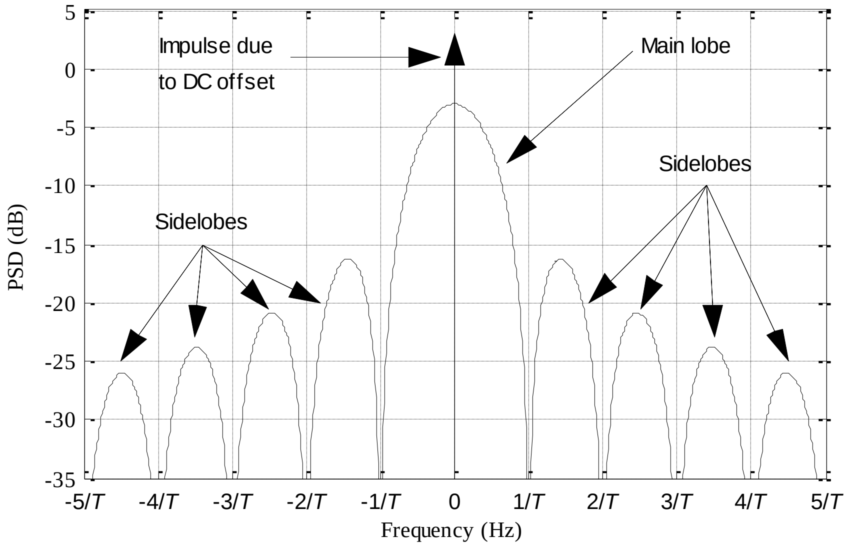
RF Systems Course: Advanced Modulation and Channel Issues I

Signal Spectral Density

- probability of error is important parameter of a com sys.
- If BER is too high, need for retransmission increases ->reduce system throughput.
- equally important measure is spectral efficiency of system, measured in part by PSD of Tx signal
- PSD also important for ensuring Tx signal meets regulatory requirements to prevent interference with other wireless users.
- Fourier transform of normalized rectangular pulse is

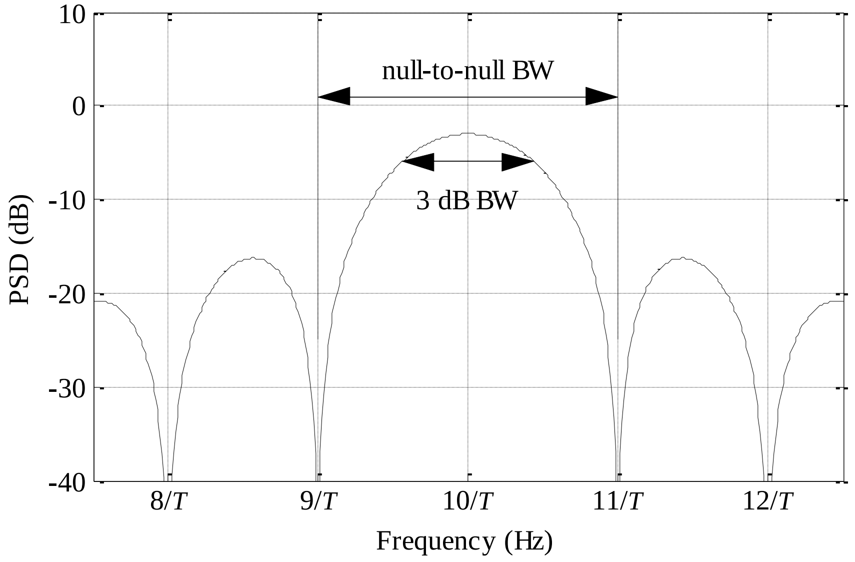
$$H_T(f) = \sqrt{T}\,\frac{\sin \pi f T}{\pi f T}\,e^{-j\pi f T}$$



- bulk of sig power is contained in main lobe centered around 0 Hz
- also some signal power contained in sidelobes at higher frequencies.
- also an impulse at 0 Hz, due to DC offset of signals (i.e., the signal points are not centered about origin in ASK signal constellation.
- PSD of Tx bandpass signal, similar, except centered $\pm f_c$, scaled by a factor of ½.

Signal Bandwidth

- useful wireless spectrum is limited resource -> shared by every user -> important to understand how much of freq band is required to transmit a signal.
- BW of sig defined as size of range of freq for which PSD is non-zero.
- definition of little practical use, all practical signals have infinite BW
- PSD of most signals is *essentially* non-zero over finite range of freq, several practical definitions of BW that capture this reality.
- E.g. null-to-null bandwidth, 3 dB bandwidth, fractional power bandwidth.
- consider PSD of 4-QAM as e.g. where $f_c = 10/T$ and $E_s = 1$



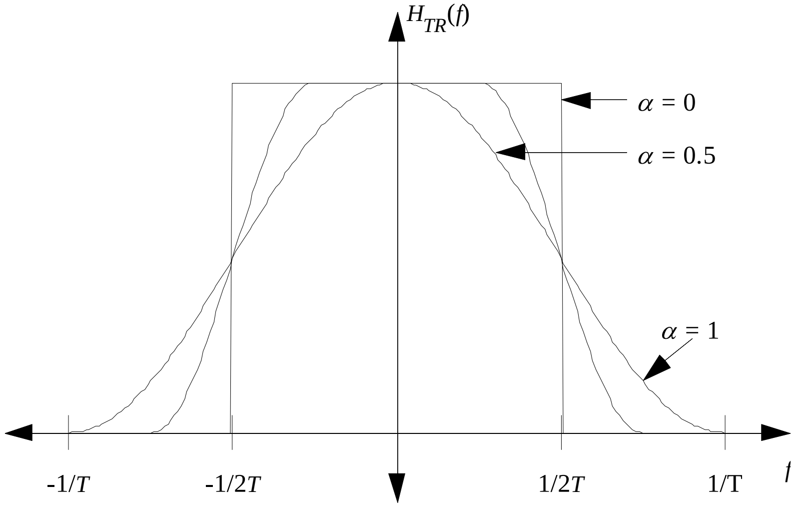
- null-to-null BW is width of main lobe $2/T$.
- 3 dB BW is separation between points to left and right of carrier frequency where PSD drops 3 dB below its peak value, approximately $0.89/T$.
- fractional power BW gives range of freqs which contain a specific percentage of total sig power.
- typically computed numerically, in this example 99% power BW ~ $20/T$.
- null-to-null BW most widely used to quickly characterize amount of spectrum occupied by sig.

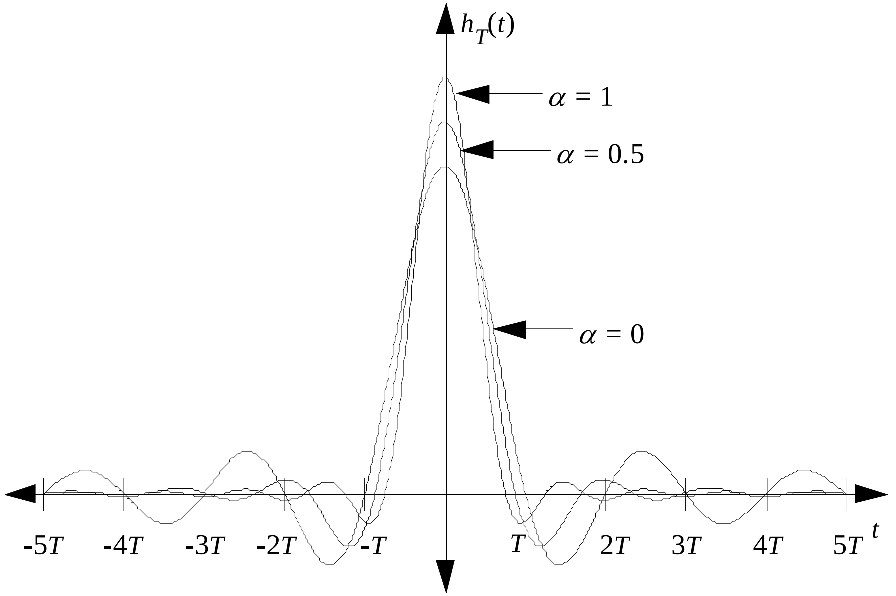
Pulse Shaping and Intersymbol Interference

- desirable to use small BW for symbol transmission rate, $1/T$, while using a pulse shape that has very low sidelobes.
- if pulse duration limited to T seconds not possible to have both low sidelobes and a null-to-null BW less than $1/T$.
- IS possible to use pulse shapes longer than T seconds, while still Tx new signals every T seconds.
- will result in signals that overlap in time.
- Each transmitted symbol may interfere with next few symbols -> *intersymbol interference* (ISI).
- effects of ISI can be mitigated by using equalization techniques at Rx, these techniques either substantially increase complexity of Rx, or yield inferior BER.
- not all longer pulse shapes result in ISI.
- only condition on pulse shape to avoid ISI:

$$h_{TR}(nT) = \begin{cases} K & \text{if } n = c \\ 0 & \text{if } n \neq c \end{cases}$$

- Some popular pulse shapes meet Nyquist condition are based on raised cosine representation in freq domain
- pulse shape is non-causal, so in practice it cannot be used.
- However, truncating pulse shape to few symbol periods and delaying it, possible to use an approximate version root-raised cosine pulse shapes.
- When α small, h_T(t) decays more slowly, so truncation has a bigger impact causing these sidelobes to be more pronounced, $\alpha \geq 0.2$ is used in practice.





Bandwidth Efficiency

- Although BW of Tx signal important, also important to use spectrum efficiently.
- spectral efficiency of a modulation scheme is defined as #bits that can be transmitted per unit time per unit of frequency, bits/second/Hz.

$$\eta = \frac{\log_2 M}{TB}$$

- $\log_2 M$ is #bits transmitted per symbol
- PSK, ASK, QAM signal BW depends only on pulse shape
- rectangular pulse shape: null-to-null BW of the modulated signal is $2/T$
- BW = $(1+\alpha)/T$ when root raised cosine pulse shape with roll-off factor α is used.
- root raised cosine pulse the spectral efficiency is

$$\eta = \frac{\log_2 M}{1+\alpha}$$

Example: Find spectral efficiency of 4-QAM when used with a root raised cosine pulse shape with a roll-off factor of $\alpha = 0.25$.

Solution: Since $M = 4$ and the BW $= (1 + 0.25)/T$,

For 4-QAM spectral efficiency is $\eta = \log_2 4/(1 + 0.25) = 2/1.25 = 1.6$ bits/second/Hz.

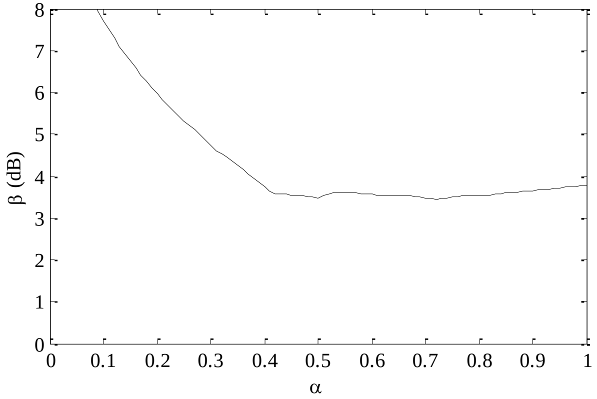
Peak-to-Average Power Ratio

- When choosing pulse shape also important to pay attention to its effect on *peak-to-average power ratio* (PAPR).
- PAPR measures how much instantaneous signal power can deviate from its average at any given time.
- Signals with a high PAPR will suffer from greater distortion due to nonlinearities in the RF components of communication system.
- For our common modulation schemes PAPR is given by (rectangular pulses):

Table 2.1. Maximum vs. average symbol energy.

	PSK, FSK	ASK	QAM
$\frac{E_{\max}}{E_s}$	1	$3\frac{M-1}{M-\frac{1}{2}}$	$3\frac{\sqrt{M}-1}{\sqrt{M}+1}$

- Root raised cosine filter adds a modification factor to this:



Example: Find PAPR of 16-QAM when root raised cosine pulse shape is used with $\alpha=0.3$.

Solution:

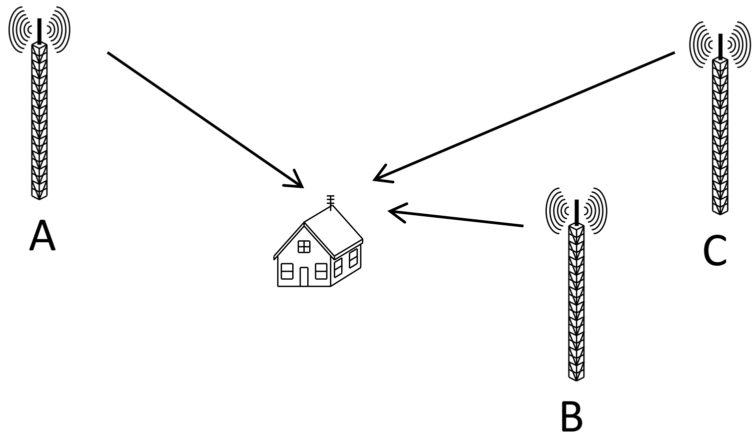
$$\frac{E_{\max}}{E_s} = 3\frac{\sqrt{M}-1}{\sqrt{M}+1} = 3\frac{4-1}{4+1} = 1.8 = 2.6 \text{ dB}$$

excess PAPR when $\alpha = 0.3$ is $\beta = 4.7$ dB.

PAPR=2.6+4.7=7.3dB

Frequency Division Multiple Access

- digital communication signals have BW that is proportional to inverse of the signal duration
- The shorter the signal duration (faster transmission rate), the higher the signal BW.
- Because practical signal BW is limited, it is possible for multiple users to simultaneously share the wireless channel, using a technique known as *frequency division multiple access* (FDMA).
- Each user in a given geographical area is assigned a distinct frequency band in which they can transmit their signals.



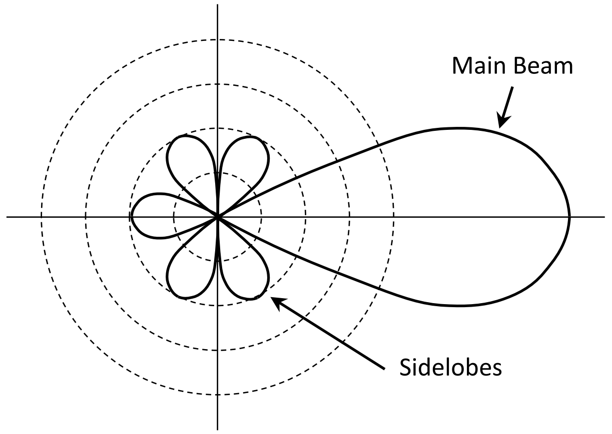
- FDMA -> signals do not overlap in freq domain -> Tx signals have a finite BW.
- In practice, impossible to achieve, all time-limited signals have infinite BW.
- all Tx signals will provide some radiated signal power in freq bands outside of assigned freq band, which will result in interference.
- Because out-of-band signal power typ. strongest in immediately neighboring freq bands, known as *adjacent channel interference* (ACI).

- necessary to carefully design Tx so they limit amount of power transmitted outside of allocated freq band by careful selection of pulse shaping filter and avoiding unwanted nonlinear effects in RF components of Tx.
- Guard bands (unallocated frequency bands) can also be placed between assigned bands to reduce effects of ACI.
- related issue with FDMA is *co-channel interference* (CCI).
- it is desirable to reuse freqs. in different geographical areas.
- CCI arises when signal from a distant Tx arrives at sufficiently high power to interfere with signal from a nearby Tx using same freq band.

Signal Attenuation in the Channel

- AWGN channel model only reflects small aspect of issues facing wireless communication.
- communication channel is much more complicated.
- signal attenuation, propagation delay, multipath interference.

- In wireless communication systems Tx signal is usually severely attenuated, so Rx signal often extremely weak.
- factors that affect the attenuation: antenna gains, distance-dependent pathloss, shadowing due to obstructions between Tx and Rx.
- Antennas transform RF signals in electronic circuits to electromagnetic (EM) signals in the air.
- antenna attached to Tx radiates EM signal into air, and receiving antenna collects energy from the air and provides it to Rx
- As with any conversion process there is always an associated loss.
- define *antenna efficiency* as ratio of these two energies.
- Antennas can be omnidirectional (also called isotropic) -> energy radiates equally in all directions, or directional with more energy focused in a particular direction.



- directivity of an antenna coupled with its efficiency can be described by the *directional antenna gain*
- antenna gain refers to amount of excess energy radiated in a given direction above which would have been radiated in same direction by an isotropic antenna
- usually expressed in units of decibels-isotropic (dBi).
- Although radiation pattern is 3-dimensional, it is common to plot it using 2-dimensional cross-sectional views

Antennas

- antenna gain often quoted as its maximum value, $G_A = \max G_A(\theta, \phi)$, along with width of main beam (in degrees).
- 3-dB beamwidth is often used to specify range of directions for which gain is within 3 dB of its max.
- the more directional an antenna is the greater the max gain is.
- Since total radiated energy does not depend on antenna, when less energy is radiated in unwanted directions more can be radiated in desired direction.
- energy radiated from Tx antenna becomes more diffuse the farther it travels.
- Rx antenna will only capture small fraction of Tx energy, so if a transmit antenna radiates a signal in all directions through free space, power at receive antenna:

$$P_R = P_T \frac{A_R}{4\pi d^2}$$

- P_T is Tx power, A_R is effective cross-sectional area of Rx antenna, d is distance between Tx and Rx, $4\pi d^2$ is surface area of a sphere with radius d.
- As d increases smaller fraction of surface area of sphere will pass through an area of A_R, so less of the Tx energy can be collected.
- effective area of Rx antenna is related to antenna gain in direction of Rx signal:

$$A_R = G_R \frac{\lambda_c^2}{4\pi}$$

- $\lambda_c = c/f_c$ is wavelength, c is speed of light, f_c is carrier freq, G_R is gain of Rx antenna.
- Isotropic antennas have gain $G_R = 1$
- taking into account gain of a directional antenna at Tx, with gain G_T in direction of Rx, Rx signal power is:

$$P_R = P_T \frac{G_T G_R}{(4\pi d/\lambda_c)^2}$$

$$P_{R\|dB} = P_{T\|dB} + G_{T\|dB} + G_{R\|dB} - L_{P\|dB}(d)$$

Antennas

- In practice, Rx signal power decays more quickly than square of distance
- there is considerable variation between measurements taken at different locations at same distance from Tx, due to shadowing effects from obstructions, such as buildings, trees and rainfall, in transmission path.
- A better model for the received signal power is

$$P_{R\|dB} = P_{T\|dB} + G_{T\|dB} + G_{R\|dB} - L_{P\|dB}(d_0) - 10\rho \log_{10}\frac{d}{d_0} - L_{\sigma\|dB}$$

- d_0 is close-in reference distance (a distance close to the transmit antenna but still in the far-field of antenna), ρ is pathloss exponent which measure how quickly pathloss increases with distance, and $L_{\sigma\|dB}$ represents shadowing.
- pathloss at close-in reference distance is either calculated according to $L_{P\|dB}d_0$=10log(10*4$\pi d_0\lambda_c$) or is taken from measurements.
- pathloss exponent usually in range 2 to 6 depending on environment.

Table 2.2. Path loss exponent in various environments.

Environment	Path Loss Exponent, ρ
Free Space	2
Urban Cellular Radio	2.7 to 3.5
Shadowed Urban Cellular Radio	3 to 5
In building line of sight	1.6 to 1.8
Obstructed in buildings	4 to 6
Obstructed in Factories	2 to 3

- Suppose Tx with transmit antenna gain of $G_{T\|dB} = 8$ dBi transmits a signal with power = 20 dBm, carrier freq = 2.4 GHz to Rx 100m away.
- Rx antenna $G_{R\|dB} = 6$ dBi.
- Find Rx signal power, using a close-in reference distance $d_0 = 1$m, pathloss exponent $\rho = 3.5$. Ignore the log-normal shadowing.
- $\lambda_c = 3 \times 10^8/2.4 \times 10^9 = 0.125$
- pathloss is $L_{P\|dB}(d_0) = 10\log_{10}(4\pi/0.125)^2 = 20$ dB.
- Rx signal power $P_{R\|dBm} = 20 + 8 + 6 - 20 - 10 \times 3.5 \times \log_{10}\frac{100}{1} = 14 - 70 = -56$ dBm
- 76 dB less than Tx power.

- because wireless communication environment constantly changing, attenuation due to pathloss and shadowing time-variant.
- Some modulation schemes, such as ASK and QAM, require knowledge of Rx signal strength in order to make reliable decisions, so time-varying attenuation must be estimated, tracked, and compensated for.
- On the other hand, decision rules for PSK and FSK do not depend on signal strength, allowing for less complex receiver design in this regard.

Propagation Delay

- Because radio waves only travel at speed of light through free space, there will be a transmission delay corresponding to time it takes for the signal to reach the receiver.
- Although this delay may be only a few nanoseconds, because it is time-varying as the user moves around, delay causes synchronization issues that need to be addressed.
- propagation delay causes a corresponding delay in complex lowpass equivalent signal, and a phase rotation of carrier
- Both these artifacts of propagation delay are addressed separately, by clock recovery and carrier synchronization techniques.

Clock Recovery

- Uncertainty in delay requires clock recovery techniques to determine optimal times to sample Rx lowpass signal.
- can express propagation delay as sum of large-scale delay (# of full symbol periods in the delay) and a small-scale delay (fractional delay within one symbol period)
- large and small scale delays have different effects on Rx samples, are handled using different techniques at Rx
- Rx must have knowledge to determine when first symbol in packet arrives so that prior samples can be discarded.
- This is accomplished by *frame synchronization*.
- One simple method is to transmit a known training sequence prior to transmission of data symbols.
- With knowledge of training sequence Rx can observe output of decision device until training sequence is found, and following sample would be for first data symbol.

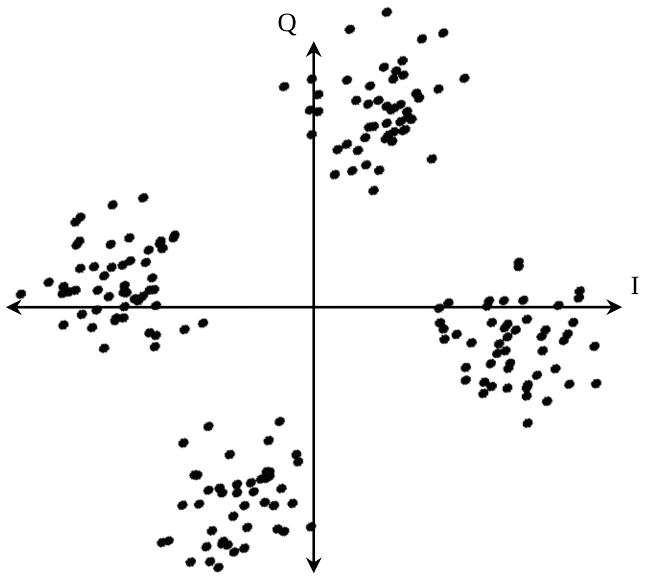
Clock Recovery

- An analogue clock recovery circuit, such as an early-late gate synchronizer, can be used to dynamically delay or advance sampling times slightly in an attempt to lock onto optimal times.
- samples are collected with a delay which is dynamically adjusted over time
- Digital clock recovery techniques typically involve collecting multiple samples per symbol and analyzing several symbols-worth of these samples in an attempt to determine delay
- analysis can be aided with the use of a training sequence.
- With a training sequence Rx knows what samples should be if they were collected at correct times.
- An estimate of the fractional delay, can be determined as that value of the fractional delay that would give received samples closest to their expected values.
- initial estimate of τ_o can be further refined by using feedback of decisions made by decision device, allowing for Rx to track changes in propagation delay and to handle small mismatches between clock freqs at Tx and Rx.
- frame synchronization and clock recovery with training sequences should be carried out jointly, since frame synchronization requires detection of training sequence, which can only be achieved if correct fractional delay has been determine, which in turn requires knowledge of when training sequence begins.

Carrier Synchronization

- When information is carried in the phase of carrier wave (PSK or QAM) important for Rx to maintain carrier synchronization with Tx.
- received signal is demodulated by mixing it with a LO signal, which should have same phase as received carrier.
- phase of received carrier depends on reference phase of transmitted carrier, phase rotation due to propagation delay.
- all the received samples are rotated

- phase rotation will cause BER to be much worse.
- If phase rotation is greater than ±45°, majority of samples will not be detected correctly, even if there is no noise.
- One technique to avoid this problem is to ensure that carrier reference signal is in phase with data.
- known as *coherent demodulation*, and can be accomplished by using a carrier recovery circuit



Carrier Synchronization

- Building a circuit that recovers absolute phase of Rx signal is difficult, so *noncoherent demodulation* is often used
- noncoherent demodulation Rx signal is demodulated with a carrier reference signal with arbitrary phase, all received samples are rotated
- phase rotation is same for all received samples in a packet, or varies fairly slowly.
- DSP perhaps aided by known training sequence or pilot symbols, can be used to estimate this -> received samples can be rotated back to their correct positions.
- modulation schemes that do not require knowledge of carrier phase (ASK and FSK) can be used.
- With ASK receiver only needs to know amp of carrier
- if noncoherent demodulation is used then demodulation must be performed using both I and Q phase carriers, even if data only transmitted on inphase carrier, because phase rotation may move a significant portion of Tx signal to only Q phase carrier.
- Because noise on both I and Q phases affects decision, noncoherently detected ASK and FSK have higher BER (require 3 dB more signal power) than when detected coherently, but have more simple receiver design without carrier recovery circuit.
- It is also possible to use a version of PSK that does not need any knowledge of the absolute phase of the transmitted signal.
- called *differential phase shift keying* (DPSK).
- With DPSK information is transmitted not directly in phase of carrier, but as change in carrier phase over 2 symbols.
- Rx compares phase of current sample to phase of previous sample, change in phase tells Rx what symbol was transmitted.
- binary DPSK if there was no change in phase 0 was transmitted and if phase changes by 180º then a 1 was transmitted.
- Because decision on current symbol is affected by noise in both current symbol and previous one, DPSK suffers from a higher BER than coherently detected PSK.