What's all this Modulation Stuff, Anyway?

From Spark Gaps to QPSK

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Summary

How We Got from CW to Digital Radio: Exploring the quest to force more information through a narrow pipe.

Before radio, digital transmission had been around for centuries. DW (Damped Wave) officially became CW (Continuous Wave) when the spark gap was outlawed in 1938. Both were the first forms of digital radio communications. The regulatory groups spurred by the broadcast industry lobbyists inadvertently forced hams to find new and clever ways to make better use of their shrinking band allotments.

What’s it All About?

- Historical Digital Transmission
- Early Radio and CW Morse Code
- What’s an RF Carrier?
- Analog AM & FM Carrier Modulation
- Bandwidth and Data Rate
- Modulating the Modulation
    - AFSK and APSK
    - Multi Tone
    - QAM
    - Packet

Early Digital

- Smoke Signals
- Drums
- Horns
- Flags
- Mirrors

Early Digital

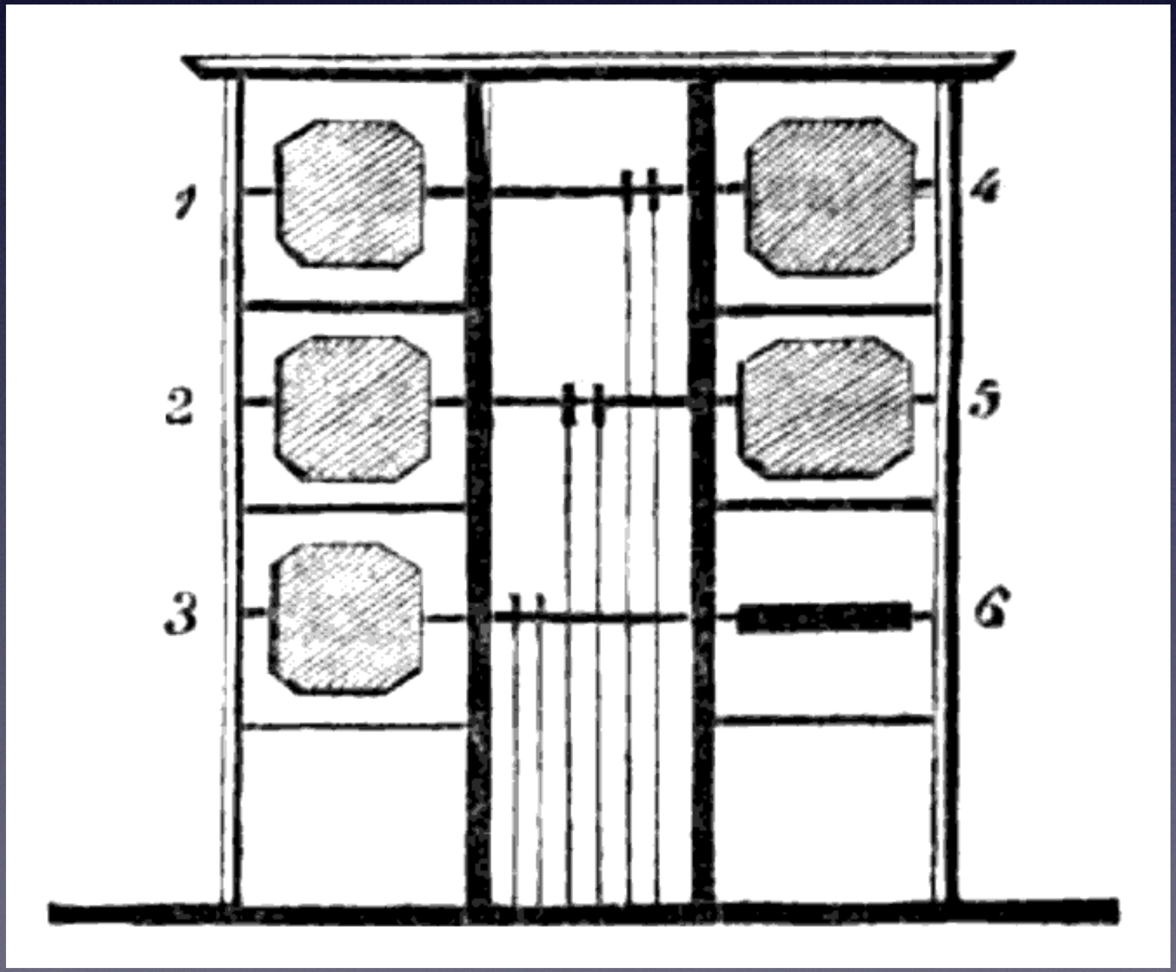
AD 26–37 – Roman Emperor Tiberius rules the empire from the island of Capri by signaling messages with metal mirrors to reflect the sun.

1520 – Ships on Ferdinand Magellan's voyage signal to each other by firing cannon and raising flags.

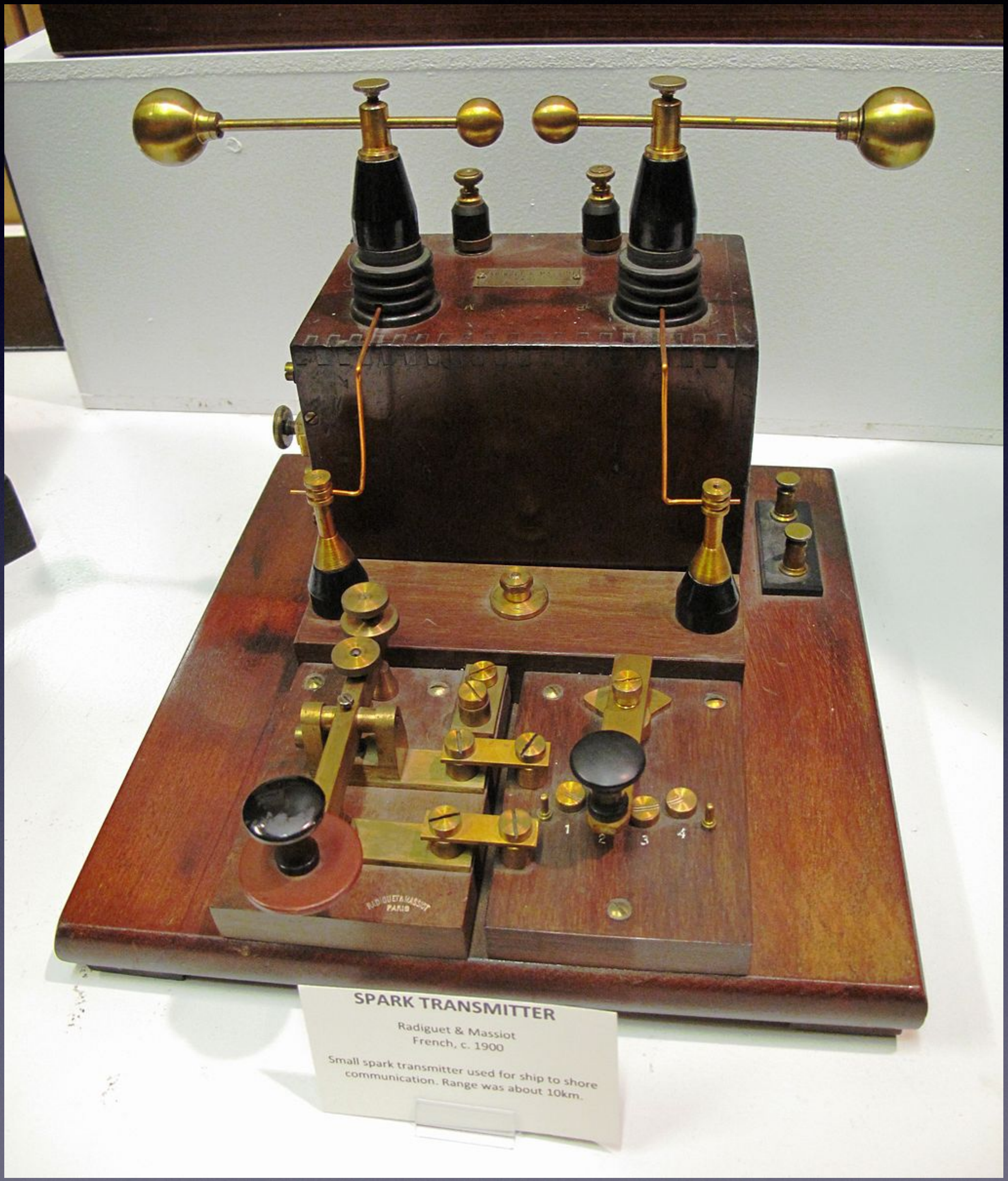
18th century France - Illustration of signaling by semaphore. The operators would move the semaphore arms to successive positions to spell out text messages in semaphore code, and the people in the next tower would read them.

Early Digital

Diagram of UK Murray six-shutter system, with shutter 6 in the horizontal position, and shutters 1-5 vertical. Early 19th century.

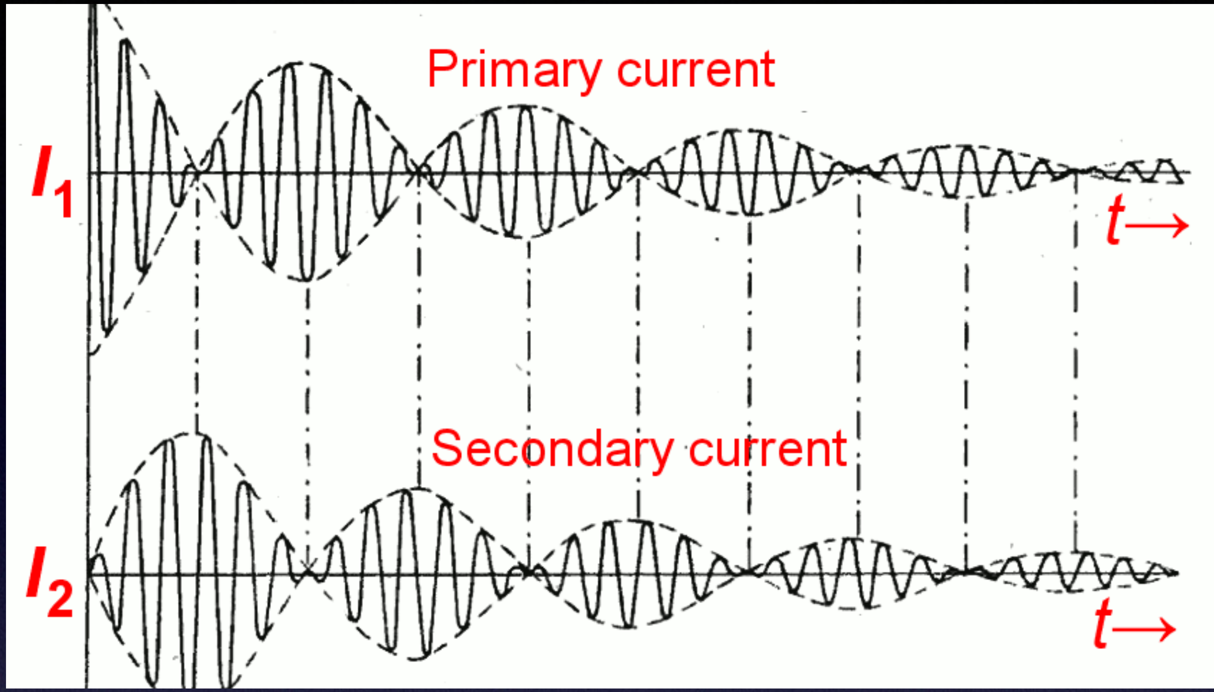


Spark Transmitter

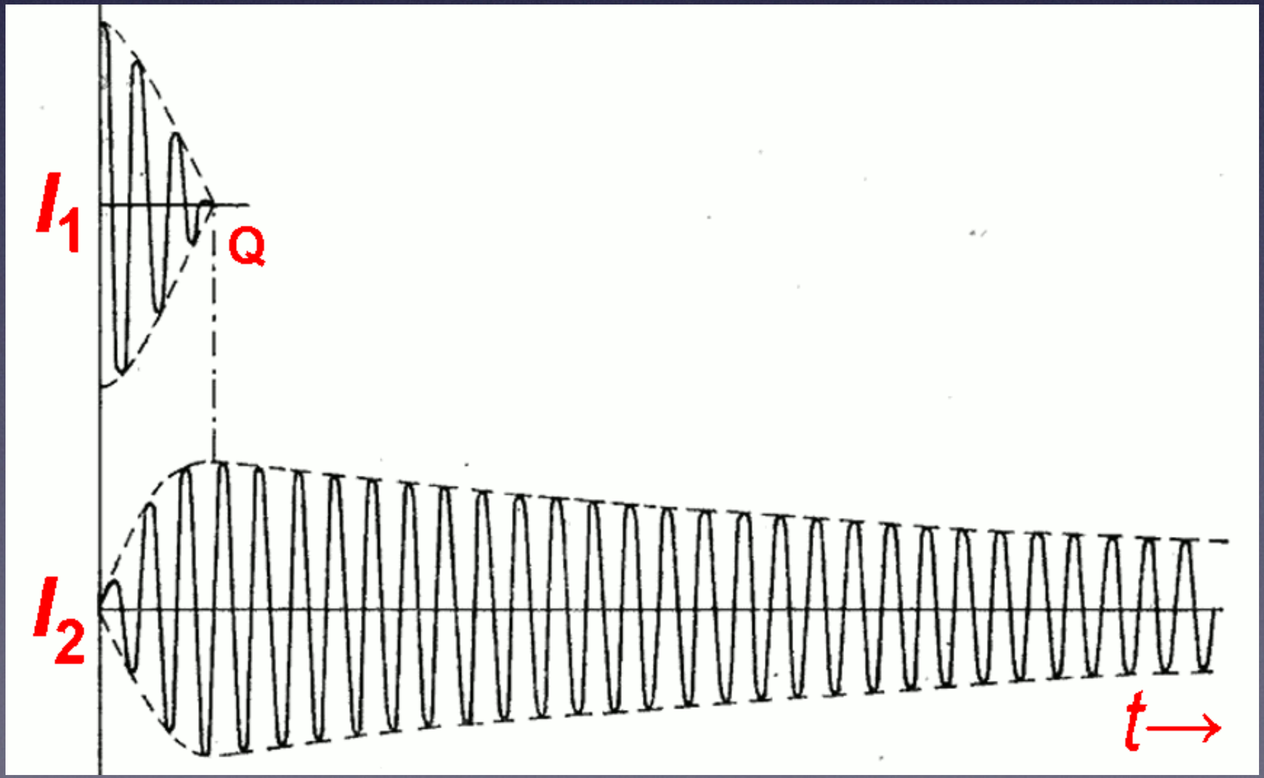


Spark Gap Transmitter (Range ~10km)

DW to CW



Inductively coupled



Quenched Spark

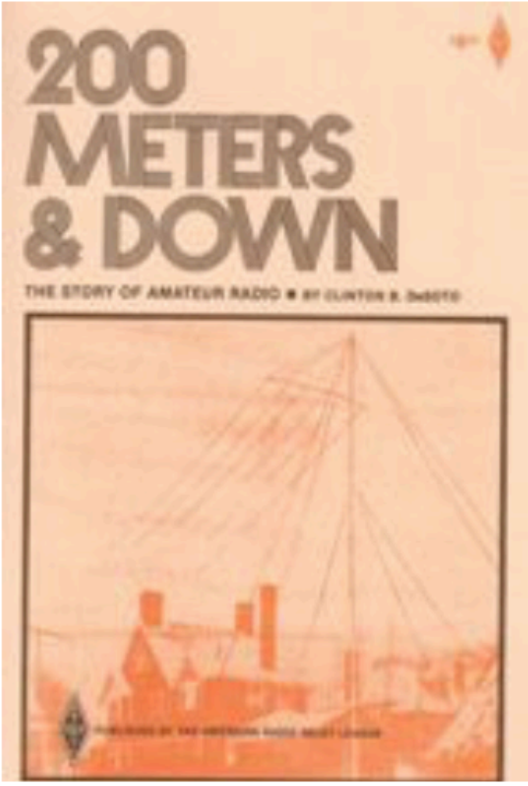
200 Meters and Down

200 Meters & Down

The Story of Amateur Radio!

This book chronicles the exciting evolution of Amateur Radio from the pioneers who perfected the wireless art, through the technical advances of the mid-1930s.

192 pages.



Author: Clinton B. DeSoto

ISBN: 978-0-87259-001-4

Hams Relagated to 1.5MHz - Infinity

The Broadcast Industry and the Navy wanted the hams and their key clicks to be as far from their broadcast bands as possible. So, they gave them the “useless” bands above 1.5MHz.

In return, hams world wide experimented with communication between each other on HF and developed radios that worked as high as 30 and even 50 MHz.

The licensing agencies took notice and began the process of taking over the ham bands and eventually compressing them down to tiny slices we use today.

The broadcast industry hired experienced hams to work on developing their equipment and antennas.

When Hams Ruled

Radio frequencies used by spark transmitters during the wireless telegraphy era[118]			
Uses	**Frequency (kilohertz)**	**Wavelength (meters)**	**Typical power range (kW)**
Amateur	> 1500	< 200	0.25 - 0.5
Ships	500, 660, 1000	600, 450, 300	1 - 10
Navy	187.5 - 500	1600 - 600	5 - 20
Moderate size land stations	187.5 - 333	1600 - 900	5 - 20
Transoceanic stations	15 - 187.5	20,000 - 1600	20 - 500

200 Meters and Down

Audion CW Oscillator

The vacuum-tube feedback oscillator was invented around 1912, when it was discovered that feedback ("regeneration") in the recently invented audion vacuum tube could produce oscillations. At least six researchers independently made this discovery, although not all of them can be said to have a role in the invention of the oscillator.

But, there's a good chance they were all hams.

What’s a CARRIER?

A Carrier ‘carries’ the desired information.

Simplest form AM (OOK):
Carrier ON, Carrier OFF

ONE BIT of information

Simple remote control logic:
Carrier OFF, turn OFF the light
Carrier ON, turn ON light

What’s wrong with OOK?
No Carrier == Carrier OFF

What if you want to send more data?

More Data, Scottie!

CW modulation is anything but Continuous.
CW is an early digital radio mode.
Need ~6 bits of data to send all 40 (English) characters A-Z, 0-9, .,/?

Symbols:
Carrier ON dit (speed dependent)
Carrier ON dah (traditionally 3 x dit).
Carrier OFF INTRA-character space between dits and dahs (1 x dit).
Carrier OFF INTER-character space between charcters (3 x dit).
Carrier OFF word space (7 x dit)

Variable-Length Encoding (Compression)
Uses a variable number of symbols per character (1-6) unlike fixed-length digital data which sends constant number.
Fewer symbols make for higher data rate and operator ease.

Bits, Bauds, Symbols, oh my!

You want to send a block of information
And you have unlimited processing power

Maybe you compress it first
Then maybe you add overhead bits, addresses, error detection.
Then maybe you have a way to send more than 1 bit at a time.

The channel bandwidth is proportional to the baud or symbol rate

The bit rate will be higher than the baud rate if more than 1 bit is sent per symbol

bit rate = baud rate * bits/symbol

Information rate is reduced when adding overhead bits

No Free Lunch

The the faster you want to send data, the more bandwidth you'll need, and the more received noise you will have to deal with.

The DOWNSIDE:

Transmitter occupied bandwidth increases.

Received noise increases (lowering SNR) because you need a wider filter to get the data through, letting in more noise.

I was told there'd be NO Math

The Shannon–Hartley theorem states the channel capacity C, meaning the theoretical tightest upper bound on the information rate of data that can be communicated at an arbitrarily low error rate using an average received signal power S through an analog communication channel subject to additive white Gaussian noise (AWGN) of power N:

$$C = B\log_2\left(1 + \frac{S}{N}\right)$$

where

- C is the channel capacity in bits per second, a theoretical upper bound on the net bit rate (information rate, sometimes denoted I) excluding error-correction codes;
- B is the bandwidth of the channel in hertz (passband bandwidth in case of a bandpass signal);
- S is the average received signal power over the bandwidth (in case of a carrier-modulated passband transmission, often denoted C), measured in watts (or volts squared);
- N is the average power of the noise and interference over the bandwidth, measured in watts (or volts squared); and
- S/N is the signal-to-noise ratio (SNR) or the carrier-to-noise ratio (CNR) of the communication signal to the noise and interference at the receiver (expressed as a linear power ratio, not as logarithmic decibels).

Analog AM

AM modulation
Smoothly varying the Carrier amplitude from 0 to 2x.
Carrier plus two mirror image sidebands
Needs lots of Bandwidth

SSB suppressed carrier modulation
All the information is contained in just one sideband,
so why send the carrier and the other sideband?
Much more efficient than AM at less than 1/2 bandwidth.
Demodulation is trickier without the carrier.

Analog FM

Vary Carrier Frequency instead of Carrier Amplitude.

Receiver looks at the instantaneous carrier frequency vs the average carrier frequency to extract the information.

Higher peak deviation and higher frequency modulation both increase occupied bandwidth

Carson's rule

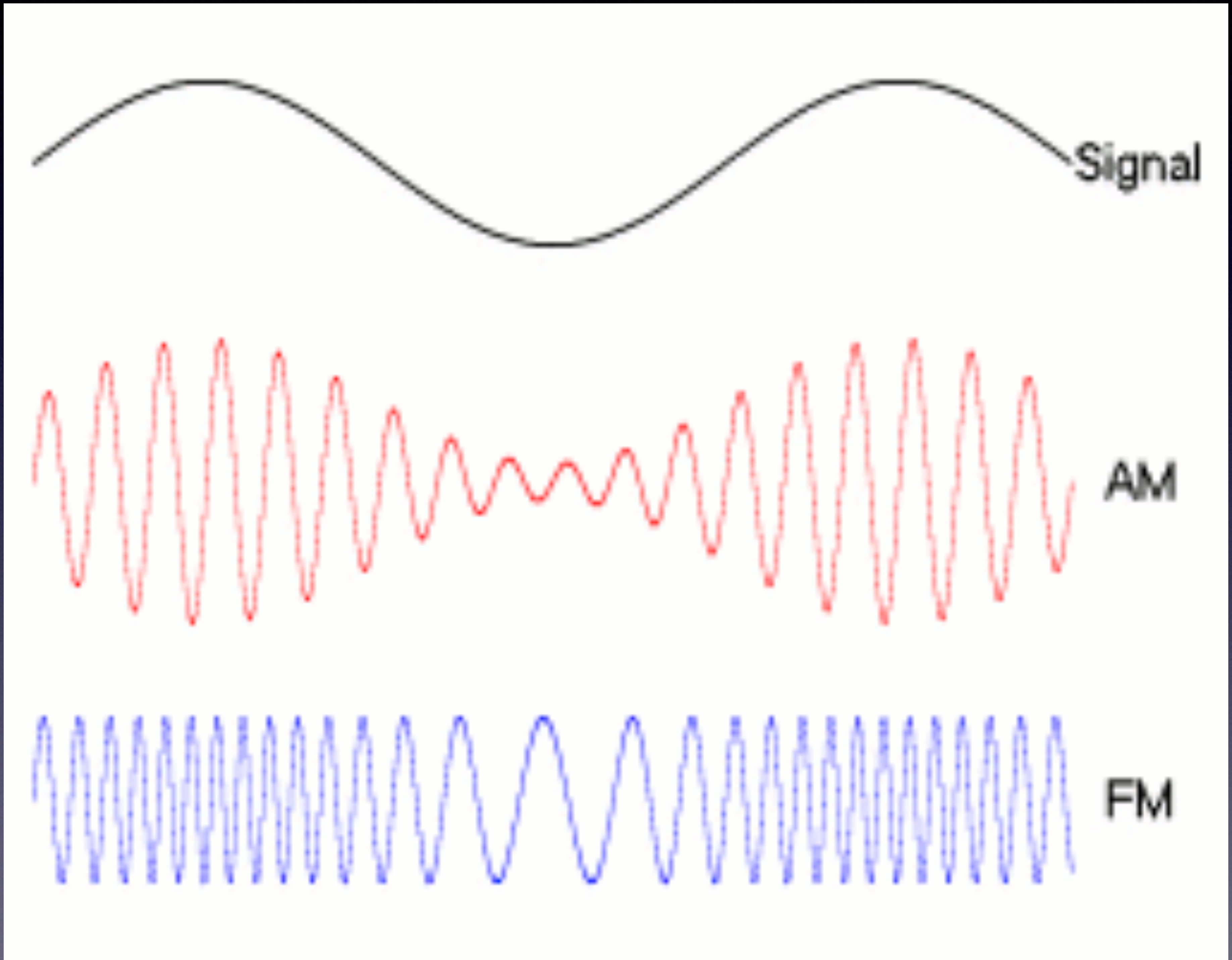
BW = 2 x (Dpeak + Fmax)

Typical Dpeak is 5kHz

Fmax for voice is about 3kHz

HT voice FM bandwidth $\approx$ 2 x (5kHz + 3kHz) = 16kHz

AM & FM Modulation



RF Carrier vs Modulation Sub-Carrier

The RF carrier may be SSB or FM mdulated but…

The Sub-Carrier can be AM, FM, or Phase Modulated or some combination of these.

AFSK Audio Frequency Shift Keying

TOR (Teleprinting Over Radio)

RTTY
5 bit code
170Hz shift
1445Hz -1275Hz

APRS
AX.25 protocol
1200 bps Bell 202 Modem 1200/2200Hz

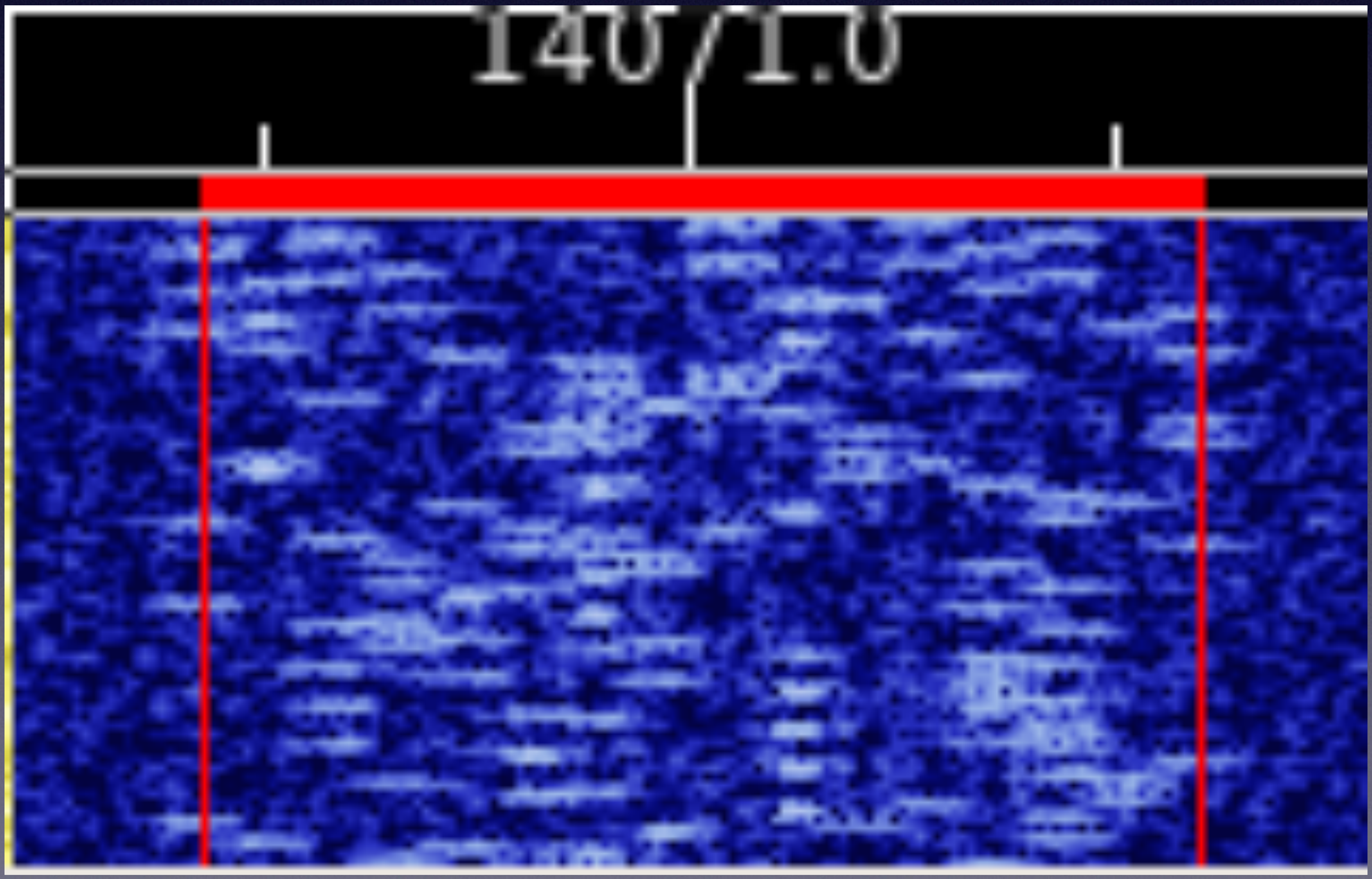
AMTOR (1981)
Similar to RTTY
Adds Error Detection and ARQ (Re-send)

PACTOR (Proprietary SCS 1991)

HF PACKET

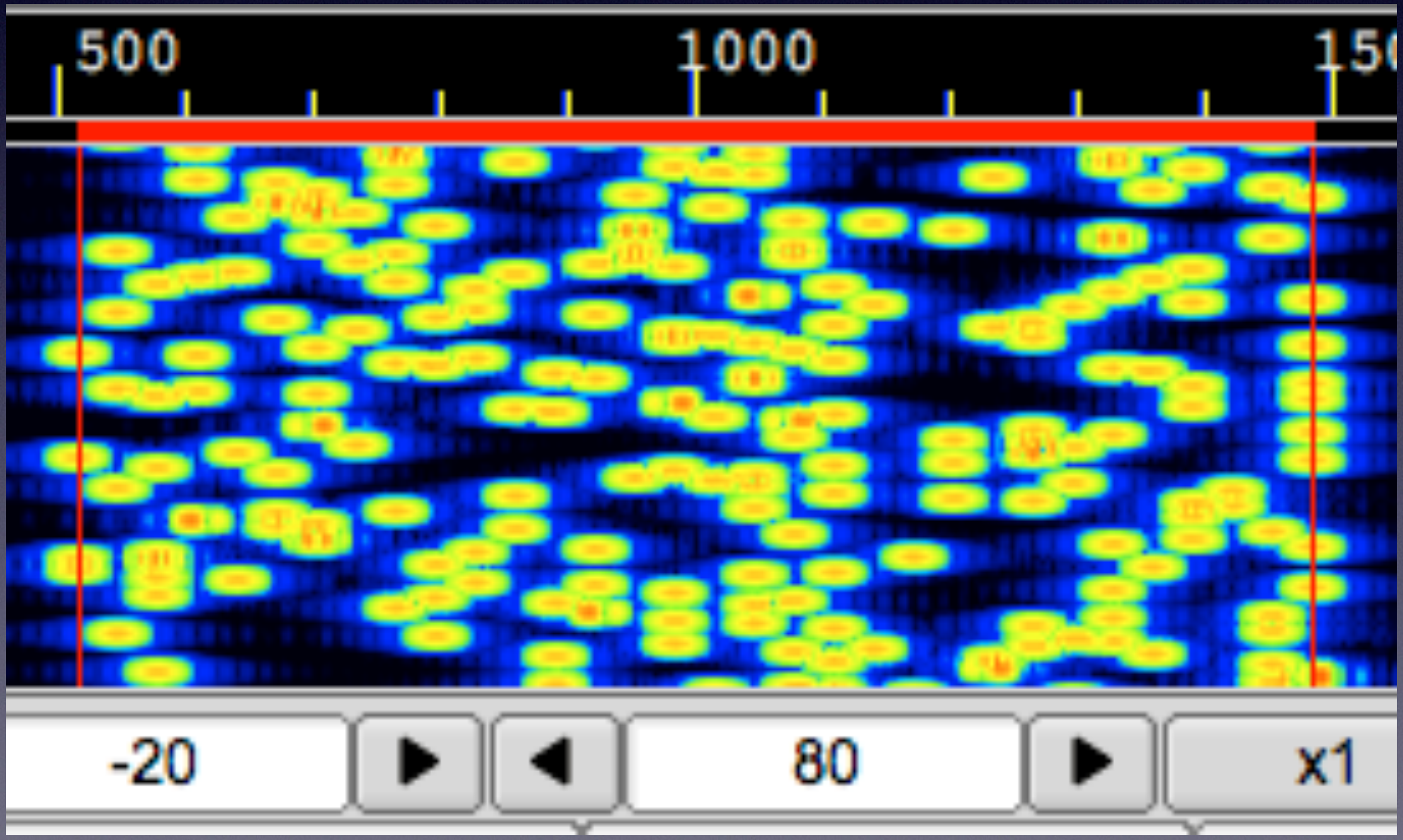
MFSK16

Mulit Tone FSK



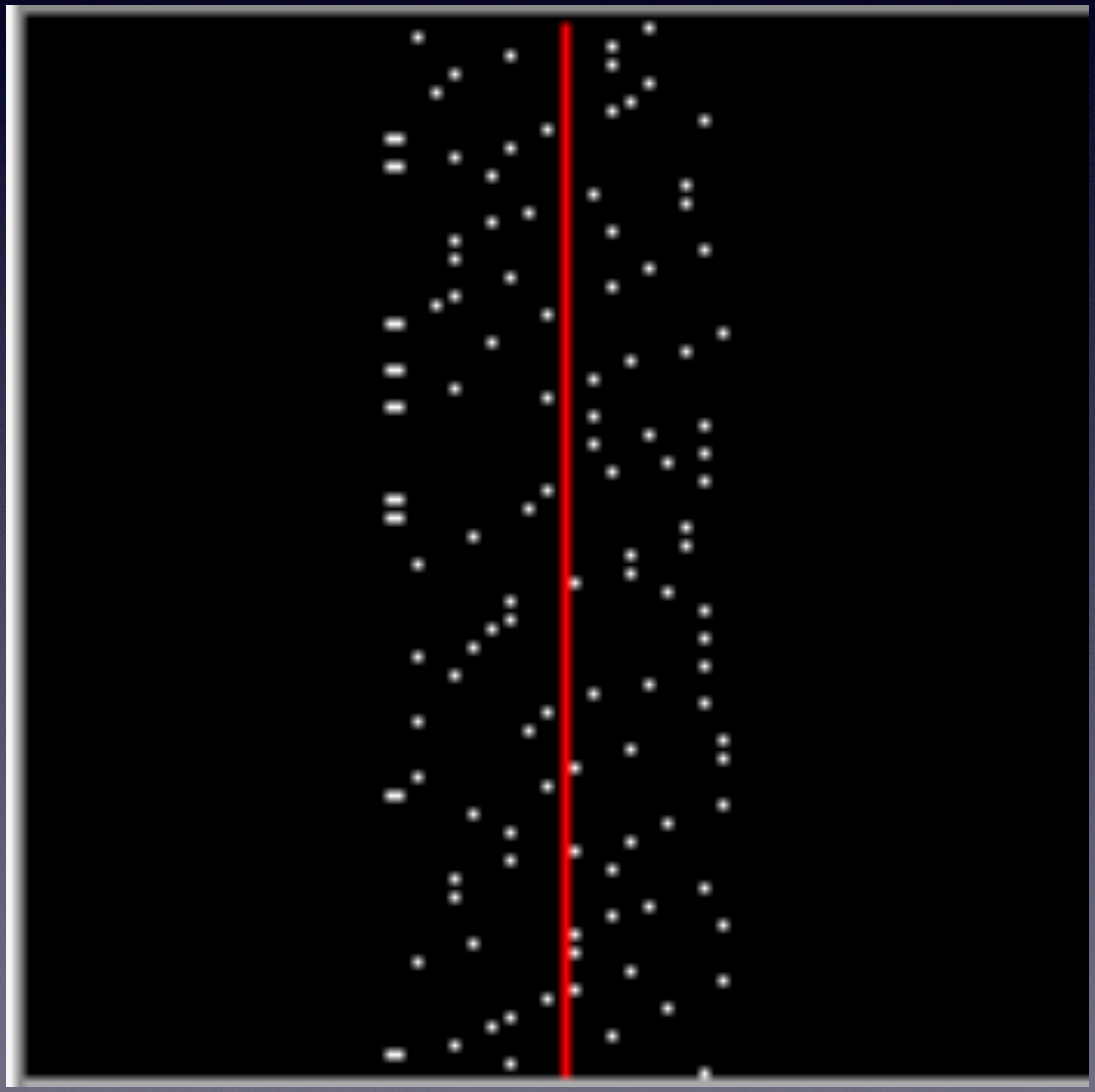
Olivia 500-16 (Shaped Tones)

Multi Tone FSK



DominoEX-8

Incremental Frequency Modulation



PSK Audio Phase Shift Keying

Phase is the measure of the location on a sinewave relative to something else at the same point in time. It can vary over 0 to 359 degrees.

Receiver looks at the instantaneous phase of the MODULATION to extract the information.

PSKnn
BPSKnn
QPSKnn

What’s your Vector, Victor?

Graphical way to express magnitude and direction

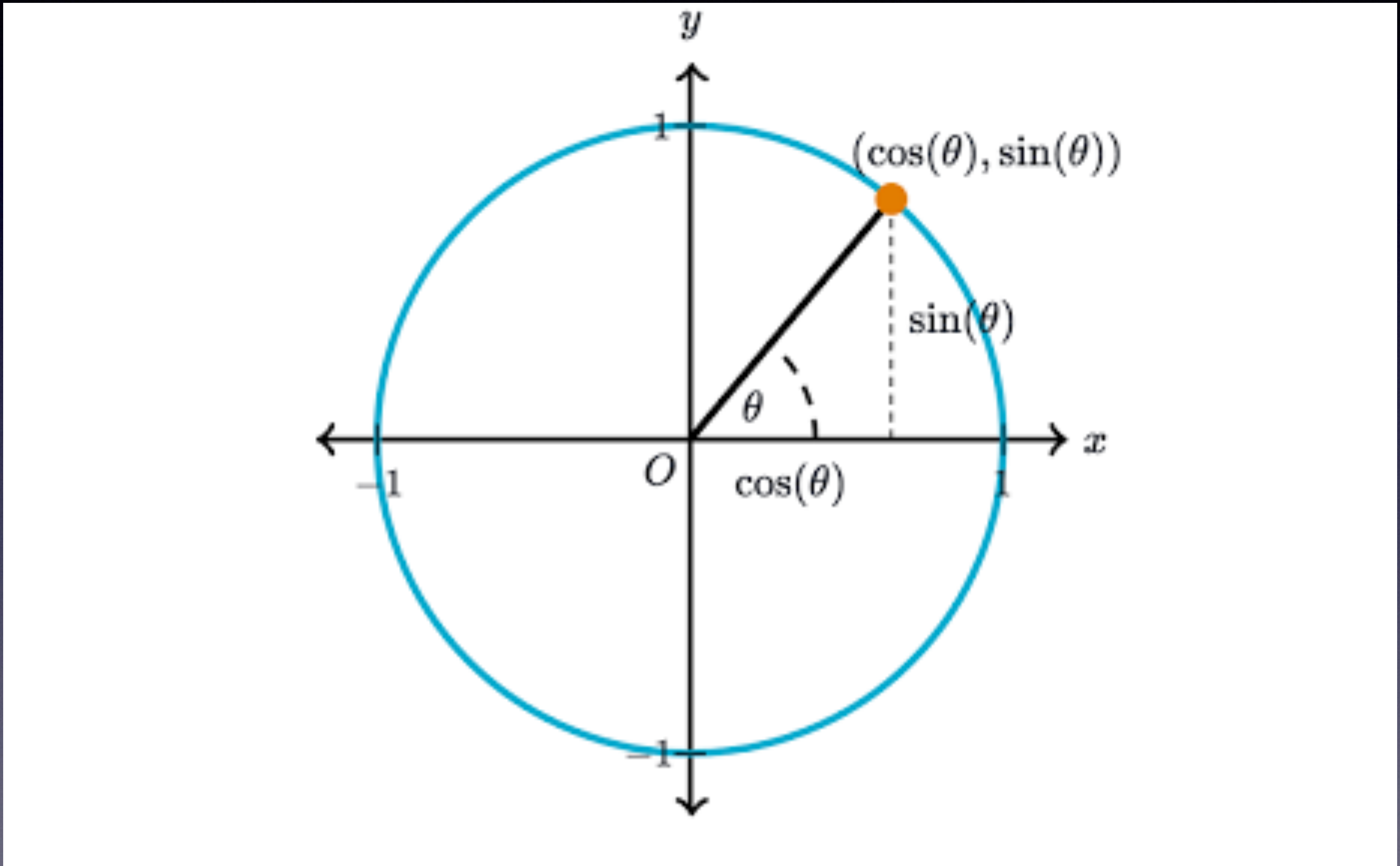
It is a line, sometimes ending in an arrow head

Its lenght is its magnitude

Its direction is the angle measured CCW from the +x axis

Wind speed and direction

Rotating Unit Vector



Sine and Cosine from Rotating Vector

[Khan Academy Rotating Vector]

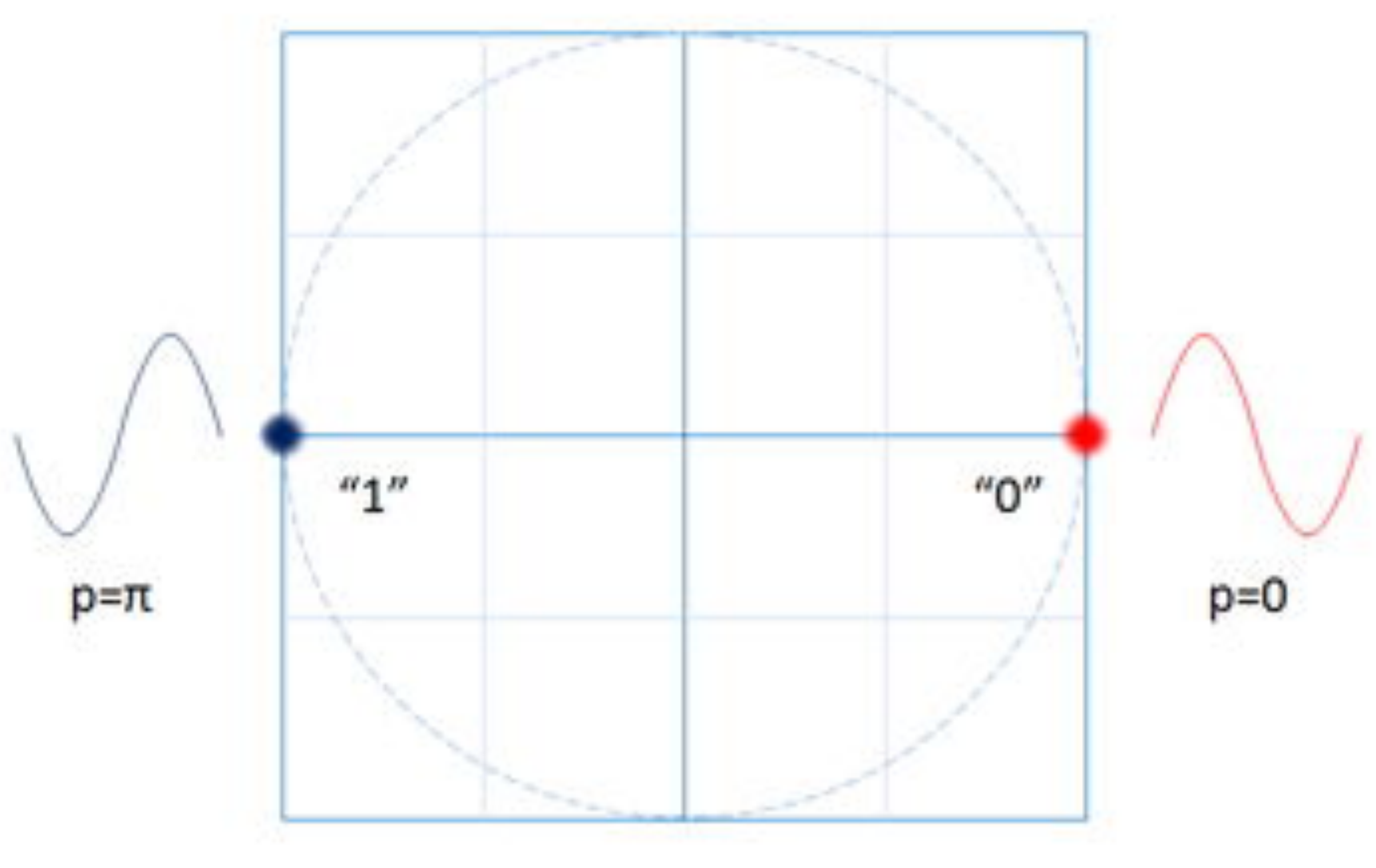
Quadrature modulation

Two sinewaves when 0 degrees apart are “In Phase”,
When 180 degrees apart are “Out of Phase”,
When ±90 degrees apart in “Quadrature”.

Quadrature (meaning at right angles) describes using two or more signals that can be detected at the receiver and are independent.

PSK Phase Shift Keying

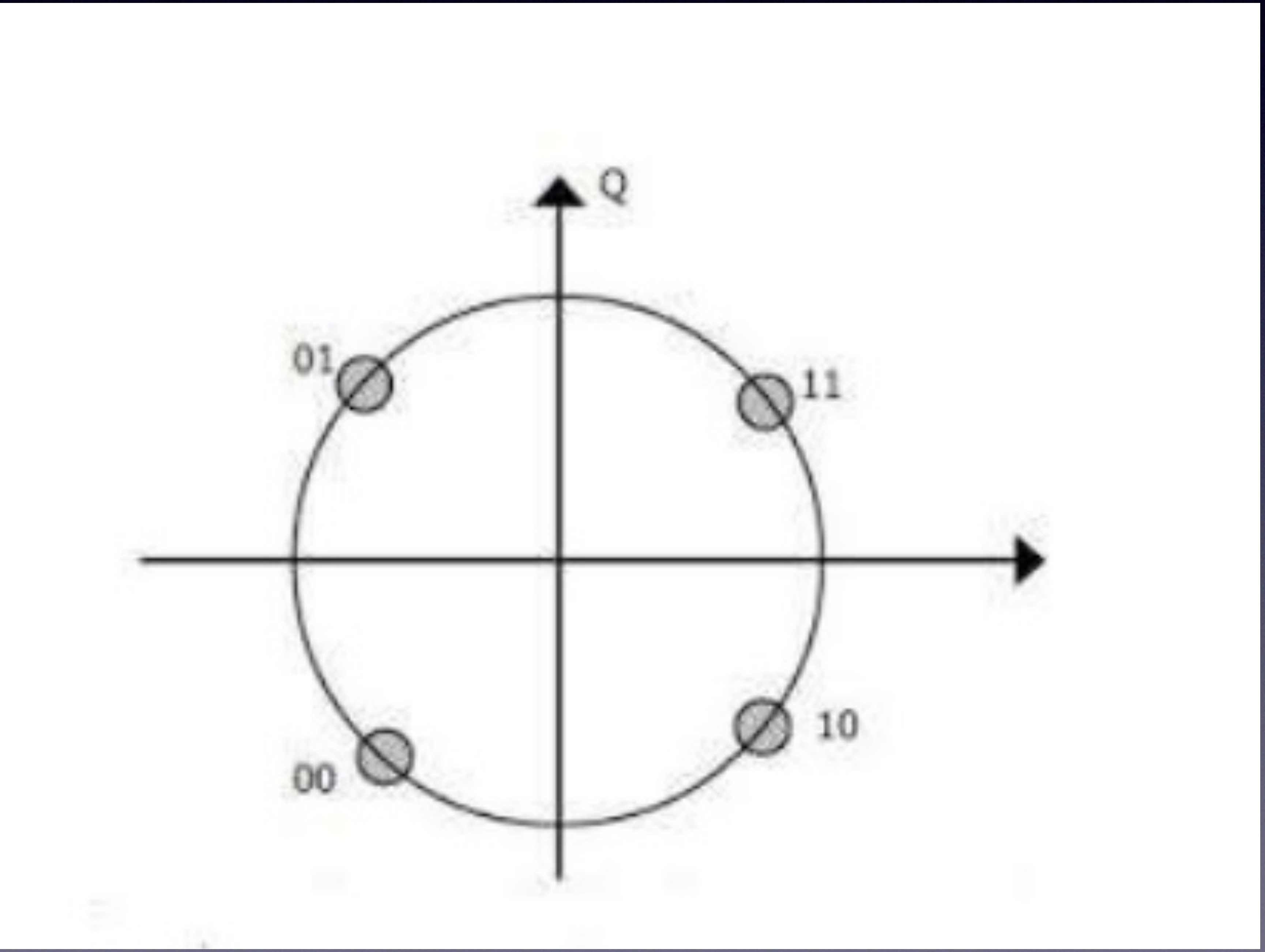
BPSK uses 0 and 180 degrees of shift
Bit rate = Baud rate



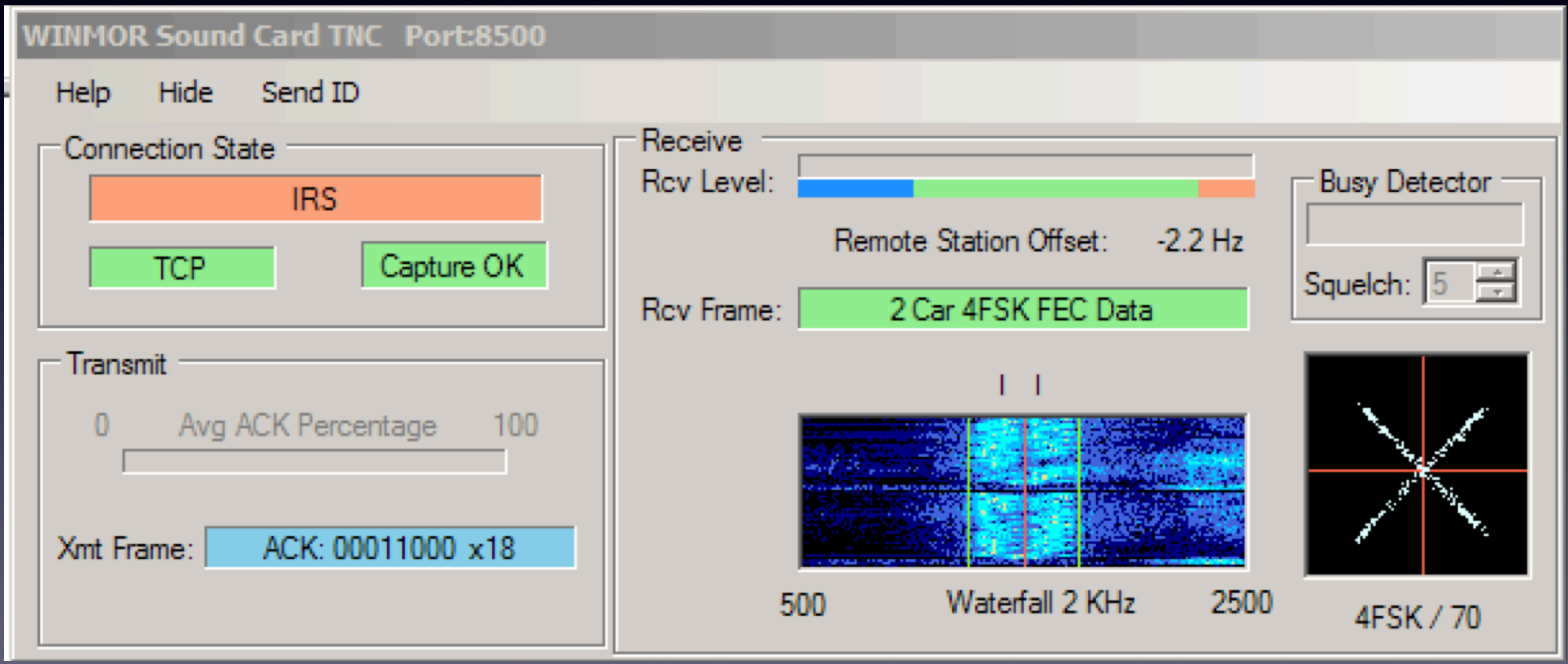
BPSK constellation (1bit/symbol)

QPSK uses 0, 90, 180 and 270 degrees of shift

Bit rate = 2 x Baud rate



Winmor 4FSK



WINMOR Sound Card TNC Port:8500
Help
Hide
Send ID
Connection State
IRS
TCP
Capture OK
Transmit
0
Avg ACK Percentage
100
Xmt Frame:
ACK: 00011000 x18
Receive
Rcv Level:
Remote Station Offset:
-2.2 Hz
Rcv Frame:
2 Car 4FSK FEC Data
500
Waterfall 2 KHz
2500
Busy Detector
Squelch:
5
4FSK / 70

Surely, you're joking?

More data in the same bandwidth?

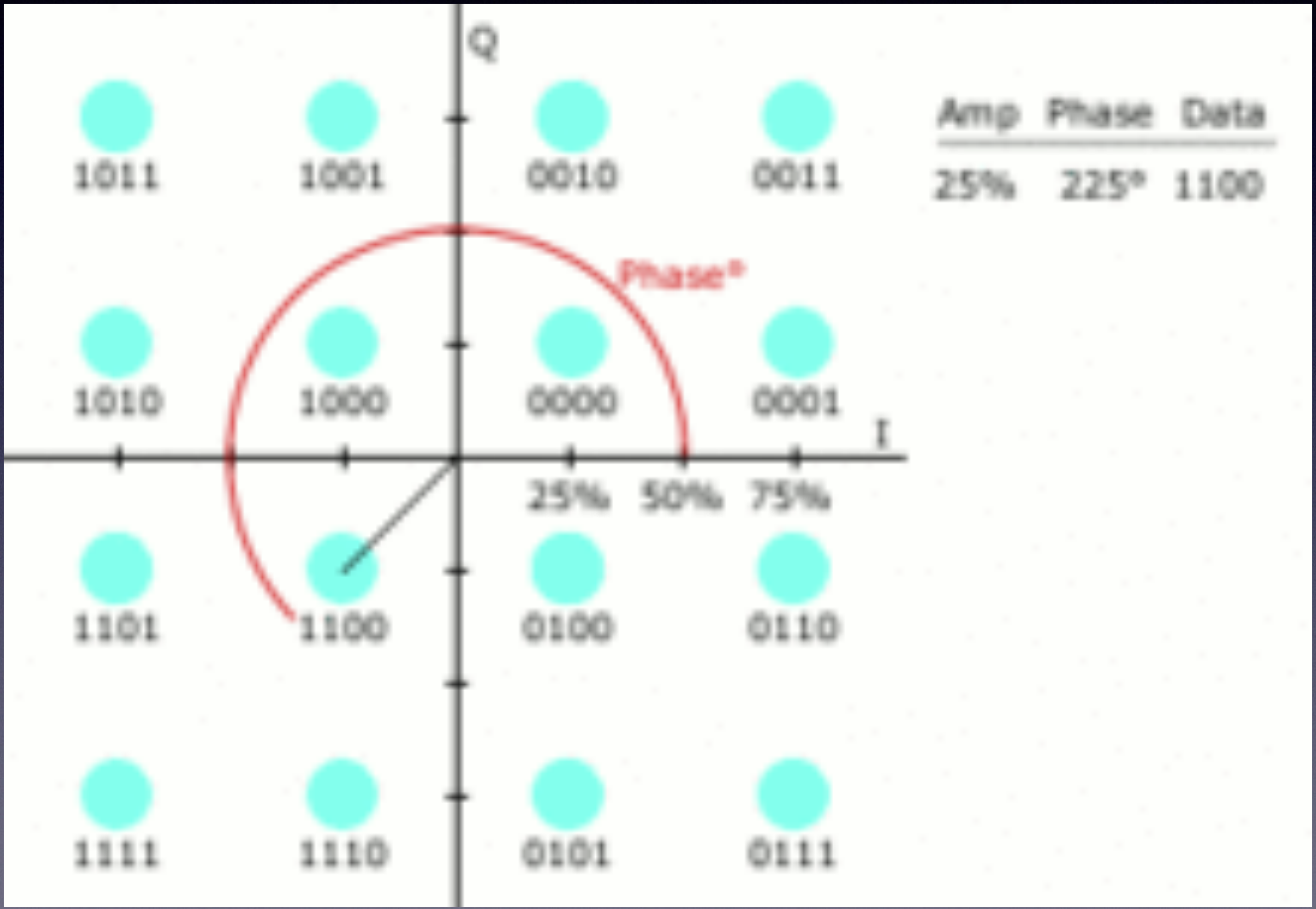
Multi Phase Modulation (nPSK)

Phase + Amplitude Modulation (nQAM)

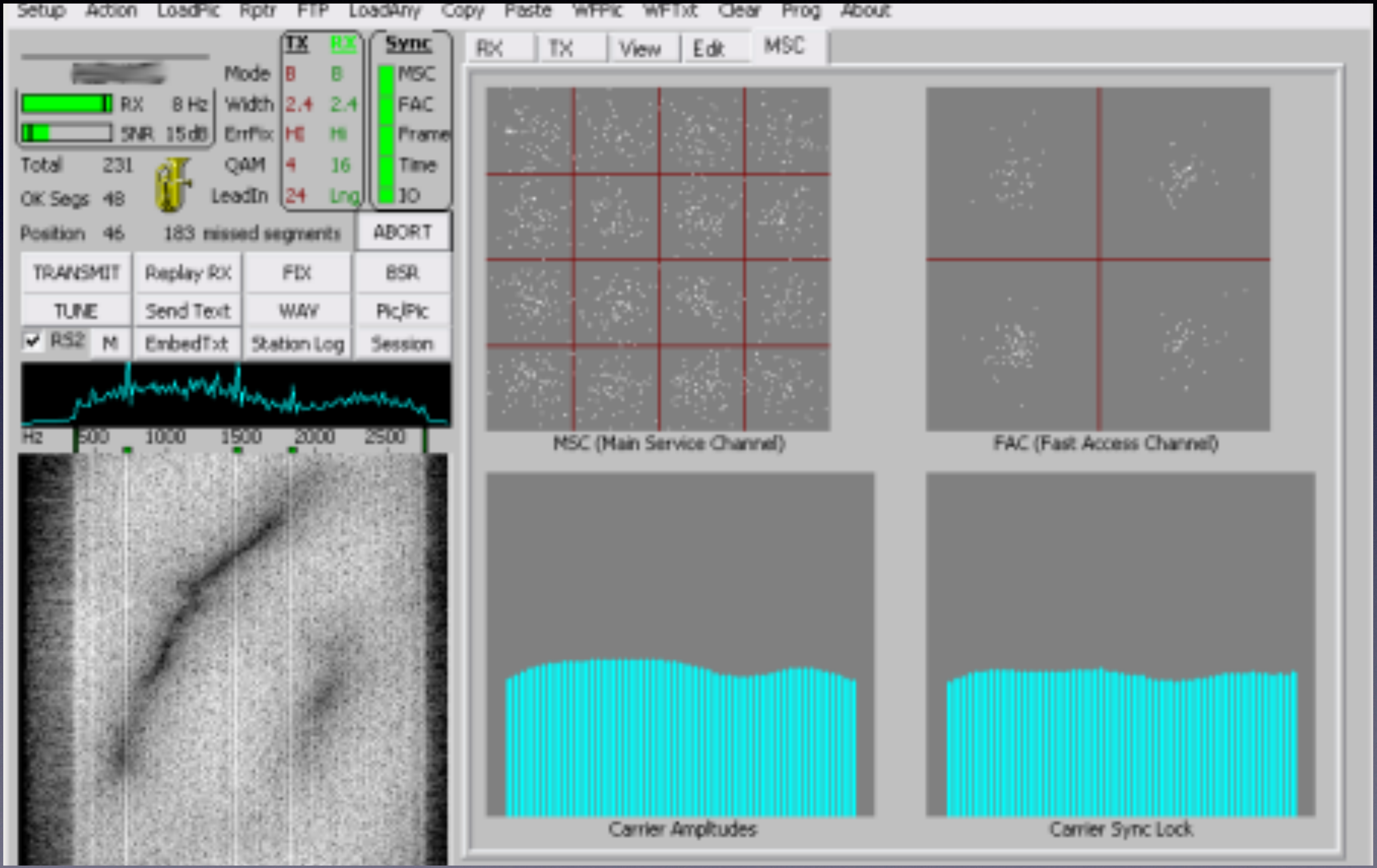
Multi Audio Carrier Modulation (nPSK)

16QAM, Send 4 Bits at a Time

Bit rate = 4 x Baud rate



EasyPal 4QAM, 16QAM



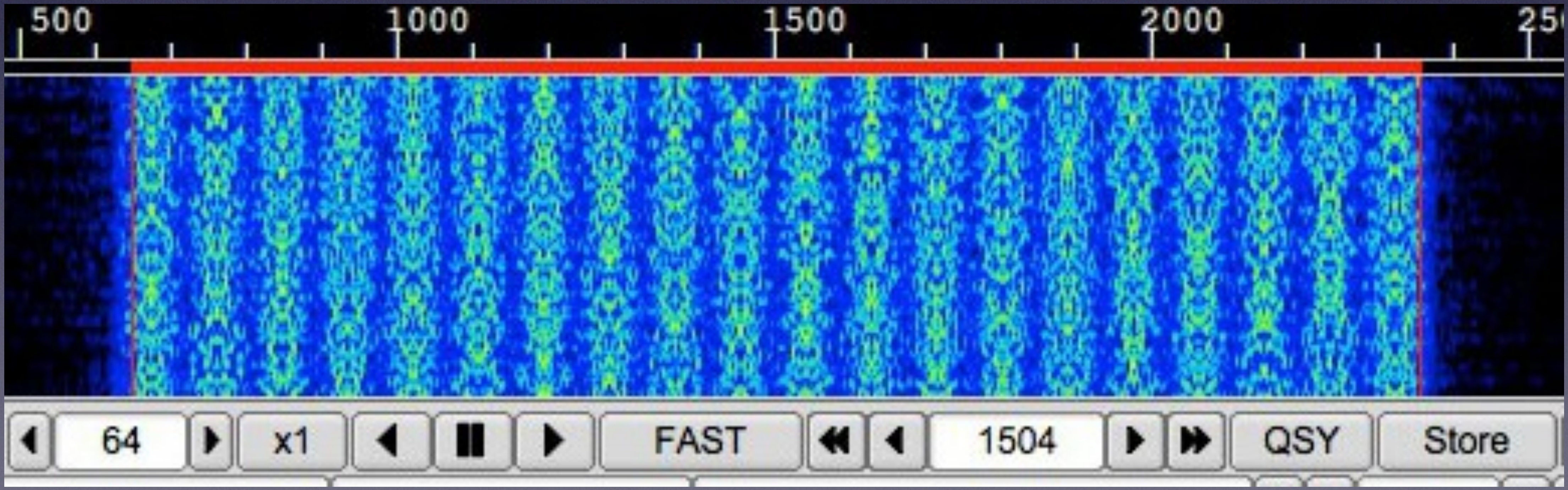
MTM (OFDM), what?

MultiTone Modulation

For Instance:

DTMF (pair of 8 tones)

PSK63R20C (20 subcarriers)



Can you handle the truth?

The more bits packed into a signal the poorer the signal to noise ratio (higher Bit Error Rate) and the stronger the received signal needs to be (for higher SNR).

Send the data in chunks (blocks, packets).

CHK, CRC & FEC
ADDITIONAL bits can be sent with the data to do error detection and and, possibly, correction at the receiver. Those extra overhead bits are in place of data potentially lowering the data rate.

Error Correction

ARQ (Automatic Repeat Request)

One obvious way to fix bad data is to automatically request a block resend. This is time consuming, blocks the channel especially if it requires many resends to fix the data.

Redundancy

Send multiple copies

FEC (Forward Error Correction)

If there are a small number of errors, the receiver may be able to detect them and correct them

Do You Sudoku?

You can find the missing data from the data you were given combined with the known structure of the data and some simple rules.

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

Packet Radio

What is Packet Radio?

- One of many digital modes available in Amateur Radio
- Transmitted information is received 100% error free!
- Divide data stream into bite-sized packets
- Sends a “packet” of data (envelope + payload) at a time
- At VHF/UHF, typically operates at 1200 baud (AFSK on FM) or 9600 baud (G3RUH FSK)
- At HF, typically operates at 300 baud (FSK/AFSK on SSB)

High level structure of a packet

Summary

- Digital transmission has been around a long time
- You can understand digital techniques without hairy math
- Carrier modulation and sub-carrier modultion can be different
- Sub-carrier modulation can be AM, FM, PM or some combo
- Error Detection and Correction can make for 100% copy
-

References

Thanks to Steve KB1TCE and Richard WD1O for their suggestions

https://en.m.wikipedia.org/wiki/Shannon–Hartley_theorem

http://w1hkj.com/FldigiHelp-3.21/html/modems_page.html

http://wb8nut.com/digital/

http://www.arrl.org/digital-data-modes