Equation Sheet (Y3S1) – Digital Mobile Communications

$$X(dB) = 10\log_{10} X$$

$$P(dBW) = 10\log_{10} P(W)$$

$$P(dBm) = 10\log_{10} P(mW) = P(dBW) + 30\text{dB}$$

$$SNR = \frac{P_S}{P_N}\ (\text{analog} - \text{linear scale}) \quad || \quad SNR = \frac{E_S}{N_0}\ (\text{digital})$$

$$C = B\log_2(1 + SNR)$$

1. Baseband Digital Transmissions

2. Bandpass Digital Transmissions

3. Radio Propagation & Diversity

$P_r = \frac{P_1 G_t G_r \lambda^2}{(4\pi d)^2} = \frac{P_t G_t G_r}{PL}$ (received power-free space model)

$P_r(dB) = P_t(dB) + G_t(dB) + G_r(dB) - PL(dB)$ (received power dB-free space model)

$PL(dB) = -10\log\frac{\lambda^2}{(4\pi d)^2}$ (path loss-free space model)

$\overline{PL}\,(d) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right)$ (path loss exponent model)

$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^n$ (path loss exponent model)

$PL(d) = \overline{PL}(d) + X_\sigma$ (shadowing model)

$PL(d) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) + \sum_{p=1}^{P} WAF(p) + \sum_{q=1}^{Q} FAF(q)$ (indoor model)

$P_n = kT_0 B = N_0 B$ (thermal noise model)

$P_n^{out} = F \times G \times kT_0 B$ (noise figure model)

$F_{sys} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots$ (cascaded system model)

$F_{sys} = F_A + F_1 - 1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots$ (cascaded system with antenna model)

$SNR = \frac{P_r}{P_n} = \frac{P_t G_t G_r G_{sys}}{PL \times L_{sys} P_n} = \frac{P_t G_t G_r}{PL \times L_{sys} F_{sys} k t_0 B}$ (received SNR of a system → BER)

$P_t = SNR + PL + L_{sys} + P_n - G_t - G_r - G_{sys}$ (Tx power required in dB)

$h(t,\tau) = \sum_{k=0}^{L-1} A(t,k\Delta\tau)\, e^{j\theta(t,k\Delta\tau)} \delta(\tau - k\Delta\tau)$ (Impulse response)

$P(\tau) = \sum_{k=0}^{L-1} A(t,k\Delta\tau)^2\, \delta(\tau - k\Delta\tau) = \sum_{k=0}^{L-1} P_k\, \delta(\tau - k\Delta\tau)$ (Power at the k^{th} bin)

$\bar{\tau} = E[\tau] = \Sigma_k\ Prob(k)\tau_k = \Sigma_k \left(\frac{P_k}{\Sigma_k P_k}\right)\tau_k$ (mean excess delay)

$\overline{\tau^2} = E[\tau^2] = \Sigma_k\ Prob(k)\tau_k^2 = \Sigma_k \left(\frac{P_k}{\Sigma_k P_k}\right)\tau_k^2$ (second moment)

$\sigma_\tau = \sqrt{\overline{\tau^2} - \bar{\tau}^2}$ (RMS delay spread)

$B_C = \frac{1}{50\sigma_\tau}$ & $B_c = \frac{1}{5\sigma_\tau}$ (correlation higher than 0.9 & 0.5)

$f_{d-max} = \frac{v}{\lambda}$ (Doppler shift)

$B_D = 2f_{d-max}$ (Doppler spread)

$T_C \approx \frac{9}{16\pi f_{d-max}}$ (Coherence Times)

4. Multiple Access Techniques

$SNIR = \frac{P_s}{R_s N_0 + \frac{1}{PG}} = \frac{E_b R_s}{R_s N_0 + \frac{IR_S}{B_c}} = \frac{E_b/N_0}{1+\frac{I}{N_0 B_C}}$ (SNIR before detection)

$SNIR^{(1)} = \frac{SNR^{(1)}}{1+\Sigma_{k=2}^{K}\frac{SNR^{(k)}}{PG^{(k)}}}$ (SNIR analysis of user 1)

$SNIR^{(1)} = \frac{\frac{|\alpha^{(1)}|^2 E_b^{(1)}}{N_0}}{1+\Sigma_{k=2}^{K}\frac{|\alpha^{(k)}|^2 E_b^{(k)}}{N_0}\frac{R_S^{(k)}}{B_C}}$ (SNIR in wireless channels)

5. Cellular Network Design

$N = i^2 + ij + j^2$ (cluster size)

$Q = \frac{D}{R} = \sqrt{3N}$ (co-channel reuse ratio)

$\frac{S}{I} = \frac{\left(\frac{D}{R}\right)^n}{i_0} = \frac{\left(\sqrt{3N}\right)^n}{i_0} = \frac{Q^n}{i_0}$ (SIR)

$A_u = \lambda H$ (traffic per users)

$A_{tot} = UA_u$ (total traffic)

Revision Sheet (Y3S1) – Digital Mobile Communications

Advantages of digital: **noise immunity**, **multiplexing**, **security**, **DSP** support (wireless: +**mobility** +flexibility)

Difference between wireless & mobile: wireless is any (wifi, voice, hand signs…), mobile is **subset which supports mobility**

Mobile challenges: **channel impairments** (wireless channels varying & adversely affect performance), **limited bandwidth** (expensive or limited in unlicensed band), **transmission power** (minimise to avoid interference, power consumption and health risks), **interference** (transmission causes interference to other user/system &VV), **handheld power consumption** (battery must last as long as possible), **processing power & memory** (available power on mobiles is limited), **size**, **security**, **robustness** (all environments).

dB scale: logarithmic scale, very useful and prevalent in comms

$$X(dB) = 10\log_{10} X$$

dBW scale: signal power in Watts in dB

$$P(dBW) = 10\log_{10} P(W)$$

dBm scale: signal power in mW in dB

$$P(dBm) = 10\log_{10} P(mW) = P(dBW) + 30\text{dB}$$

Bit Error Rate (BER): number of bit errors out of all transmitted bits, common performance measure (+symbol/frame ER)

Signal to Noise ratio (SNR): commonly used at receiver to determine quality of received signal compared to noise

$$SNR = \frac{P_S}{P_N}\ (\text{analog} - \text{linear scale}) \quad || \quad SNR = \frac{E_S}{N_0}\ (\text{digital})$$

Additive White Gaussian Noise (AWGN): common model for noise, white (uncorrelated & occupies all frequencies) &Gdist

Capacity: maximum data rate achievable with negligible error rate. For AWGN:

$$C = B\log_2(1 + SNR)$$

Baseband: normal frequency range (-W to +W) close to frequency of original signal

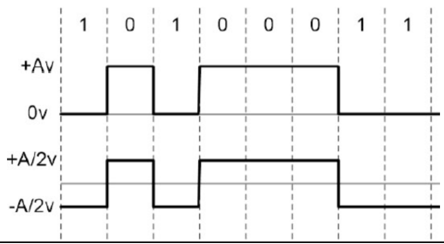
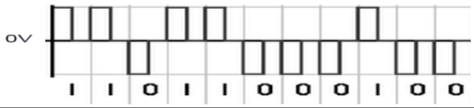
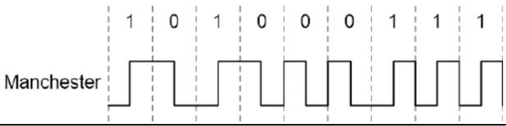
Bandpass: higher frequency range (f_0-W to f_0+W) of modulated signal

Types of comms (3→7): point-to-point - **simplex** (one way), **half duplex** (one way at a time), **full duplex** (two way, FDD || TDD) || point-to-multipoint - **broadcast** (single source to all Rx e.g. radio/TV), **multicast** (single source to group of Rx e.g. mobile TV), multipoint-to-multipoint - **multiplexing** (FDM, TDM), **multiple access** (FDMA, TDMA, CDMA, OFDMA…)

1. Baseband Digital Transmissions

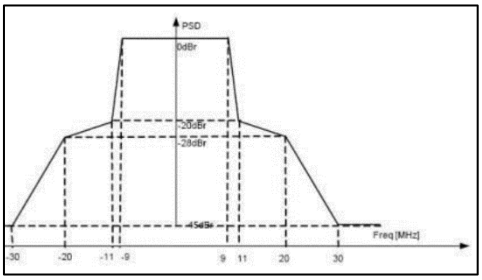
Nyquist rate: for **digital transmission of originally analog signals**, sampling needed with sa**mpling frequency of at least two times source frequency**.

Wired: line coding (baseband)

Coding scheme	Encoding	Notes
Non-Return to Zero (NRTZ)		**Unipolar**: (0 to +AV) [P=A²/2] **Bipolar**: (+A/2 V to -A/2 V) [P=A²/4] - *no DC component*
Return to Zero (RTZ)		Can also use 0 to +AV (**unipolar**) +A/2V to -A/2V (**bipolar**) *Requires twice bandwidth of NRZ*
Manchester (M)		**Manchester**: $+_{ve}$ trans. for 1, $-_{ve}$ trans. for 0 (always mid-bit trans.) *Used in ethernet*

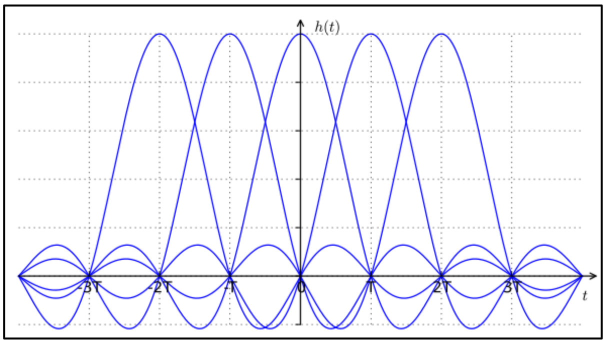
Pulse shaping: although **line coding is good for wired comms**, in **frequency domain sharp edges occupy wide bandwidth** so **pulses must be reshaped** to avoid **expensive** and **inefficient bandwidths** (otherwise multiple user transmission will create **adjacent channel interference**)

Spectral mask: given to operators to **fit signal into frequency band** for signal transmission with **some leakage allowed either side of band with restricted power** (reduces adjacent channel interference). **Square pulse converted to pulse shape of spectral mask** by **multiplying filter response** to signal **frequency response**.



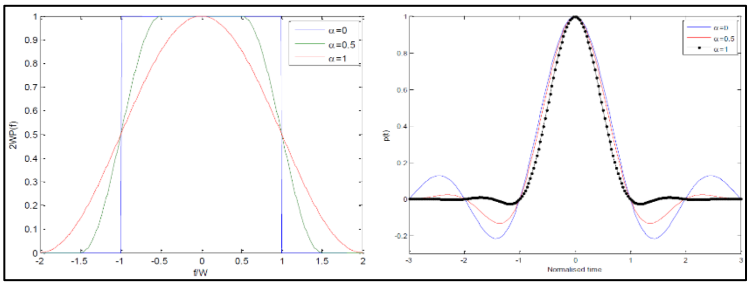
Pulse design: **smooth shape with no sharp edges**, transmitted **continuously without interference to neighbouring symbols (no ISI)**.

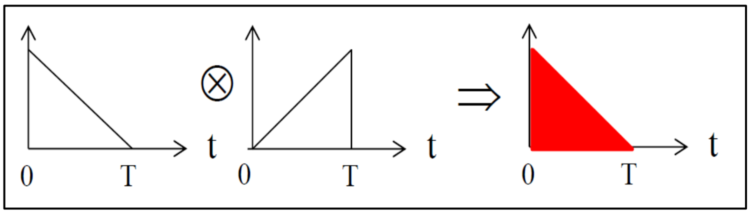
Nyquist criterion for zero ISI: to ensure zero ISI for a pulse, since sampling occurs at receiver - **pulse signal must exist at corresponding sampling instance and zero at all other sampling instances**.



Raised cosine pulse shaping: **commonly** used as **theoretically zero ISI**. As seen aside for **each sampling instance (T)** only the **signal** is read while **all others are zero**.

Can increase roll-off factor α for smoother pulse (wider bandwidth)





Receiving pulse methods (2): pulse is transmitted, must be detected. **Sample of peak of pulse** (does not guarantee best SNR) || **Integrate signal over symbol period** (better SNR, achieved via convolution)

Matched filter: for **maximum output** pulse must be **convolved with a time reversed and delayed version** of same pulse (triangular pulse assumed aside).

Matched filtering: like integration, outputs a sequence of values which is fed to a detector.

Detector: must guess transmitted symbol, uses threshold detector for AWGN (more complex for wifi)

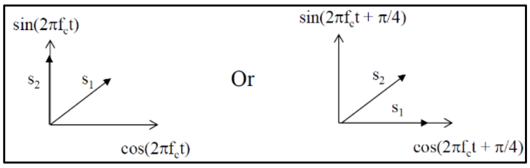
2. Bandpass Digital Transmissions

Problems with baseband transmission (3): channel might be poor in transmission frequency range, too many users would use that range (license needed to transmit at a certain frequency)

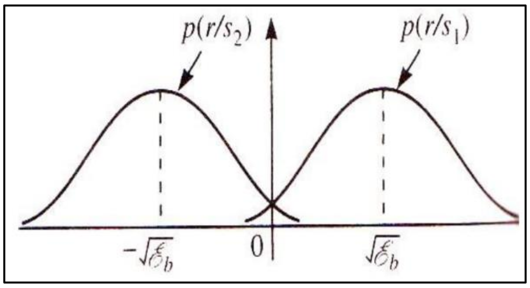
Modulation: transmits signals at higher frequency by **mapping the digital binary data to an analog signal waveform**, convert baseband signal to one suitable for transmission - bandpass.

Modulation factors (6): **bandwidth / spectral efficiency** (throughput of data rate per Hertz i.e. $\eta_S = R/B$ bps/Hz), **power efficiency** (required SNR to achieve certain BER/FER, how efficient power used for transmission), **implementation complexity**, **non-linearity of power amplifier**, **adjacent channel interference** & **robustness**.

Signal space concept: carrier signal used for modulation (can only change **phase θ, amplitude A & frequency f_c**). Any signal **can be represented by a set of orthogonal basis**. Space spanned by these basis is called **signal space**. (*math OOS*)

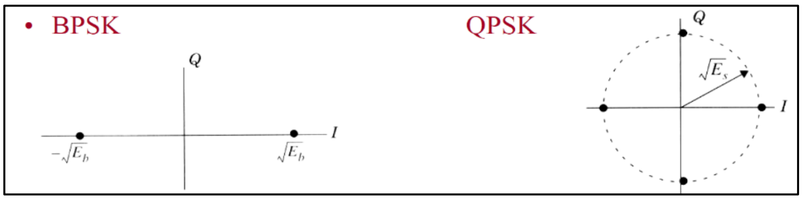


Decision statistic: received signal in **baseband** has a **detection threshold** (if 0 then both 1 or 0 equally probable, if larger than 0 the $d = 1$, if smaller than 0 $d = 0$.



- Phase shift keying (PSK): data modulated into phase of carrier signal **binary (BPSK)**, **quadrature (QPSK)**, **M-ary (MPSK)**… (see final table)

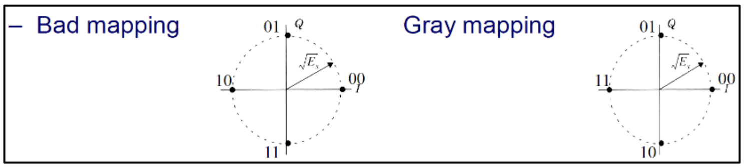
Constellation diagram: representation of modulated signals on in-phase (real) & quadrature (complex) phase plane.



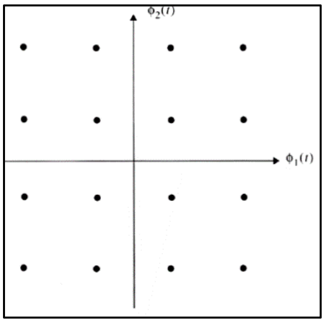
Euclidian distance (d_E): **distance between 2 closest constellation points** (**shorter** Euclidian distance means **more prone to symbol error** as AWGN can more easily move over detection threshold). Here $d_E^{BPSK} = 2\sqrt{E_b}$, $d_E^{QPSK} = \sqrt{2E_S}$

Energy per bit (E_b): given by modulation scheme. Note that here: $E_s = 2E_b$ for QPSK. So same d_E and thus same BER.

Gray mapping: **maps input bits to constellation** such that only **1 bit different between two adjacent constellations**.



PSK implementations (3): **MPSK** like **QPSK** & **BPSK** but with more constellation points such that 1 symbol carries more **bits equally spaced** where M is a power of 2 (M=2^k). Uses quadrature carrier signal: $s(t) = A_I \cos[2\pi f_c t] + A_Q \sin[2\pi f_C t]$ where in phase amplitude (A_I) & quadrature phase amplitude (A_Q). I & Q are **orthogonal** (no Itf). Occupies **same bandwidth** as I or Q so can be used to **enhance data rate**.

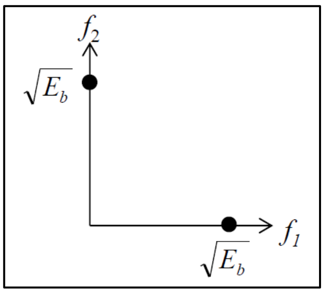


- QAM: use amplitude of carrier signal to carry data.

M-QAM: **same bandwidth as MPSK, less power (SNR) for same BER** in higher order modulation. **Advantage** of ability to use high order modulation for **high data rate** (802.11ac uses up to 256QAM, 802.11b uses QPSK). **Disadvantage** of having a symbol energy different leading to the use of **inefficient power amplifiers**.

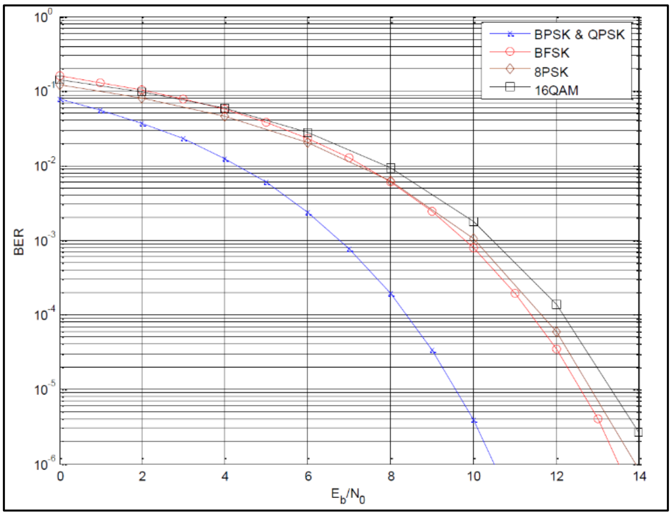
Average symbol energy (E_{av}): in 4-QAM = 2, 16-QUAM = $10\ldots$

- FSK: uses **two orthogonal frequencies of carrier signal to carry data**. **Worse performance than QAM**. MFSK high signal bandwidth as occupies **lots of bandwidth**. **Envelope constant** (good for wireless comms). **Euclidian distance always the same**.



BFSK: $d_E = \sqrt{2E_b}, BER = Q\left(\sqrt{\frac{E_b}{N_0}}\right)$

Modulation types: **linear modulation** (PSK, QAM) & **non-linear modulation** (FSK, MSK)



Linear modulation: signal amplitude varies with modulating signal $m(t)$ → **spectrum efficient** (good), **non-constant envelope** (bad, requires either: **P-inefficient linear amplifiers** with 30-40% loss using more battery || **P-efficient** non-linear amps but introduces distortion making spectrum inefficient again)

Non-linear modulation: signal frequency varies with modulating signal → **spectrum inefficient** (bad), **constant envelope** (good, can use power efficient non-linear amplifiers)

Modulation trade-off: either **bandwidth efficient** applications → **linear modulation** || **power efficient** application → **non-linear modulation**

Regular QPSK issue: 180° phase transition causes **rapid change in signal** (generates HF components, even worse for NL amps) but allows **high spectral re-generation with rapid zero-crossing**.

Offset QPSK: **aims to avoid rapid 180° phase transition** via **delay** of 0.5 T_s (i.e. 1 bit-period T_b). Phase **transitions at half a symbol period** limited to ±90. **Same spectral occupancy** as QPSK. (delay in time, change in f-domain). **Less spectral regeneration** with NL power amp.

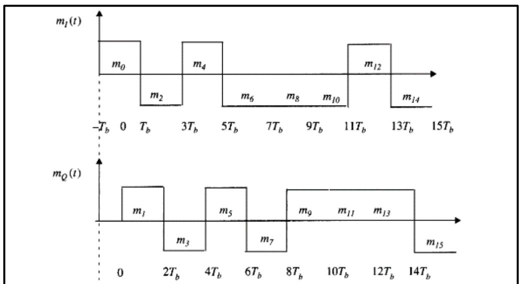
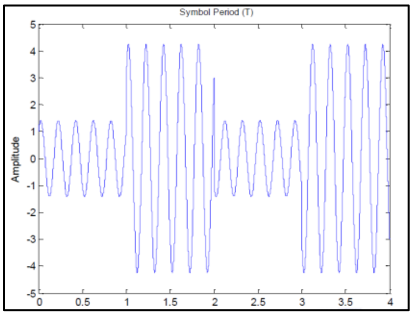
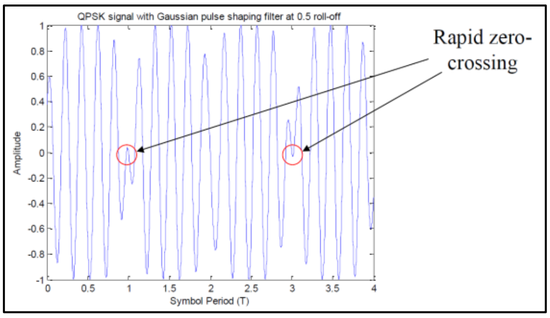
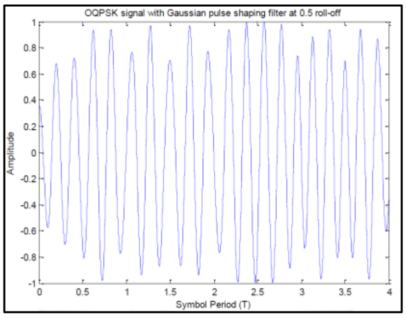


Figure 6.30 The time offset waveforms that are applied to the in-phase and quadrature arms of an OQPSK modulator. Notice that a half-symbol offset is used.







$\pi/4$-QPSK: **compromise between OQPSK & QPSK**, shift $\pm\pi/4$ in signal constellation for consecutive symbols (transmit even symbols with $\pi/4$ phase shift). **Maximum phase transition limited to 135°**.

$\pi/4$-QPSK characteristics: **compromise** as less spectral regrowth than QPSK but higher than OQPSK, **simpler receiver design** with non-coherent detection.

$\pi/4$-DQPSK: works with **differential encoding** (difference between past and current symbols contain current data). Current phase given by: $\theta_k = \theta_{k-1} + \phi_k$.

Input bits: 11, 01, 00, 10

ϕ_k: $\frac{\pi}{4}, \frac{3\pi}{4}, -\frac{3\pi}{4}, -\frac{\pi}{4}$

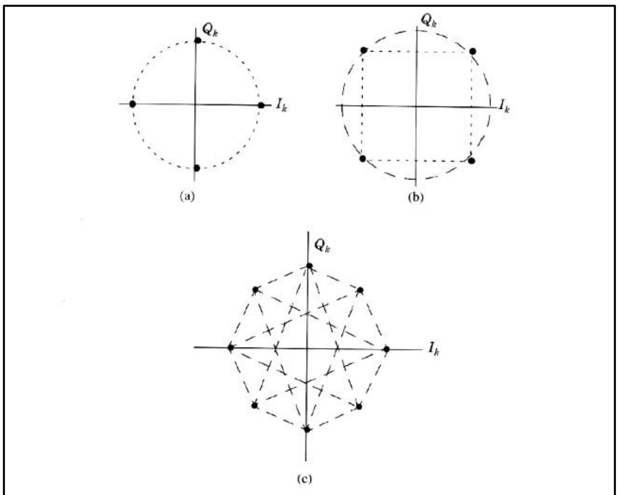
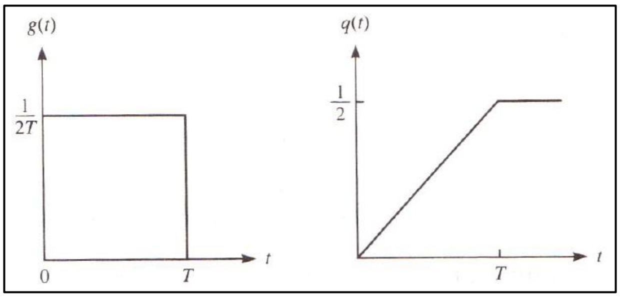


Figure 6.31 Constellation diagram of a $\pi/4$ QPSK signal: (a) possible states for θ_k when $\theta_{k-1} = n\pi/4$; (b) possible states when $\theta_{k-1} = n\pi/2$; (c) all possible states.

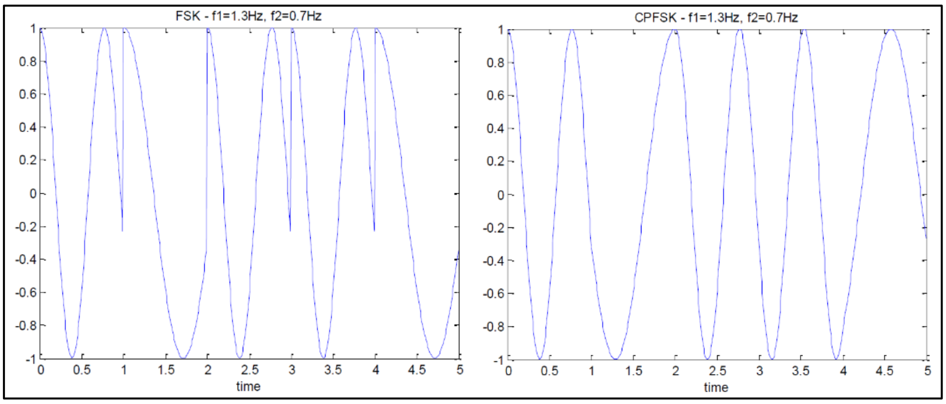
Non-linear modulation: **modulate baseband into phase of carrier**. Constant envelope so can use NL amps.

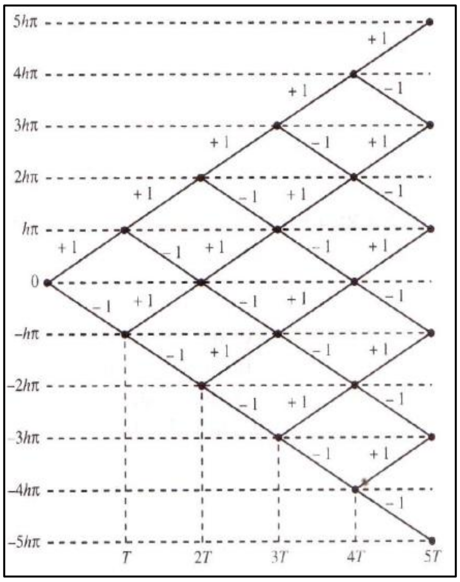


Continuous Phase SK (CPFSK): If $\phi(d;t)$ **continuous in amplitude** - modulated **signal continuous in phase** & instead of data bit (discontinuous) used to modulate carrier, **integral of data bit** (continuous) is used. Step 1: integrate data, step 2: modulate into phase. Continuous phase.

CPFSK phase trajectory: every **+/- is the input bits, line represents phase of carrier signal & phase continuous**.

E.g. for data = 1 0 1 1 0,





Minimum Shift Keying (MSK): in orthogonal FSK signals, **minimum frequency separation must be 1/2T** & FSK signals must be **orthogonal to have minimum error**. **CPFSK should also** have this **minimum frequency separation**. At this separation **CPFSK scheme is called MSK** (special case of CPFSK). Constant envelope with continuous phase.

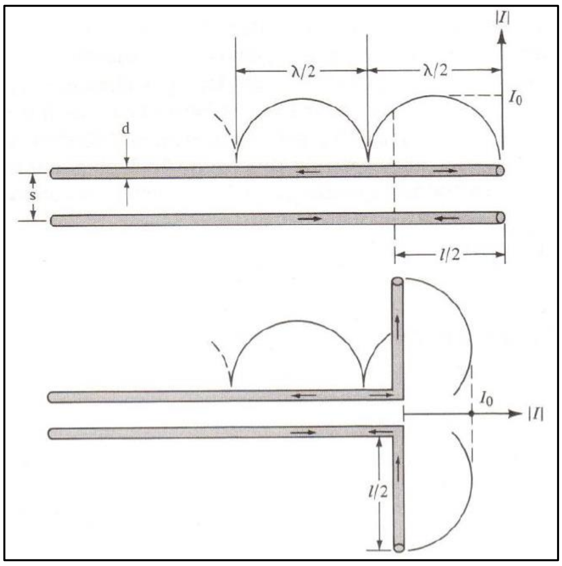
Gaussian-filtered (GMSK): **gaussian filter** (filter with Gaussian-shaped frequency response) applied to **data** (rectangular pulse, before MSK modulator). Reduces sidelobe of signal spectrum → **bandwidth efficient**. More power efficient amplifier can be used → **power efficient**. **Creates ISI**. *Used in GSM.*

(needs practice)

Wireless: modulation (bandpass)

Modulation scheme	Equations	SNR BER	η_P	η_S	Power amp	Linearity (L/NL)	d_E	Pro/Con
BPSK	$d \begin{cases} 1\ iff\ \theta = 0° \\ 0\ iff\ \theta = 180° \end{cases}$	X Y	bad	1bps/Hz	L: loss ~~NL: distr.~~	L	$2\sqrt{E_b}$	
QPSK	$d = 00,01,10,11$ $\theta = 0, 90, 180, 270$	X Y	bad	2bps/Hz	L: loss ~~NL: distr.~~	L	$\sqrt{2E_S}$	
MPSK	(as above, segmented)		bad	good	L: loss ~~NL: distr.~~	L	→ low	+ spectral regen / fast 180
O-Q**PSK**	$\frac{\pi}{4}, \frac{3\pi}{4}, -\frac{3\pi}{4}, -\frac{\pi}{4}$ (map: 00,01,11,10)			2bps/Hz	L: loss NL: ok	L		avoid fast 180 / - spectral regen
$\pi/4$-Q**PSK**	Mapping 1: as above Mapping 2: $0, \frac{\pi}{2}, \pi, -\frac{\pi}{2}$				Simple	L		compromise of M & O-Q PSK
$\pi/4$-DQ**PSK**	Mapping: as O-QPSK					L		Differential
Q**AM**	$d = 00,01,10,11$ $A_I, A_Q = \{1,1\}, \{-1,1\}$ $\{1,-1\}, \{-1,-1\}/\sqrt{2}$		bad	good	L: loss ~~NL: distr.~~	L		
M-Q**AM**	(as above, but $/\sqrt{E_{av}}$)	<X Y	bad	good	L: loss ~~NL: distr.~~	L	→ high	High data rate / E_S dif., bad amp
BFSK	$d \begin{cases} 1\ iff\ A_c \cos 2\pi f_1 t \\ 0\ iff\ A_c \cos 2\pi f_2 t \end{cases}$		good	bad	NL: ok	NL	$\sqrt{2E_b}$	
QFSK	(as above, segmented)		good	bad	NL: ok	NL		
MFSK	(as above, segmented)		good	bad	NL: ok	NL		Const. envelop / high bandW
CP**FSK**	+/- is input bits, line is phase of carrier					NL		Continuous ϕ /
MSK	(as above & $f_{sep} = \frac{1}{2}T$)					NL		Const. envelop /
GMSK	(as above, G filtered d)		better	better	better	NL		all / creates ISI

3. Radio Propagation & Diversity



Antenna radiation: RH grip rule of field around a current carrying wire → resultant EM field. Transmission line theory dictates the requirement of an antenna dipole to radiate/propagate signal.

Antennas: various types, **passive** device (just a piece of metal - **no inherent gain**).

Isotropic antenna: **hypothetical lossless antenna** having **equal radiation in all directions**. Used as a **reference for 0dBi**.

Realistic antennas: maximum gain larger than 0dBi as beam concentrates power (i.e. dBi is the **power gain over an isotropic antenna** at a particular direction). Does not imply active device, just directional power distribution.

Propagation: occurs when signal is injected into antenna generating a radio wave. Subject to distortion.

Free Space Propagation: radio wave with power P_t being transmitted from an antenna at a distance d.

For **Isotropic Antennas**, flux density given by:

$$\phi_d = \frac{P_t}{A_{surface}} = \frac{P_t}{4\pi d^2}$$

Power captured by an antenna with effective area A_e is:

$$P_r = \phi_d A_e = \frac{P_t}{4\pi d^2} A_e$$

For isotropic receive antenna:

$$A_{iso} = \frac{\lambda^2}{4\pi}$$

Hence received power for isotropic antenna is

$$P_{r-iso} = \phi_d \frac{\lambda^2}{4\pi} = \frac{P_t \lambda^2}{(4\pi d)^2} = \frac{P_t c^2}{(4\pi d f)^2}$$

Thus, power attenuates inverse squarely to distance and frequency.

For **Realistic Antennas**, antenna is given a gain G_t (when not given assume maximum gain used). Receive antenna with gain G_r. Max antenna gain given by:

$$G = \frac{A_e}{A_{iso}} \therefore A_e = \frac{\lambda^2}{4\pi} G$$

Hence received power for realistic antennas is (Friis eq.):

$$\boldsymbol{P_r = \frac{P_1 G_t G_r \lambda^2}{(4\pi d)^2} = \frac{P_t G_t G_r}{PL}}$$

$$\boldsymbol{P_r(dB) = P_t(dB) + G_t(dB) + G_r(dB) - PL(dB)}$$

Path loss given by:

$$\boldsymbol{PL(dB) = -10 \log \frac{\lambda^2}{(4\pi d)^2}}$$

Which describes degradation of distance.

Assumptions (3): **receiver is far** such that $d \gg \lambda$ (plain wave model can be used - E, H & propagation direction orthogonal) & **max beam of Tx antenna points to max beam of Rx antenna** (both G_t & G_r are at max) & **free space propagation** (no obstacles or reflectors)

Reference distance (d_0): used as a reference point with a known received power (measured or predicted) to map powers beyond this distance via:

$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^2$$

Propagation mechanisms (3): **reflection** (off large hard surfaces - direct path and reflected path must be combined), **diffraction** (off curved surfaces or sharp-edged objects - most of the signal is blocked & causes degradation) & **scattering** (off small or rough surfaces that cause reflected waves to spread out).

Generic propagation models (3): **path loss** (models signal attenuation caused by wave propagation at large Tx-Rx separations - generally increases when separation increases), **shadowing** (models signal power at same Tx-Rx separation but different locations to investigate variation due to change of environment in a circular loci), **multipath fading** (rapid variation within a distance of a few wavelengths causes by destructive or constructive interference from multiple arrival paths)

- Path loss exponent model: average path loss exponent used (since $d \gg \lambda$). Mean path loss (dB) at d given by:

$$\overline{PL}\,(d) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right)$$

And received power at distance d given by:

$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^n$$

- Shadowing model: log-normal distribution used to model effect. Path loss at d given by:

$$PL(d) = \overline{PL}(d) + X_\sigma$$

where $\overline{PL}(d)$ modelled as before, X_σ log-normal shadowing effect μ=0 & variance σ (PL rand. var. of $\mu = \overline{PL}$ variance σ)

- Indoor attenuation factor model: losses by different partitions, walls & floors are modelled as follows:

$$PL(d) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) + \sum_{p=1}^{P} WAF(p) + \sum_{q=1}^{Q} FAF(q)$$

where P & Q are the number of walls between Tx & Rx respectively and WAF/FAF are wall/floor attenuation factors

Noise: system performance determined by SNR (received signal power can be estimated from models, noise must be separately calculated). Thermal noise is given by:

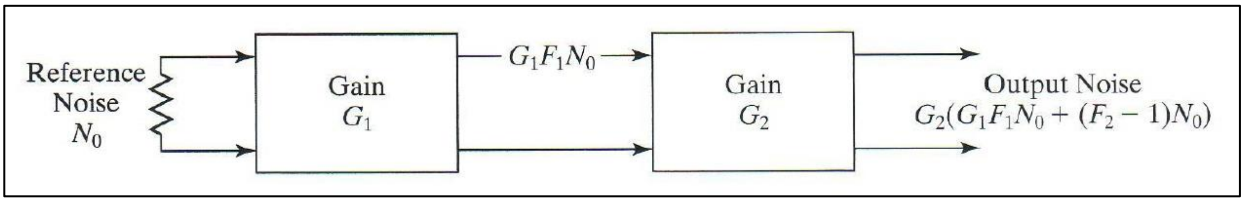
$$P_n = kT_0B = N_0B$$

where B is the bandwidth, T_0 is the room temperature, k is the Boltzmann constant & N_0 is the noise power spectral density

Noise figure: measures additional noise generated by device (ratio increase on noise power at output of device in dB). Thus smaller F, smaller the noise until noiseless ($F = 1$). Given by:

$$F = \frac{P_n^{actual\ output}}{P_n^{noiseless\ output}} = \frac{P_n^{actual\ output}}{G_{device} \times P_n^{input}} \therefore P_n^{out} = F \times G \times kT_0B$$

Noise in two cascaded devices: noise output of device 1 fed into input of device 2 for a total output noise as below.



Output of device 2 is given by: $gain \times (input\ noise + additional\ noise)$

$$F = \frac{G_2\{G_1F_1N_0 + (F_2 - 1)N_0\}}{G_1G_2N_0} = F_1 + \frac{F_2 - 1}{G_1}$$

Cascaded system: overall noise figure given by:

$$F_{sys} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1G_2} + \cdots$$

Antenna has unity gain in noise calculation i.e. **antenna gain does not amplify noise** thus system with antenna given by:

$$F_{sys} = F_A + \frac{F_1 - 1}{G_A} + \frac{F_2 - 1}{G_AG_1} + \frac{F_3 - 1}{G_AG_1G_2} + \cdots = F_A + F_1 - 1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1G_2} + \cdots$$

Noise significantly reduced if first device has high gain but low noise (shows important of a low noise amplifier LNA).

Received SNR in cascaded system: given by

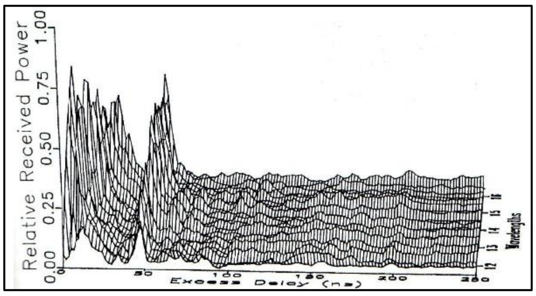
$$SNR = \frac{P_r}{P_n} = \frac{P_tG_tG_rG_{sys}}{L_pL_{sys}P_n} = \frac{P_tG_tG_r}{L_pL_{sys}F_{sys}kt_0B}$$

Link budget (2): **calculation** to **ensure sufficient power available at receiver** to meet SNR required for a **certain BER** in a given modulation scheme. 2 approaches: **estimate required transmit power given channel path loss and system loss** (suitable for applications without max limit for P_t) | | **calculate maximum distance for link with fixed P_t** (suitable for fixed P_t applications such as mobile network design where P_t given by standard). Link budget considers uplink because max P_t for mobile is much smaller than base station (health issue & battery consumption) to calculate how far a mobile can be located.

$$\boldsymbol{P_t = SNR + PL + L_{sys} + P_n - G_t - G_r - G_{sys}}$$

$$PL = P_t + G_t + G_r + G_{sys} - SNR - L_{sys} - P_n$$

Types of propagation (2): **large-scale propagation** (mean signal strength at large distances - **path loss**, **shadowing**…) important for site planning & **small-scale propagation** (rapid fluctuations in short distance or time - **fading**) important for receiver design.



Multipath propagation (3): signal **arrives at Rx through different paths** (reflection, diffraction & scattering), paths could arrive with **different gains, phase & delays**, small **distance variation can have large amplitude variation**.

Excess delay: **relative time delay compared to the first arrival path** used to describe how multipath channel changes with time/distance

Filter model: impulse response is a good way to characterise a channel as it is the **summation of all paths** (each path has its gain, phase & arrival time) varying with time and distance. **Discrete-time impulse response used** for digital systems as normal channel impulse response is **continuous time** (**complex analysis** via integration).

Excess delay bins: used to split CT channel response into DT bins associated with a sampling instance. Variables used - **time variation due to motion** (t) & **time variation due to channel delay** (τ). $\Delta\tau$ is **delay bin width** up to max path delay L.

$$\boldsymbol{h(t,\tau) = \sum_{k=0}^{L-1} A(t,k\Delta\tau)\, e^{j\theta(t,k\Delta\tau)} \delta(\tau - k\Delta\tau)}$$

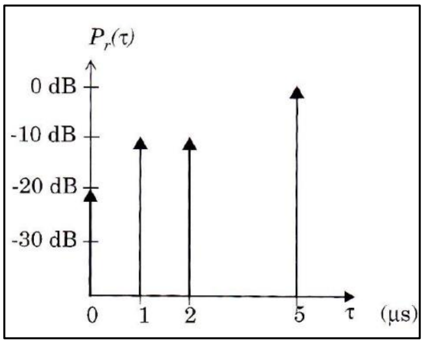
$A(t,k\Delta\tau)$ *is amplitude of* k^{th} *bin at time* t, $\theta(t,k\Delta\tau)$ *phase shift due to* k^{th} *bin at time* t, $\delta(\tau - k\Delta\tau)$ *arrival time at* k^{th} *bin*

Multipath channel impulse response: if **multiple paths arrive in one delay bin**, these **paths arrive in between two sampling instances** thus **cannot be resolved into individual paths** and will be **combined** (different gains/phase will be combined leading to constructive or destructive interference and rapidly changing channel gains from one bit to another).

Multipath fading: effect of **large variation** in received signal amplitude within short period of time or distance (particular received symbol could be very strong or weak in amplitude)

Deep fade: when the channel is particularly weak (in this case symbol cannot be detected correctly, diversity technique required)

Inter-Symbol-Interference (ISI): if some paths arrive after one symbol period, transmitted symbol will interfere with Tx symbols (equalisation techniques required).



Power at the k^{th} delay bin given by:

$$\boldsymbol{P(\tau) = \sum_{k=0}^{L-1} A(t,k\Delta\tau)^2\, \delta(\tau - k\Delta\tau) = \sum_{k=0}^{L-1} P_k\, \delta(\tau - k\Delta\tau)}$$

Common delay profiles (2): **uniform delay profile** (P_k same over all bins) & **exponential delay profile** (P_k c*exp)

Time dispersion parameters (3): very useful in categorising channel types, determined from power delay profile (treat power delay profile as a probability mass function, calculate **mean**, **second moment** & **standard deviation**).

Mean Excess Delay: $\bar{\tau} = E[\tau] = \Sigma_k \, Prob(k)\tau_k = \Sigma_k \left(\frac{P_k}{\Sigma_k P_k}\right)\tau_k$

Second moment: $\overline{\tau^2} = E[\tau^2] = \Sigma_k \, Prob(k)\tau_k^2 = \Sigma_k \left(\frac{P_k}{\Sigma_k P_k}\right)\tau_k^2$

RMS delay spread: $\sigma_\tau = \sqrt{\overline{\tau^2} - \bar{\tau}^2}$

Coherence bandwidth: **parameter to describe frequency varying nature of channel**, frequencies separated by less than this bandwidth will have fades highly correlated (**flat frequency spectrum** within B_c - think drawing with thin rectangle in pulse). Signals will be affected differently (frequency selective fading) when frequency separation goes beyond B_c.

Frequency correlation: to obtain certain correlation (similarities) how far should signals be separated in frequency?

Correlation higher than 0.9 $B_C = \frac{1}{50\sigma_\tau}$ and 0.5 $B_c = \frac{1}{5\sigma_\tau}$

Trend 1: RMS delay spread ++ → coherence bandwidth --

Trend 2: Frequency correlation ++ → coherence bandwidth --

Time variation: movement of **mobile/surrounding objects induces Dopper shift** & the **channel will change in time**

Doppler shift: change of frequency due to movement of Tx or Rx, given by

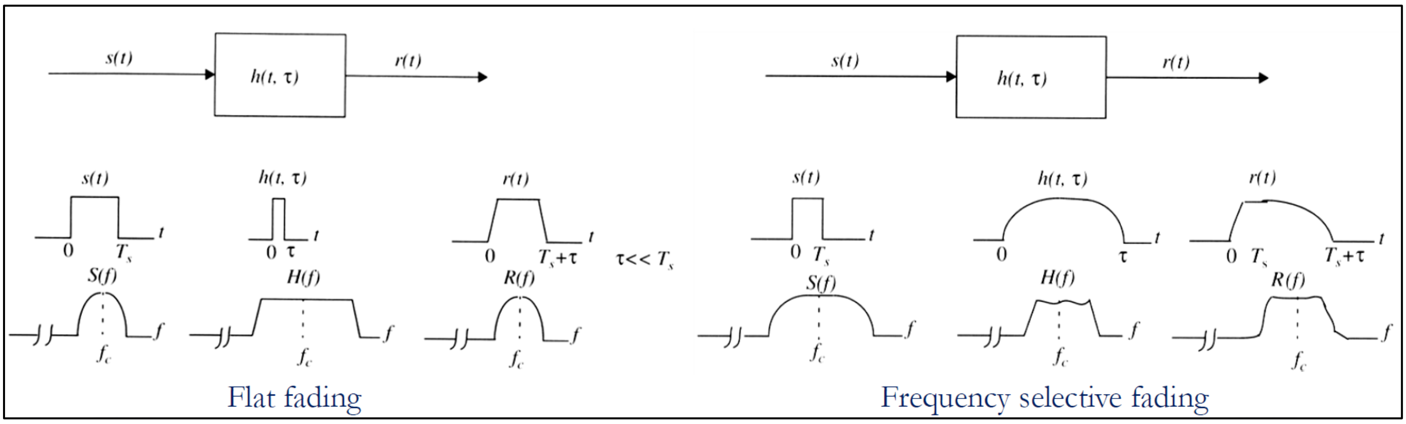
$$f_{d-max} = \frac{v}{\lambda}$$

Parameters to describe time varying nature of channel (2): **Doppler spread** B_D (measure of spectral broadening due to time variation) & **coherence time** T_c (time duration that the fading parameters remain fairly constant)

$$B_D = 2f_{d-max} \qquad T_C \approx \frac{9}{16\pi f_{d-max}}$$

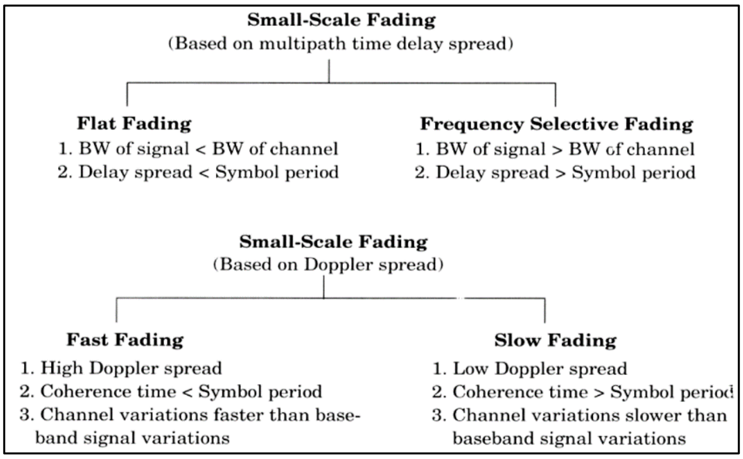
Trend 3: mobile speed ++, doppler spread ++, coherence time --

Types of fading - delay spread (2): **flat fading** ($B_S < B_C$ - **deep fade can degrade the system performance significantly**) || **frequency selective fading** ($B_S > B_C$ - **ISI occurs → equalisation technique needed**)



Types of fading - Doppler spread (2): **fast fading** (time selective fading - $T_S > T_C$, $B_S < B_D$ - channel impulse response changes within symbol duration, occurs for very low data rates, with packetized transmission fast fading is referred to as rapid channel changes within one packet or frame) || **slow fading** ($T_S \ll T_C$, $B_S \gg B_D$ - channel changes at a rate much slower than symbol duration, v. common especially at high data rate apps)

Fast / Slow & frequency flat / selective fading are not mutually exclusive.



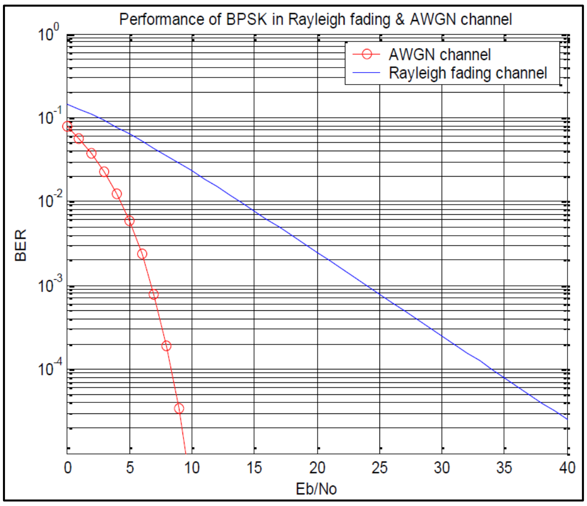
Common channel models (2): channel gain at k^{th} bin with N_k arriving paths (assumptions: infinite arrival paths at the same time, all paths have zero mean and similar variance i.e. no dominant path, all path gains are statistically independent, paths have uniform arrival angle from 0-360) → **Rayleigh fading** & **Ricing fading**.

Central limit theorem: I and Q Gaussian distributed - Rayleigh distribution = envelope of the sum of 2 quadrature Gaussian sources (x, y)

Rayleigh fading: commonly used model for no line-of-sight (NLOS)

$$\tilde{a}_k = a_k^I + ja_k^Q = a_k e^{j\theta_k} \qquad a_k = \sqrt{a_k^{I^2} + a_k^{Q^2}} \qquad \theta_k = \tan^{-1}\left(\frac{a_k^Q}{a_k^I}\right)$$

Rician fading: a channel with dominant path and numerous weak multipath, channel fading statistics is Rician distributed (when dominant component fades away, statistics degenerates to Rayleigh).



Effect of fading: **performance measure is probability of having errors** (BER/FER), **fading significantly affects system performance** (e.g. BPSK in fading and AWGN channel caused by deep fades, BER dominated by deep fade).

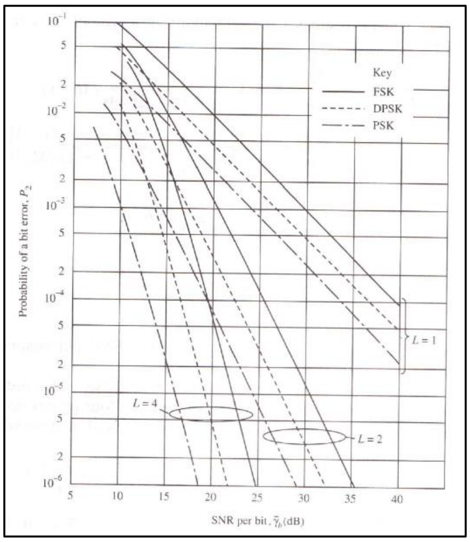
Fading mitigation approaches (2): **power control** (control P_t to achieve fixed received SNR so that **when symbol is in fade P_t increased to make sure SNR is high enough**, try to obtain AWGN performance - needs perfect power control) || **diversity** (send signals in replicas of some sort such that there are **multiple received signals observed for the same source because chance all will be in deep fade is much lower**, try to average out channel variation to reduce SNR variation and improve average performance).

Power control (2): **open loop** (no downlink info only uplink used to control downlink P_t &VV, cannot 100% control received power in FDD since uplink & downlink frequencies are different so channels are different, poor at combating fading, good in combating path loss / shadowing as although f is different PL and shadowing is similar to both UL&DL) || **closed loop** (downlink used for feedback as mobile measures received strength for reporting, more accurate than open loop, overhead in feedback channel for signal strength reporting)

Power control pro/con: pro: **easy to implement** (no need for extra hardware) & if it works well **performance = fixed gain AWGN chan**, con: **cannot track fast fading channels** (closed loop) & **when mobile is in cell boundary increasing P_t will increase interference** to other users in other cells using same channel.

Diversity techniques: transmit same signal in different media which **must experience different channel gain** else no diversity is available (time, frequency, special & polarisation diversity).

Diversity combining schemes (3): when multiple observation are obtained a **scheme needed to combine signals** - **selection combining** (select signal from best channel) || **equal gain combining** (co-phase signal and sum) || **maximal ration combing** (MRC - optimal scheme maximising received SNR). All schemes make use of all observations and achieve diversity.



Performance of MRC - more diversity order (L) will provide steeper slope in BER/FER curve.

When diversity is achieved, performance is improved.

Wireless channels always have the problem of fading, requires the design of a system that **can exploit diversity**!

4. Multiple Access Techniques

Multiple access techniques (4): strategies that allow multiple users to access the channel at use. Can split the channel by **frequency** (FDMA, OFDMA), **time** (TDMA), codes (CDMA) | | **space** (SDMA).

- FDMA: each user has a **certain bandwidth so they can be packed into spectrum** (in practice leaking of power to other bands - adjacent channel interference). **Very common** (all **analogue systems use as CT cannot be divided**). **Not many applications use full bandwidth**, if a user cannot occupy full bandwidth, **remaining bandwidth must be used by others**.

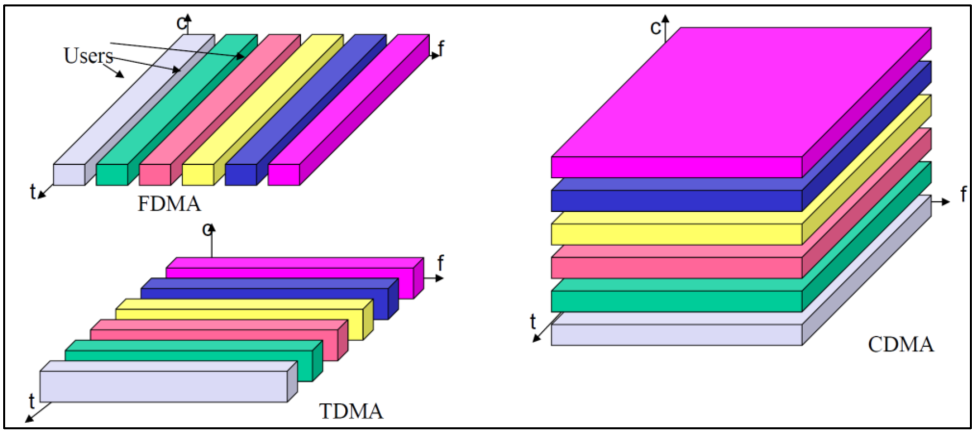
FMDA mitigation methods (3): use **pulse shaping** to reduce side lobes, allow frequency gaps between users (**guard bands**), **allow leakage to a certain level** such that adjacent channel interference is acceptable

- TDMA: timeslot used, all users using **same frequency band**. In **theory each users send 1 data bit** and waits for another timeslot to send another but in **practice burst of data (frame) transmitted** instead to **reduce overheads**.

TDMA mitigation methods: guard period added to avoid leakage

TDMA vs FDMA (5): **both allow digital Tx over analogue** (performance, security, bandwidth η…), **TDMA cheaper** since no **need for duplexer** (duplexer complicated device allowing mobiles to Tx and Rx at the same time without jamming itself - needed in FDMA not TDMA as Rx/Tx in different time slot) & **less RF chains in base station** (RF chain needed for each freq chan, FDMA needs 1 RF chain/user, TDMA only 1/group of users using same freq), **TDMA requires perfect sync** (good sync technique with fast timing acquisition → increased overheads + guard period important for small amount of sync error & widely separated users as in cellular have large propagation delay so longer guard period or timing advancement protocol) & **TDMA higher data rate → shorter symbol period → larger bandwidth** (more likely to experience frequency selective fading leading to ISI, requiring equalisation)

TDMA overlaid on FDMA: **TDMA cannot occupy entire bandwidth** as **too many** users would be sharing thus **lengthy delays** between packers per users & **symbol period too short** thus **too many ISI** → solution is **TDMA overlaid on FDMA**. Entire bandwidth divided into frequency channels over FDMA, each channel shared by fixed TDMA users (GSM)



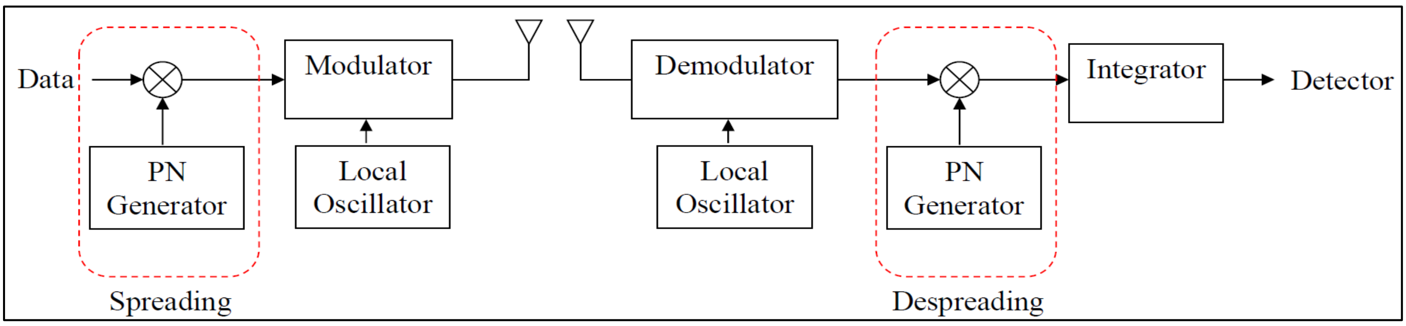
CDMA: same freq & time but using a different code (e.g. BPSK CDMA multiply code rate)

Spreading sequence: original signal spread across a wider bandwidth by these codes with each bit of spreading sequence called a **chip**

Orthogonal code generation: walsh code, Hadamard matrix… good that the cross-correlation = 0 (i.e. no inter user interference). However, **orthogonal codes limited** (total available code = total code dimension i.e. sequence length & orthogonality lost in ISI chan)

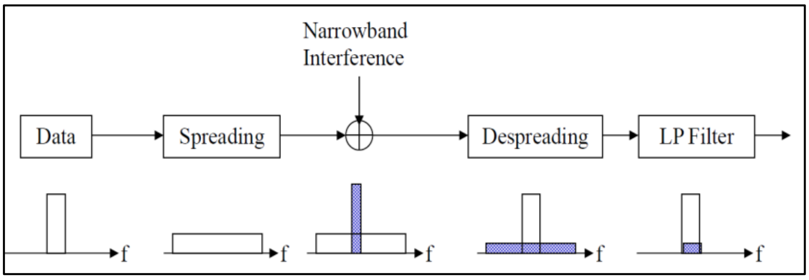
Pseudo-noise sequence: instead of having zero cross-correlation, sequences with low correlation can be used (more sequences for a fixed length). Low ISI desirable so low correlation between shifted versions of sequence. PN seq uses a seed.

Spread spectrum communication (2): spread signal over wider bandwidth. Two types - **direct sequence** (DS-CDMA) & **frequency hopping** (FH-CDMA). **Difficult to intercept or jam**. Advantage of **multipath frequency diversity**.



Processing gain (always > 1) $= PG = \frac{B_c}{B_s} = \frac{R_c}{R_s} = \frac{T_s}{T_c}$ where B/R/T is bandwidth, spreading sequ, period of symbol/chip

Narrowband Interference Rejection: when a signal is multiplied by the sequence, **power spectrum is spread over a larger bandwidth** & when spread signal is de-spread using same sequence, power **spectrum transforms back to original shape. Narrowband interference** (caused by jammer) is being **spread to a wider bandwidth**. After LPF only a **small fraction of interference remains**.



Signal to noise & interference ratio (SNIR): pre-detection SNIR (after matched filtering, before detection) given by

$$SNIR = \frac{P_s}{R_s N_0 + \frac{1}{PG}} = \frac{E_b R_s}{R_s N_0 + \frac{I R_S}{B_c}} = \frac{E_b/N_0}{1 + \frac{I}{N_0 B_C}}$$

where P_S is signal power, I is interference power

Spreading: achieved as different users' signals are **spread using different PN code**

De-spreading: power spectrum of other users still **spread wide in frequency so inter-user interface power depends on cross correlation of sequences**

SNIR analysis: without loss of generality, consider user 1 from k users has

$$SNIR^{(1)} = \frac{P_S^{(1)}}{R_S^{(1)} N_0 + \sum_{k=2}^{K} \frac{P_S^{(k)} R_S^{(1)}}{B_C}} = \frac{E_b^{(1)}}{N_0 + \sum_{k=2}^{K} \frac{E_b^{(k)} R_S^{(k)}}{B_C}} = \frac{\frac{E_b{}^{(1)}}{N_0}}{1 + \sum_{k=2}^{K} \frac{E_b^{(k)} R_S^{(k)}}{N_0\, B_C}} = \frac{SNR^{(1)}}{1 + \sum_{k=2}^{K} \frac{SNR^{(k)}}{PG^{(k)}}}$$

(needs practice)

Performance of CDMA: depends on interference power, larger PG reduces interference to others (for higher rate users R_s++, PG--, → higher interference to others), coding essential as reduces required SNR for a particular BER (→reduced interference → increased SNIR).

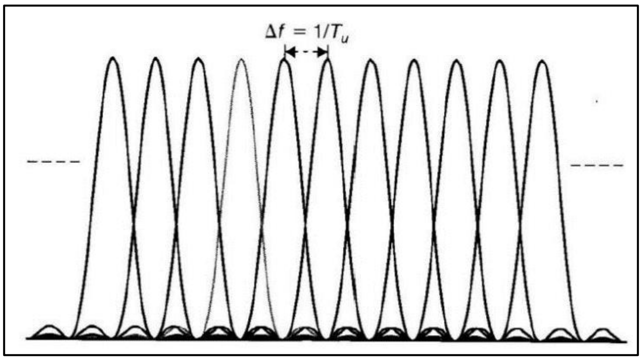
Performance of CDMA in wireless channels: if 2 users where 1 very near to BS while other near cell edge then because of PL received signal at BS from user 2 will be much smaller than user 1 so SNIR decreased for user 2 since I increased → **near far problem of CDMA requires power control**

$$SNIR^{(1)} = \frac{\frac{\left|\alpha^{(1)}\right|^2 E_b^{(1)}}{N_0}}{1 + \sum_{k=2}^{K} \frac{\left|\alpha^{(k)}\right|^2 E_b^{(k)}}{N_0} \frac{R_S^{(k)}}{B_C}}$$

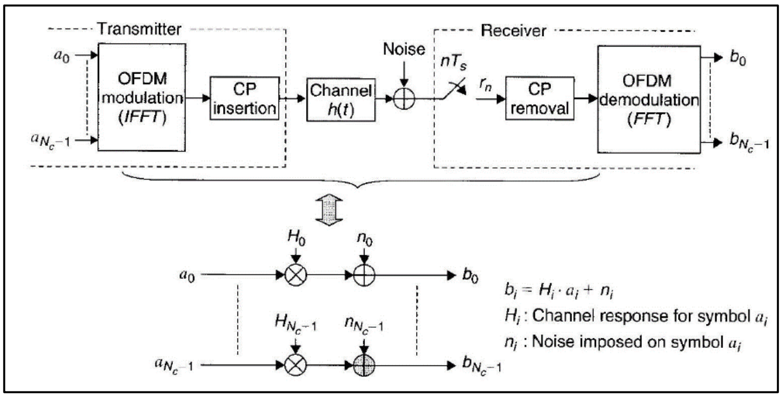
where α^k is channel gain (including PL, shadowing & fading) for k^{th} user

CDMA problems (2): **interference limited** (more users, higher I, poorer performance), **difficult to expand to very wide bandwidth for high data rate** (chip rate will need to be very high, chip period very short → expensive electronics & more ISI as more multipath can be resolved) → solution: use FDM (single user different frequencies unlike FDMA multi-user) as no interference, can expand easily & if bandwidth for each signal narrow, no ISI

OFDM: FDM wastes too much bandwidth as needs guard bands → orthogonal FDM packs carriers are close as possible without any interference (each symbol modulated using separate **orthogonal** carrier experiencing flat fading channel so no need for equalisers → easily expanded to wideband transmission by adding more subcarriers).



Analog implementation of OFDM: **multiply each symbol with orthogonal carrier signal** (at receiver demodulate each individual symbol by multiplying conjugate i.e. **down-conversion** → **convert wideband frequency selective fading channel** into number of **parallel narrowband flat fading channels**.



Digital OFDM implementation: multiply each symbol with different orthogonal carrier is **almost identical to taking Inverse Discrete Fourier Transform** (IDFT). Equivalent to modulating to carrier frequency. But signal model must be in cycling convolution form to use IDFT (requires insertion of a cycling prefix before the transmitted symbol). Use IFFT for more efficient implementation.

OFDM models (2): signal model (OOS) & system model (equivalent to symbol transmission at different carriers)

OFDM Advantages (3): **efficient implementation with IFFT**, **easy expansion to wideband** for high data rate, **no ISI**

OFDM Disadvantages (3): **high Pk-average power ratio** PAPR (because adding multiple carrier signals will have larger variation & high PAPR requires linear power amplifier which is inefficient), **sensitive to frequency noise** (slight change in frequency will result in larger inter-carrier interference) & **long CP required for high excess delay channel** (reduces spectral efficiency)

OFDMA: **OFDM derived** where **multiple users use different subcarriers** rather than one user transmitting with all

OFDMA Downlink: **each user assigned subcarriers**, signals inserted into **respective input for IFFT size M**, user uses FFT of size M to **demodulate**, signal from **assigned subcarrier extracted & detected**

OFDMA Uplink: each user **inserts signals into assigned subcarrier slots**, **add zeros to all other slots**, **take IFFT**, if all **synchronised** each will **transmit assigned subcarrier with no interference**.

OFDMA advantages (2): **easily expandable to wideband transmission for very high data rate**, **resource allocation easily applied** (very high data rate to fully exploit wireless channel) - widely accepted as best MA scheme (wifi, Bluetooth…)

Multiple access techniques:

MA techniques	Dividing by	Price	EQ	Pros	Cons
FD**MA**	frequency	medium		digital over analogue	need duplexer many RF chains
OFD**MA**	frequency			best: easily expandable to wideband very high data rate & easy FFT	-
TD**MA**	time	cheap	Y	digital over analogue	sync overhead large BW (ISI)
CD**MA**	code				I-limited coding essential
DS-CD**MA**	code			hard intercept hard to jam	less secure than FH-CDMA
FH-CD**MA**	code			hard intercept hard to jam	
SD**MA**	space	-	-	-	-

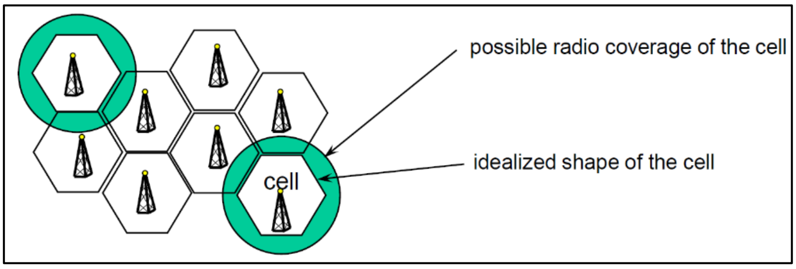
5. Cellular Network Design

Licensing: spectrum is split into license categories (3G licenses, 4G license, unlicensed for academia…)

Mobile service provider (MSP) challenges: limited/expensive frequency spectrum, numerous mobile subscribers, high mobility, poor channel conditions (especially in urban areas)

MSP goals: good quality of Tx, seamless connection (no call drops), call always possible (no blocked calls), high system Cpcty

Cellular concepts: **segment area into cells with base stations (BS)** to allow multiple BS **reliability**, more **capacity**, **cheaper license fees** & lower **power levels** w.r.t. singular base station. All users in cell communicate with that BS only (ideal shape is **hexagonal for tessellation**, but overlap occurs)

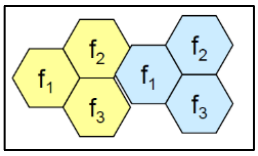


Cell size: **varies** from 100m-35km depending on user density, geography, transceiver power… (microcell, microcell, picocell, femtocell & emergency BS)

Advantages of cellular: increase system capacity (users × cell), reduce transmission power (increase mobile unit battery life)

Problems & solutions of cellular (3,4): **inter-cell interference** causes signal interference from different cells using same frequency channel (S: **frequency reuse** except for CDMA systems) & **call congestion** causes calls blocked if too many users in one cell (S: **channel assignment scheme**) & **users moving outside cell** causing calls to drop when signal goes below minimum requirement (S: **handoff strategy**). Optimisation S: **Sectoring**.

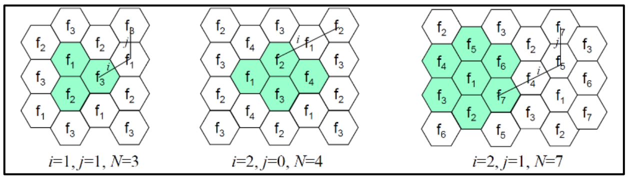
- Frequency reuse: each cell is assigned a fixed number of frequency channels (k) from total frequency channels used in system (F). Different channel groups are assigned in neighbouring cells to form a cluster of size (N) used (M) times.



Co-channel cells: are cells using **same set of frequency channels**.

Co-channel interference: is interference **caused by signals from co-channel cells.**

Total mobile user: $M \times F \times users/chan$



N exists for $\boldsymbol{N = i^2 + ij + j^2}$ (1, 3, 4, 7, 9, 12, 13)

Co-channel reuse ratio: ratio of centre-to-centre distance between co-channel cells w.r.t. within a cell - $\boldsymbol{Q = \frac{D}{R} = \sqrt{3N}}$

Signal to Interference Ratio (SIR): considers downlink and mobile at edge of cell - $\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i} = \frac{PR^{-n}}{\sum_{i=1}^{i_0} P_i D_i^{-n}}$ (assumes all antenna gains are equal with path loss exponents from all BS to mobile being the same). If $P = P_i$ and $D \approx D_i$ (i.e. D≫R such that all D_i can be approximated equal and all base stations transmit the same power)

$$\frac{S}{I} = \frac{\left(\frac{D}{R}\right)^n}{i_0} = \frac{\left(\sqrt{3N}\right)^n}{i_0} = \frac{Q^n}{i_0} \text{ (independent of Tx power)}$$

- Channel assignment (2): schemes of assigning channels to different groups for the reuse pattern to **minimise co-channel interference** (interference from users/BS in co-channel cells transmitting at same frequency), **minimise adjacent channel interference** (interference from users transmitting at adjacent channel caused by power leaking in modulation scheme) & **avoid cell congestion** (calls may be **blocked** if all channels are occupied even though channels in other cells are available).

Cell *example*	Frequency channel number *example*
1	1, 4, 7, 10, 13, 16, 19, 22, 25
2	2, 5, 8, 11, ,14, 17, 20, 23
3	3, 6, 9, 12, 15, 18, 21, 24

Schemes are **fixed assignment** (according to reuse pattern adjacent frequency channels not assigned same cell to prevent adjacent channel interference) or **dynamic assignment** (channel allocated to cells on demand, MSC assigns channels based on co-channel & adjacent channel interference).

- Handoff: switching of a mobile call from BS to BS. Threshold handoff $P_{handoff}$ after which handoff should occur. This should include a handoff margin $\Delta = P_{handoff} - P_{\min usable}$. If Δ too small → drop call as handoff not done in time, if Δ too large → **ping-pong** effect (switching to&fro between 2 BS when mobile is in cell boundary, avoid by handoff only when signal strength in new cell is much higher). If no free channel, call dropped → guard channel reserves channels for handoff.

Types of handoff (2): **hard handoff** (switch of BS & frequency by connecting to 1 BS at a time) || **soft handoff** (CDMA uses the same frequency in all cells & at cell boundary device connects to two BS, uses both for downlink detection & both for uplink MSC selection - better quality in cell boundary than hard handoff, no ping-pong effect)

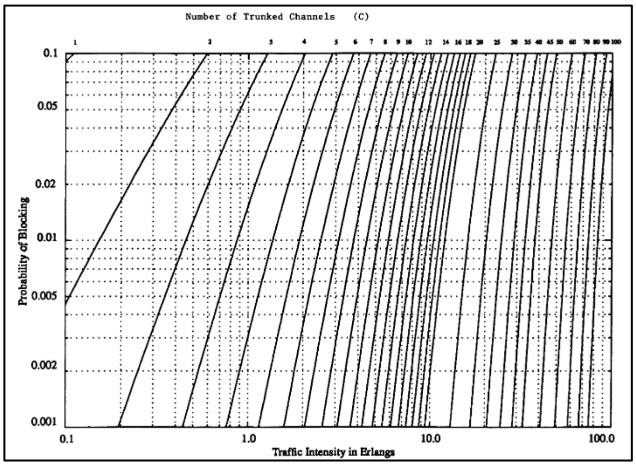
Traffic calculations: still too many subs even with frequency reuse (only a small number of subs making calls at once so not all channels are occupied and can use lesser number of channels for same service)

Trunking (voice calls only): allows **a large number of subs to share a fixed number of channels**. Uses **statistical behaviour** of calls to **determine channels required** for each cell. **Traffic intensity measured in Erlangs** (1 Erlang = 1 channel occupied completely for 1h over 1h). Users generate a certain amount of traffic per user (A_u):

$$\boldsymbol{A_u = \lambda H} \text{ where H is average call duration, } \lambda \text{ is average call requests per unit time per user}$$

Total traffic intensity (A_{tot}):

$$\boldsymbol{A_{tot} = UA_u} \text{ where U is the total number of users/subs}$$



With a certain number of chans, system can sustain a level of traffic at a certain **Grade of Service** (GOS - measure of subs accessibility to a trunked system): $GOS = P(blocking)$. A_{max} maximum traffic intensity offered by system at a GOS.

$$P(blocking) = GOS = \frac{A_{max}^C/C!}{\sum_{k=0}^{C}\frac{A_{max}^k}{k!}} \text{ (Erlang B)}$$

Max subscribers to system: A_{max}/A_u

Trunking efficiency: **measures max traffic intensity** A_{ma} provided by system with **fixed number of channels** at a **fixed GOS**, can be considered A_{ma}/C. **Trunking efficiency improves as number of channels increases**. Increasing number of channels **tremendously increases max traffic intensity**.

- Sectoring: uses directional antenna to divide cells into sectors (usually split into 3 @120° or 6 @60°). Co-channel cells drop from 6 to 2 for 120° sectors or 1 for 60°.

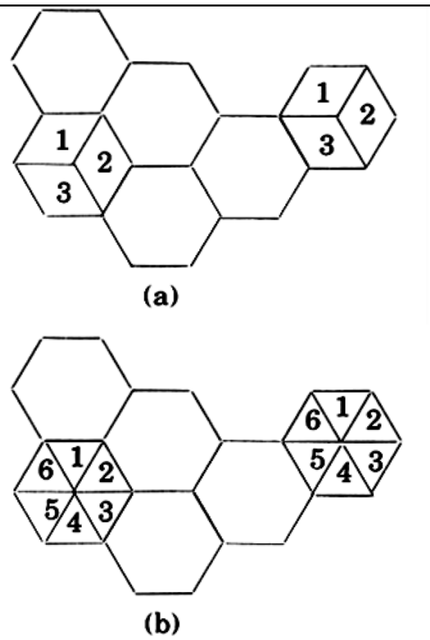


Figure 3.10 (a) 120° sectoring; (b) 60° sectoring.

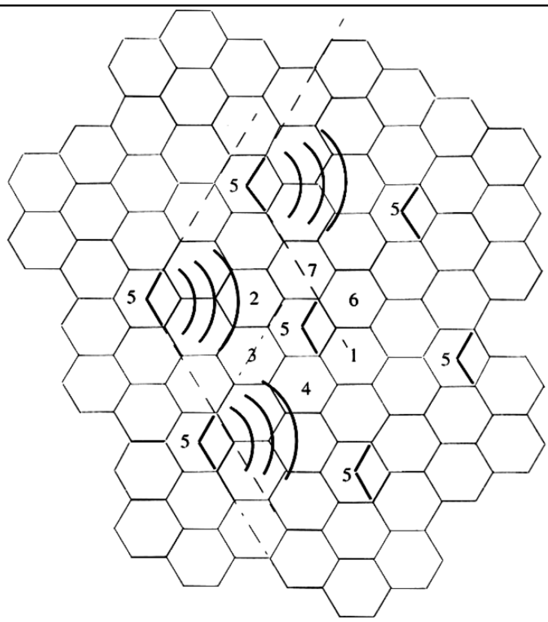


Figure 3.11 Illustration of how 120° sectoring reduces interference from co-channel cells. Out of the 6 co-channel cells in the first tier, only two of them interfere with the center cell. If omnidirectional antennas were used at each base station, all six co-channel cells would interfere with the center cell.

Advantages: **increases system capacity** (SIR increases → reduce cluster size (N--) → reuse pattern user more (M++) → increase system capacity (C++)

Disadvantages: **loss of trunking η** (chans divided into sectors, less trunked chans → less max traffic), **more handoffs** (BS can handle handoff between sectors without MSC, better with DCA because no handoff required between sectors) & **hard to control radio propagation in urban area** (cannot have clear cut on sector coverage, more co-chan cells than expected)