic radio that can be controlled with software, we would need a method to convert an analog signal to a digital signal. Thus, we use an Analog to Digital Converter (ADC) which takes a continuous signal and returns an array of discrete values. However, if the sampling rate of the ADC is slow, the digital signal could greatly differ from the original signal. Therefore, a mixer is utilized (as shown in Figure 2) to shift the analog signal to a lower frequency range that the ADC can handle by calculating the sum and the difference of the original signal and a local oscillator.

With only one mixer, we are unable to determine whether the analog signal is leading or lagging the local oscillator. To distinguish the signals, we add in another mixer that is 90° shifted in phase which is displayed in Figure 3.

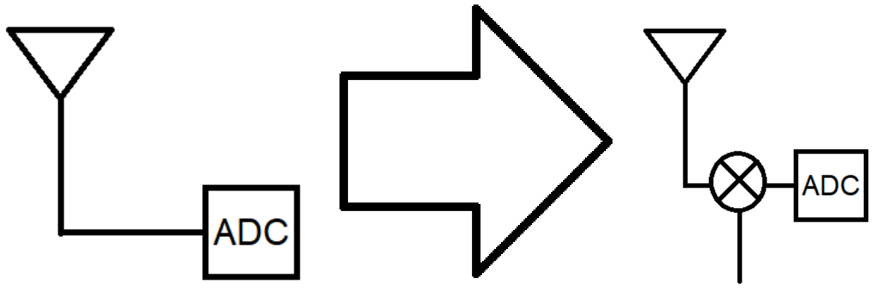

Figure 2: Circuit with and without mixer

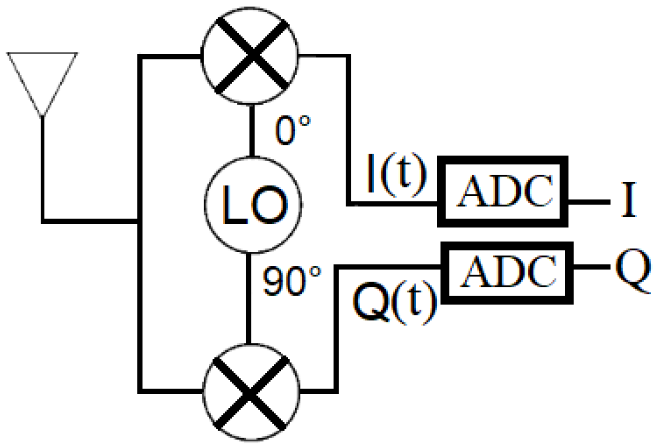

Figure 3: Circuit with two mixers

1.3 Phasors

A phasor is a counter-clockwise rotating vector which has both a magnitude and direction/phase value to represent a sinusoidal signal. A sinusoidal signal would generally have the form

$$v(t) = v_m \sin(\omega t + \phi) \tag{1}$$

where v_m is the peak amplitude, ω is the angular frequency, t is time, and ϕ is the phase shift.

The rectangular form of a phasor is represented as a complex number such that

$$v = A \pm jB \tag{2}$$

where $A = v_m \cos(\phi)$ and $B = v_m \sin(\phi)$. The amplitude of the phasor can be found by calculating

$$v_m = \sqrt{A^2 + B^2} \tag{3}$$

and the phase can be found by calculating

$$\phi = \tan^{-1}(\frac{B}{A}) \tag{4}$$

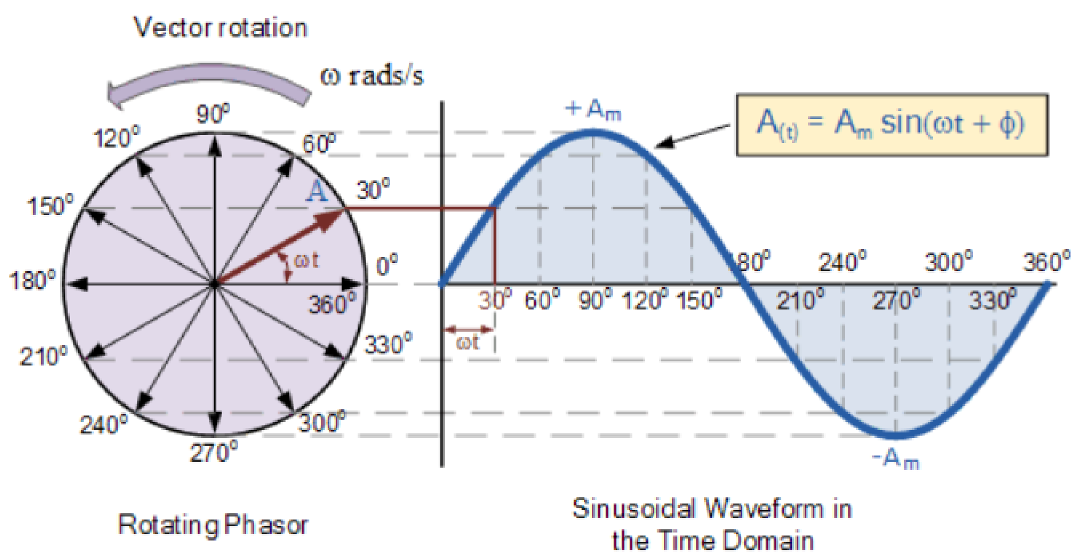

Figure 4: Phasor

1.4 Quadrature Signals

Quadrature signals, also known as IQ signals, are a pair of periodic signals that differ in phase by 90° where I is the reference signal and Q is the phase shifted signal which is displayed on Figure 3. The IQ signals are retrieved after sampling through the ADC and can be represented as a tuple (I,Q) or as a complex number.

1.5 Software Defined Radio

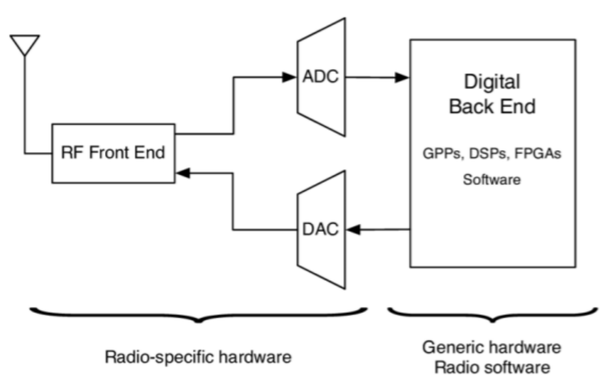

Figure 5: SDR Block Diagram

A software defined radio (SDR) is a radio communication system that is implemented by means of software which then uses a analog-to-digital converter preceded by a Radio Frequency (RF) front end as shown in Figure 5. This means we can listen to anything in the RF spectrum and we have a lot of access to the physical layer using only software. In Figure 6, example code for an SDR is displayed below:

```python
from rtlsdr import RtlSdr

sdr = RtlSdr()
# configure device
sdr.sample_rate = 2.048e6 # Hz
sdr.center_freq = 70e6 # Hz
sdr.gain = 'auto'

print(sdr.read_samples(12))
```

Figure 6: SDR Code

The output of the code is

$$
\begin{aligned}
3.8327988140722237246e-03-3.8144421188020839 75e-03j \\
-3.8411289568189687 51e-03-2.0640525280901178 90e-03j \\
-2.1702160426700423 98e-03-1.5655523419097552 85e-03j \\
-2.9318138357587058 59e-03-3.2572859202913578 32e-03j \\
-2.5139697280808534 32e-03-2.9346896257576482 63e-03j \\
-3.1993190002188179 67e-03-1.2258066728467091 96e-03j \\
-3.8028036832013960 64e-03-2.2219956245970273 57e-03j \\
-2.4258618205199146 76e-03-3.9927237716072799 12e-03j \\
-2.6061265653940794 87e-03-2.1612007696324504 92e-03j \\
-2.3307597428396716 75e-03-3.4008286059987214 18e-04j
\end{aligned}
$$

These complex numbers are the aforementioned IQ values that require extraction from an altered (modulated) signal in order to retrieve the information of the real signal and this process is called demodulation.

1.6 Radio Frequency Modulation

An unmodulated RF carrier is a simple sine wave with the form of equation 1. Information such as voice can be transported by an RF carrier through modulation by altering the RF signal. For example, changing the amplitude over time for an RF signal is called amplitude modulation (AM) while changing the frequency over time for an RF signal is called frequency modulation (FM).

For FM, the change in phase with time is directly related to the change in frequency which means the values of the original signal can be recovered by calculating the change in phase (demodulation).

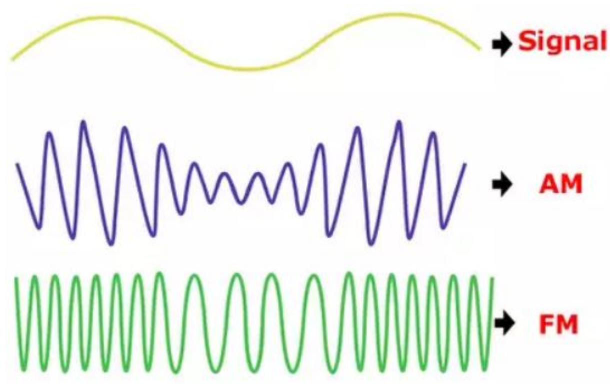

Figure 7: Amplitude Modulation and Frequency Modulation

In Figure 8, the angles of the two phasors can be calculated using equation 4 where $I = A$ and $Q = B$ in order to find the difference between the phases. For example, the angle of $A1$ is found by calculating

$$\phi_1 = \tan^{-1}\frac{Q_1}{I_1}$$

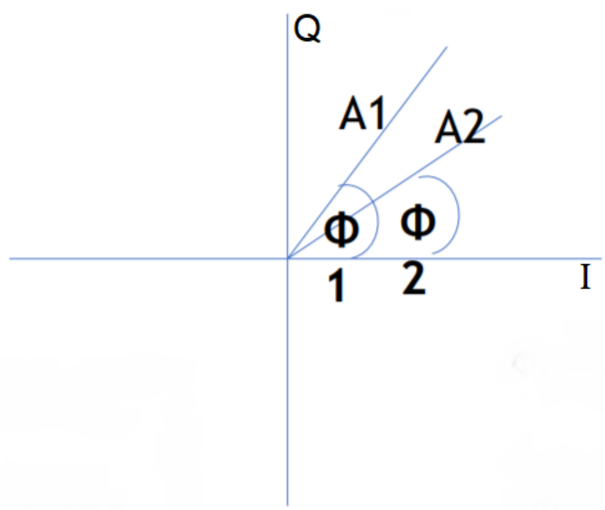

Figure 8: Two IQ Phasors

Euler's Formula

$$e^{j\phi} = \cos(\phi) + j\sin(\phi) \tag{5}$$

To improve the previous method of demodulation, we will use a **polar discriminator** which utilizes Euler's Formula. With two phasors of the form $e^{j\phi}$, the difference in phase can be found by getting the complex conjugate of one phasor and multiplying it to the other phasor:

$$e^{j\phi_2} \cdot e^{-j\phi_1} = e^{j(\phi_2 - \phi_1)} \tag{6}$$

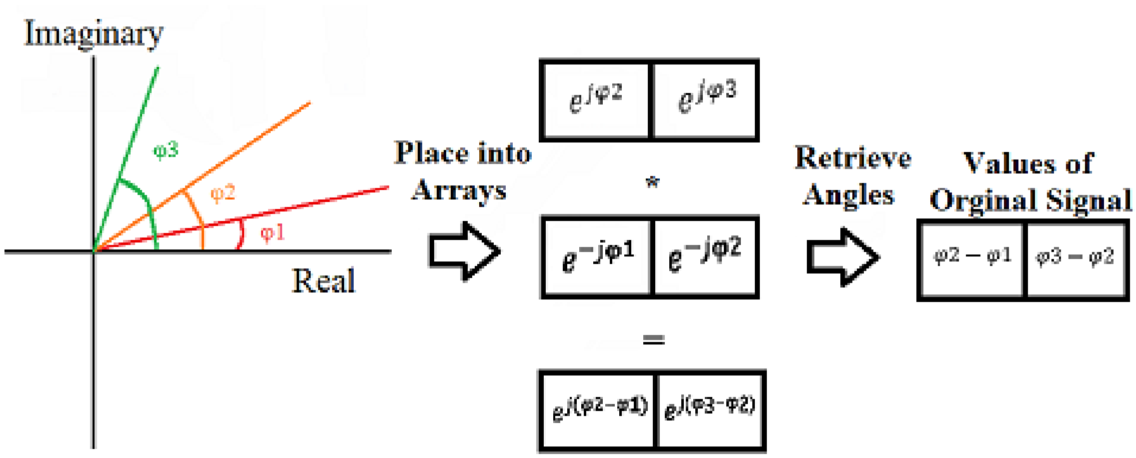

Figure 9: Polar Discriminator Example

1.7 Phase Shift Keying and Quadrature Amplitude Modulation

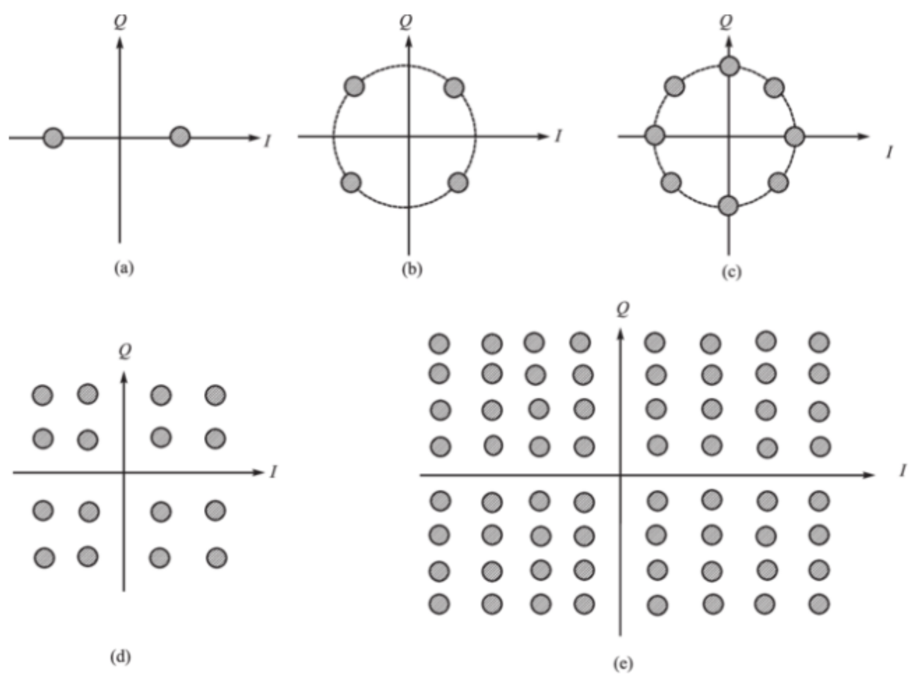

Figure 10: Constellation Diagrams

Phase shift keying is another RF modulation technique where the phase is changed over time. In Figure 10, various digital RF modulation methods are displayed by changing I and Q over time.

(a) A Binary Phase Shift Keyed (BPSK) RF signal is when $Q = 0$ and I over time alters between $+1$ and -1 by a controlled digital bit. When $I = +1$, the sum of the quadrature signals is in $0°$ phase while when $I = -1$, the sum of the quadrature signals is in $180°$ phase.

(b) Quadrature Phase Shift Keying (QPSK) modulation is when two digital bits are utilized to control the values of Q and I. One bit changes the value of Q to -1 and $+1$ and the other bit does the same for I. When I and Q are both equal to $+1$, the sum of the quadrature signals is in 45° phase with the other three phases being separated by either 90° or 180° depending on the I and Q values.

(c) Eight Phase Shift Keying (8PSK) adds more states by implementing three digital bits where each adjacent phase is separated by 45°.

(d) Sixteen Quadrature Amplitude Modulation (16QAM) utilizes four digital bits where I and Q have four discrete values to choose from. Furthermore, the amplitude is no longer the same for every state, so there are 16 total states of phase and amplitude.

(e) Sixty-Four Quadrature Amplitude Modulation (64QAM) is an even more complex modulation which uses six digital bits such that there are 64 possible states of phase and amplitude.

1.8 Packets

Packets are fixed-size units of data to be transmitted across a network. For example, imagine sending an image to another computer. There are too many bits within the image to send the data all together, so the computer breaks down the picture to multiple smaller parts called packets which have a source and destination. Routers move these packets through "routes" in the network and if these routes are congested, the router will redirect the packets to another path to get the packets to their destination.

1.9 Upsampling and Downsampling

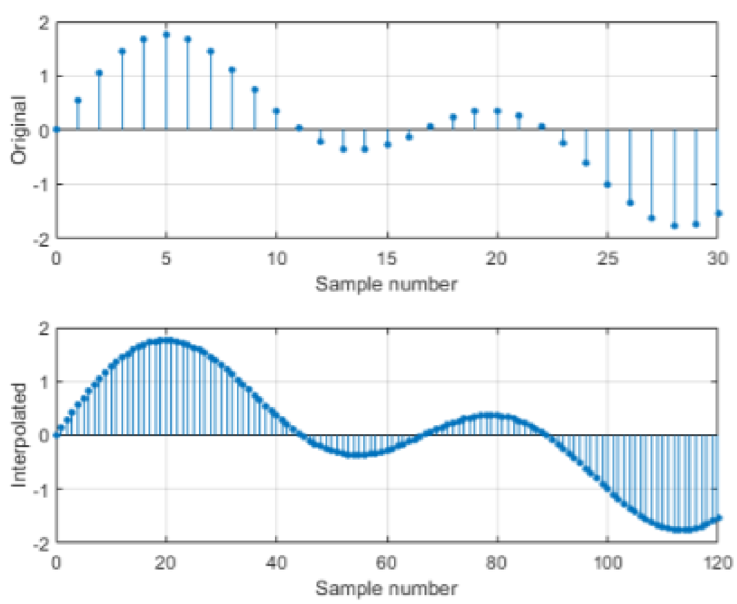

Figure 11: Upsampling Example

Upsampling is the process of increasing the sampling rate by interpolating between samples. This means that for neighboring samples, an averaged sample value of those consecutive samples is placed in between as a guess to better represent the original signal.

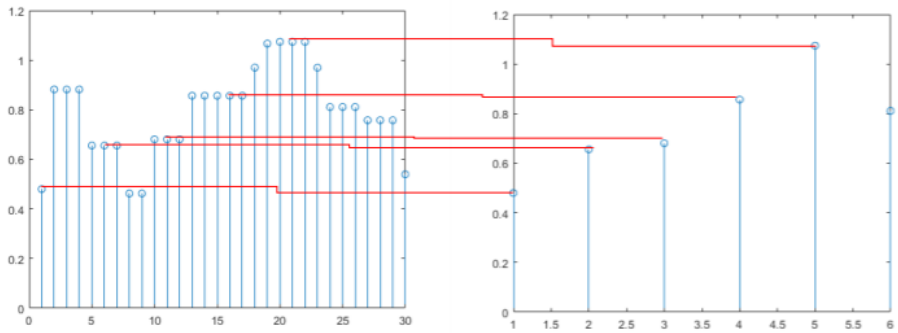

Figure 12: Downsampling Example

Downsampling is the process of decreasing the sampling rate by selecting one sample in a sliding window of some number of samples to represent the original signal. For example, in Figure 12, for every five samples, the first sample is chosen.

While upsampling is a safer method as information will not get lost, downsampling is computationally efficient due to less samples having to be taken.

1.10 Amplitude Demodulation and Envelope Detection

The envelope detector takes an inputted signal and returns an "envelope" of the signal, it basically flows the peaks of the signal shown in Figure 13. Amplitude demodulation is the process in which a signal is applied to a carrier. This process extracts the original signal containing the information desired.

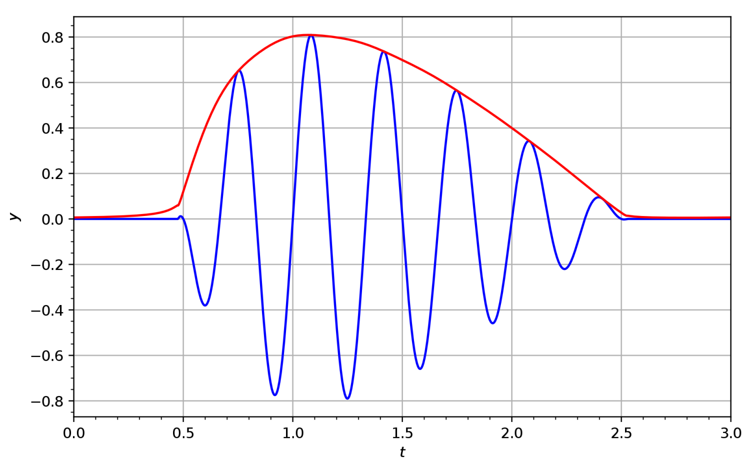

Figure 13: Envelope Detector

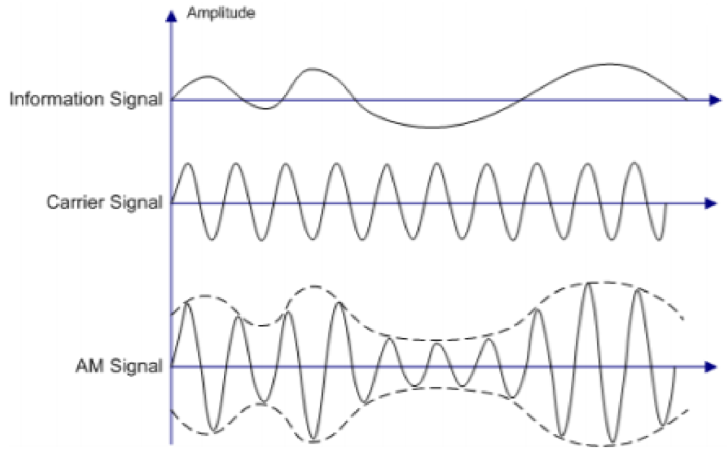

Figure 14: Amplitude Demodulation