May NVARC Meeting Agenda!

16July20

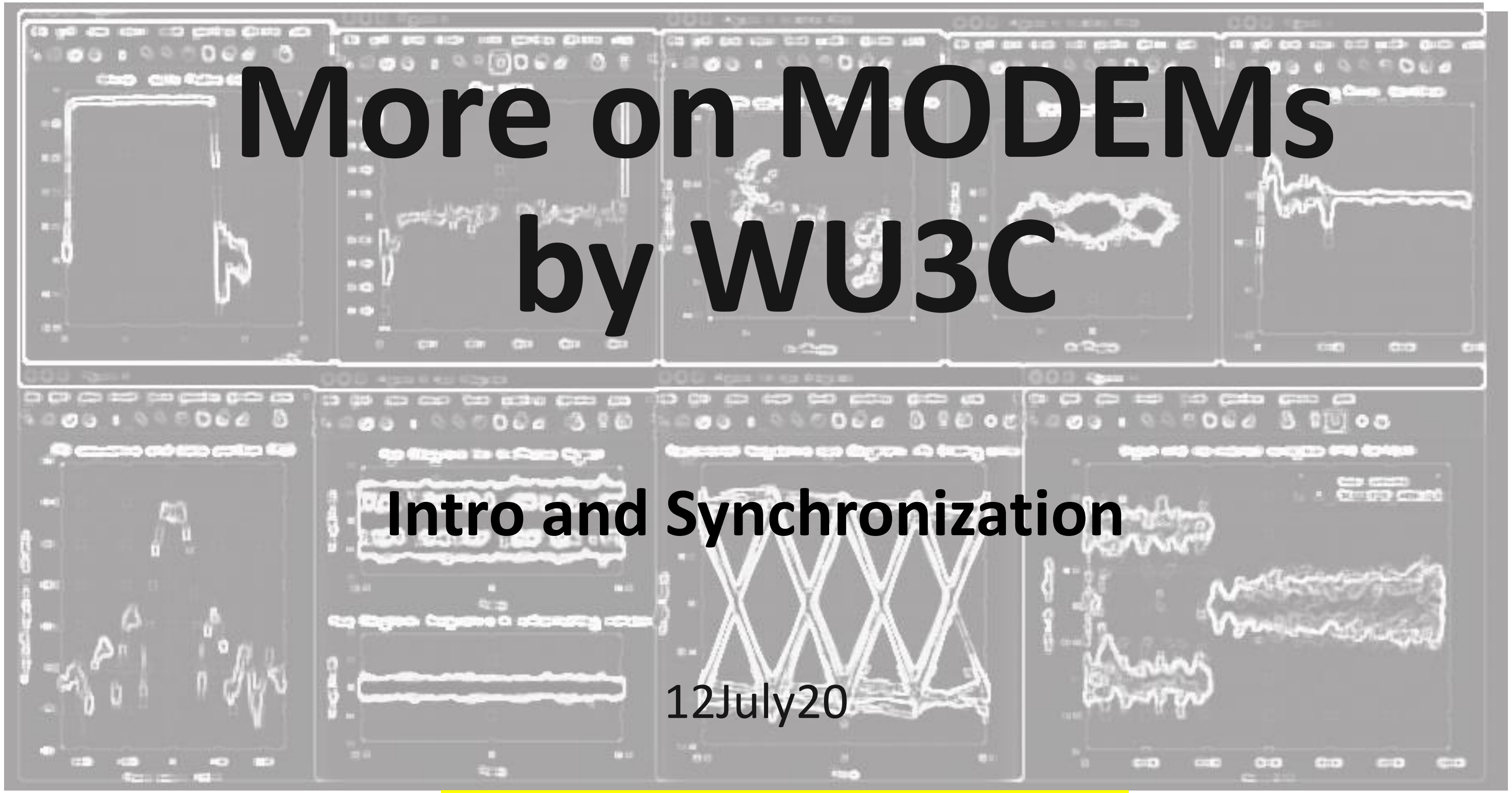
Activities New and Old

- Activities status
  - Member’s items of interest!
    - [Anything anyone wants to talk about for a ½ minute or 2]
    - HSMM mesh – Skip ?
  - contests and operating events
    - FD report
  - Seeds
    - How about the 2x18650 vs. lantern battery challenge?
    - Jessica’s Mobile radio ralley!

THE MAIN EVENT

WU3CC presentation of Synchronization in MODEMS

Providing interest is present



More on MODEMs by WU3C

Intro and Synchronization

12July20

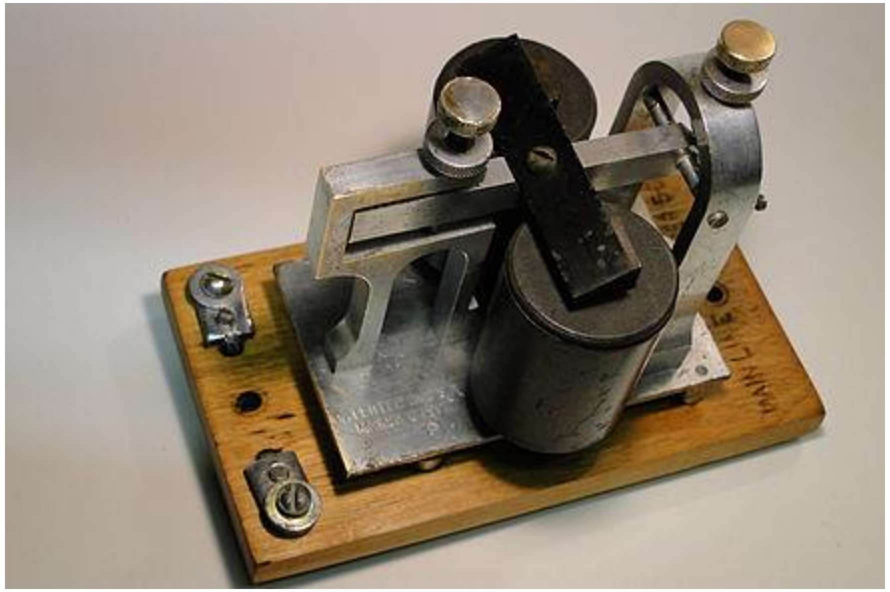
Caution: this is a fairly raw presentation!

MODEM old and new

<u>A system that allows reliable transmission of information over a channel</u>

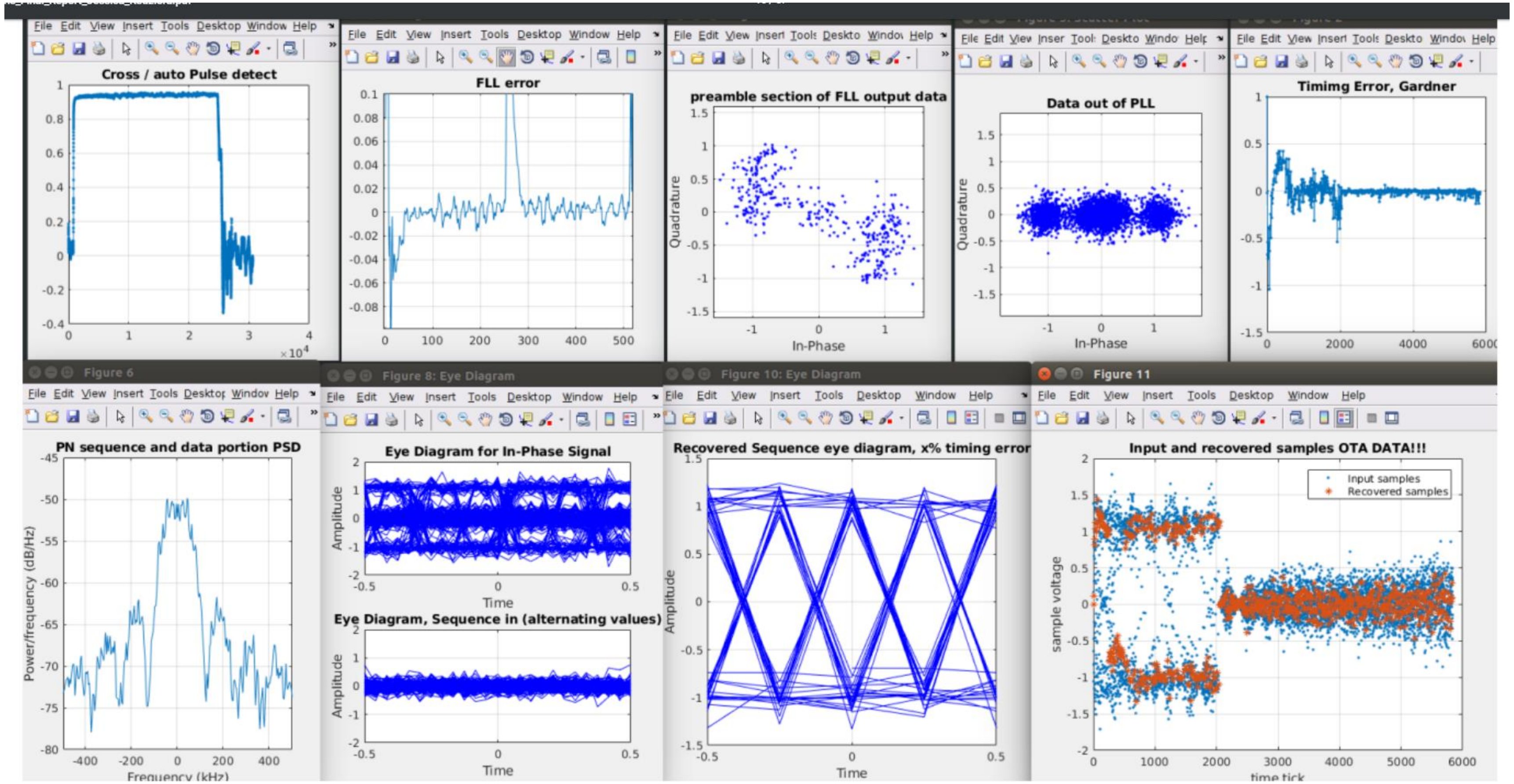
The MODEMs job is ubiquitous, and taken completely for granted

~45BPS



~100 000 000 000 bps

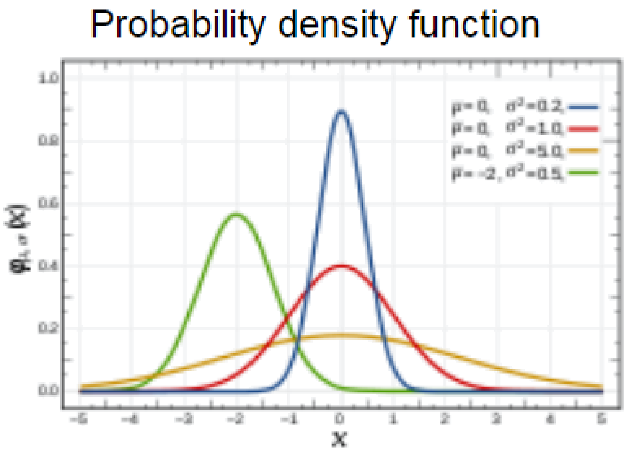
Goal: understand these images



Signal to noise ratio? REVISIT

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

- Also pretty easy for hams:
  - Ratio of signal power to noise power
  - Handy to normalize to 1Hz to avoid confusion (not common in HR)
  - AWGN: jargon, Additive White Gaussian Noise



The red curve is the *standard normal distribution*

- Confusion results when signal occupied bandwidth is much smaller than bandwidth used to compute noise power.

- “Boiled down” Eb/No – energy per bit to the noise power in 1 hz BW (GAUSSIAN)
- “SNR” is then C/N = Eb/No * (R/B), where

  R = bit rate B = channel bandwidth

http://www.sss-mag.com/ebn0.html

BER: Bit error rate

- The charts are ubiquitous in comms
  - Could spend hours just on this!
- They allow equal comparison of modulation schemes.
- Coherent modulation advantage is the basic motivation of this talk!
- Need to understand what it is and how to implement it

<u>Coherent = better, but comes with burden</u>

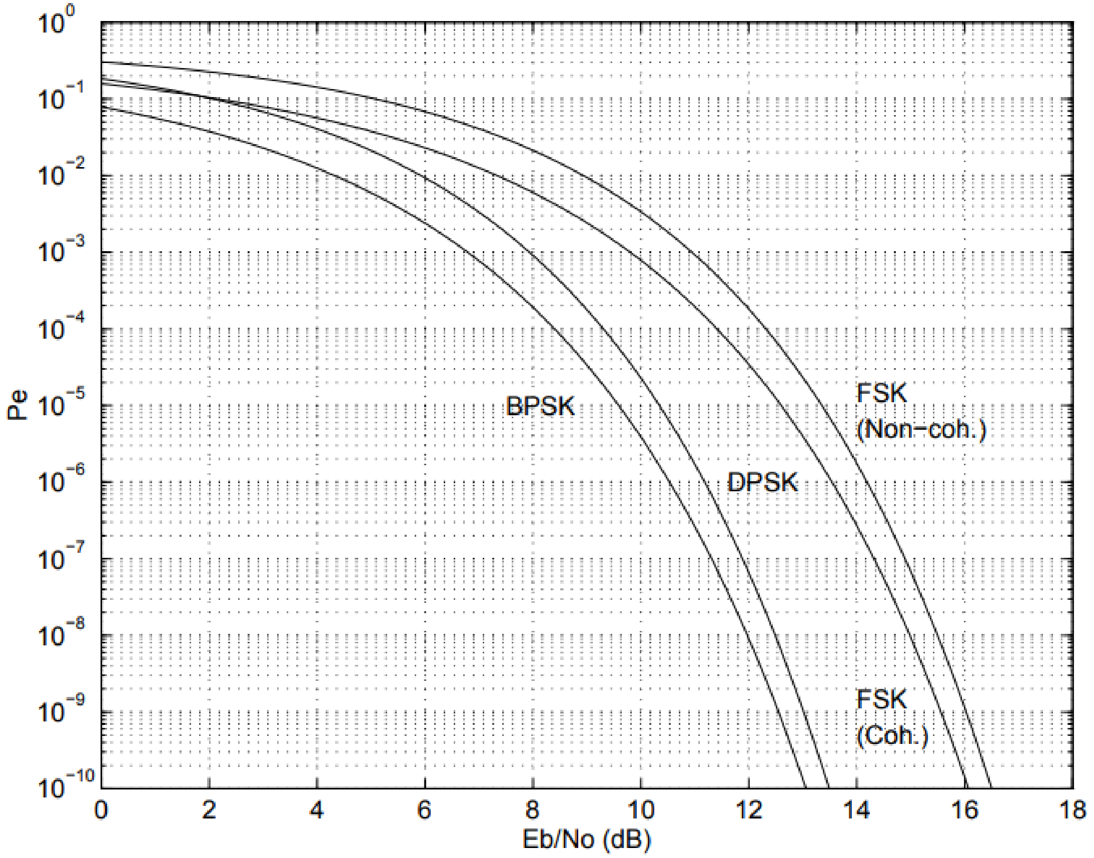


Figure 2.21: P_b for BPSK, DBPSK, and FSK

Symbol error rate vs. bit error rate

- Some confusion occurs in error rate graphs when symbol error rate is reported vs bit error rate
- Not super simple actually
  - Given N bits per symbol, Bit error rate is *approximately* symbol error rate / N
  - How bits are mapped and symbol probability change this though.

https://dsp.stackexchange.com/questions/58124/why-is-bit-error-rate-symbol-error-rate-number-of-bits-per-symbol-in-qpsk

What is a channel: a big question, but to chop it down:

- A medium with
  - Finite delay
  - AWGN noise (flat frequency noise)
  - Could contain impairments:
    - Multipath or echoes (memory and delay spread)
    - Fading not from multipath (variable loss)
    - Doppler
    - Interference
    - Distortion, dispersion
  - Where hardware is included, fixed and nonstationary
    - Frequency and phase error
    - Timing error
    - Distortion
    - Non AWGN noise

$$H(f,\tau,t)$$

What is a channel: a big question, but to chop it down:

$$H(f,\tau,t)$$

- Wireless channels are generally linear (very helpful!)
  - Not always.EG:
    - when plasma's are present
    - Fiber under high power
- Can be represented as a linear frequency dependent transfer function with memory
- *Hams deal with VERY MILD channels: human ear can tolerate very little impairment.*

Shannon's Channel Capacity

- Absolute lower limit computed using the Information matrix
  - Proof is difficult
- Channel Capacity = C = Bw * Log_2 (1+ S/N) *for an arbitrarily low error rate*
- This is really a amazing thing akin to $E=MC^2$
- Simply because it gives the absolute limit of how good you can do
- There are not many things where that can be known.

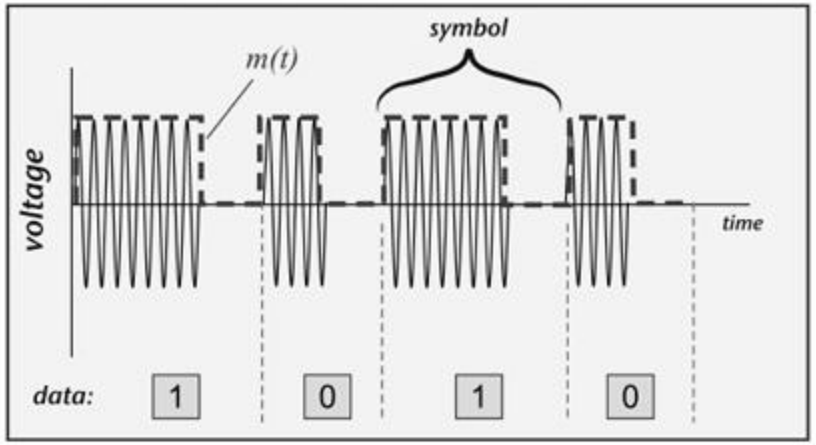
Lets take a CW channel

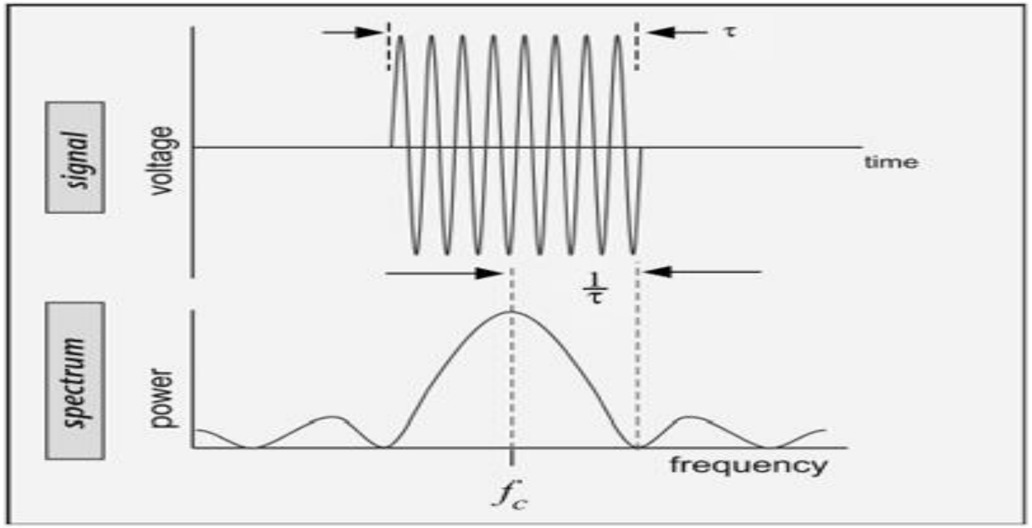
- Using a 250Hz filter
- Assume a just barely detectable signal at 4dB SNR
- C = 250 * Log_2 (1+ 2.55) = 250*1.82 ~=457 bits/ second!!
- Using PARIS as a standard word, 50WPM ~=41.66bps (dit time)
- It is possible to send about 549 WPM inside this channel.
  - NOT possible with OOK!!!!

- <u>Higher SNR = more capacity! </u>This is not usually obvious.

What is possible with OOK?

- Nyquist criterion
  - BW must be ≥ larger than 2 sided BW
  - 250 HZ = 125BPS
  - 125BPS ~= 150wpm
- Ok, so how does Shannon fit 549WPM in that channel?
- It is NOT just coding!
  - N bits/ symbol – modulation selection
  - Fix channel problems implied and necessary





https://www.eetimes.com/tutorial-radio-basics-for-uhf-rfid-part-iii/#

Back to Why’s about MODEM’s

- Two big points:
  - 1: You can put a lot of information though a channel, way more than CW, but complex things are required.
  - 2: Very severe channel impairment can be dealt with, way beyond what an “operator” could do
  - 3: in all cases synchronization is required

Now how do you get to the Shannon limit?

- As a broad brush 2 things:
  - Modulation degrees of freedom, methods of synchronization, impairment compensation
  - Coding : *assuming synchronization has been established*

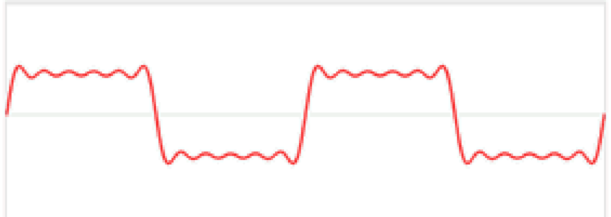
- The second is where most people have some experience, but not the first. That is what this series of presentations will address.

Coherent modulation

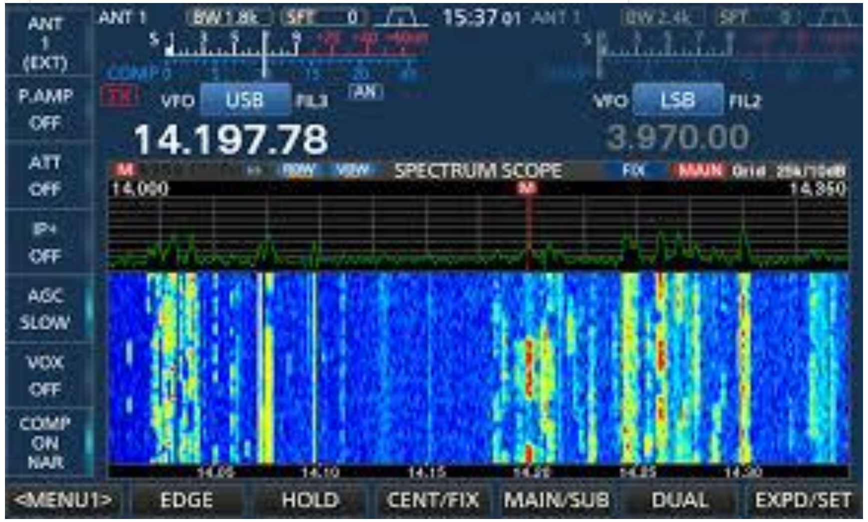
- To understand synchronization, the concept of coherent modulation / demodulation is important.
- Broadly, coherent means - modulation where the signal frequency is aligned nearly perfectly and the phase has been adjusted (and the clock)
- Requires tracking as the channel changes
- To examine this problem, a little more background is useful on complex base band signals
- I’ll start with another important concept for visualization and computation: the Modulation domain

The modulation domain

- Mostly we all know what the “Time domain” and “Frequency domain” are



Time



Time-frequency

Frequency

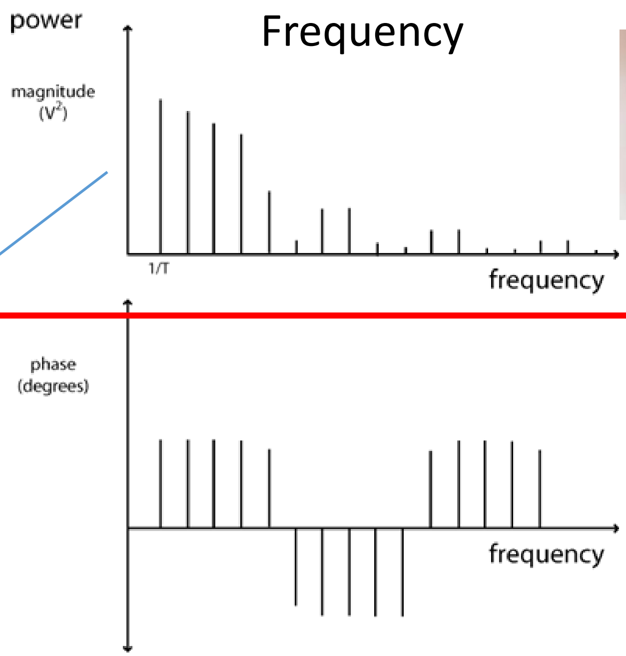
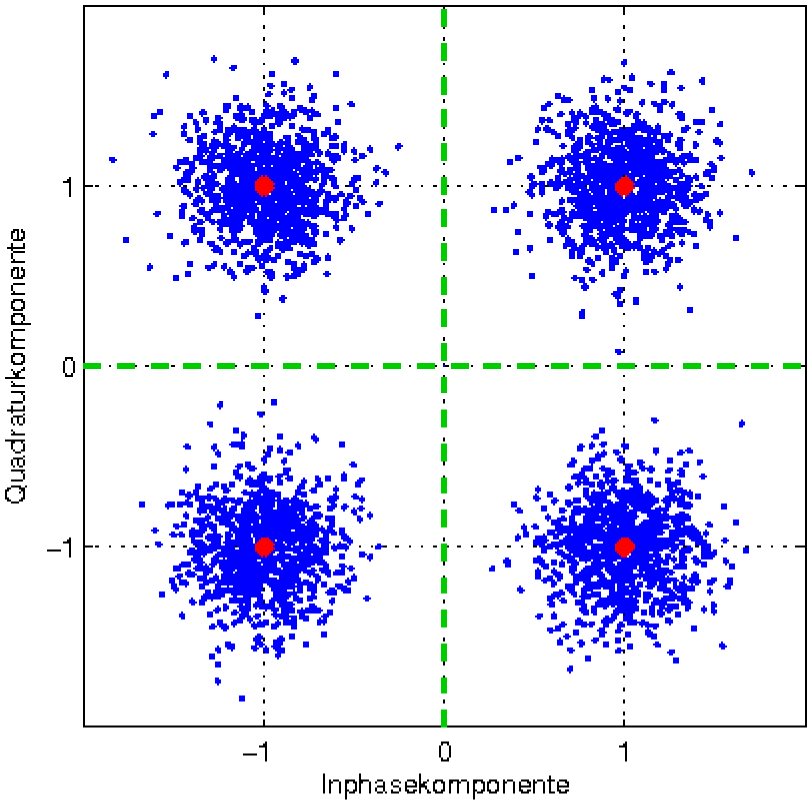


Figure 2. Power spectrum of a periodic signal.

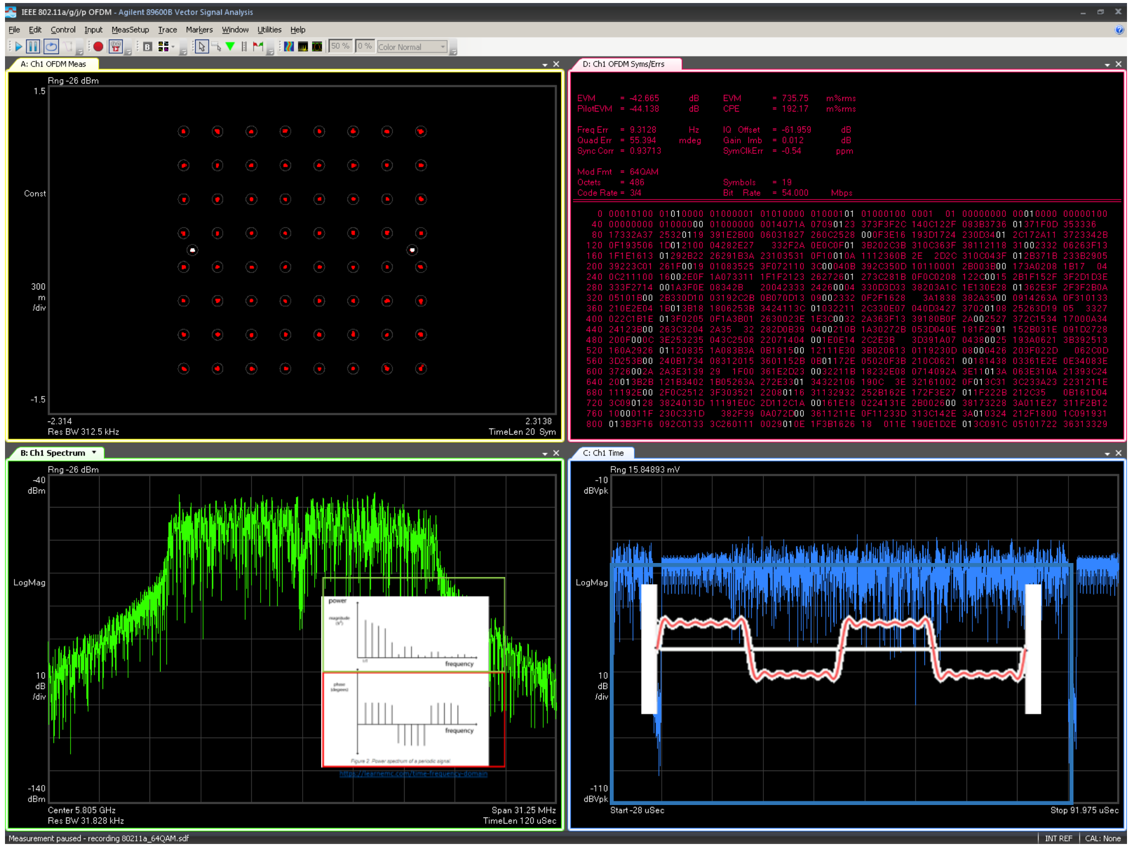
https://learnemc.com/time-frequency-domain

The modulation domain

- The modulation domain is where ALL the information is



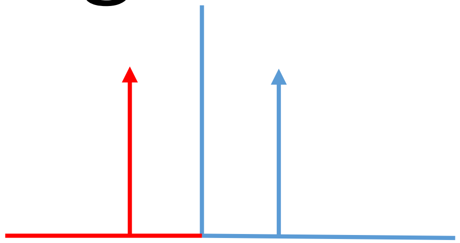
Time is the series of points



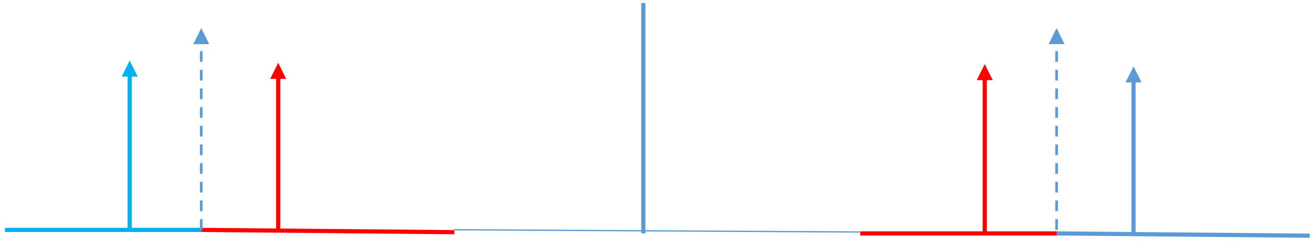
Modulation domain: past OOK

- The modulation domain is the complex (I and Q) envelope of any signal (can be frequency, polarization, etc)
- The “carrier frequency” is a stationary parameter, and contains no information
  - Though it must be determined!
- So called I and Q are orthogonal basis functions in the same way as the “X” and “Y” axis!
- These basis rotate at the carrier frequency, but their orthogonality is preserved always
  - Nonlinear distortion can mess it up!

Analytic signal, AKA special complex signal



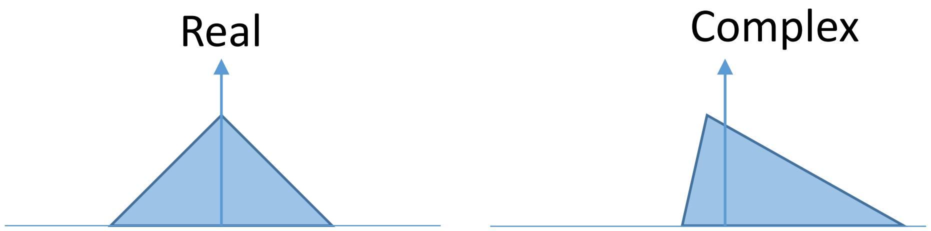
- A so called “real signal” is easy to understand
  - Cos, Sin Etc.
- An analytic signal is a special kind of signal that has a one sided spectrum

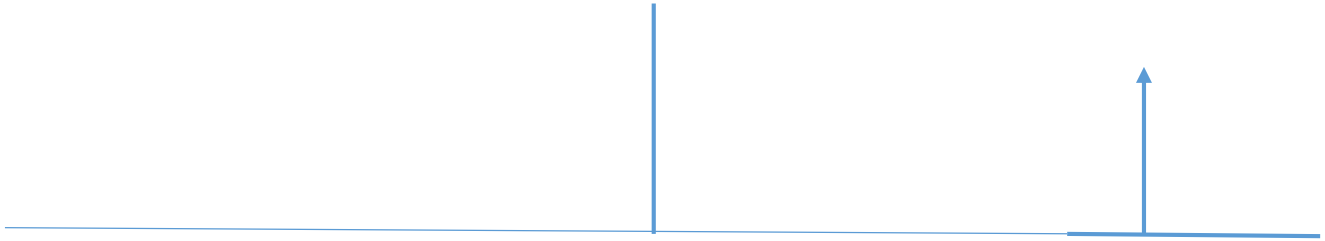


- $S'(t)=\cos(\omega t)+ j \sin(\omega t) =Ae^{j\omega t}$

More generically (any signal)

- $S'(t)=A_I(t)*\cos(\omega(\tau)t+k_1(\tau)\theta(\tau,t))+ j* A_q(t)* \sin(\omega(\tau)t+k_2(\tau)\theta(\tau,t))$

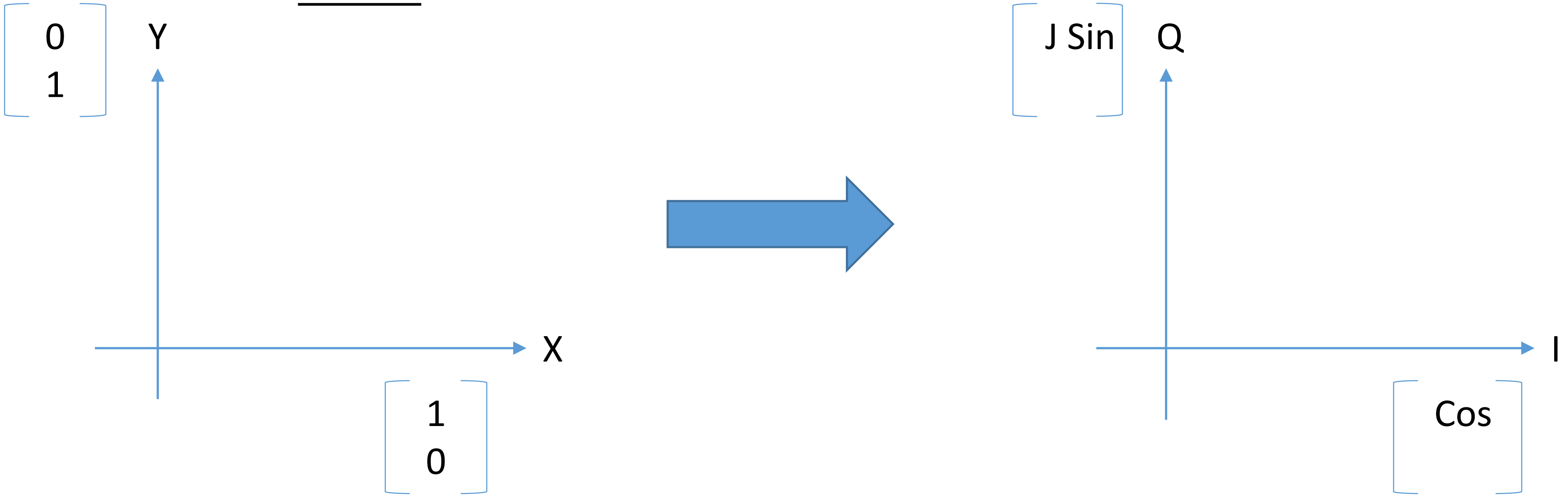




http://bme.elektro.dtu.dk/31610/notes/complex.signals.pdf

Basis functions for complex base band

Vectors → **Functions!**



$$\begin{bmatrix} 0 \\ 1 \end{bmatrix} \bullet \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \mathbf{0*1 + 1*0 = 0}$$

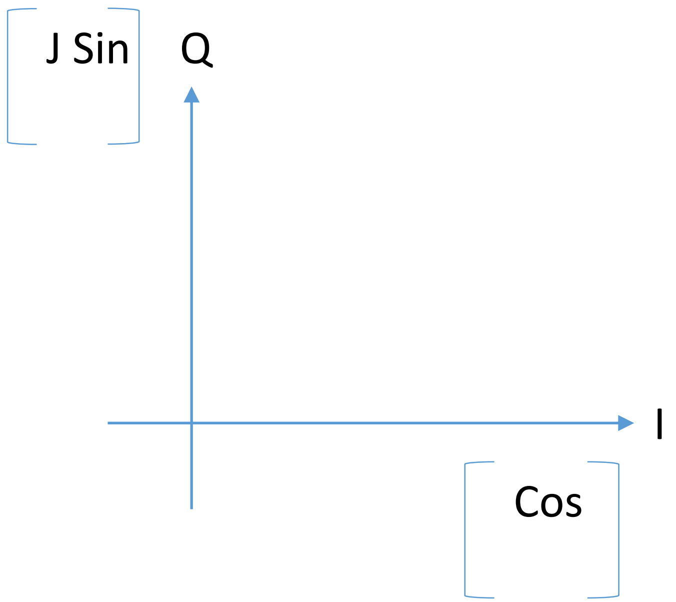
$$\begin{bmatrix} J\,Sin \\ \ \end{bmatrix} \bullet \begin{bmatrix} Cos \\ \ \end{bmatrix} = \mathbf{0*cos + sin*0 = 0}$$

Complex dot product!

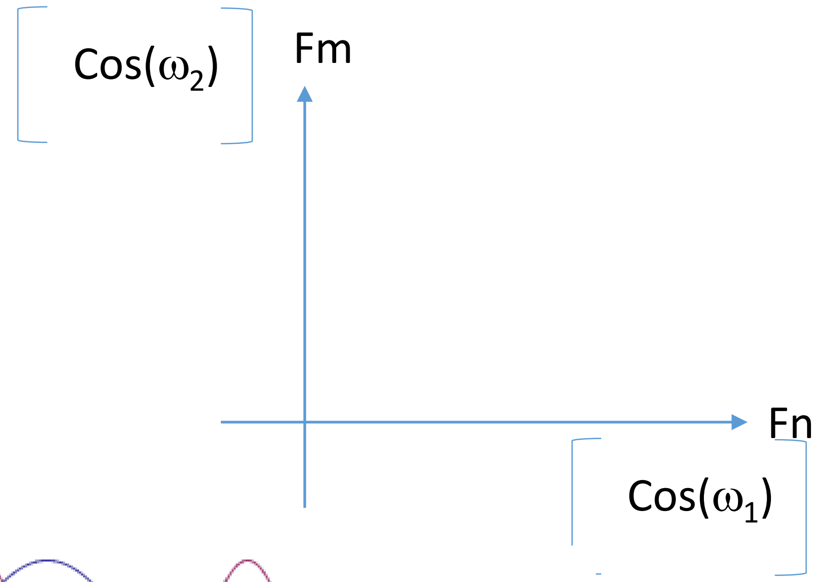
https://www.bookofproofs.org/branches/dot-product-of-complex-numbers/

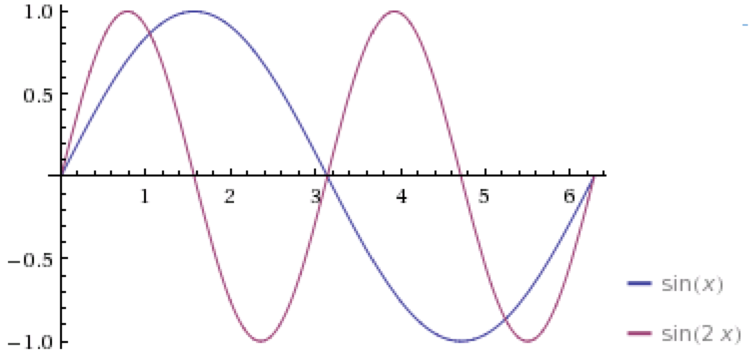
Basis functions for complex base band

Functions of same frequency



Functions of same different frequency!





[J Sin] ● [Cos] **= 0*cos + sin*0 = 0**

Complex dot product!

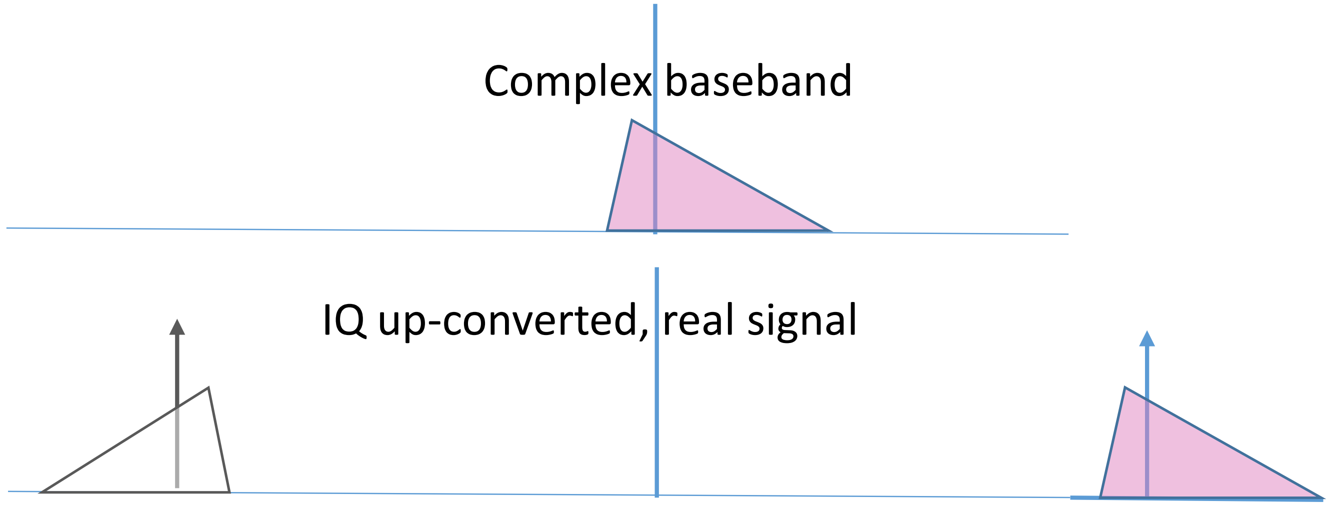
https://math.stackexchange.com/questions/474398/waves-of-differing-frequency-are-orthogonal-help-me-understand

Complex base band

- Allows a two sided signal to be asymmetric
- Realization of any waveform
- Includes all AM,PM,FM
- Finite BW (Low pass) signal

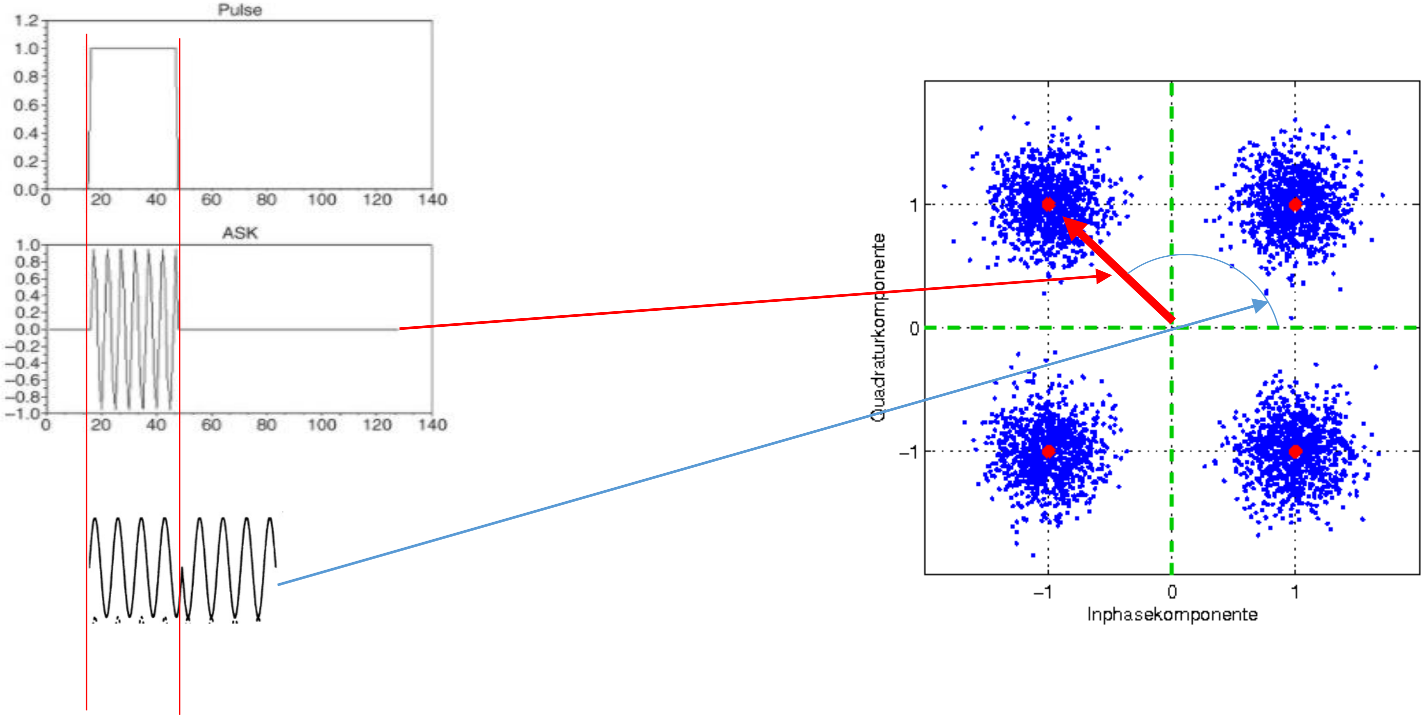
$$S'(t)=A_I(t)*\cos(\omega(\tau)t+k_1(\tau)\theta(\tau,t))+ j* A_q(t)* \sin(\omega(\tau)t+k_2(\tau)\theta(\tau,t))$$

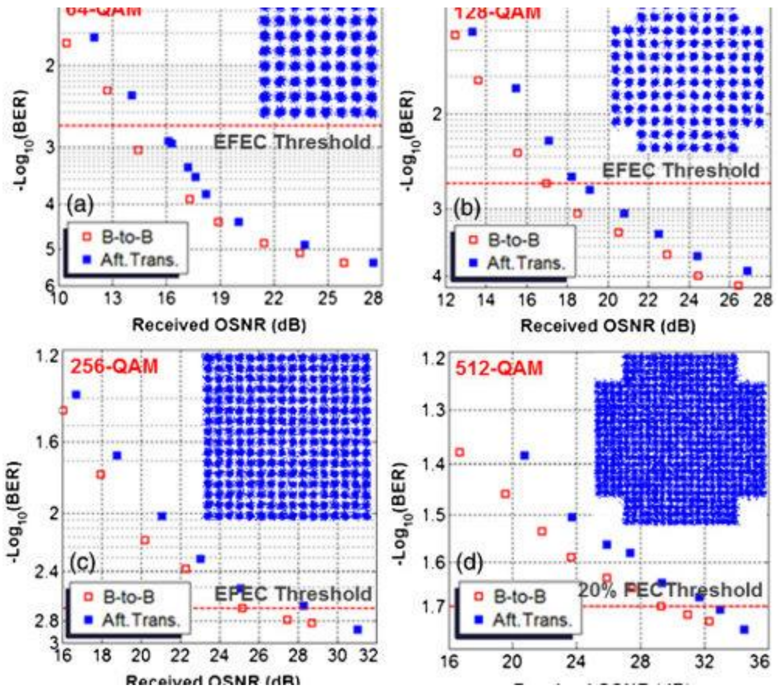
OOK
FSK
SSB
mPSK
MSK /GMSK
LFM
QAM
OFDM



Bit to symbol mapping: define the states

- Starting with complex base band as our signal chalk board we can define “states” in the tuple of I and Q basis.
- Each state corresponds to a complex number.

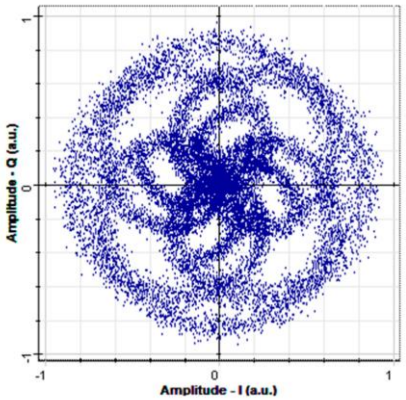




https://www.sciencedirect.com/topics/computer-science/modulation-method

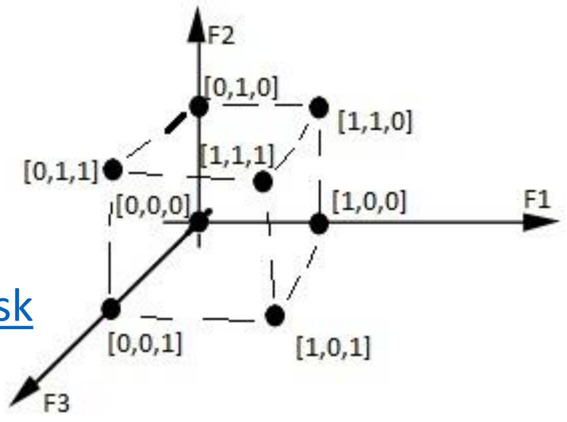
https://blog.solidsignal.com/tutorials/what-is-qam/

Can do the same thing with frequency



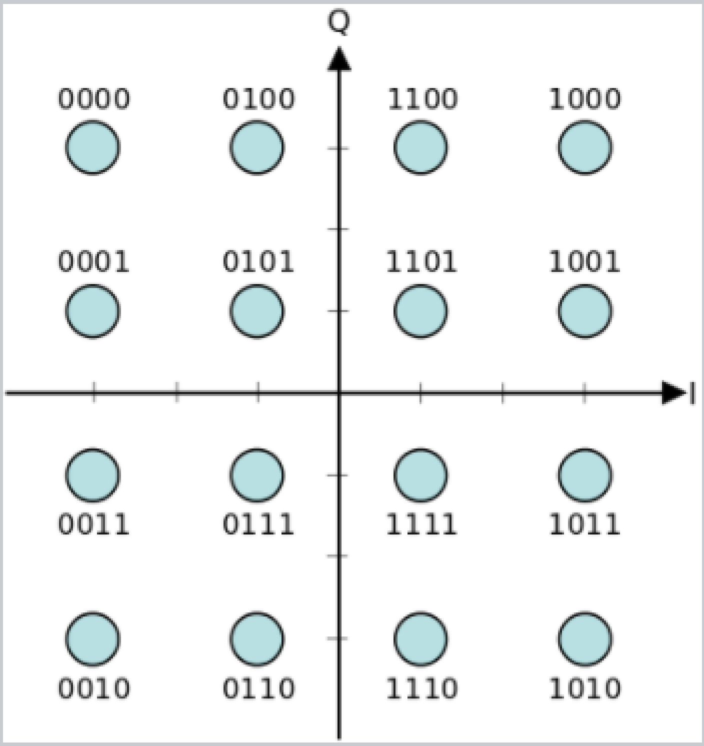
- It is more difficult to visualize, but with a set of orthogonal frequencies, there is a vector of complex coefficients that describe the amplitude of each component
- The amplitude is simple FSK systems is either 1 or 0
- OFDM- this is not true, each frequency can be modulated in phase and amplitude also!

https://electronics.stackexchange.com/questions/22615/constellation-diagram-of-fsk



Bit mapping

- For each valid modulation state a bit pattern is assigned according to the binary order of the “constellation”
- Good mapping ensures equal binary distance between elements (gray coding)
- Symbol probability is also valid (infrequency symbols get largest amplitudes – to reduce average power)



A constellation diagram for rectangular 16-QAM.

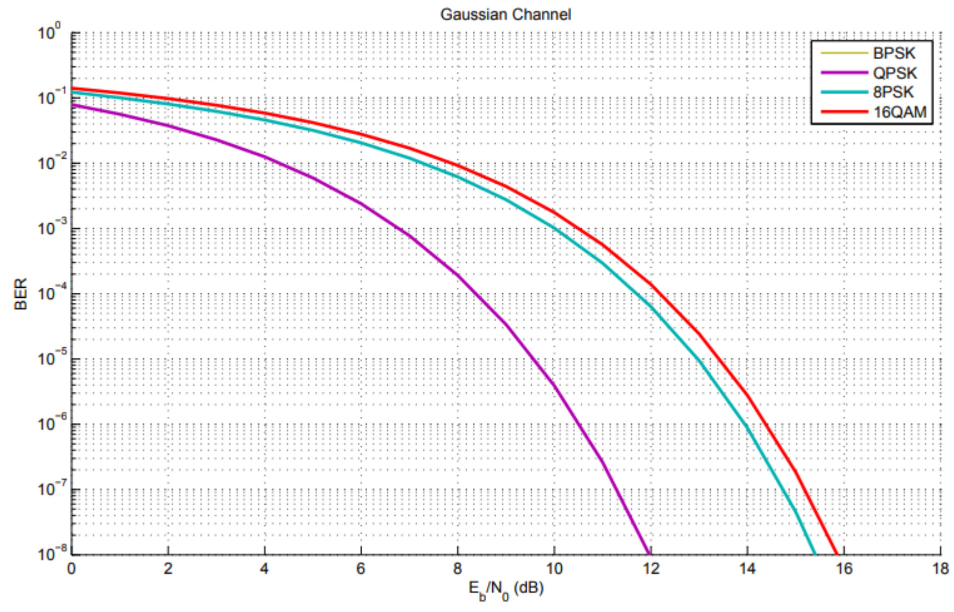
How did this increase channel capacity?

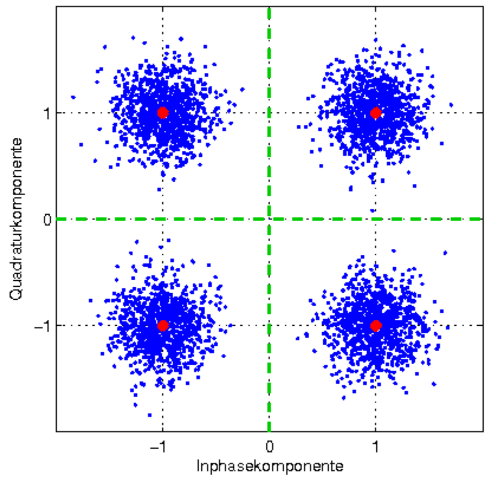
- For a given constellation, the required bandwidth is proportional to the rate of change.
- In modulation containing more than one bit per state, for a given rate, (BW) more bits per second are sent

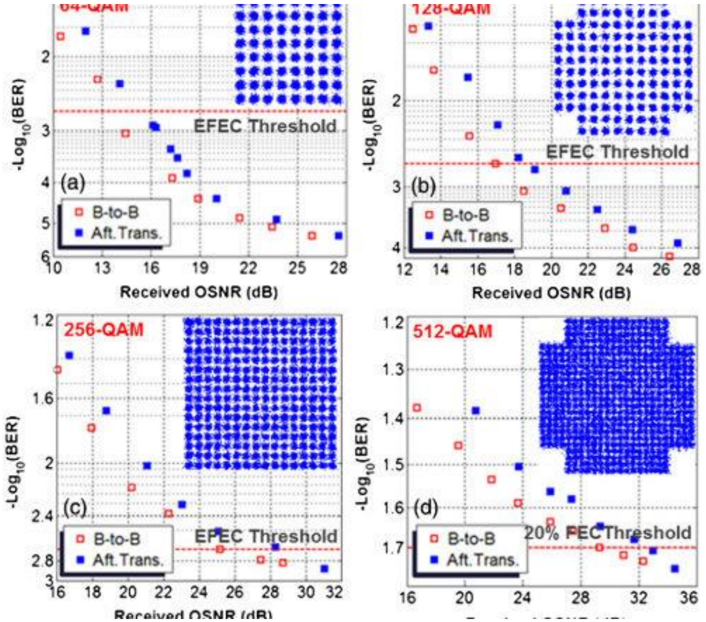
CW = 1 bit per symbol ← → 128QAM = 7 bits per symbol
~Same bandwidth, 7x more information!

What is the cost?

- Because nothing is free.
- More bits per symbol means the Euclidean distance between the symbols is lower for identical power
- But this is also where CODEING comes in



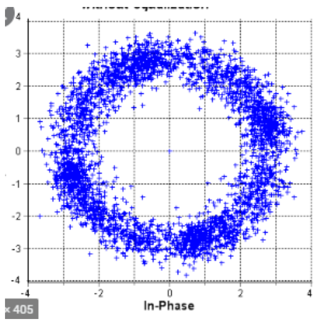


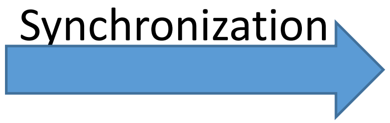


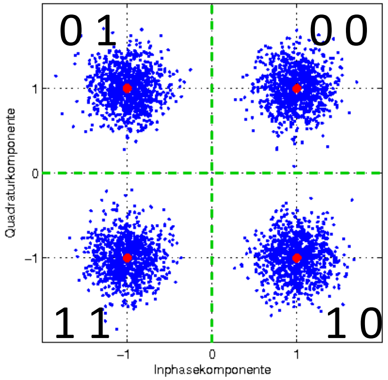
https://www.unilim.fr/pages_perso/vahid/notes/ber_awgn.pdf

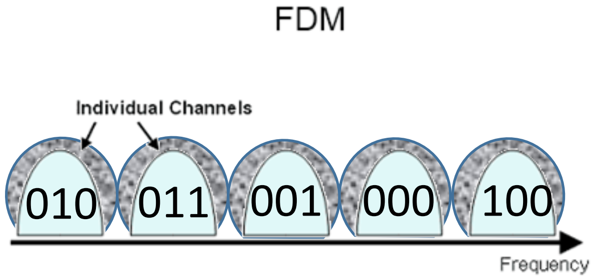
Assuming synchronization, how detect?

- This discussion is for hard decision detection only
  - Soft decision also possible, but more advanced topic
- For QAM variants (OOK, BPSK,QPSK, nPSK, nQAM) comparators in I and Q are used to “slice” the modulation domain
- Massively oversimplifying, a reverse look up of the symbol tuple that is closest to the value of the complex base band signal at that instant in time.









What encompasses synchronization?

- BER curves, link budgets, channel capacity are all reported “assuming synchronization has been established”
- If not stated, it is understood.

- Frequently performance is also after channel equalization and gain adjust
- This means transmitter and receiver deficiencies as well as the channel effects are removed.
- We need to fix: amplitude variation, frequency offset, phase offset, clock rate and sample position, channel impairments

- IMO, these are the cool things about modems!!!!

What goes wrong: why is synchronization needed?

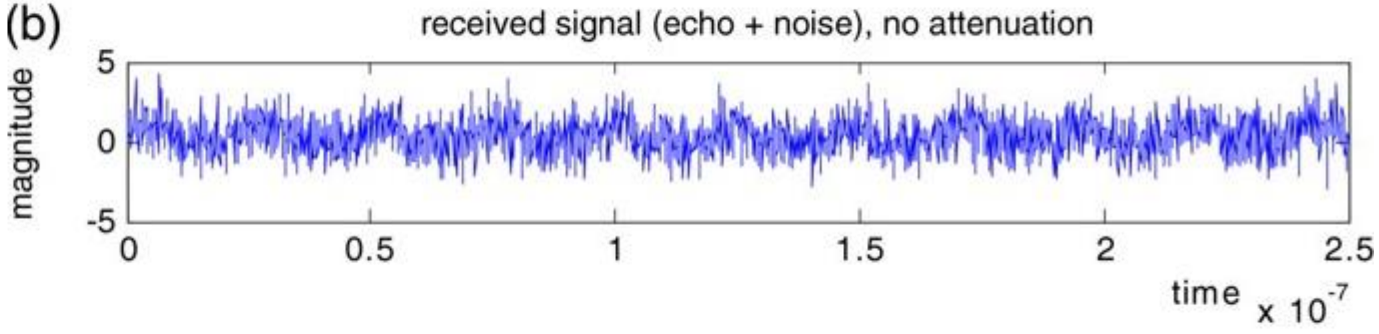
- Start with ignoring what the channel does (primarily multipath) other than attenuate the signal
  - Look at synchronization, leave equalization for another time!
- The things we need to figure out:
  - What should the RX gain be
  - Is there a signal, where does the frame / packet / message start?
  - What is its frequency – adjust and track
  - If coherent: what is its phase – adjust and track
  - Where are the symbol boundaries – clock recovery

Synchronization: fixing the things that go wrong

- Each of these can easily occupy many hours of slides: methods, performance, algorithms, specifics for each modulation type etc.
- Instead just an overview here now that we have enough background

- Detection
- Frequency adjust
- Phase adjust
- Clock recovery

Detection: Is there a pulse?

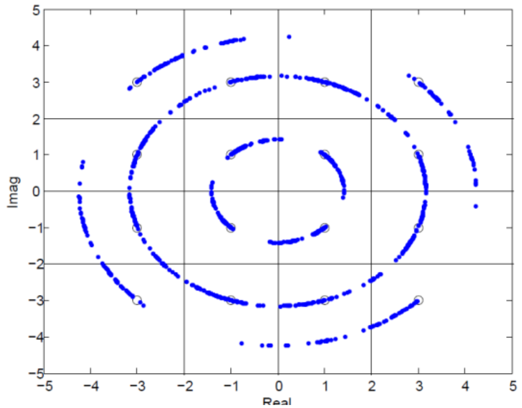


Yes, but where?

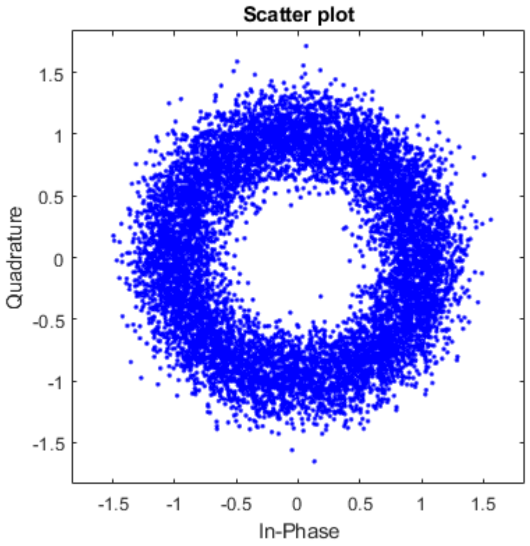
Detection of the signal

- Why do we need to do this?
  - In packet based systems (mostly everything) all of tasks of the modem dealing with equalization and coding need to know precisely where the start of message is.
  - Error of a fraction of a clock period can cause everything to fail.
- Thresholding: the obvious way
  - The trick is, in low SNR conditions it is very difficult to set a threshold
  - Properly implemented, modulation looks like noise
  - In the presence of interference, impossible to distinguish start of signal
  - The signal strength varies orders of magnitude even within a packet
- Typically ratios of auto to cross correlation of the preamble portion of the signal are used to produce a “normalized” threshold method

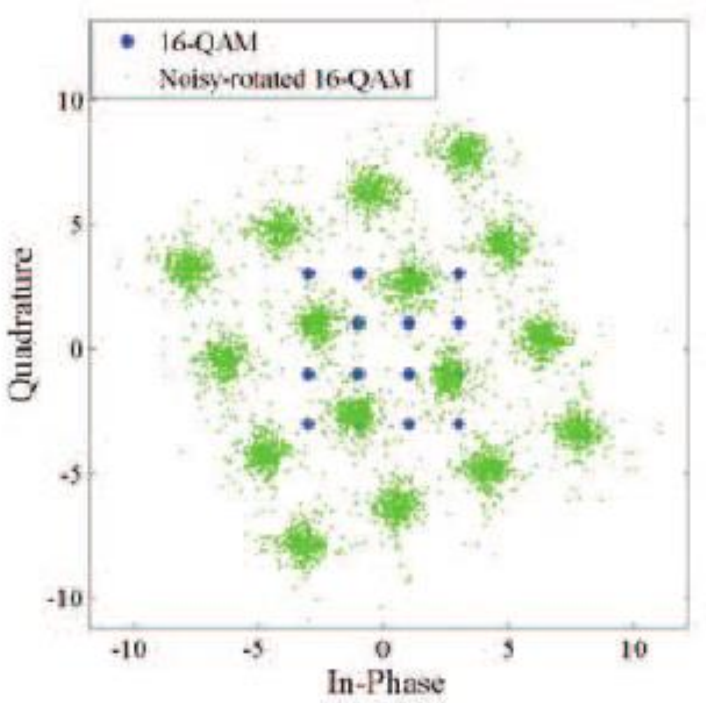
Frequency adjust



Mild 16QAM



Pretty bad, could be BPSK, QPSK, mPSK etc.



https://www.mathworks.com/help/comm/ref/comm.carriersynchronizer-system-object.html

Frequency adjust

$$\omega(t) = \frac{d\varphi(t)}{dt}$$

- Frequency is the rate of change of phase
- If we are interested in the phase, any frequency offset at all will cause a ramping phase – hard to track, not good!
- All transmitters and receivers have small frequency errors that vary with time. Simply not possible to have them both exactly the same.
- Frequency always needs to be adjusted where coherent modulation is used. PLL's can track small offsets.
- It may not be obvious this is being done.
- Eg. WSJT reports error – because it is correcting for the frequency.

FLL

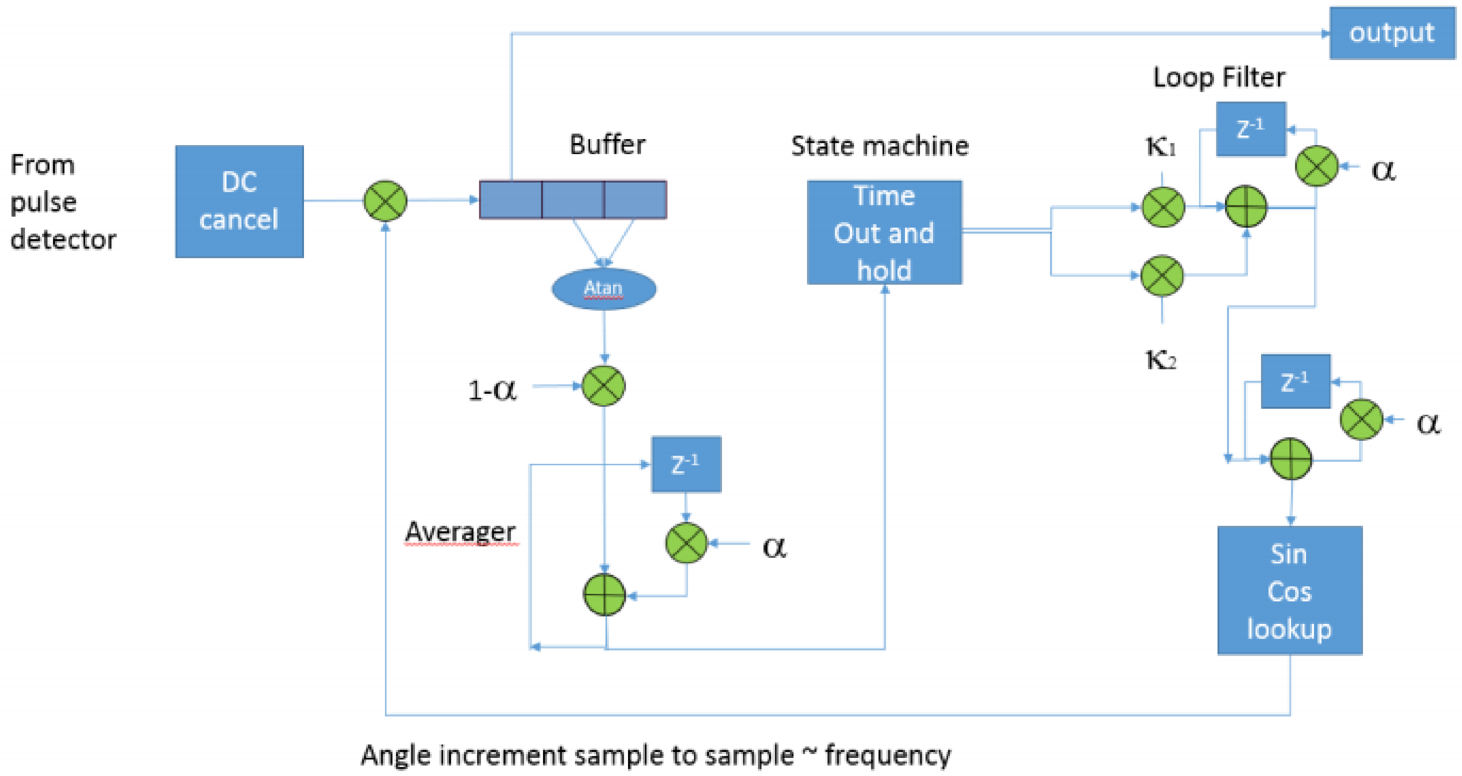
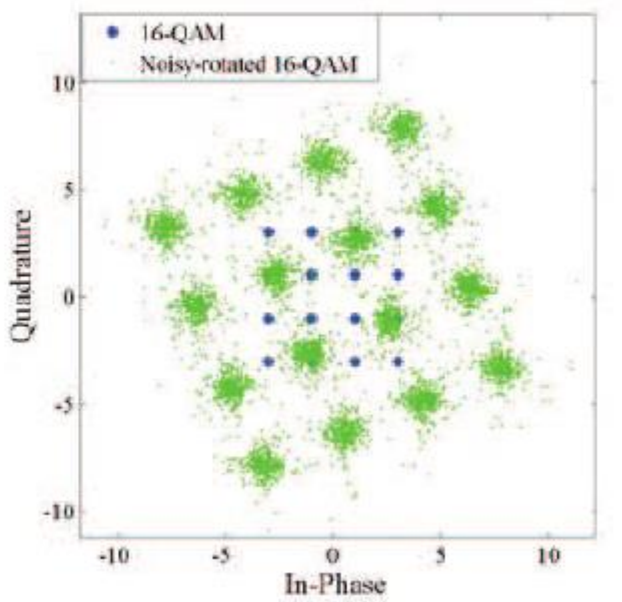
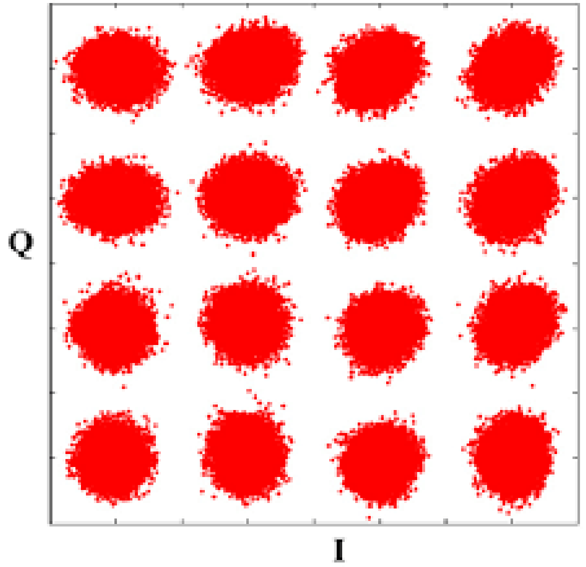


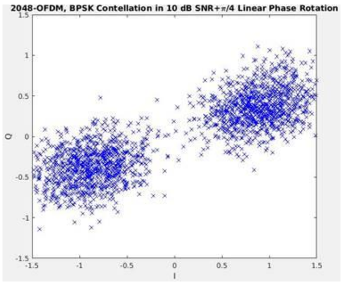
Figure 28 Improved Frequency Lock Loop block diagram

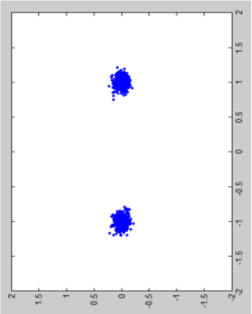
Align Phase

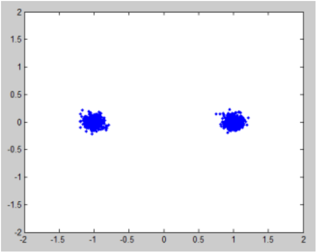




This could be moving in time also!

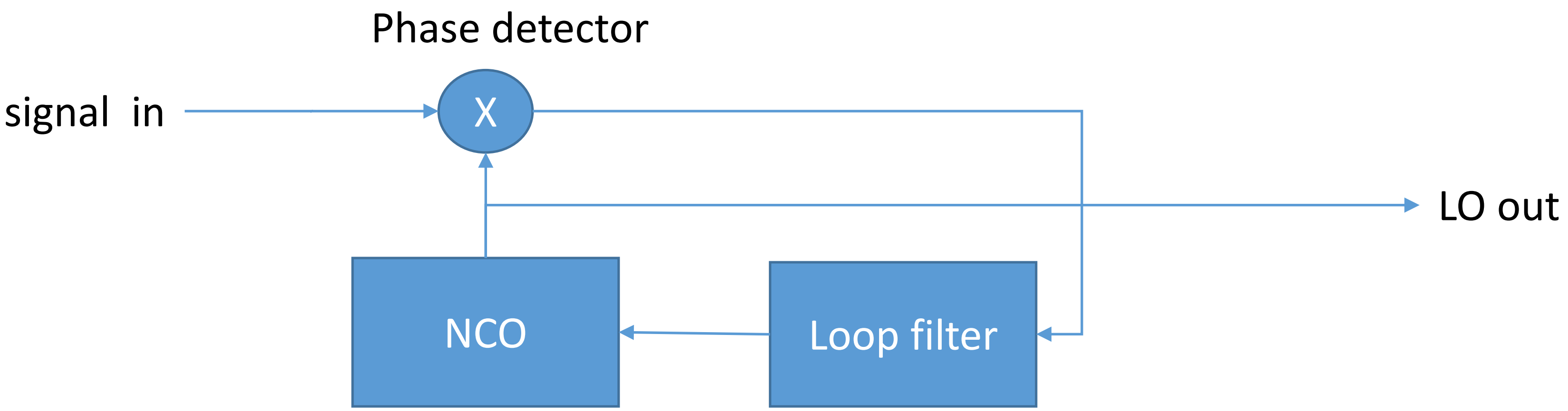


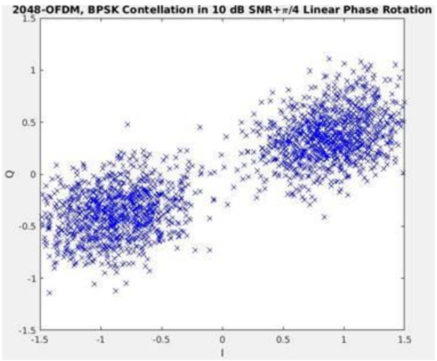




https://dsp.stackexchange.com/questions/8456/how-to-perform-carrier-phase-recovery-in-software

Phase locked loop





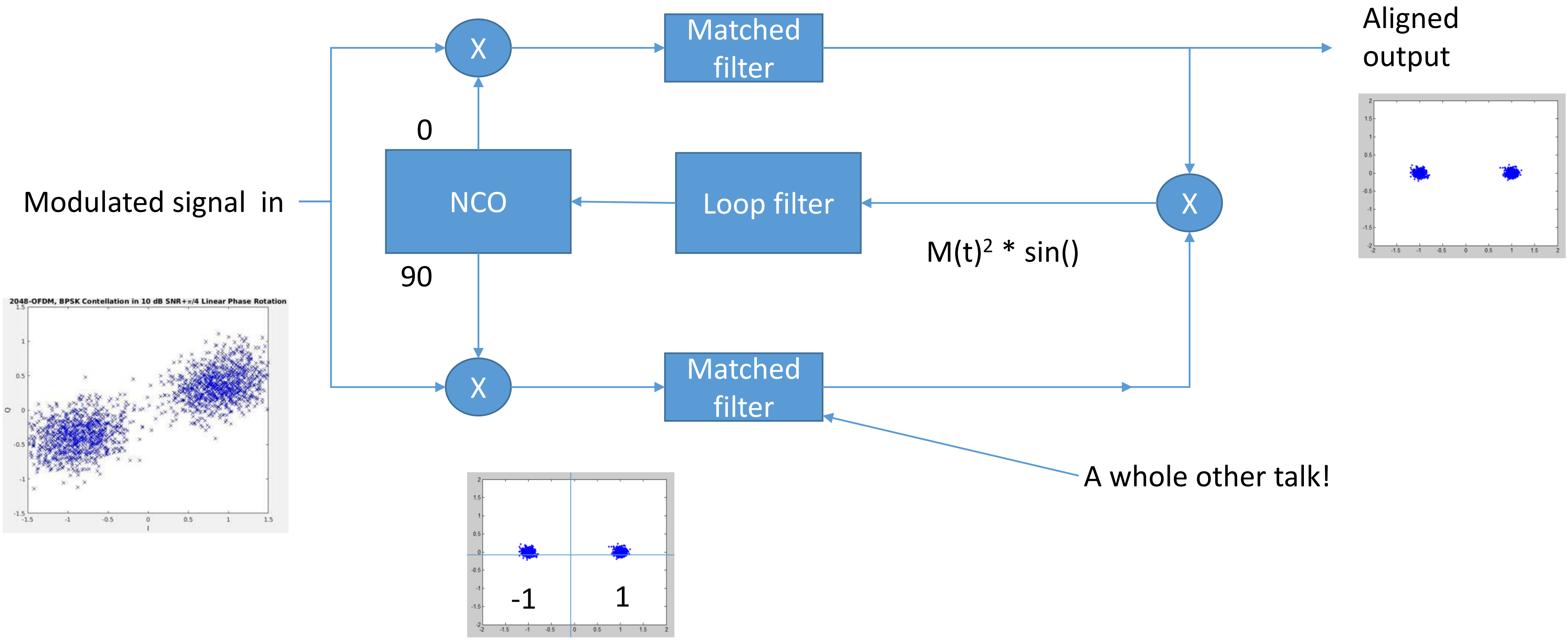
- What if modulation is present?
  - Slow modulation, tracked out
  - Fast modulation, loop fails

Phase adjust

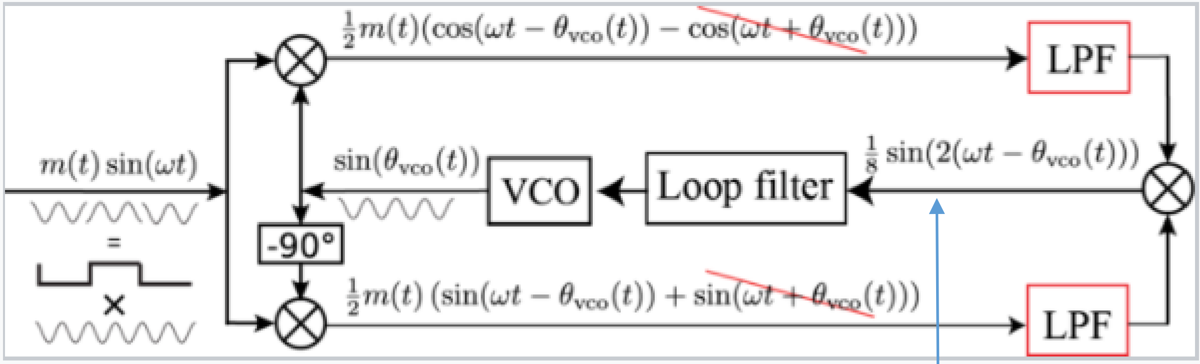
- When modulation is present, things are a bit harder
  - Modulation must be “removed” from error signal
  - Many methods exist, a common one is the Costas loop

https://www.researchgate.net/figure/COSTAS-loop-for-BPSK demodulation_fig4_221909933

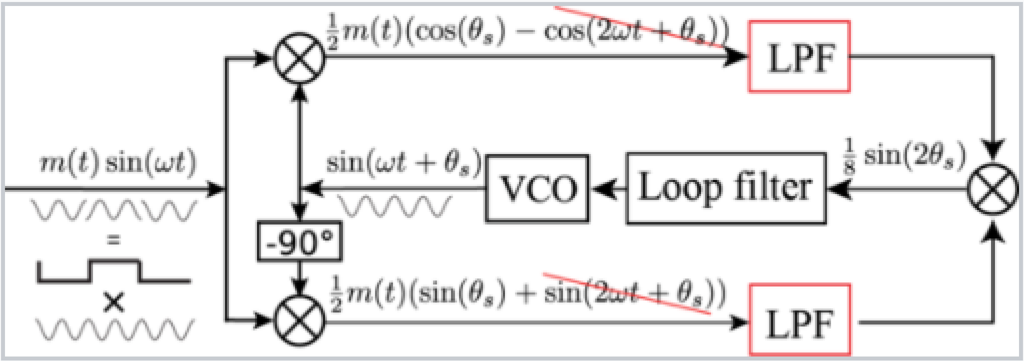
Costas loop for BPSK



Costas loop for BPSK



Costas loop before synchronization

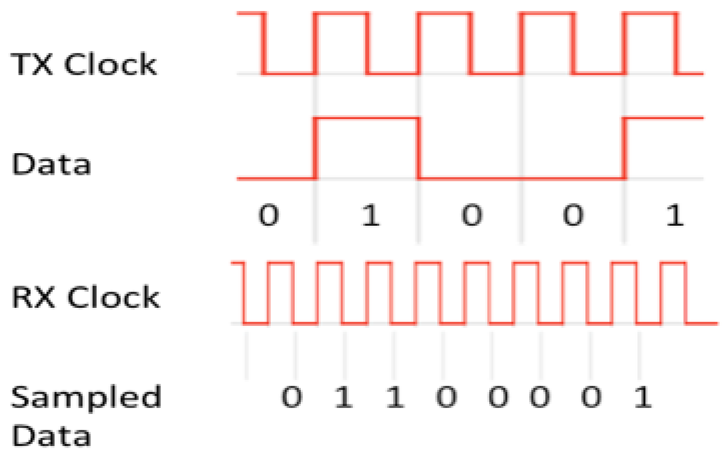


Costas loop after synchronization

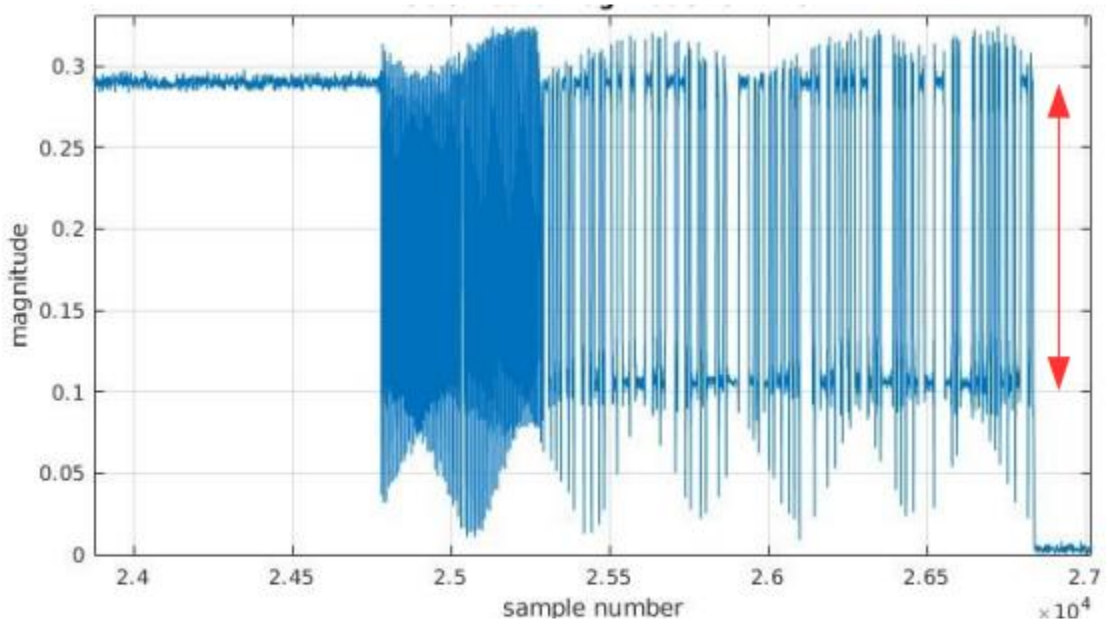
https://en.wikipedia.org/wiki/Costas_loop

Clock recovery: when to sample?

Obvious

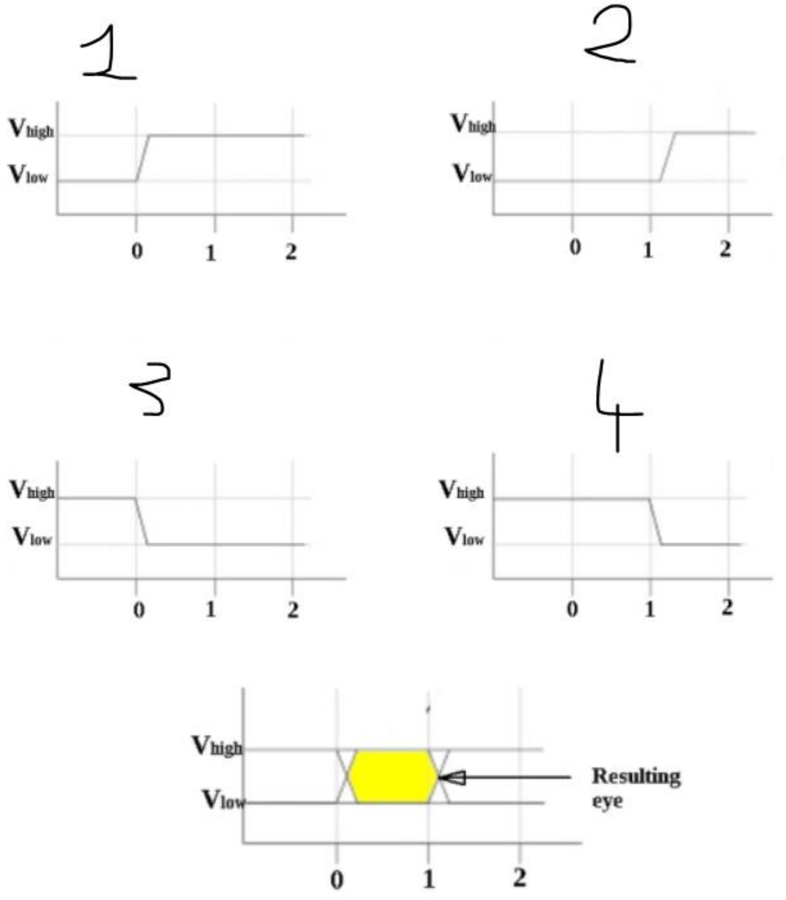


NOT So Obvious



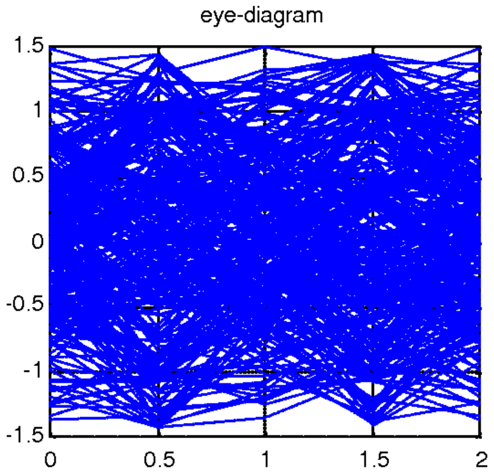
Eye diagrams

https://dsp.stackexchange.com/questions/64613/eye-pattern-construction-and-interpretation

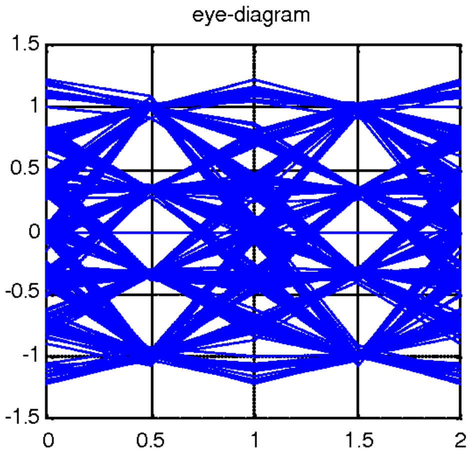


Eye diagrams: clock recovery

Clock unknown



Clock recovered



https://www.semanticscholar.org/paper/Teaching-MODEM-Concepts-and-Design-Procedure-with-Harris/0d8f7db7882739c7b49b634f40cde3f569d99bd2/figure/3

Clock recovery

- Once the frequency is adjusted so the phase does not ramp
- Then the phase is adjusted to align the constellation
- Then the slicer can make a decision on what the symbol is – but it is changing at the clock rate, so how do you know when to sample?
- In low SNR case, it is not at all obvious
- Methods include
  - Delay locked loop
  - Early late method
  - Garner algorithm
  - Polyphase interpolation
  - Etc etc
- Just a taste here

Some examples

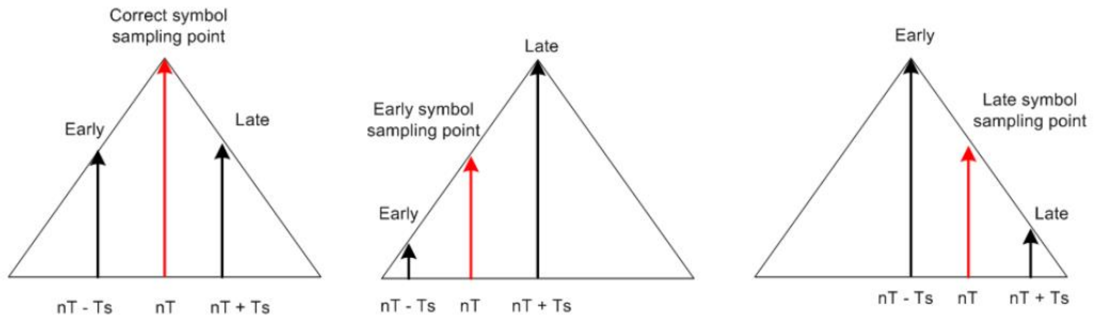
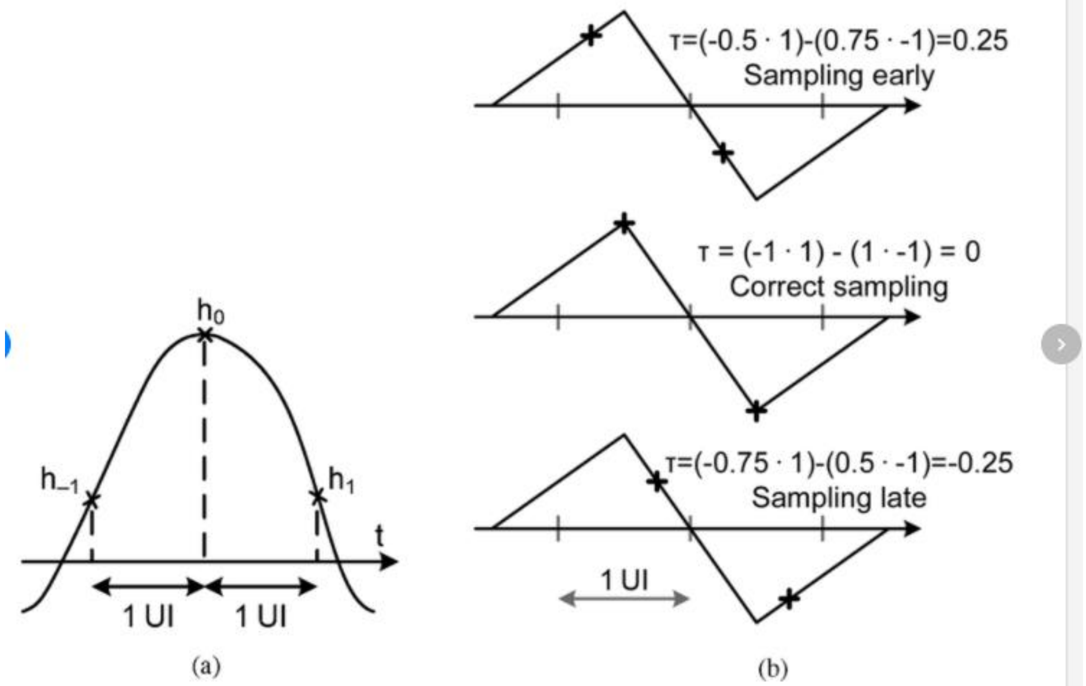


Figure 1: Late-early timing error computation



Mueller-Müller timing recovery scheme. (a) Impulse response. (b) Continuous data.

https://www.nutaq.com/blog/symbol-timing-recovery-methods-digital-iq-demodulator

https://www.researchgate.net/figure/Mueller-Mueller-timing-recovery-scheme-a-Impulse-response-b-Continuous-data_fig1_224144594

Equalization: last taste

- Pretty advanced topic, but needs mention
- The frequency response of a channel is typically not “flat” and can be rapidly changing
- Primarily caused by multipath.
- These echos act as delay taps to form a filter function that is not flat in frequency, and introduce inter-symbol interference
- Not seen so much at narrow channel on HF bands since wavelength is very long, but still present.
- Extreme at microwave frequencies with Wi-Fi bandwidths
- All modern wireless standards must include equalization

Wrap up

- This presentation was a fast gloss over a huge subject
  - At least six graduate level classes
- I hoped to only get enough info out that it would be easier to penetrate the subject if interested
- I added links to the image sources to help in that case
- I would like to spin a talk about each one of the things touched on here if interest exists
- Thank you!