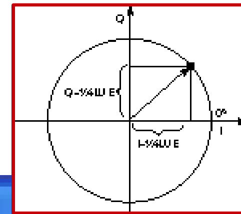
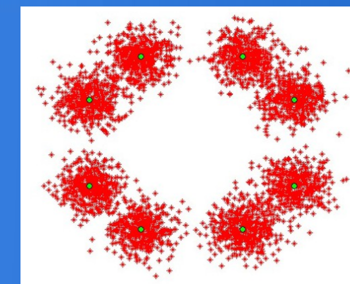
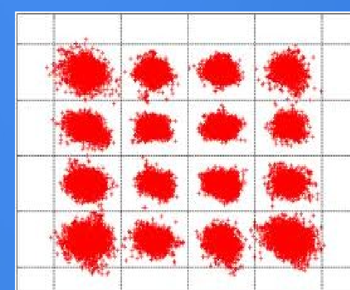


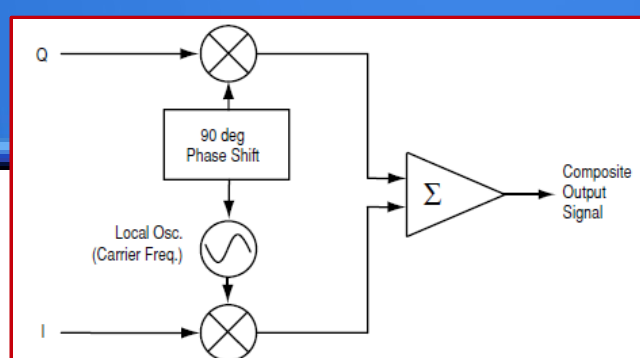
A Primer on
Digital Modulation

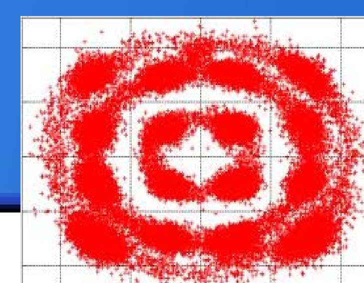


By Bertrand Zauhar, VE2ZAZ
http://ve2zaz.net



August 2013





In this Presentation

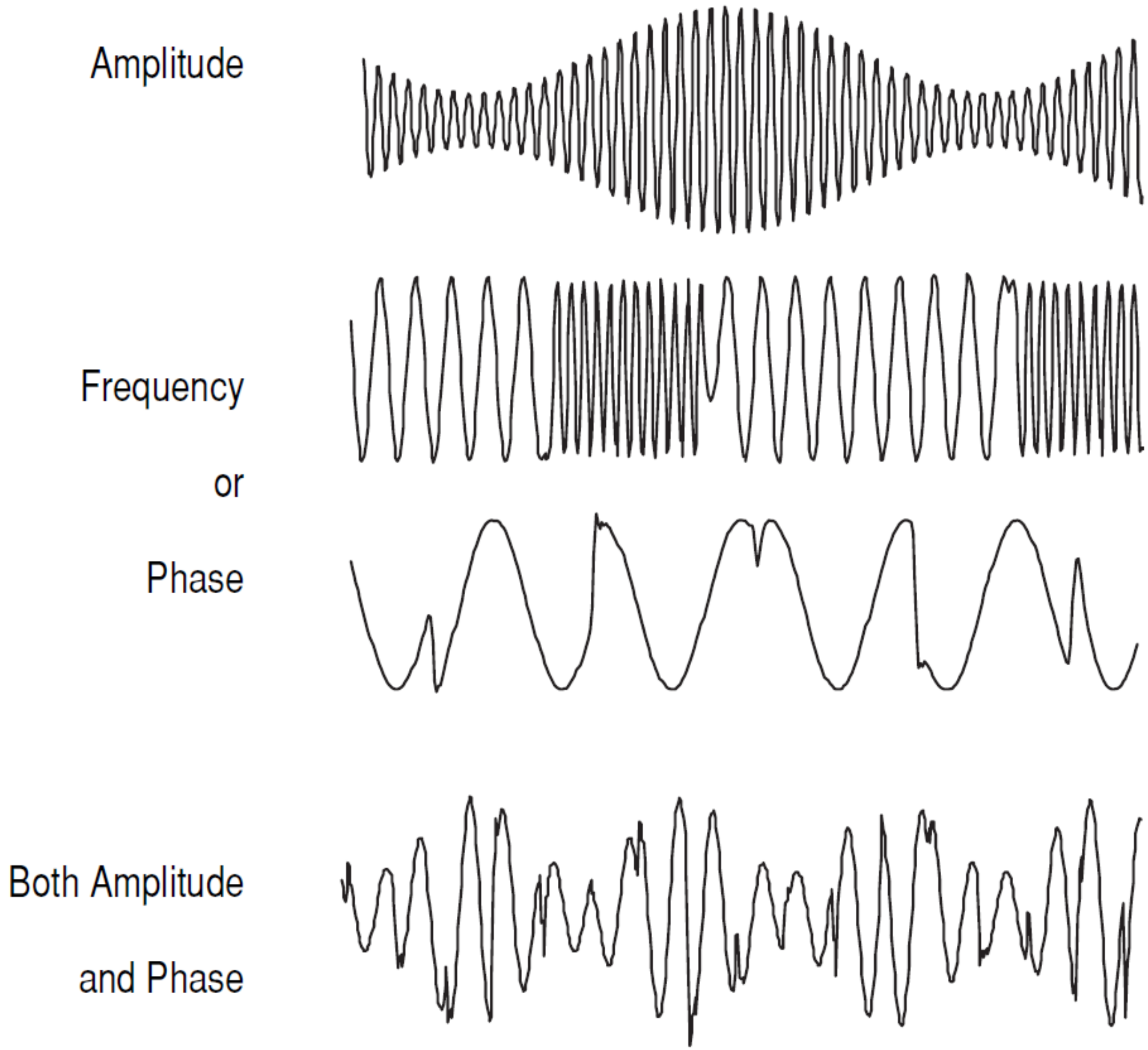
- Modulation Fundamentals
- Real Life Communications Design Constraints
- Digital Modulation (DM) Tradeoffs
- DM Graphical Representation
- Specifics of several DM schemes
- DM Mod./Demod. Generation
- Typical Digital Radio
- Existing DM Protocols

An Analog World...

- Only three fundamental ways to modulate:
  - Amplitude Modulation (AM),
  - Frequency Modulation (FM),
  - Phase Modulation (PM).

Any modulation format, whether analog or digital, must use one or more of the above analog schemes.

Modulation Fundamentals



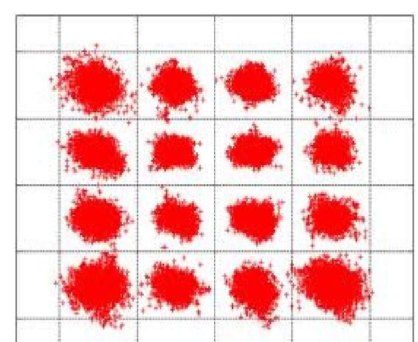
Constraints in Comm Systems Design

- The Communications Systems designers face the following constraints
  - Available bandwidth,
  - Permissible power,
  - Inherent noise level and other impairments of the system.
  - Electrical energy availability.
  - Cost
  - ...

Digital Modulations (DM)

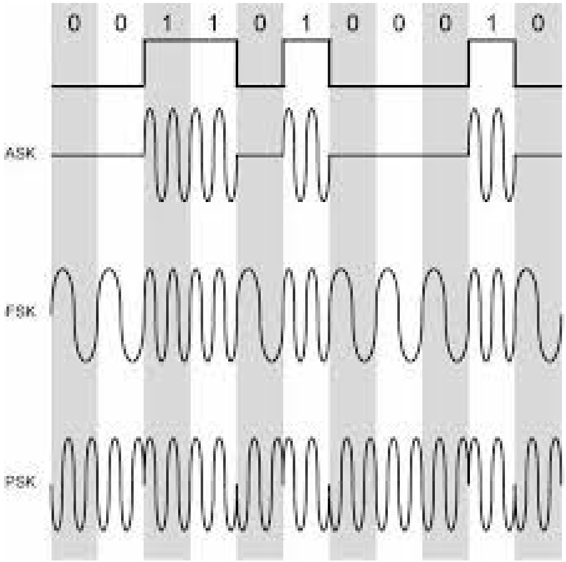
- Analog modulations
  - continuously variable over amplitude, frequency and/or phase.
- Digital modulations similar to analog modulations,
  - varying RF amplitude, frequency or phase,
- BUT
  - The parameters being modulated take on a specific set of waveform states or symbols.

vs.



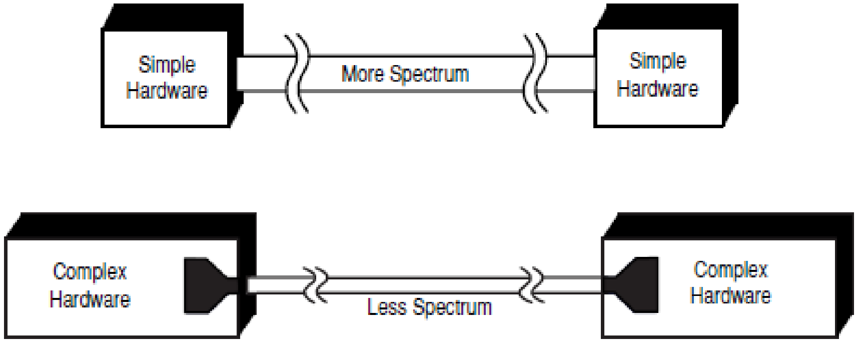
Known Benefits of DM

- More information capacity,
  - For any given bandwidth
- More bandwidth-efficient,
- Higher data security,
  - Encoding, Encryption
- Better quality communications,
  - Noise-Free, error correction



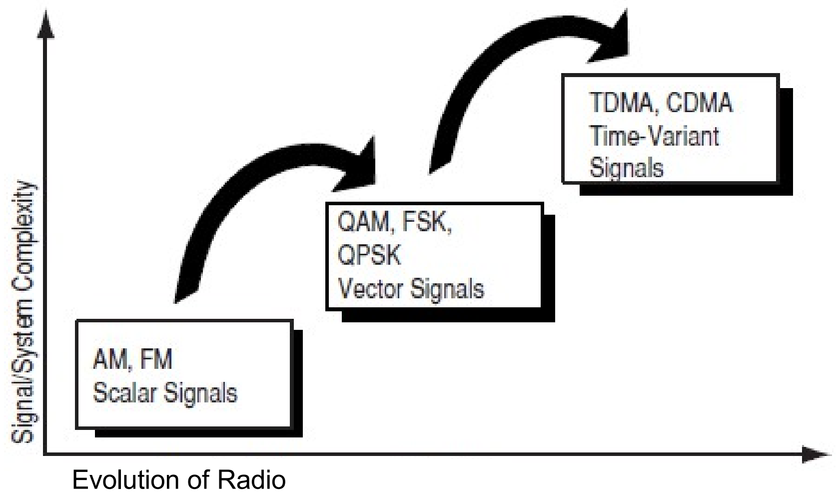
Fundamental Tradeoff

- Analog Modulation simple to create and detect, but is bandwidth inefficient.
- Digital modulation (DM) is more bandwidth and/or power efficient, but more complex to generate and decode.



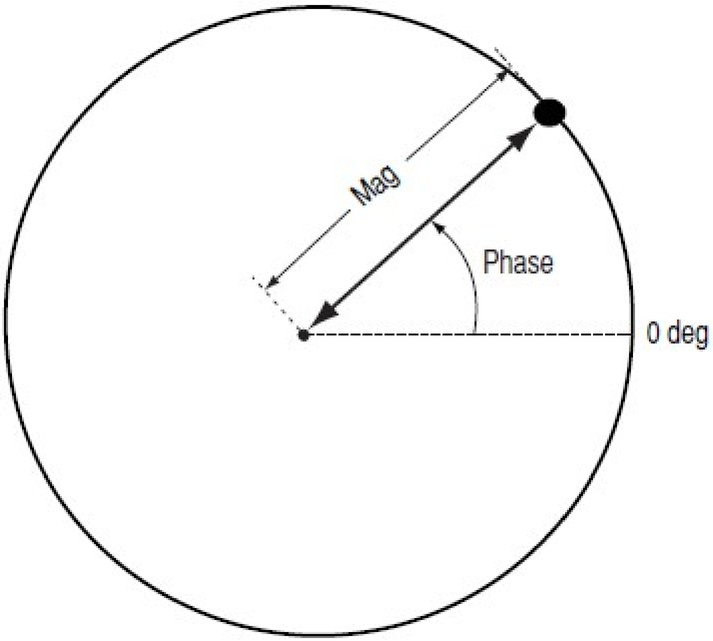
Industry Trends

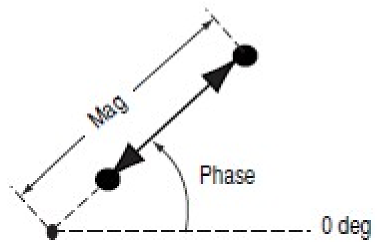
- From Analog...
- To digital (vector-based)
- To digital (multiplexed, complex encoding, ...)



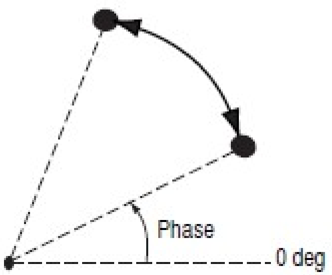
Polar Representation

- Simultaneous magnitude and phase representation.

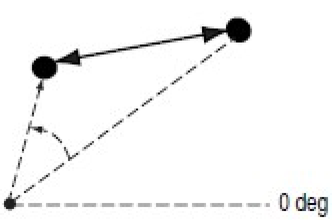




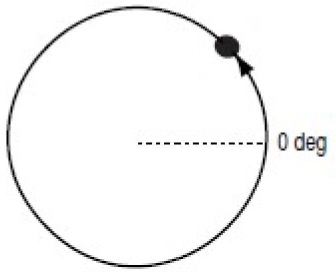
Magnitude Change



Phase Change



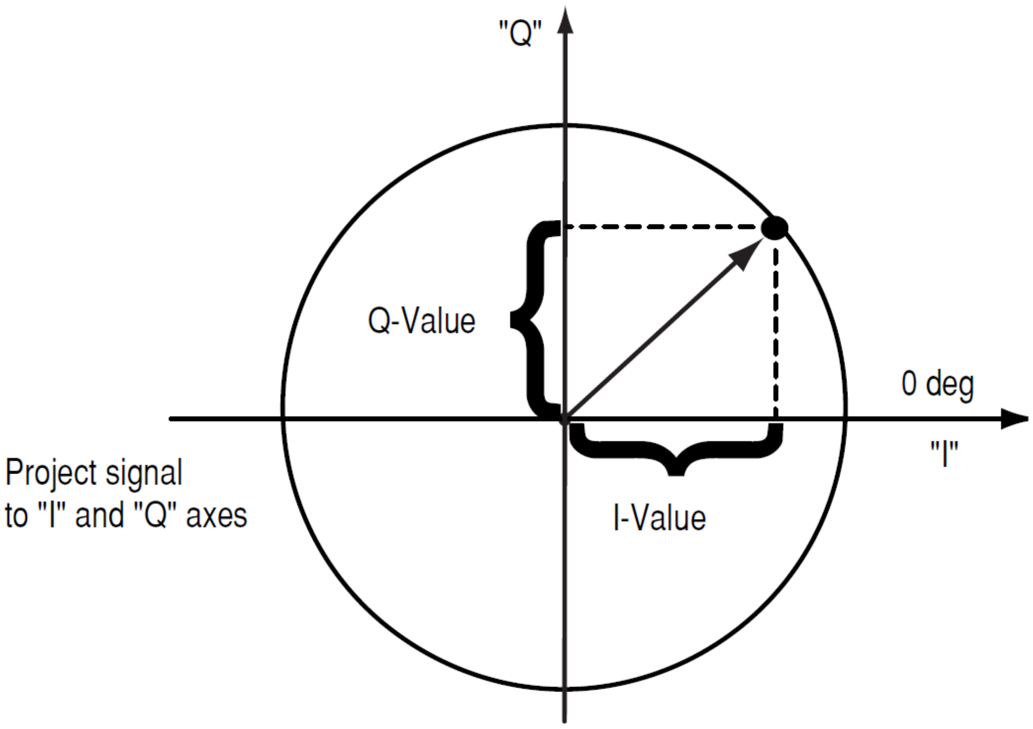
Magnitude & Phase Change



Frequency Change

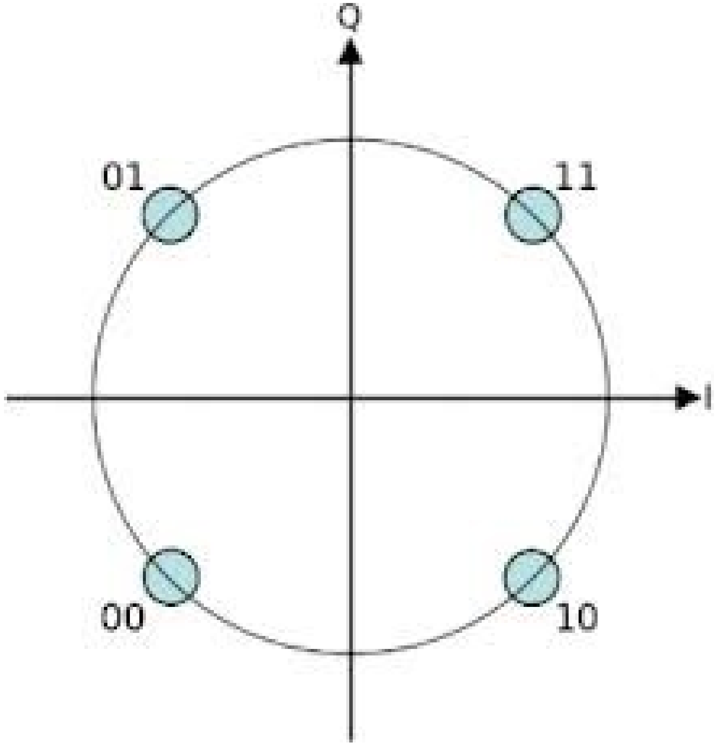
I - Q Representation

- Rectangular representation of the polar diagram using coordinates (I,Q).
- Signal vector's projection onto I axis and Q axis.



Polar to Rectangular Conversion

Constellation Diagram

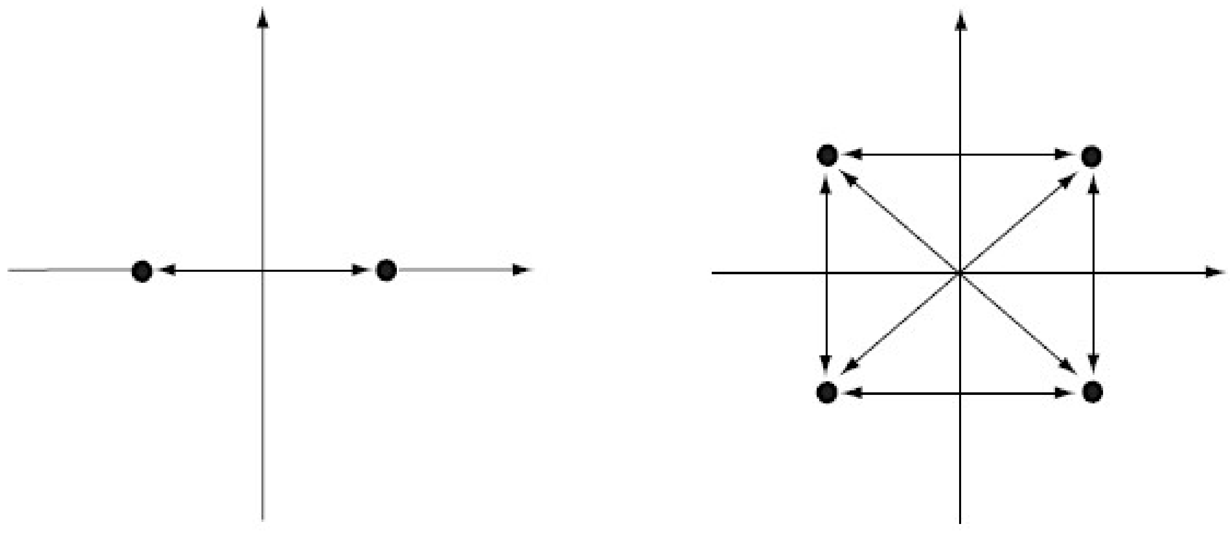


Example above is QPSK.

Num. Bits carried / Symbol = $\sqrt{\text{Number of I-Q Points}}$

Phase Shift Keying (PSK)

- Phase of constant amplitude carrier shifted 180 degrees, or 90 degrees.
- Quadrature-PSK more BW efficient than Bi-PSK.

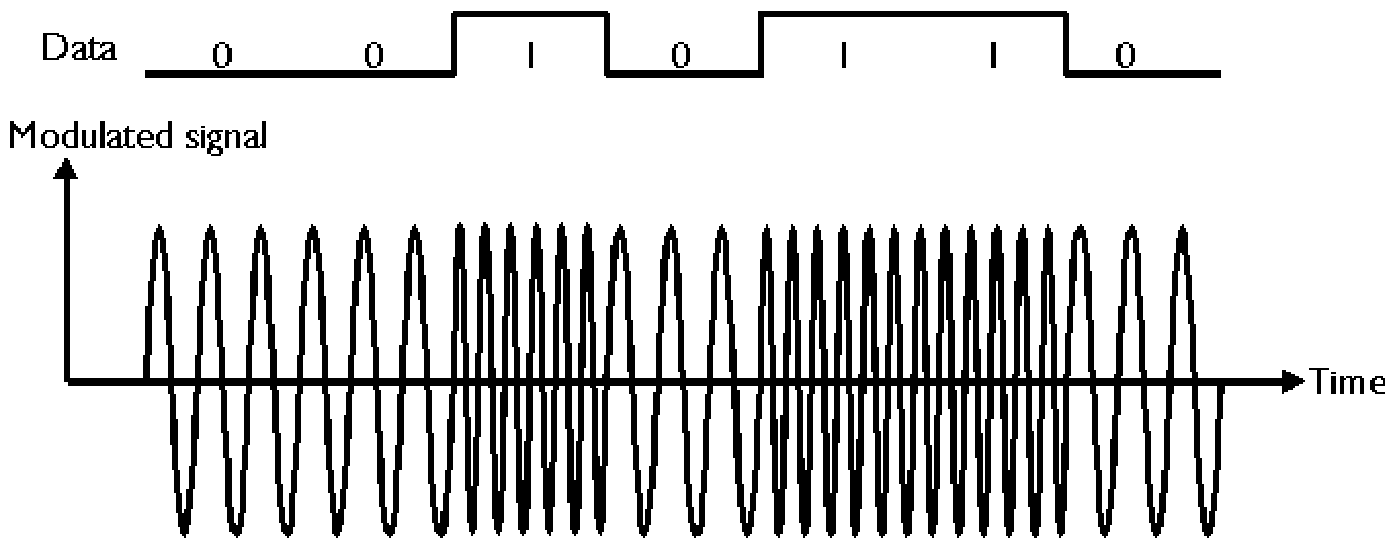


BPSK
One Bit Per Symbol

QPSK
Two Bits Per Symbol

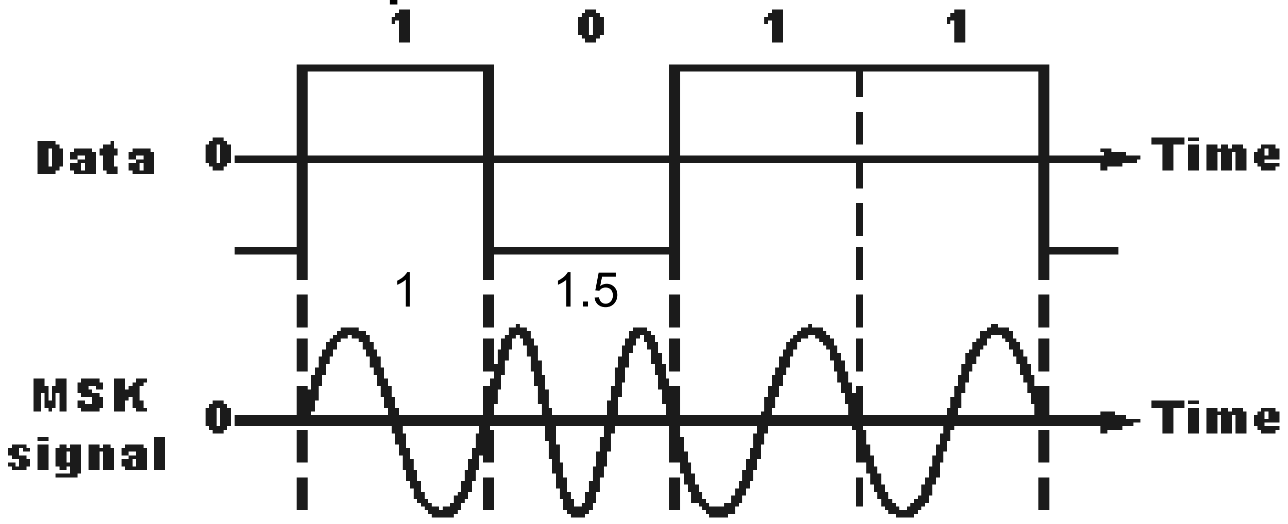
Frequency Shift Keying (FSK)

- Frequency of a constant amplitude carrier shifted or not, representing a symbol.
  - BFSK: Two frequencies represent two symbols, (0 and 1, for example)
  - Not well illustrated with an IQ constellation



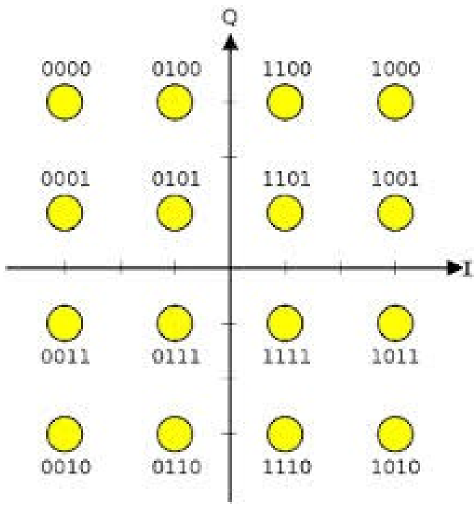
Min. Shift Keying (MSK)

- A type of FSK with constant phase/constant amplitude carrier, shifted or not, representing a symbol. Sinusoidal shaping.
  - Frequency difference between the 1 and 0 is always equal to half the data rate,
  - Reduces required bandwidth to minimum.

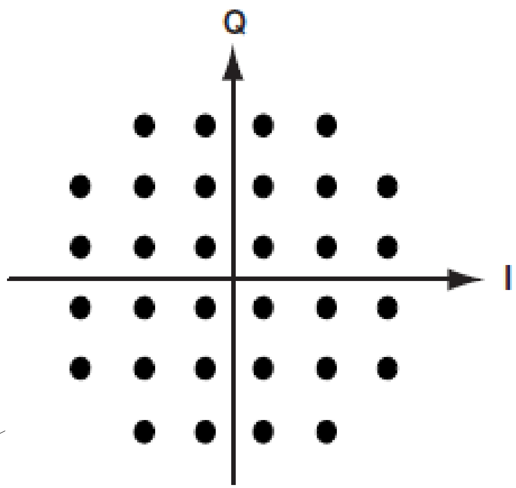


Quadrature Amplitude Modulation (QAM)

- Both Amplitude and Phase are varied to obtain a more complex constellation of symbols.
  - More efficient than BPSK, QPSK, or 8PSK.
  - Bandwidth #bit-times smaller
  - Note that QPSK = 4QAM



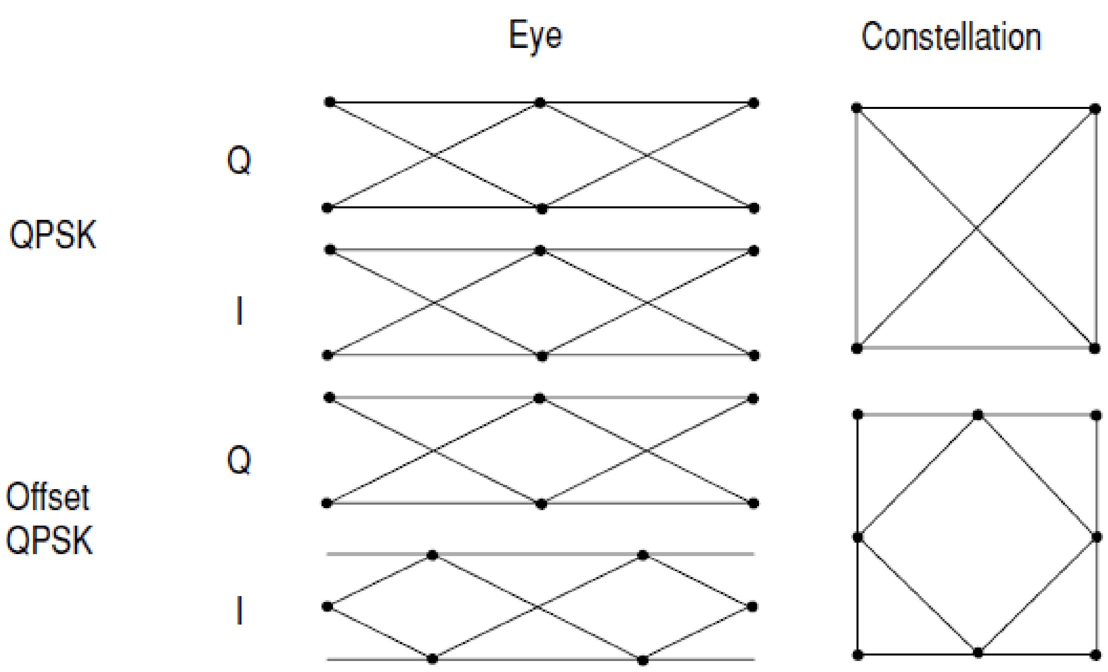
16QAM
4 bits per Symbol
Symbol rate = 1/4 bit rate



32QAM
5 bits per Symbol
Symbol rate = 1/5 bit rate

Modulation variations

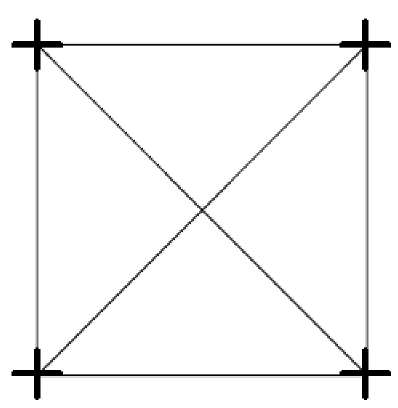
- <u>I/Q offset modulation</u>: has power efficiency advantages
  – QPSK: the I and Q bit streams are switched at the same time
  – OQPSK: the I and Q bit streams are offset in their relative alignment by one bit period



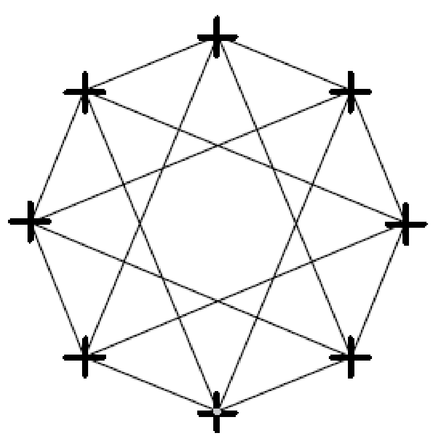
Modulation variations

- <u>Differential modulation</u>: has bandwidth efficiency advantages
  - QPSK: information is carried by the absolute state
  - DQPSK: information is not carried by the absolute state, it is carried by the transition between states.

QPSK

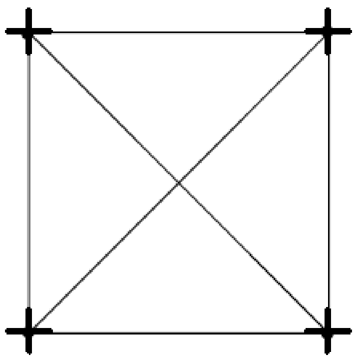


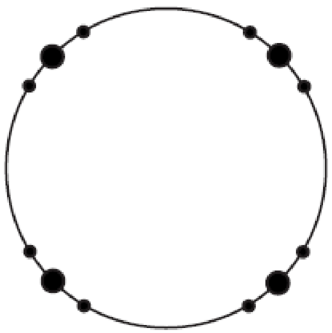
$\pi/_4$ DQPSK



Modulation variations

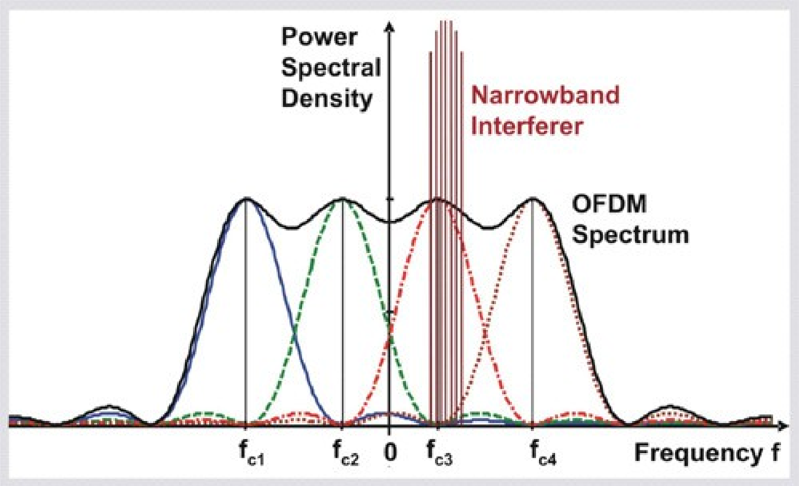
- <u>Constant amplitude modulation</u>: has power efficiency advantages. Can use Class-C stages (non-linear)
  - QPSK: amplitude of carrier varies during transitions,
  - GMSK (GSM): amplitude of the carrier is constant, regardless of the variation in the modulating signal.





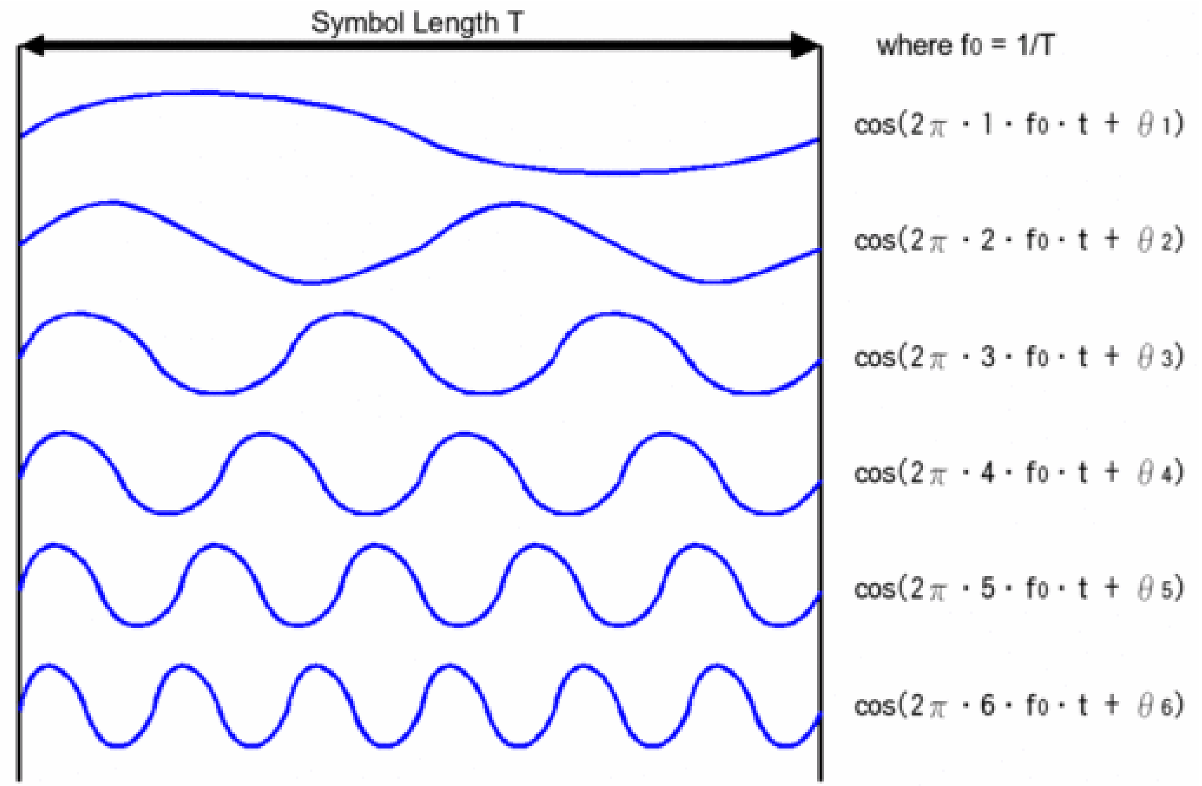
Orthogonal Frequency Division Multiplexing (OFDM)

- Not a basic modulation principle, rather a coding technique using several orthogonal sub-carriers (frequencies) to convey data.
- Each sub-carrier is modulated traditionally (such as PSK, QAM) at a slower data rate vs. single carrier system.
- Advantageous against:
  - Channel frequency roll-off,
  - Multipath fading,
  - Narrowband interference



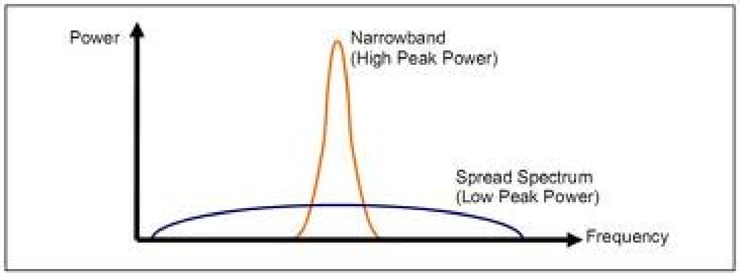
Orthogonality

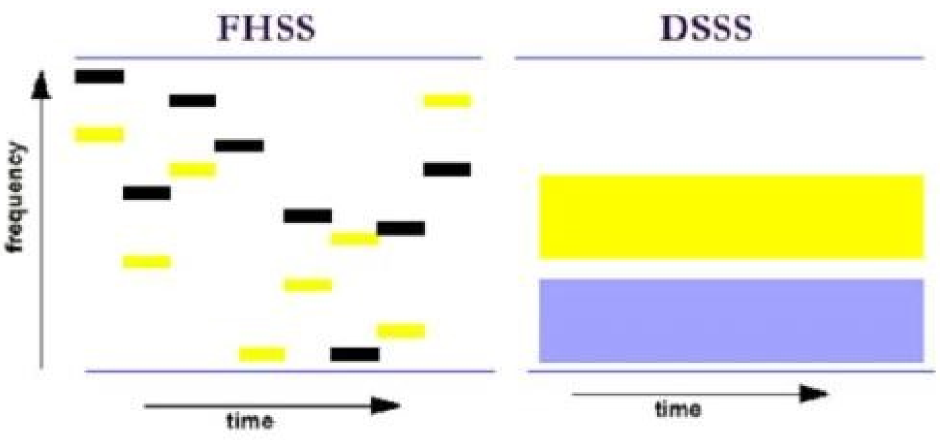
- In the symbol period T, we can use sinusoidal waveforms which have integer number of periods in the T.



Spread-Spectrum (SS)

- Signal generated with a known bandwidth is deliberately spread in the frequency domain. Typically sequential noise-like spectrum.
- Frequency Hopping (FHSS) and/or Direct Sequence (DSSS) modulation mainly used.
- Pseudo-random number sequences determine and control the spreading pattern of the signal.
- Tx-Rx Synchronization critical!
- Advantageous against:
  - Jamming,
  - Eavesdropping,
  - Fading
  -





Theoretical Bandwidth Efficiency Limits

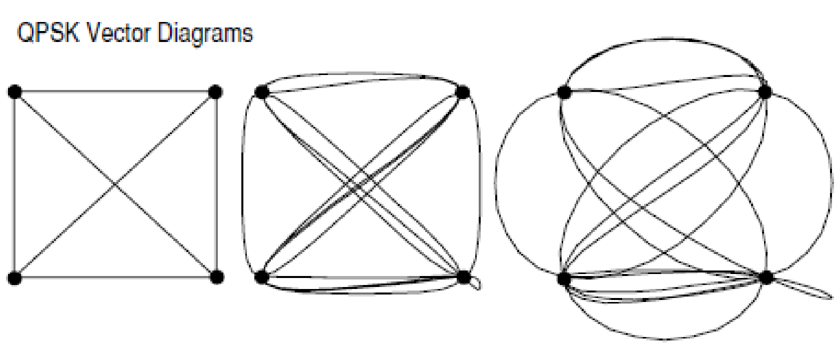
- Give a good idea of relative bandwidth efficiency.
- <u>Theoretical</u>: cannot be achieved with real radio components and links.

Modulation format	Theoretical bandwidth efficiency limits
MSK	1 bit/second/Hz
BPSK	1 bit/second/Hz
QPSK	2 bits/second/Hz
8PSK	3 bits/second/Hz
16 QAM	4 bits/second/Hz
32 QAM	5 bits/second/Hz
64 QAM	6 bits/second/Hz
256 QAM	8 bits/second/Hz

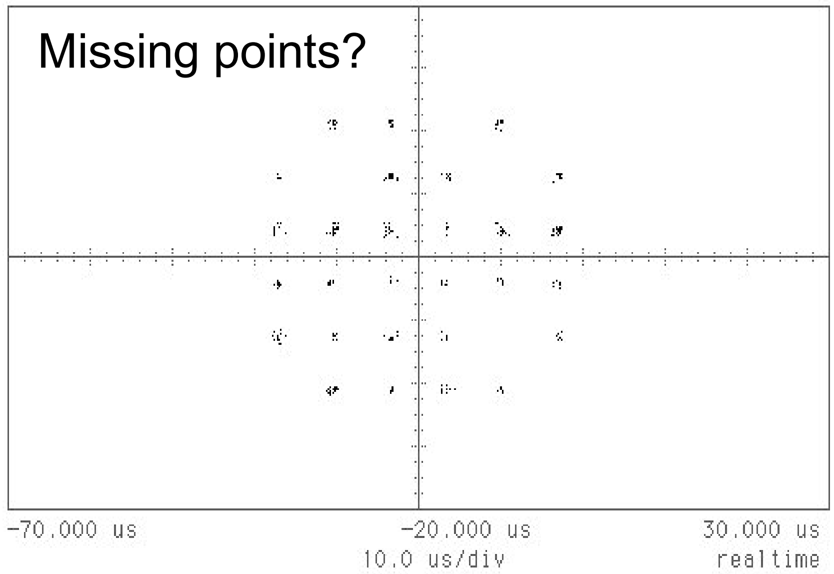
Compromises...

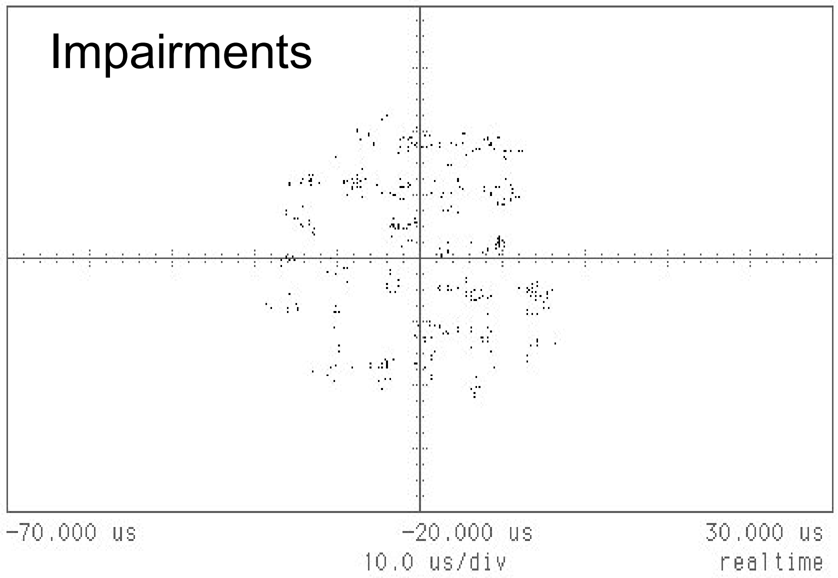
Filtering

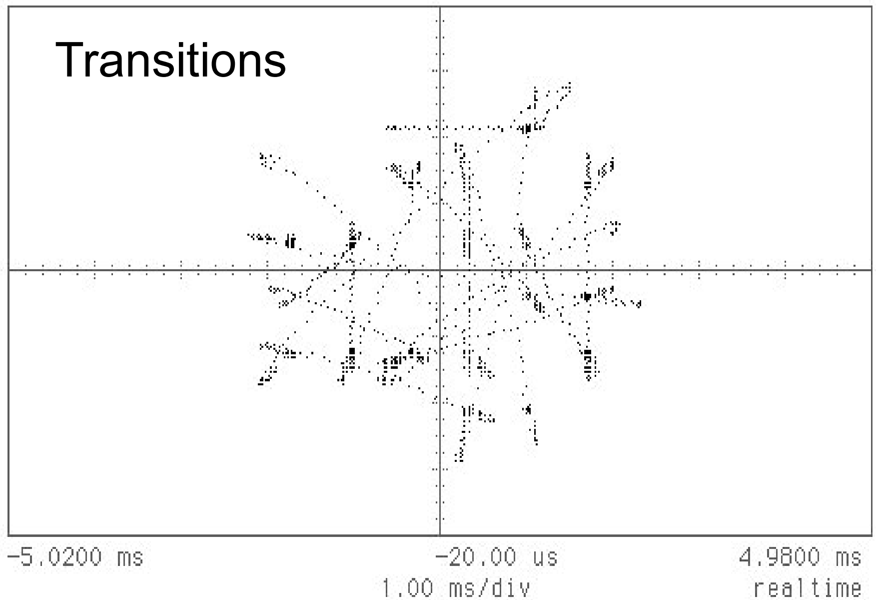
- Slows down the transitions. Allows the transmitted bandwidth to be significantly reduced.
  - Any fast transition in a signal, whether it be amplitude, phase, or frequency, will require a wider occupied bandwidth.
  - May require more power to transmit (larger excursions)
  - Tradeoffs!
    - Common Filters
      - Raised cosine
      - Square-root raised cosine
      - Gaussian filters



Real Life Constellations

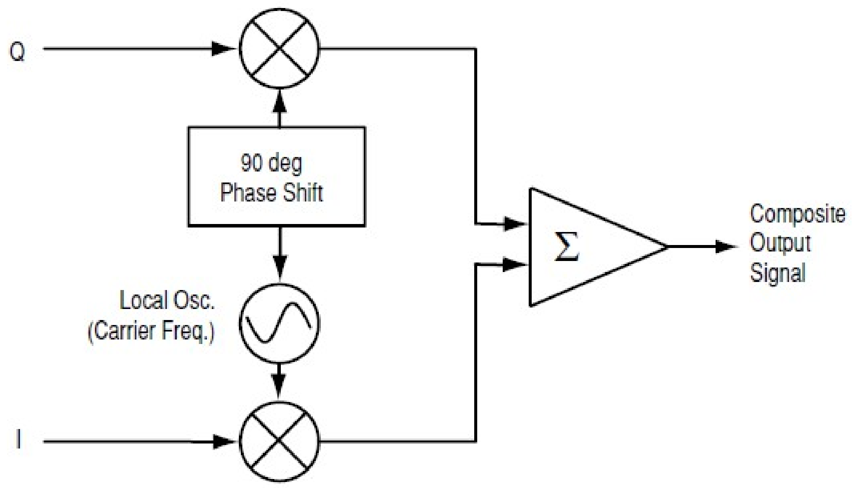




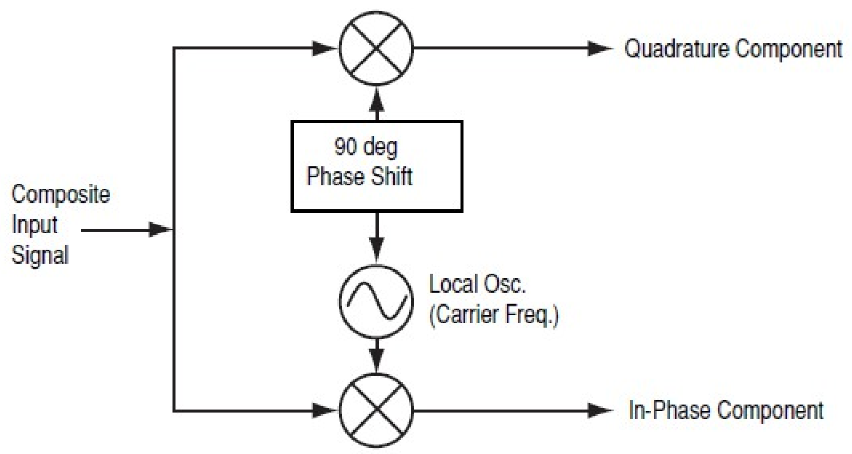


Digital Mod / Demod Generation

- I – Q format practical
  - Digital modulators and demodulators are easy to implement.
  - I – Q independence preserved



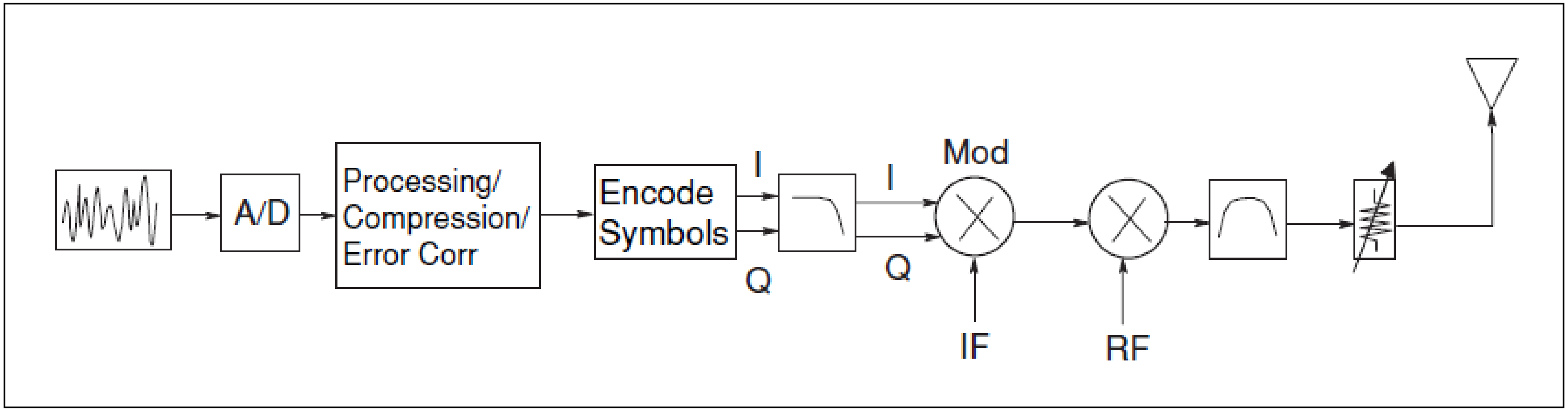
Transmitter (Modulator)



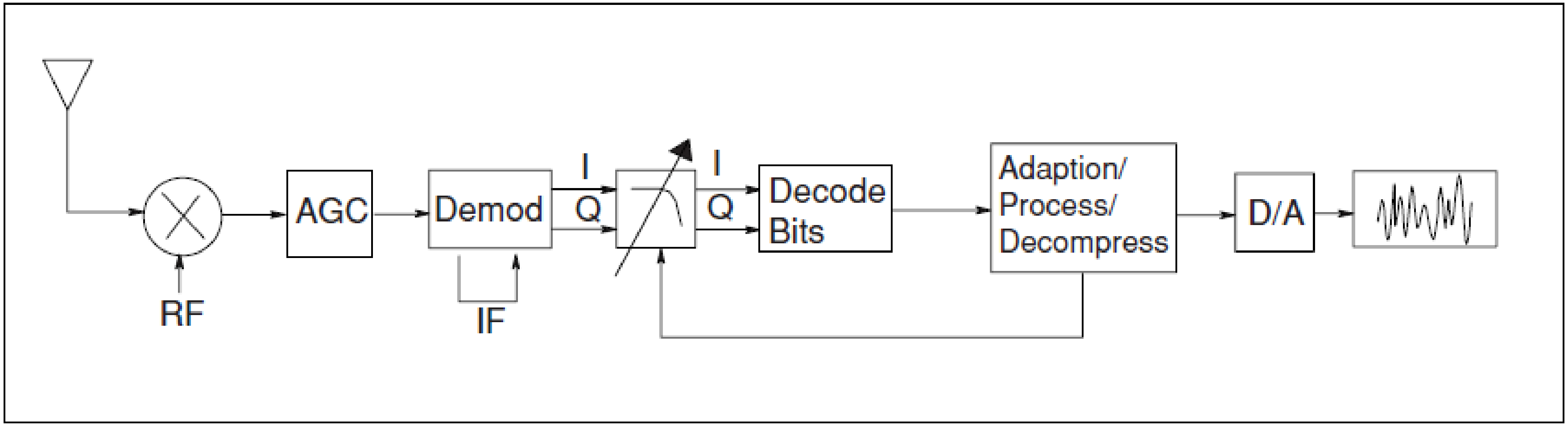
Receiver (Demodulator)

A Typical Digital Radio

Transmitter



Receiver



A Few DM Protocols

Cellular

GSM, GPRS, EDGE GMSK
W-CDMA DSSS HPSK, QPSK, 16QAM
HSDPA, HSUPA DSSS HPSK, QPSK, 16QAM
TDSCMA DSSS QPSK
TD-CDMA DSSS QPSK, 16QAM
IS-95 DSSS OQPSK, QPSK
cdma2000 DSSS QPSK, HPSK
1xEV-DO & DV DSSS QPSK, HPSK, 8PSK, 16QAM
iDEN QPSK, M16QAM
WiDEN QPSK, M16QAM, M64QAM
TETRA π/4-DQPSK

Amateur Radio

D-Star GMSK
AX-25 Packet FSK
Morse Code CW (ASK)
Repeater Morse Code Modulated CW
PSK31 PSK
RTTY FSK
FSK441, JT65 Multiple FSK
AMTOR, PACTOR, GTOR FSK

Point-to-Point Radio

Short Haul DSSS, 4FSK, 16QAM, 64QAM, 64TCM, 49QPR
Long Haul 128QAM, 128TCM, 256TCM

Radar

Chirps, BPSK, FHSS

Satellite

QPSK, 8PSK, 16QAM

HD Television

ATSC 8-VSB, 16-VSB
DVB-T QPSK, 16QAM, 64QAM on COFDM
ISDB-T BST-COFDM DQPSK, QPSK, 16QAM, 64QAM

Wireless Networks

Bluetooth FHSS, GPSK, π/4-DQPSK
WLAN DSSS CCK D8PSK, DQPSK, 52 OFDM, 64QAM
WiMax OFDM BPSK, QPSK, 16QAM, 64QAM
ZigBee BPSK, OQPSK

References

- Digital Modulation in Communications Systems – Agilent AN-1298
- Digital Modulation Fundamentals – Tektronix
- Google
- Wikipedia