TSEK02: Radio Electronics Lecture 3: Modulation (II)

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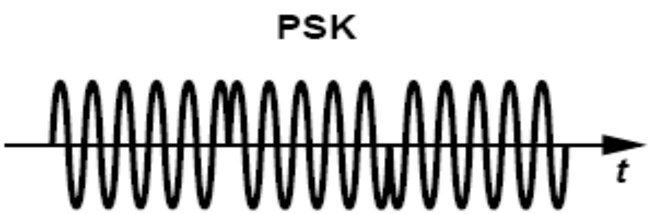
An Overview of Modulation Techniques chapter 3.3.2 – 3.3.6

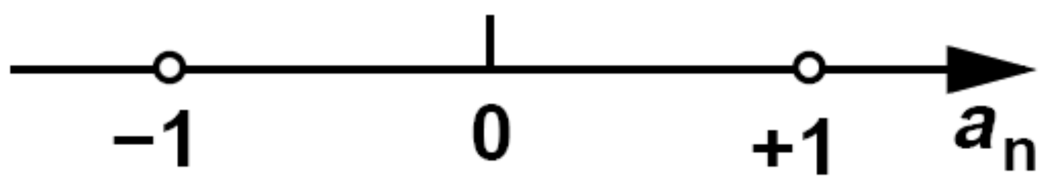
- **Constellation Diagram (3.3.2)**
- Quadrature Modulation
- Higher Order Modulation
- Quadrature Amplitude Modulation (QAM)

Signal Constellation

- Signal Constellation is a useful representation of signals
- Constellation diagram for PSK with 0 and 180°:

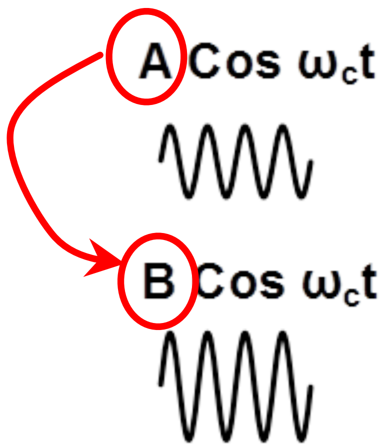


$$x_{PSK}(t) = a_n \cos \omega_c t \qquad a_n = \pm 1$$

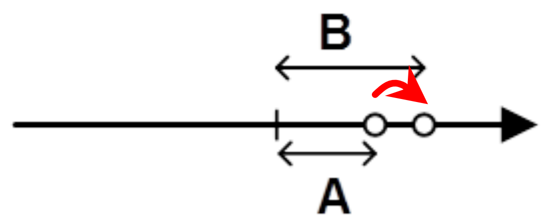


Signal Constellation

- Signal Constellation is a useful representation of signals

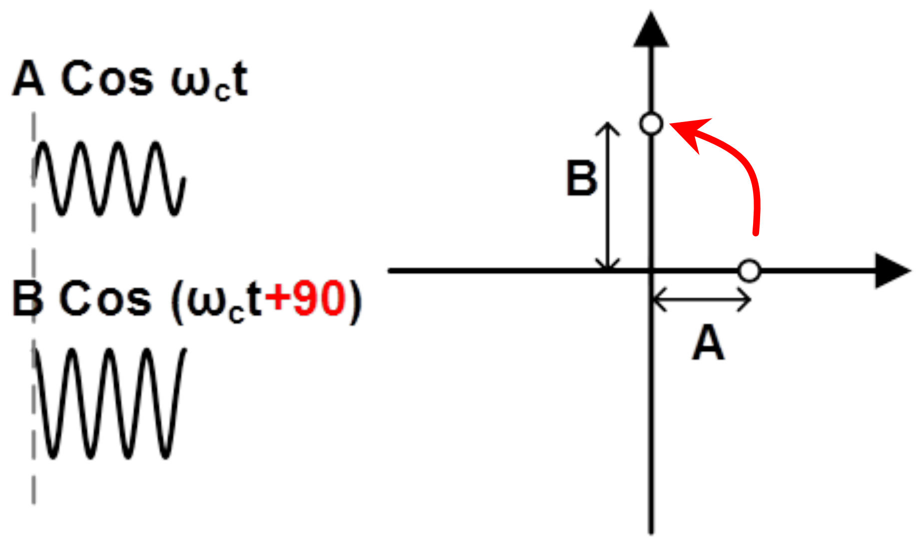


Amplitude can easily be shown



Signal Constellation

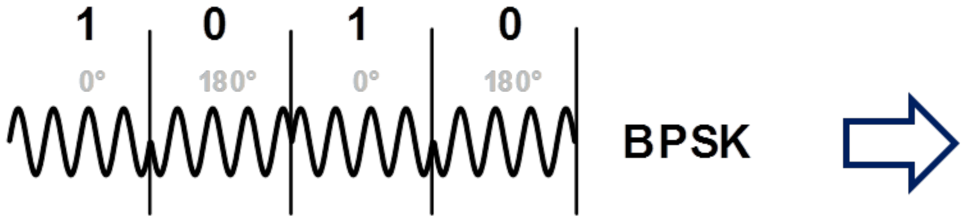
- Signal Constellation is a useful representation of signals

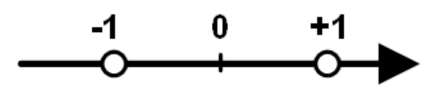


Phase may also be shown

Signal Constellation - Examples

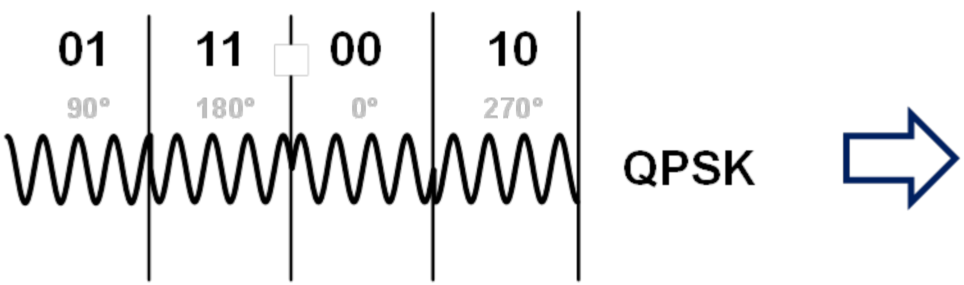
- BPSK (Binary Phase Shift Keying)

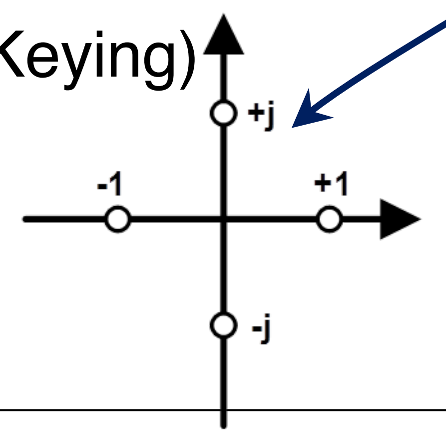




Phases chosen to maximize distance

- QPSK (4-PSK, Quadrature Phase Shift Keying)





Example 3.6

Plot the constellation of an ASK signal in the presence of amplitude noise.

Solution:

From the generation method of Fig. 3.13(a), we have

$$x_{ASK}(t) = a_n \cos \omega_c t \qquad a_n = 0,\ 1. \tag{3.27}$$

As shown in Fig. 3.21(a), noise corrupts the amplitude for both ZEROs and ONEs. Thus, the constellation appears as in Fig. 3.21(b).

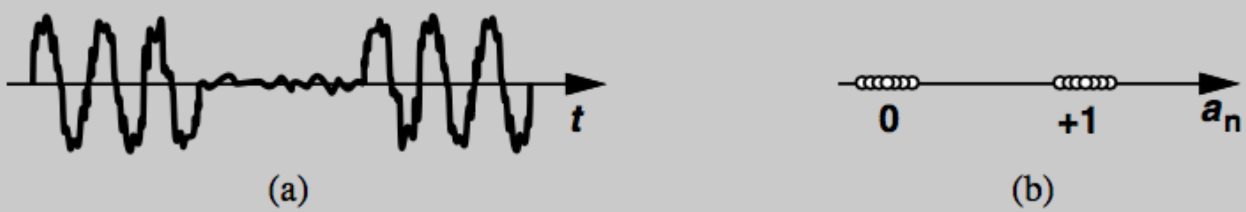
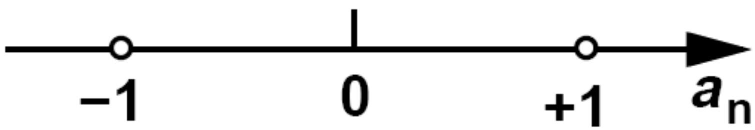


Figure 3.21 *(a) Noisy ASK signal and (b) its constellation.*

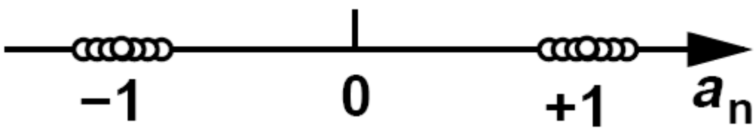
Signal Constellation – Noisy signals

- PSK

$$x_{PSK}(t) = a_n \cos \omega_c t \qquad a_n = \pm 1$$



Ideal

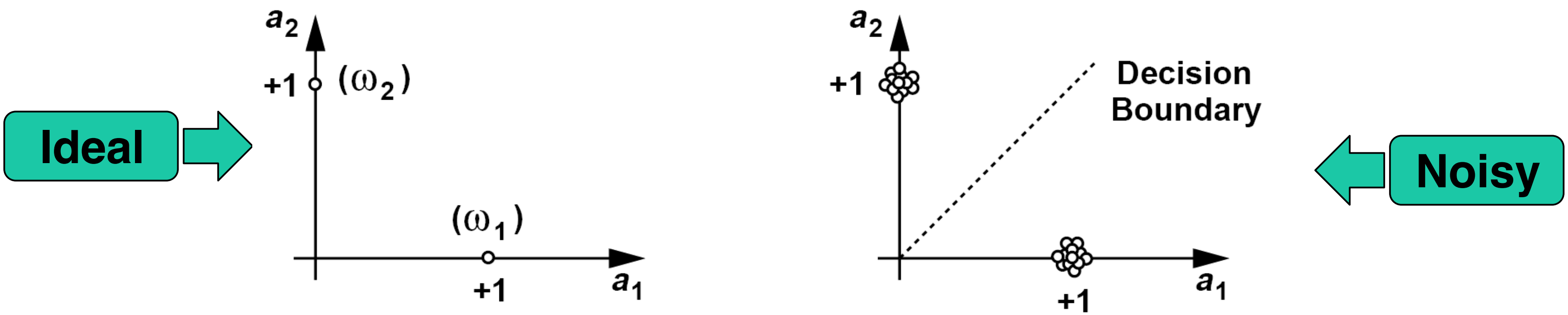


Noisy

Signal Constellation – Noisy signals

- FSK

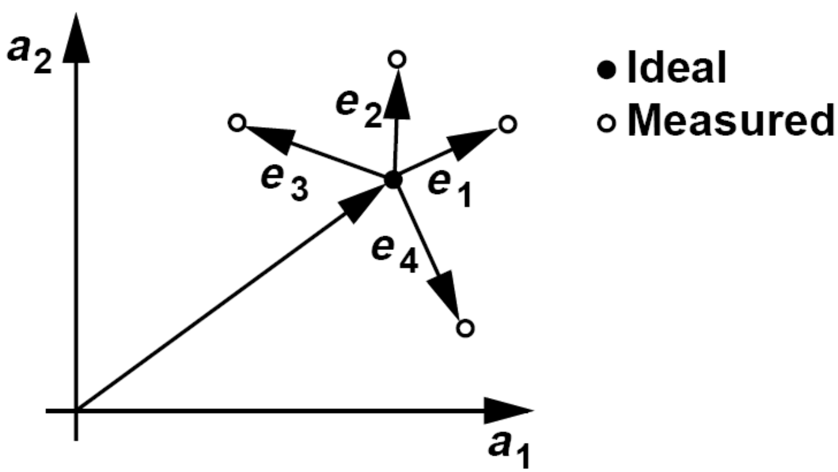
$$x_{FSK}(t) = a_1 \cos \omega_1 t + a_2 \cos \omega_2 t \qquad a_1 a_2 = 10 \text{ or } 01.$$



- Which of the ASK, PSK, FSK looks more robust to noise?

Signal Constellation – EVM

- Error Vector Magnitude (EVM): the deviation of the constellation points from their ideal positions.



$$\mathrm{EVM}_1 = \frac{1}{V_{rms}}\sqrt{\frac{1}{N}\sum_{j=1}^{N} e_j^2},$$

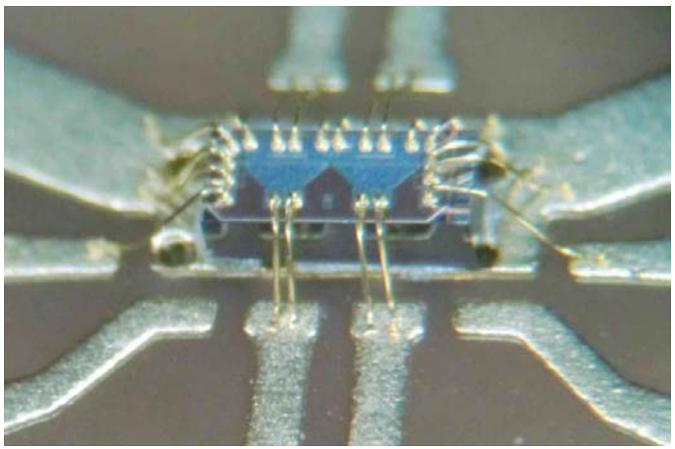
$$\mathrm{EVM}_2 = \frac{1}{P_{avg}} \cdot \frac{1}{N}\sum_{j=1}^{N} e_j^2,$$

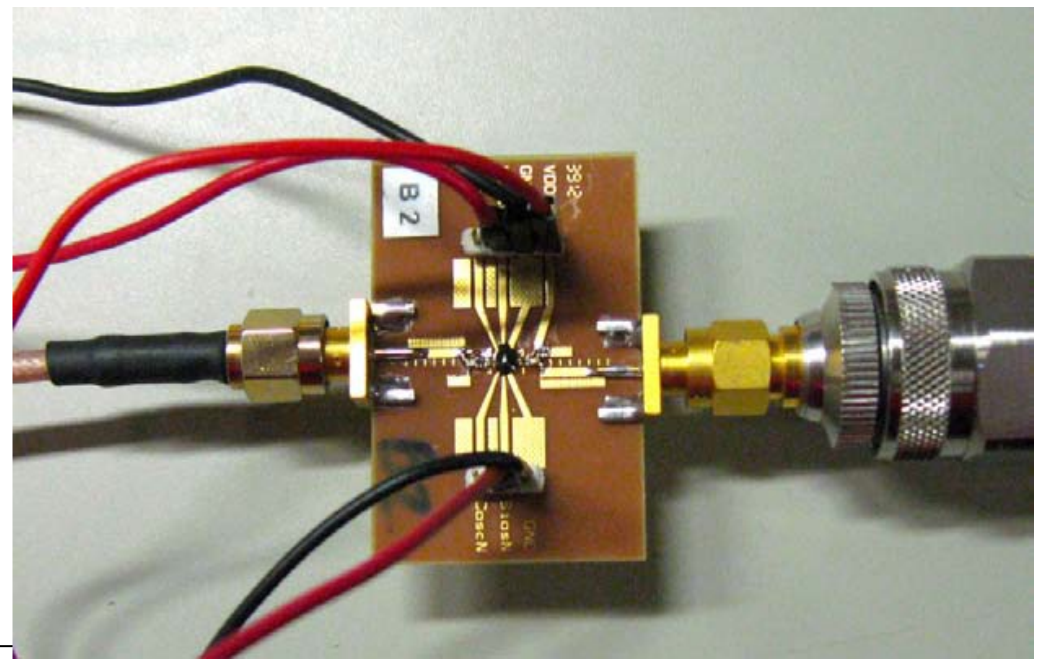
- EVM (power) is linearity measure in WLAN and TRX (% or dB).

WLAN PA

Transistors with W=5.6 mm mounted on PCB

Differential PA, Vdd=3 V, f=2412 MHz
P-1dB = 32.6 dBm (1.8 W).
Class AB, efficiency over 50 % for unmodulated signal.



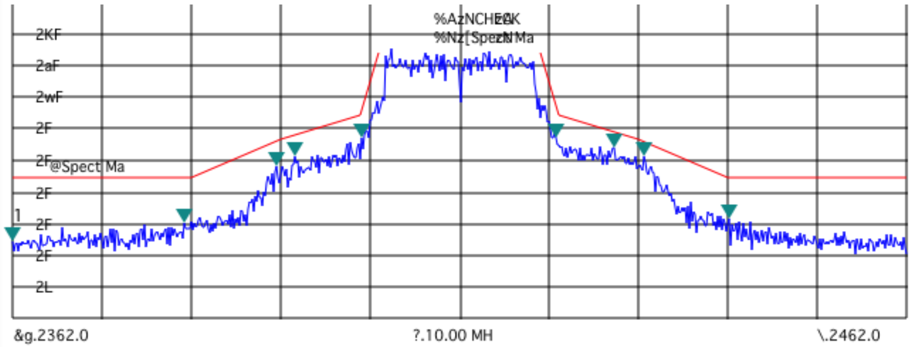


WLAN modulated signal

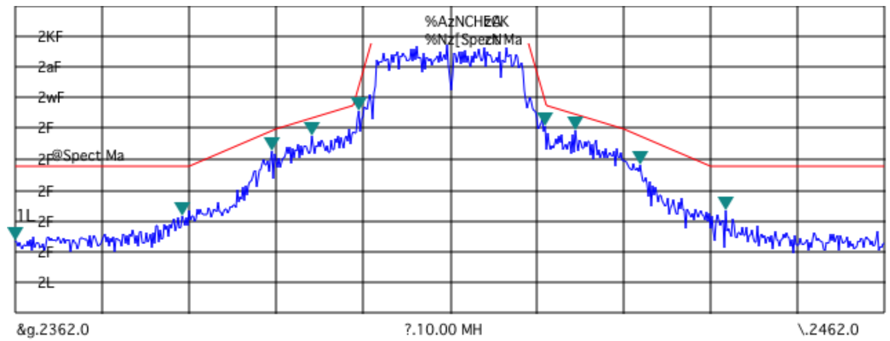
802.11g, f=2412 MHz, 54 Mbps OFDM

Johansson et al., presented at EuMIC 2013

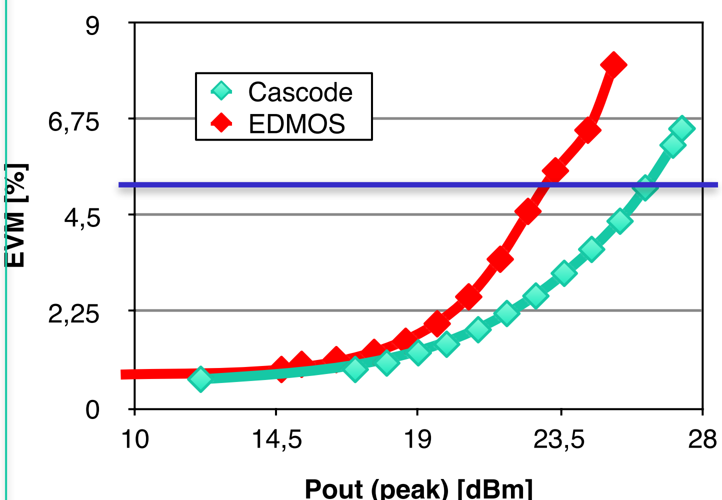
EDMOS



Cascode 2xIO



Both EDMOS and Cascode reference pass frequency mask test up to the limits of the used signal source (peak Pout >27 dBm).



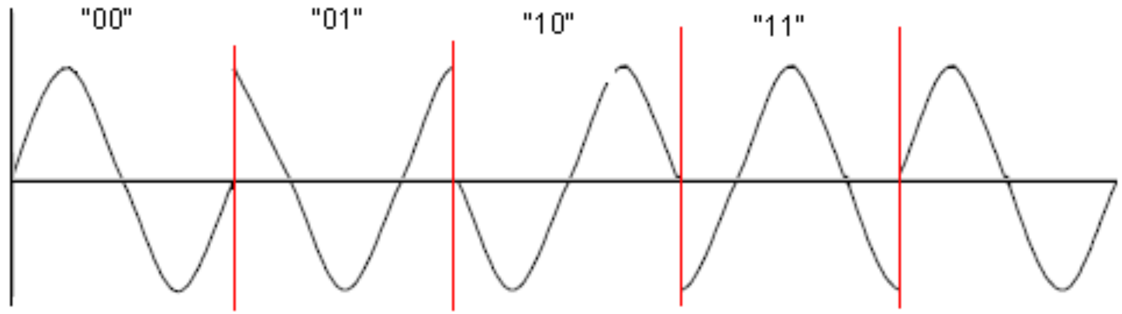
Evaluation:

1. Spectrum + "mask".
2. EVM (linearity).

An Overview of Modulation Techniques chapter 3.3.2 – 3.3.6

- Constellation Diagram
- **Quadrature Modulation (3.3.3)**
- Higher Order Modulation
- Quadrature Amplitude Modulation (QAM)

Quadrature PSK (4-PSK)



Quadrature Phase Shift keying

- The QPSK signal can be written as:

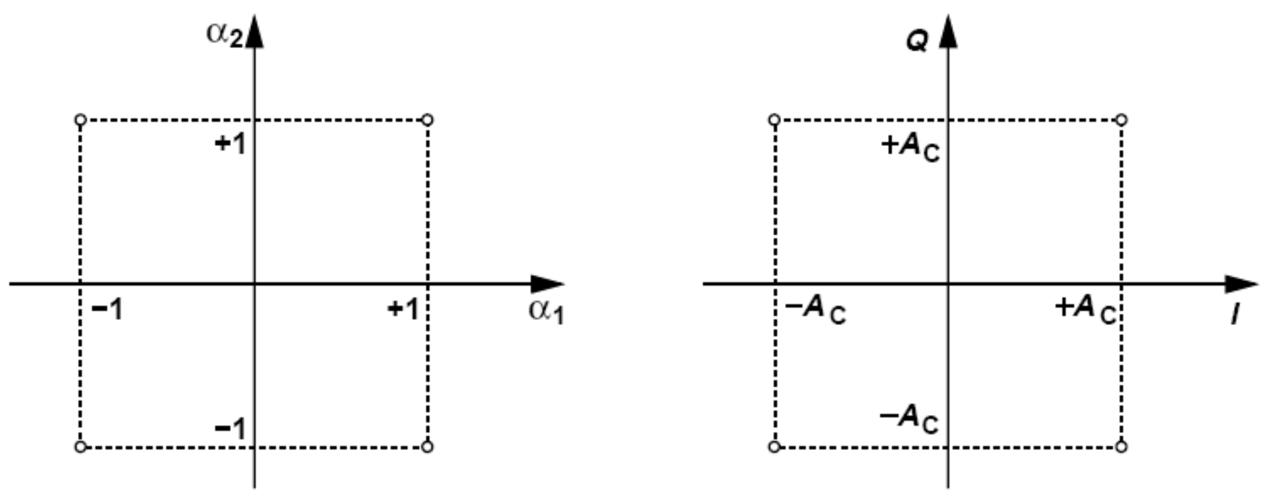
$$\begin{aligned}
QPSK &= \sum \cos(\omega_c t+\varphi_n) && , \varphi_n \in \{\varphi_1, \varphi_2, \varphi_3, \varphi_4\} \\
&= \sum \cos\varphi_n \cos\omega_c t - \sin\varphi_n \sin\omega_c t && , \varphi_n \in \{\varphi_1, \varphi_2, \varphi_3, \varphi_4\} \\
&= \sum \cos\varphi_n \cos\omega_c t - \sum \sin\varphi_n \sin\omega_c t && , \varphi_n \in \{\varphi_1, \varphi_2, \varphi_3, \varphi_4\}
\end{aligned}$$

Quadrature PSK (4-PSK)

- An interesting choice for phases is $\phi_n \in \{\pi/4, 3\pi/4, 5\pi/4, 7\pi/4\}$ since cos ϕn and sin ϕn will only take values of +/- $\sqrt{2}/2$

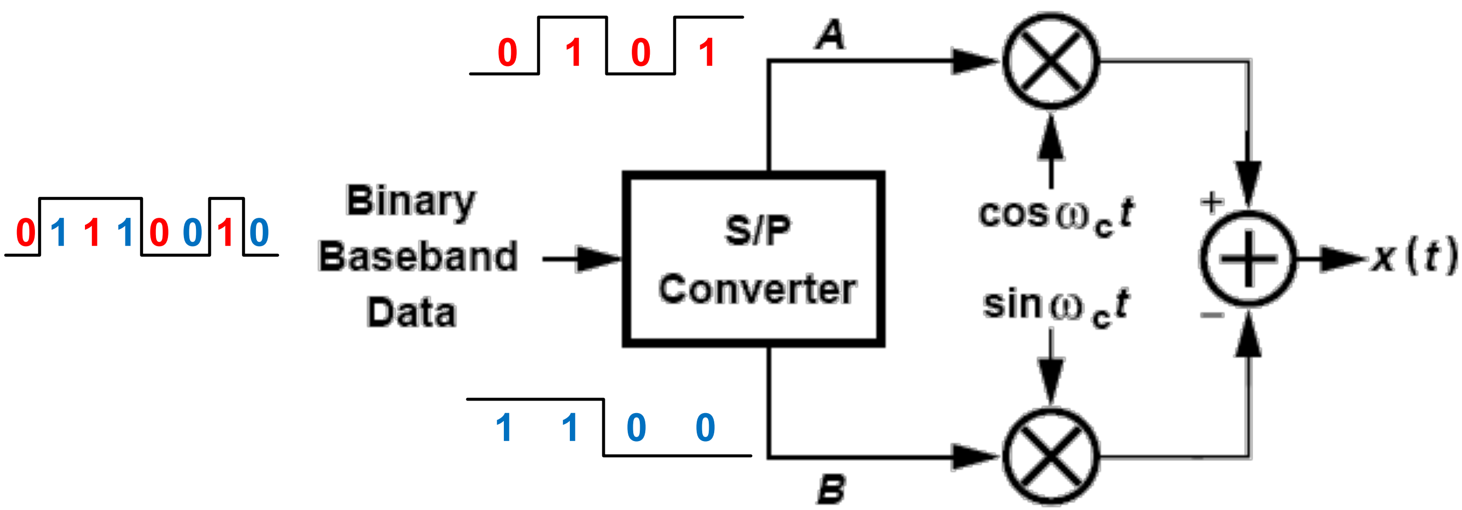
$$
\begin{aligned}
\text{QPSK} = & \sum A(t)\cos\omega_c t \qquad , A \in \{\pm 1\} \\
- & \sum B(t)\sin\omega_c t \qquad , B \in \{\pm 1\}
\end{aligned}
$$

sin and cos have 90° phase shifts so the two BPSK signals are <u>orthogonal</u> or in <u>quadrature</u>



Quadrature Modulator

- A QPSK signal could be seen as the sum of two BPSK signals and can be generated by a *Quadrature Modulator*
  - Incoming data is first divided into two slower bit streams
  - Each are BPSK modulated with **cos** or **sin**
  - Outputs are added

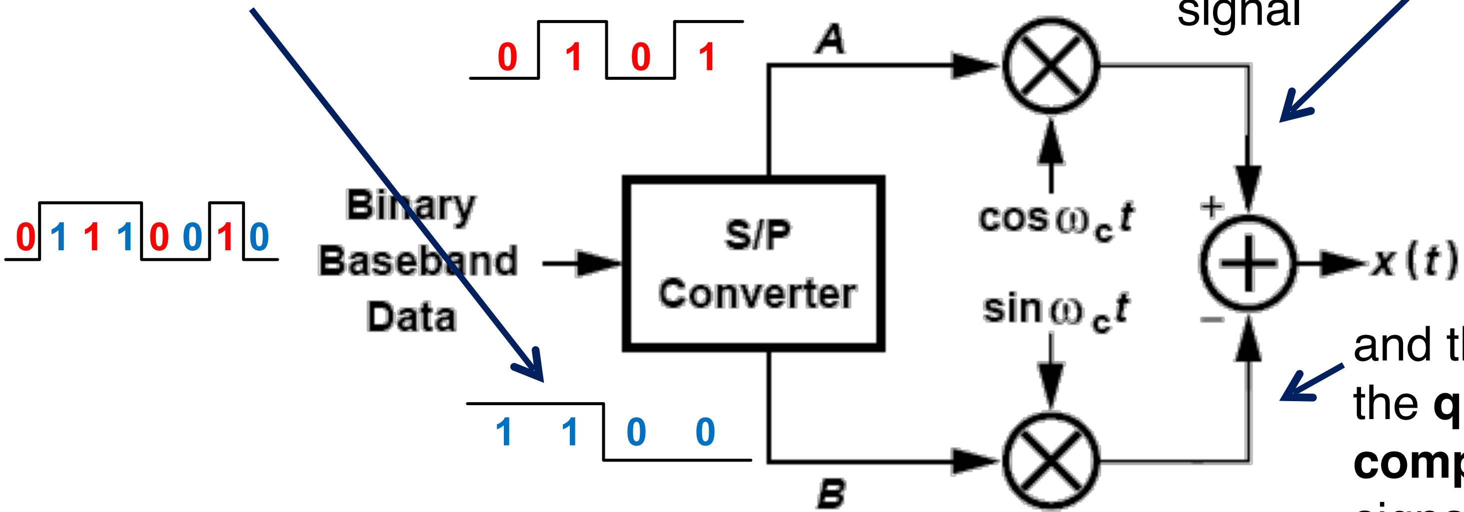


Quadrature Modulator

We therefore call this data "I"

and this one "Q"

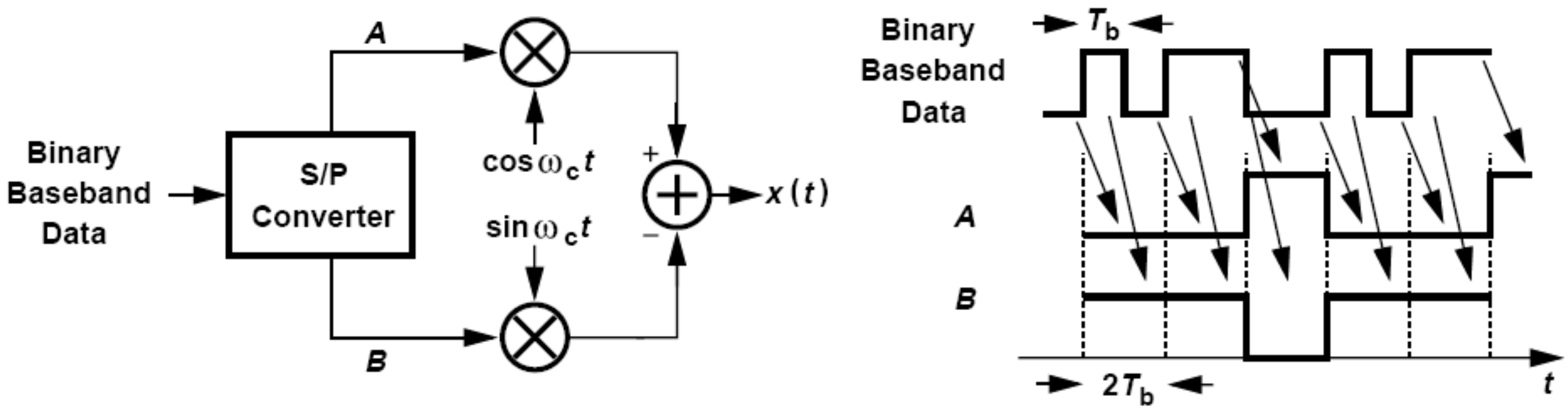
This is often called the **in-phase (I) component** of the signal



and this one the **quadrature (Q) component** of the signal

Quadrature Modulator

- Also called IQ-modulator.
- The A and B data after the S/P Converter is called IQ-data.
- Recall: BPSK-signal occupy BW>2/T_b. QPSK occupies half of the BW!



$$x(t) = b_{2m} A_c \cos\omega_c t - b_{2m+1} A_c \sin\omega_c t$$

- Pulses appear at A and B are called symbols rather than bits.

Learn more: "I/Q Data for Dummies" (http://whiteboard.ping.se/SDR/IQ)

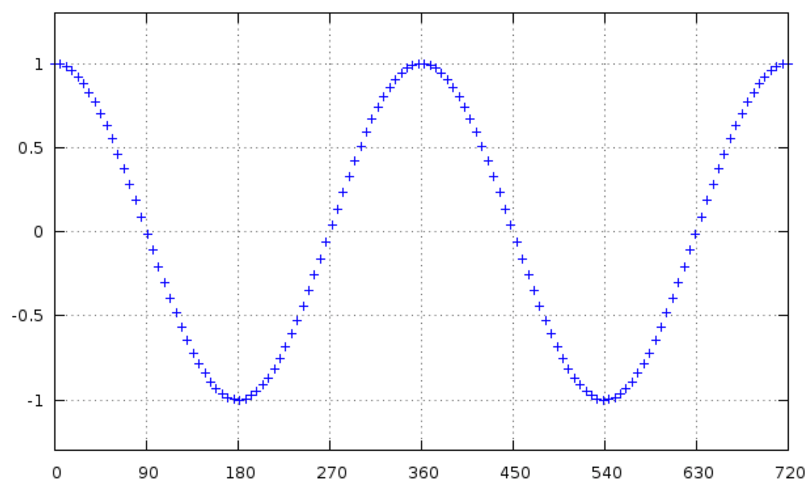
Whiteboard Web

SDR » I/Q Data for Dummies

This is a description of using I/Q Data (aka "analytic signal") representing a signal. Since the topic may be quite confusing, I've described the same thing here from different point of views. If you find the information somewhat redundant, it is because it is. Different views may appeal to different readers, and if something seems unclear, keep on reading and it may be more comprehensible later - hopefully.

Why I/Q Data?

I/Q Data is a signal representation much more precise than just using a series of samples of the momentary amplitude of the signal. Have a look at the following signal below.



Ex 3.7 QPSK with phase errors

- Due to circuit nonidealities, one of the carrier phases in a QPSK modulator suffers from a small phase error ("mismatch") of θ:

$$x(t) = \alpha_1 A_c \cos(\omega_c t + \theta) + \alpha_2 A_c \sin \omega_c t$$

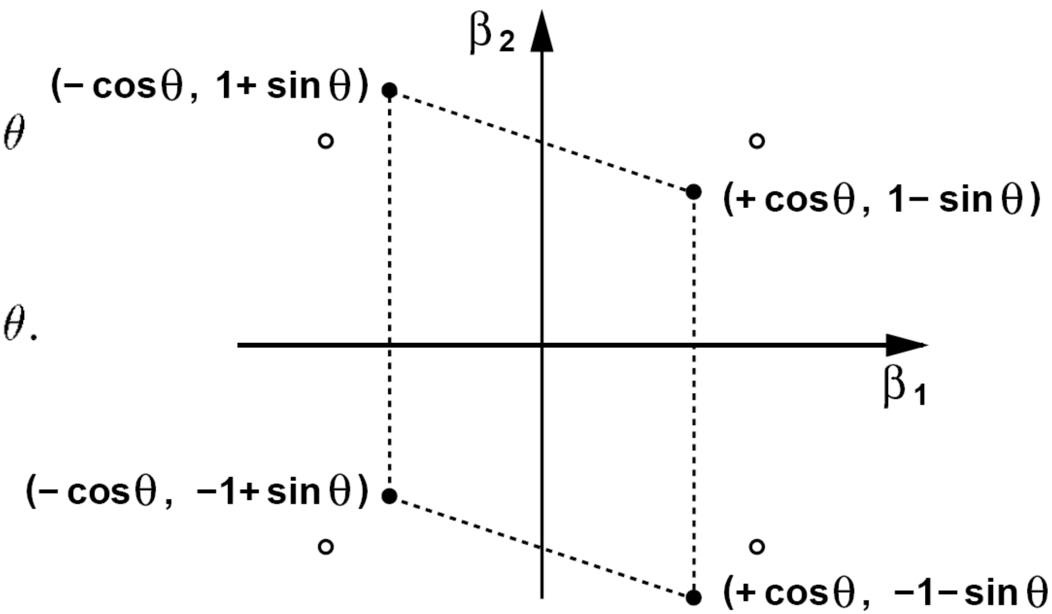
- Construct the signal constellation at the output of this modulator

Ex 3.7 QPSK with phase errors

$$x(t) = \alpha_1 A_c \cos(\omega_c t + \theta) + \alpha_2 A_c \sin \omega_c t$$

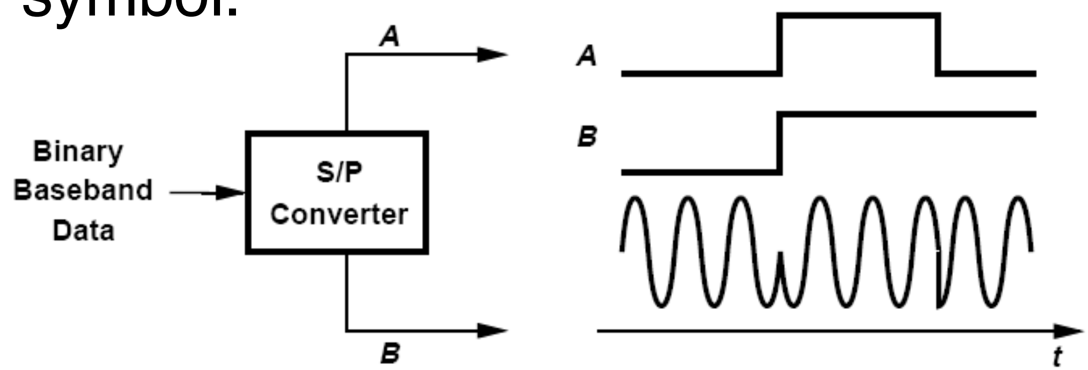
$$x(t) = \alpha_1 A_c \cos\theta \cos\omega_c t + (\alpha_2 - \alpha_1 \sin\theta) A_c \sin\omega_c t.$$

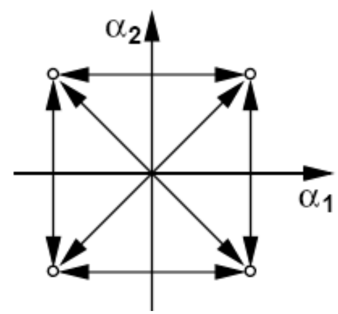
$$\begin{aligned}
\beta_1 &= +\cos\theta,\ \beta_2 = 1 - \sin\theta \\
\beta_1 &= +\cos\theta,\ \beta_2 = -1 - \sin\theta \\
\beta_1 &= -\cos\theta,\ \beta_2 = 1 + \sin\theta \\
\beta_1 &= -\cos\theta,\ \beta_2 = -1 + \sin\theta.
\end{aligned}$$



QPSK: large phase changes

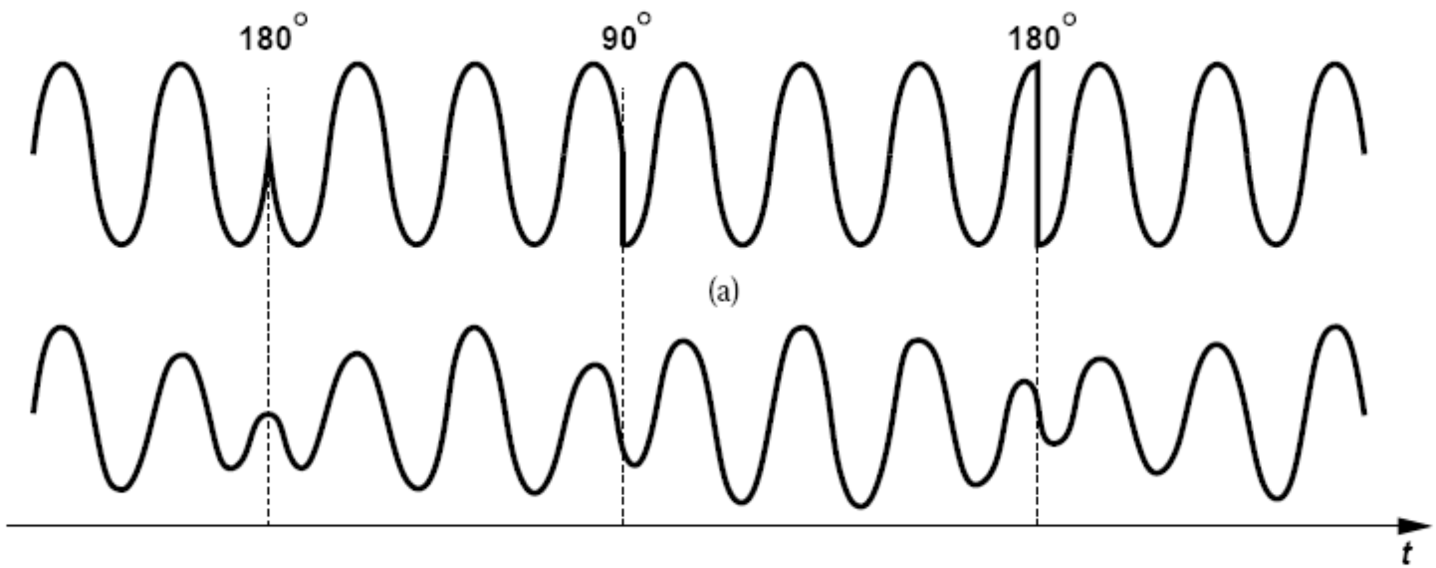
- Important drawback of QPSK: large phase changes at the end of each symbol.





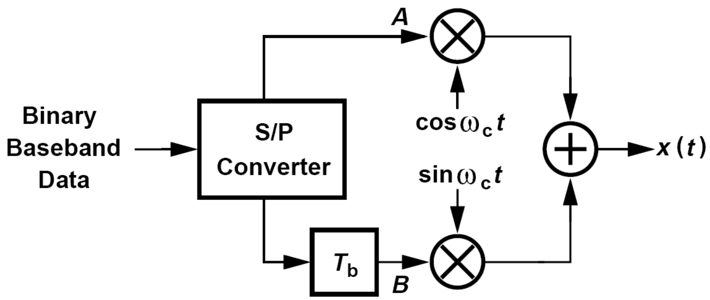
QPSK: large phase changes

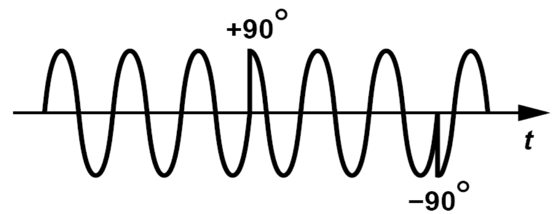
- With pulse shaping, the output signal amplitude experiences large changes each time the phase makes a 90° or 180° transition.
- Resulting waveform is called a “variable-envelope signal”. Need linear PA.

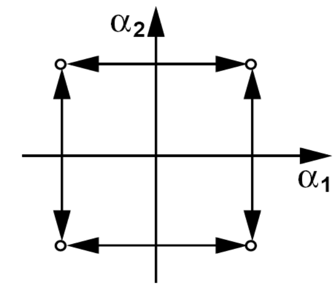


QPSK: improvements

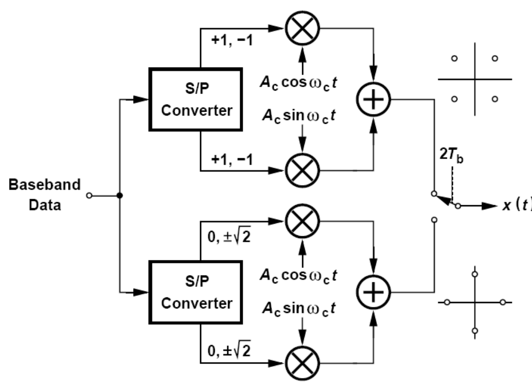
- OQPSK: only 90° shifts.

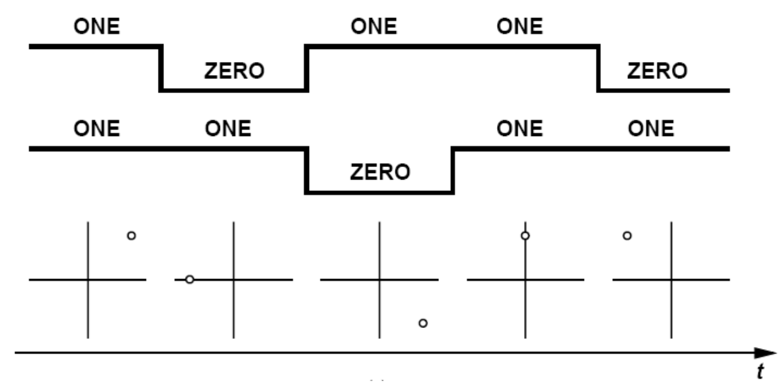


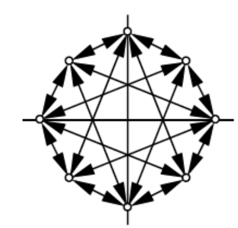




- π/4-QPSK: two QPSK with π/4 rotation=> 135° shifts.

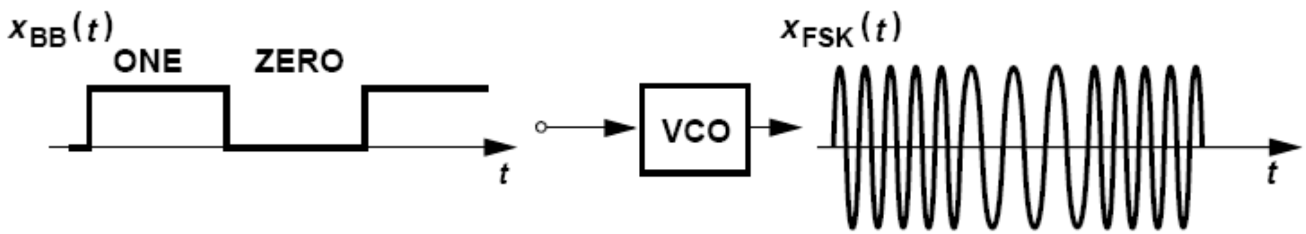




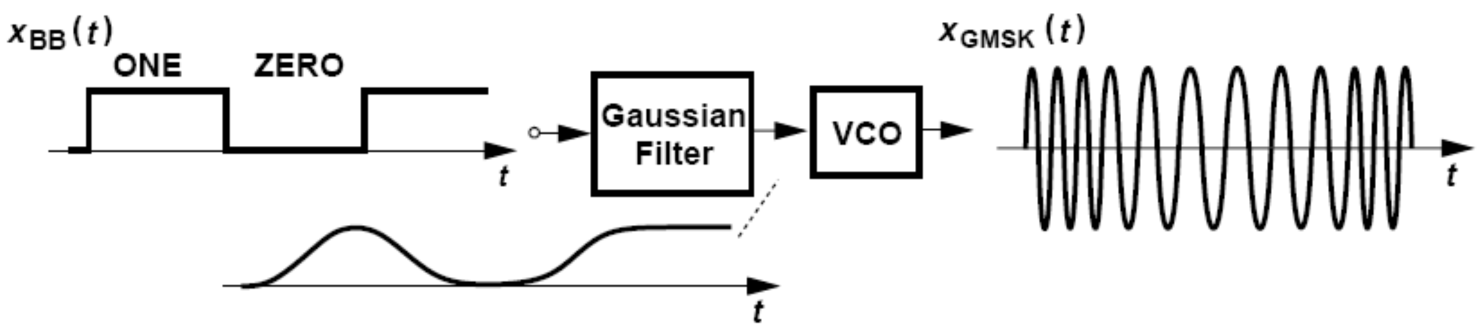


3.3.4 GMSK and GFSK

- Constant-envelope modulation



(a)



(b)

- "Gaussian" => smoother, more narrow spectrum

GMSK and GFSK

- GMSK = Gaussian minimum shift keying
  - used in GSM (2 G)
- GFSK = Gaussian frequency shift keying
  - used in Bluetooth

An Overview of Modulation Techniques chapter 3.3.2 – 3.3.6

- Constellation Diagram
- Quadrature Modulation
- **Higher Order Modulation**
- Quadrature Amplitude Modulation (QAM)

What is a Symbol?

- Each k bits may represent $M=2^k$ symbols

bit	symbol
0	-1
1	1

K=1
M=2

bit	symbol
00	+3
01	+1
10	-1
11	-3

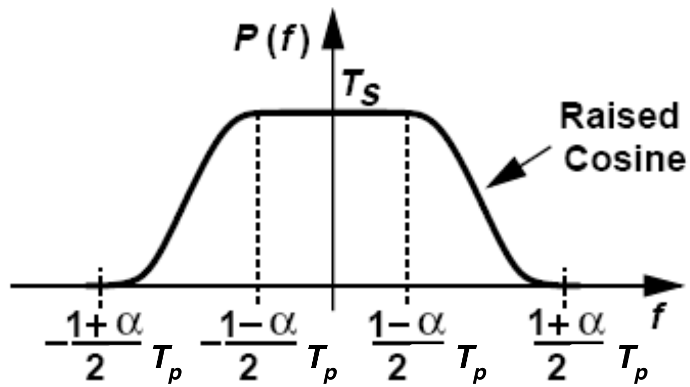
K=2
M=4

bit	symbol
000	+7
001	+5
010	+3
011	+1
100	-1
101	-3
110	-5
111	-7

K=3
M=8

Bit vs Symbol

- A stream of pulses occupies a bandwidth of R_p<BW<$2R_p$ where R_p denotes the pulse rate. The exact bandwidth depends on the pulse shape.



- In binary modulation, each pulse represents one bit.
- Pulses may however represent a symbol. Bandwidth of the signal remains the same.

Bandwidth Efficiency

Assume that we send R_p nyquist pulses per second

- The signal occupies R_p Hz — 1 pulse/s/Hz
- Each pulse represents one symbol — 1 symbol/s/Hz

In binary modulation:

Each symbol represents one bit

1 bit/s/Hz

Improved spectral efficiency (more bits in the same bandwidth)

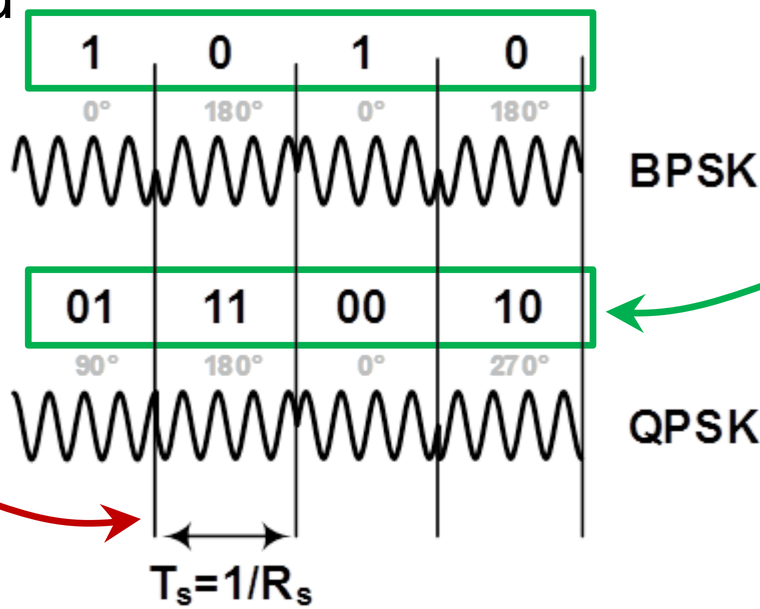
In M-ary modulation

Each symbol represents k bits ($M=2^k$)

k bit/s/Hz

Quadrature PSK

- For Binary PSK (BPSK), based on the input bit we choose one of the two phases in each symbol period
- In 4-PSK (QPSK), based on the combination of two input bits, we choose one of the four phases in each symbol period



We are however sending twice as many data bits with 4-PSK

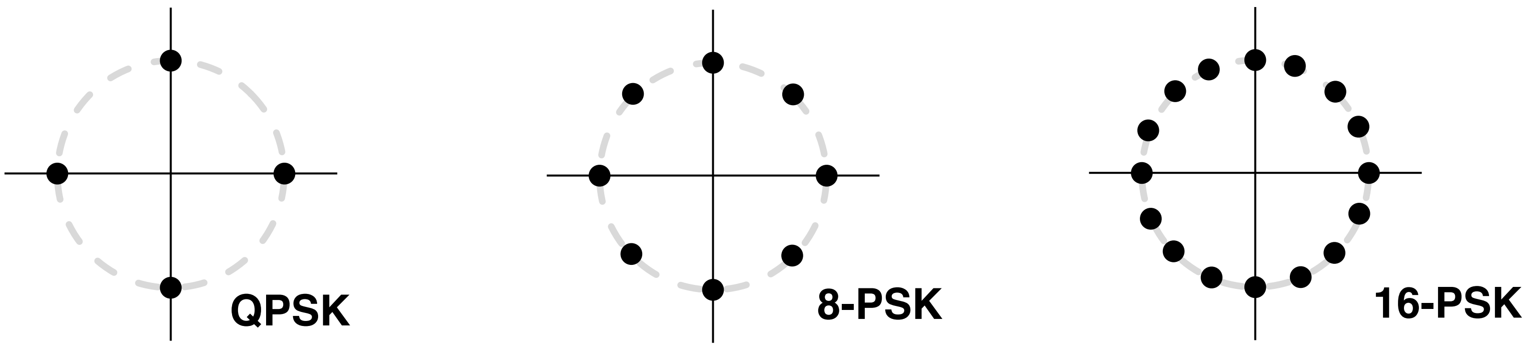
Once again, notice that bandwidths of both signals are Rs Hz

An Overview of Modulation Techniques chapter 3.3.2 – 3.3.6

- Constellation Diagram
- Quadrature Modulation
- Higher Order Modulation
- **Quadrature Amplitude Modulation (QAM) (3.3.5)**

Higher Order PSK

- You can extend QPSK to any M-PSK modulation to further increase the bandwidth efficiency



- The distance between signal points and therefore immunity to noise rapidly decreases

More data is sent over the same bandwidth

Trade-off ⟺

More signal power is needed to maintain the performance

Quadrature Amplitude Modulation (QAM)

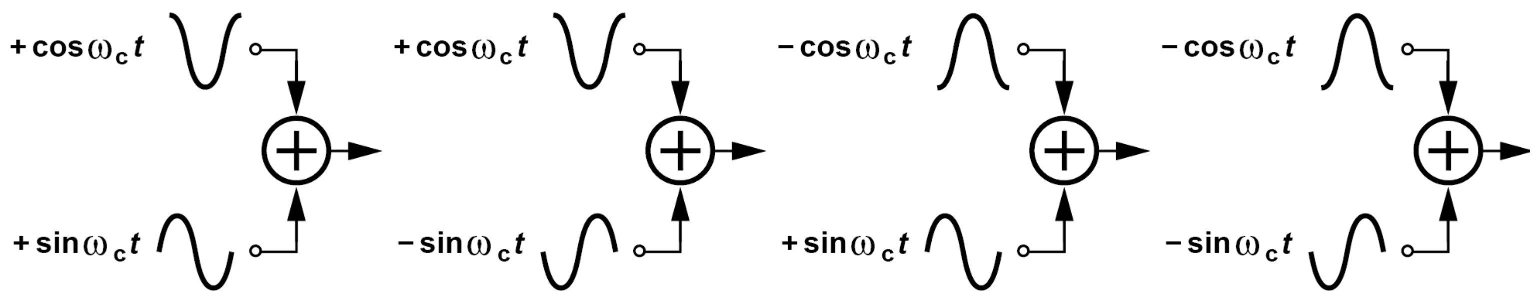
- An effective solution to increasing the bandwidth efficiency with a lesser need for signal power is to <u>combine amplitude and phase modulation.</u>
- The easiest way to compare different combinations of amplitudes and phases is to look at the constellation diagram.
- A QAM signal can be generated by a quadrature modulator. QPSK may also be considered 4-QAM.

Quadrature Amplitude Modulation (QAM)

- Many different constellations are possible for the same number of symbols
  - The minimum distance between symbols determines the immunity to noise
  - The maximum distance to the origin determines the maximum required signal power
  - Some constellations are in practice more preferable for generation and detection of I and Q signals

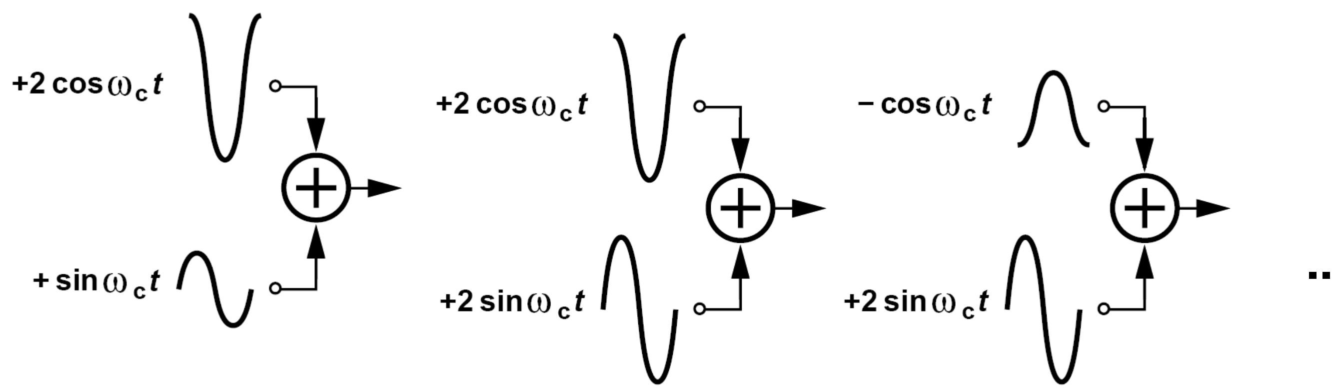
QPSK vs. 16QAM

QPSK (4-PSK)



(a)

16QAM

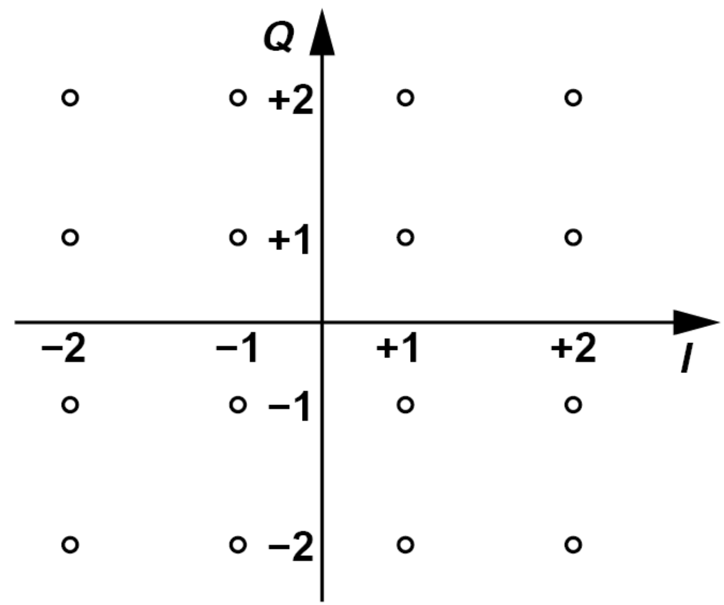


(b)

16QAM: constellation

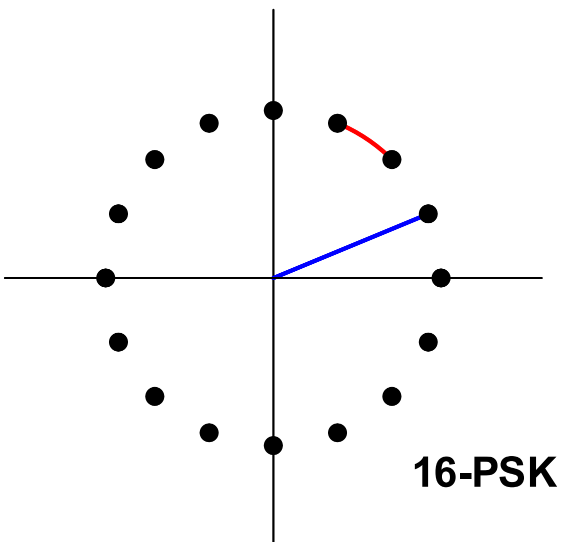
$$x_{16QAM}(t) = \alpha_1 A_c \cos \omega_c t - \alpha_2 A_c \sin \omega_c t \quad \alpha_1 = \pm 1, \pm 2, \ \alpha_2 = \pm 1, \pm 2.$$

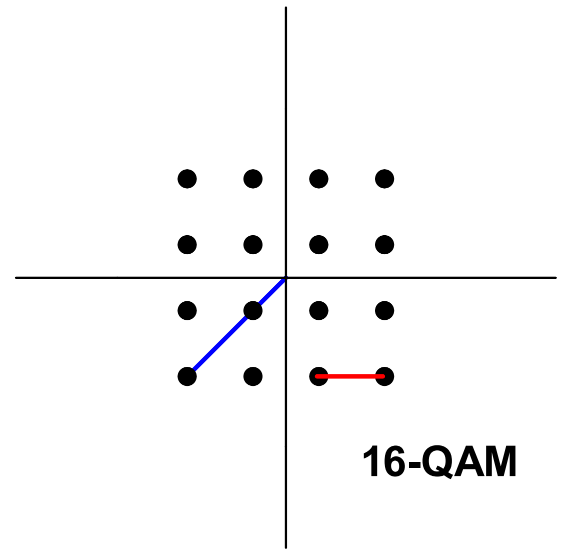
- Saves bandwidth
- Denser constellation: making detection more sensitive to noise
- Large envelope variation, need highly linear PA



Quadrature Amplitude Modulation (QAM)

- Compare 16-PSK with 16-QAM (similar bandwidth efficiency)

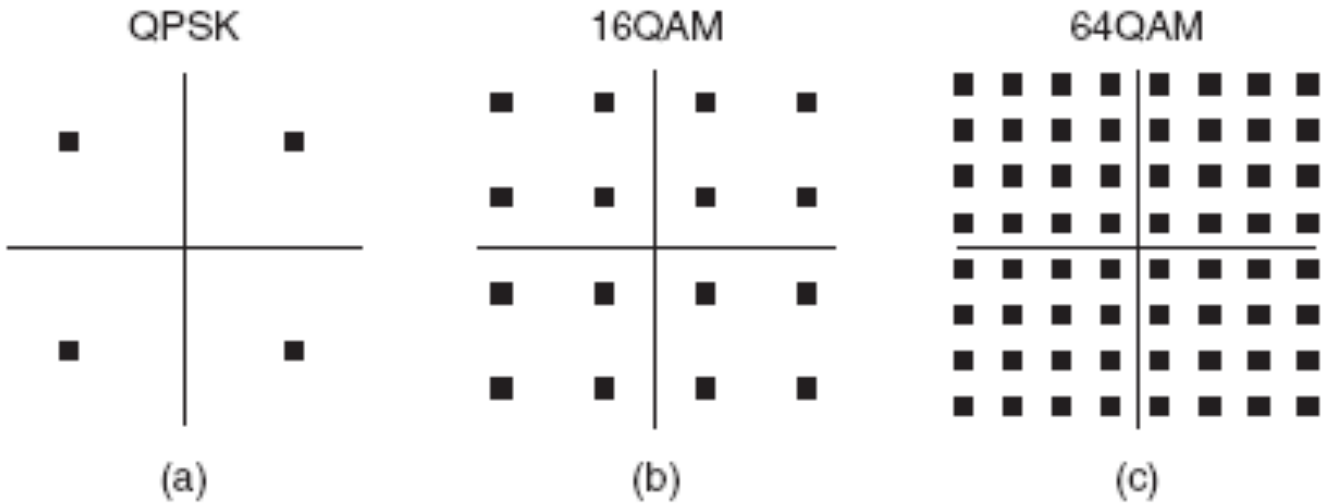




With the same minimum Euclidean distance, 16 QAM requires 1.6 dB less peak power

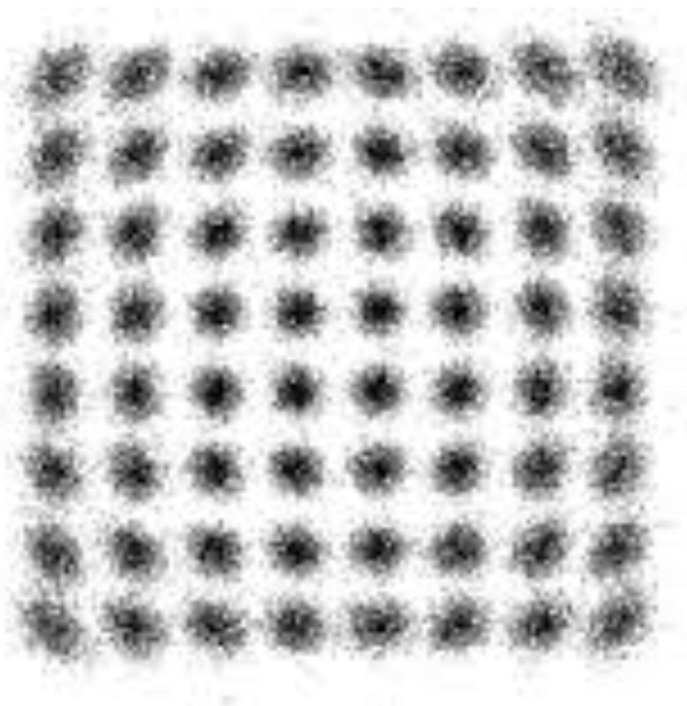
Quadrature Amplitude Modulation (QAM)

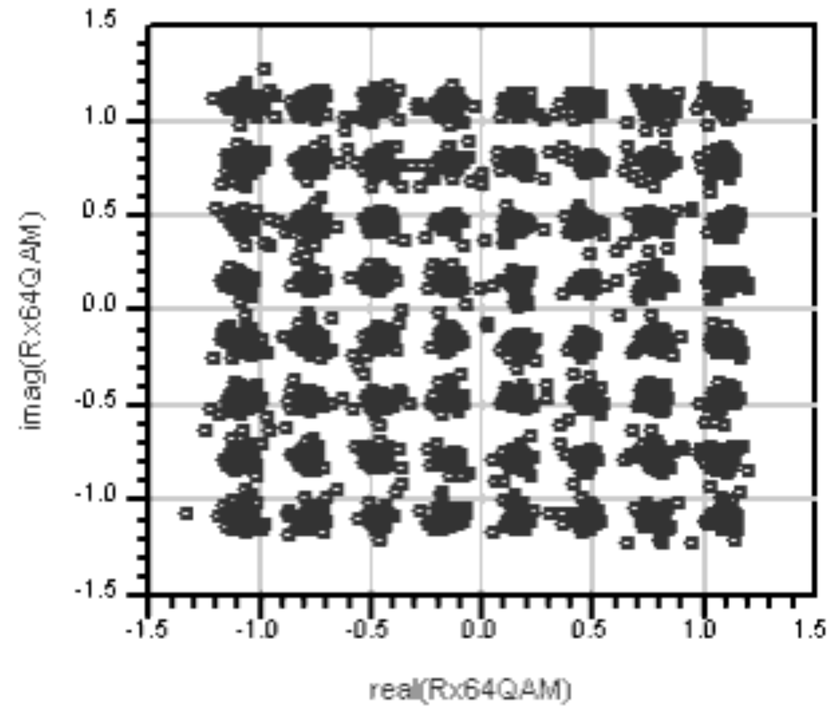
- Ex: WLAN 802.11g uses 64QAM for its highest data rate (54 Mb/s)



Quadrature Amplitude Modulation (QAM)

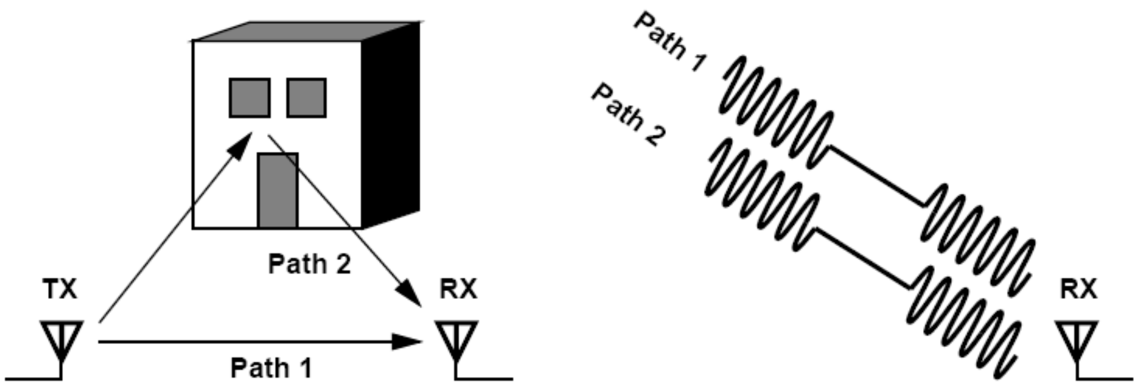
- 64QAM, received signal:



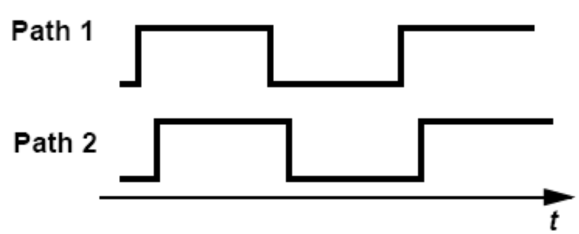


OFDM (Orthogonal Frequency Division Multiplexing)

- OFDM solves the problem of multipath propagation.



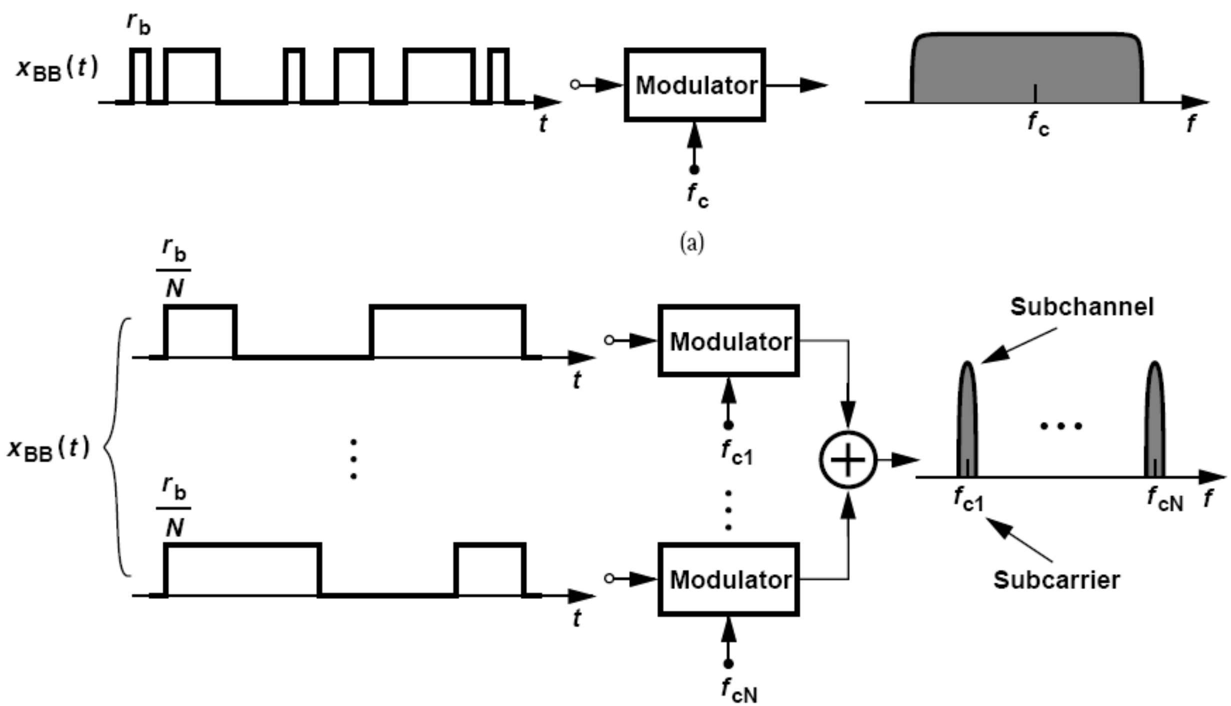
(a) (b)



=> ISI

OFDM (Orthogonal Frequency Division Multiplexing)

- In OFDM, the baseband data is first demultiplexed by a factor of *N*. The *N* streams are then impressed on *N* different carrier frequencies.

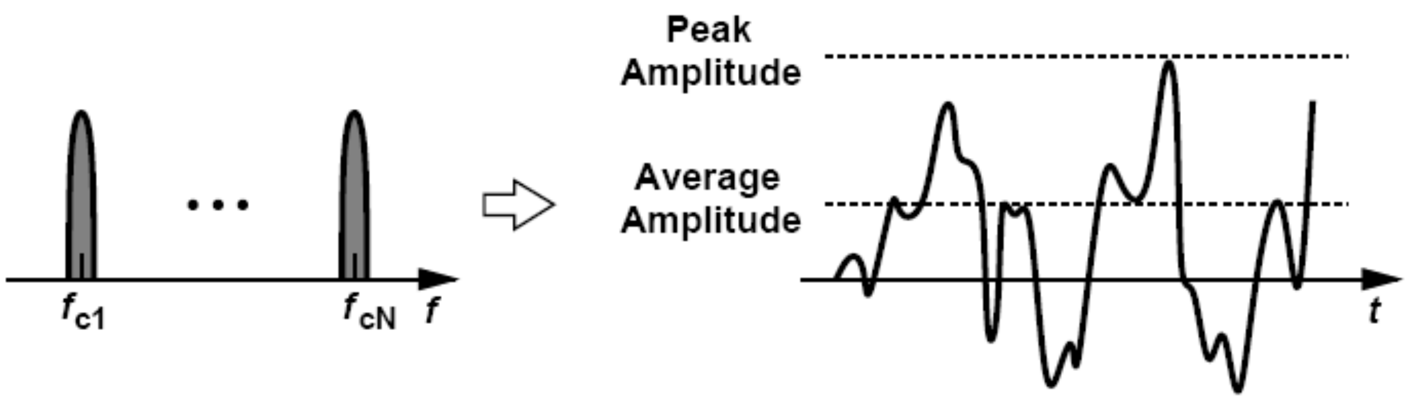


WLAN 802.11g:
54 Mb/s:
48 subchannels, 64 QAM =>
141 ksym/s per subchannel

OFDM (Orthogonal Frequency Division Multiplexing)

- Problem solved: immunity to multipath propagation.
- Drawback: higher envelope variations depends how the different subcarriers adds.

=> peak-to-average power ratio (PAR, PAPR) is a problem for the PA.



OFDM (Orthogonal Frequency Division Multiplexing)

Communication Standard	PAPR (dB)
LTE (4G) UL	4-6
LTE (4G) DL	10-12
WiMAX (4G) UL/DL	10-12
WLAN 802.11ac	10

UL = terminal to basestation
DL = basestation to terminal

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