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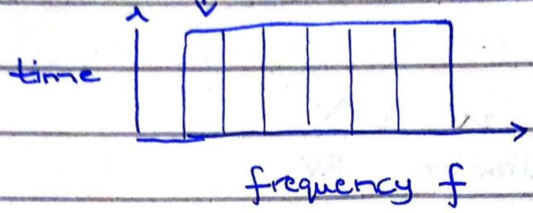
- <u>Mobile Communication Systems</u>

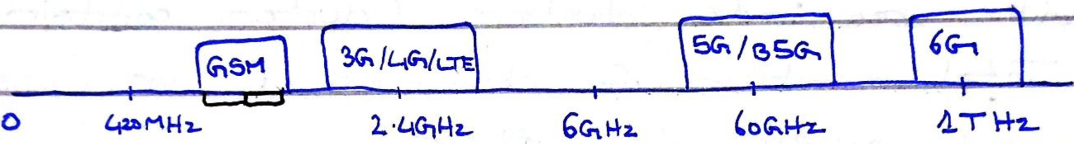
FDMA

↙ e.g. 30kHz bands for users



1G

BW = 30kHz



continued

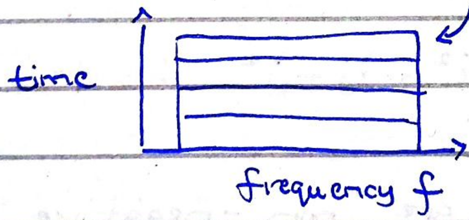
7GHz ~
Bandwidth

$$R = B \log_2 (1 + SNR) \text{ bps}$$

TDMA

e.g at each time slot, one user gets the entire band

2G



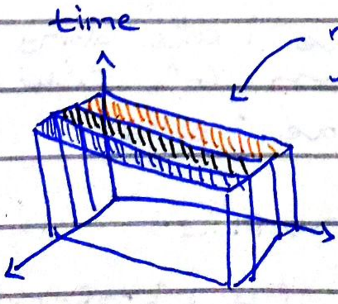
BW = 200 kHz

CDMA

resources (resource blocks)
~ data transmitted with specific code
(there is mixing)

3G

BW = 2MHz



Cellular Systems

i.i.d ~ independent and identically distributed

$$x \in X$$

realization RV

Divide area into clusters (clusters contain cells)
~ Total number of channels C are assigned and reused per cluster.
~ Added co-channel interference.

L Small cells serve more users but more BS, higher cost & more interference

Always a tradeoff

Cluster size $N = i^2 + ij + j^2$ Related to hexagonal geometry

L $i \in I, j \in J$
where I and J are non-negative integers

Location Rule ⇝ move i cells along hexagons
turn 60° CCW
move j cells

$$P_r = P_0 \left(\frac{d_{des}}{d_0} \right)^{-n}$$ ⇝ PLE

$\{P_0, d_0\}$ reference values

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- <u>Mobile Communication Systems</u>

Reuse Ratio

$q = \frac{D}{R} = \sqrt{3N}$

D → distance

R → radius

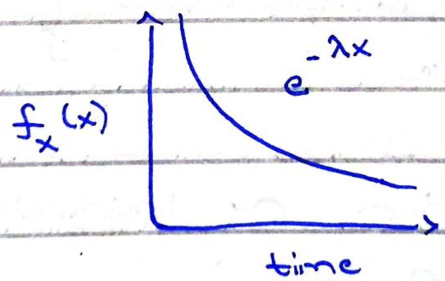
Adjacent Cell Interference

Ideal BP filters dont exist

↳ Adjacent Channels interfere

Trunking Theory

Inter-arrival times are independent exponential random variables (as calls tend to be small) ~ Focus on RVs



Server Model

Likewise, durations of service (holding times) are also independent exponential RVs with $E[x] = H$

Mobile Communication Systems

Traffic Intensity

Erlang $\triangleq$ channel occupied on average

eg one erlang can be attributed to one continuous call

Channels

Each call ~ requires a channel

↳ call ~ requires a channel Ignore

- In trunking, channels are "pooled"
- When the pool is exhausted, new call requests are simply denied

↳ "Blocks Call Cleared" ~ Erlang B

∴ Probability of Blocking

$$p = B(A, C)$$

, where $A = A_u U$, $A_u = \lambda H$

$$p = B(A, C) = \frac{A^C / C!}{\sum_{k=0}^{C} A^k / k!}$$

Erlang B Formula

A is the total offered traffic

Problem

$C = 5, 10, 50, 100$

$A_u = 0.05$ Erlangs

$A = A_u U \rightarrow U = \dfrac{A}{A_u} = ?$

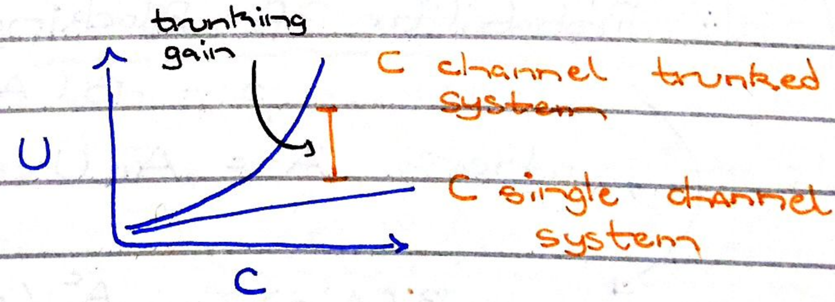
$P_B \doteq 0.01$

$C = 5 \gg U = \dfrac{1.5}{0.05} = 30$ → = A (found from Erlang B chart)

↳ Do the same for $C = 10, 50, 100$

For reference ; $C = 100 \gg U = 1900$

100 channels can serve 1900 users with $P_B = 0.01$



Blocked Calls Delayed ~ Erlang C

→ Blocked calls (users) go into queue rather than getting dropped

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Mobile Communication Systems

is bandwidth of channel

Capacity → $B \log_2(1 + SNR)$

→ # of users in the system

definition depends upon context

- We increased B by frequency reuse ; etc

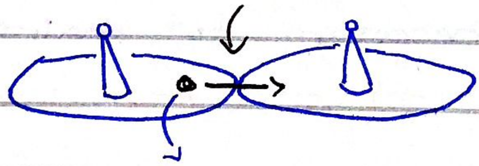
→ How do we improve SNR / SIR / SINR ?

Channels { Control → always on (beacon signals & at low data rates)
Data

RSSI : Recieved signal strength indicator

Hand - offs

moving from one cell to another



the subscriber compares recieved powers and connects to BS with higher power (frequency hand-off)

- To avoid excessive switching ;

Let $|P_a - P_b| \geq H_{(dB)}$, {a , b} are BSs

→ threshold

be the condition

after which we switch

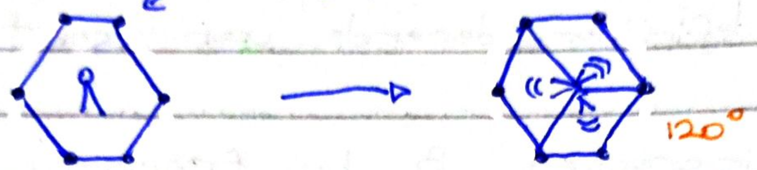
- Hand - offs have higher priority

but call will be dropped if existing channels in the new cell are exhausted

Sectoring (Increase SINR by decreasing interference)

Omnidirectional antennas are replaced with 3 or 6 directional antennas

i meant to make a hexagon ;-;



trade off
- Now, significant interference comes from 2 souces instead of 6 (T1 interferers)
- However, channels are divided into pools and thus, a loss in trunking gain is observed

- BS commands user to utilize lowest power necessary to maintain GoS (To reduce inter user interference)

~ forward $\triangleq$ downlink channel

~ reverse $\triangleq$ uplink channel

Outage

$P\{\hat{SIR} < \tau\}$ SIR drops below operating level

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Mobile Communication Systems

Path Loss

Powers $\triangleq P_n \; ; \; n \in \{t, r\}$
Feeder Losses $\triangleq L_n$
Antenna Gain $\triangleq G_n$

PL Integrated

$$P_r = \frac{P_t G_t G_r}{L_t L L_r}$$

Friis Eqn
(all in Watts)

dBm and dBW

$$1 \text{ dBm} = 10 \log_{10} \left(\frac{1 W}{1 mW} \right)$$

EIRP

$\to$ radiated

$$P_{ti} = \frac{P_t G_t}{L_t} \gg P_{ri} = \frac{\overset{\to \text{EIRP}}{P_{ti}}}{L_{PL}} \; \to \text{path loss}$$

$$L_{PL} = \frac{P_{ti}}{P_{ri}} \qquad = \frac{P_r G_r}{L_r}$$

FSPL

$$L_{PL} = \left(\frac{4\pi d}{\lambda} \right)^2$$

; d is far field distance

$d \gg \frac{2D^2}{\lambda}$; $d \gg D$ and $d \gg \lambda$

D is largest dimension of antenna

PLE of FSPL is always 2.

~ Power Flux Density

$$P_d = \frac{EIRP}{4\pi d^2} = \frac{|E|^2}{\eta}.$$

E ≜ envelope of electric field in V/m

~ Effective Aperture

$$G = \frac{4\pi A_e}{\lambda^2} \quad ; \quad A_e = \underbrace{A}_{\text{area}}\ \overbrace{\eta}^{\text{efficiency}}$$

$$P_{ri} = P_d A_e$$

- Antennas should be spaced by at least $\lambda/2$ for uncorrelated channels. Reason why cellphones have a single antenna.

~ ~~Field~~ Near Transmitter

Assuming transmitter is high enough;

$$\frac{P_t G_t}{L_t 4\pi d_0^2} = \frac{E_0^2}{120\pi} \quad ; \quad E_0 \text{ is the envelope}$$

$$E(d,t) = \frac{E_0 d_0}{d} \cos\left(w_c(t - d/c)\right)$$

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Mobile Communication System

Flat Earth PL

$$P_r = \frac{P_t G_t G_r h_t^2 h_r^2}{L_t d^4}$$

$$L = \frac{d^4}{h_t^2 h_r^2}$$ now depends on heights

→ 10 dB SNR (conservative System)

$$y = hx + n$$

stochastic process

goal is to use signal processing to extract x from y

→ $n\lambda/2$ must hold for antennas in order for channels to be uncorrelated ; $n \in \mathbb{R}$

Analytical: { Free Space ~ Flat Earth }

Empirical : { All the rest ; }

→ Flat earth model was derived using horizontal polarization

Log Normal Shadowing [Large Scale Fading]
slow fading

Fade Margin should be present in the system

Shadowing effect

- Sample outage by moving on the locus of radius of base station;

Likelihood of Coverage

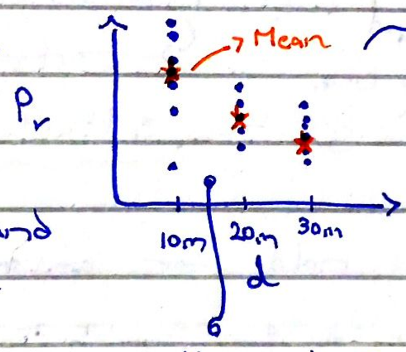
$$P(P_r(d) > \gamma) = P(X_o > \beta)$$

If X is an RV $\sim N(\mu, \sigma^2)$

$$aX \sim N(\mu, a^2 \sigma^2)$$

$$a + X \sim N(\mu + a, \sigma^2)$$

To find PLE, we fit a linear line through the means and compute the slope



Shadowing itself is 0 mean, σ^2 variance, but pathloss gets added and it follows $a + X$ property

Means decrease due to pathloss

$$L(d) = \bar{L}(d_0) + 10\, n \log_{10}\left(\frac{d}{d_0}\right) + \boxed{X_o}$$

Zero mean, σ^2 Gaussian RV

→ Q - Function:

$$Q(z) = \frac{1}{\sqrt{2\pi}} \int_{z}^{+\infty} \exp\left(-\frac{x^2}{2}\right) dx$$

$$P(x > b) = Q\left(\frac{b - \alpha}{\sigma}\right)$$; α, σ are params of RV X

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Mobile Communication System

Inverse Q Problems

$\alpha = -30\,dBm,\ \sigma = 9\ dB$

$P_r = 0.95$

$$P(P_r > b) = Q\left(\frac{b-(-30)}{9}\right) = 0.95$$

From table and ; $Q(z) = 1 - Q(-z)$

$$-\frac{b+30}{9} = 1.65$$

$\Rightarrow$ $b = -44.85\ dBm$

Likelihood of Coverage or Fraction of Time

$P(P_r(R) > \gamma)$ $\leadsto$ $R \triangleq$ radius of cell

$\gamma \triangleq$ threshold

Useful Service Area

$\rightarrow$ polar integral & error functions

$\therefore$ should use the chart instead ; slides

Mobile Communication System

Example

d (m)	P_r (dBm)
100	0
200	−20
1000	−35
3000	−70

a) Find n

$d_0 = 100 \qquad P_r(d_0) = 0$ dBm

Let $\hat{p}_i$ be P_r at d_i

$$\rightarrow \hat{p}_1 = P_i(d_0) - 10n \log(d_1/d_0) = 0$$

$$\hat{p}_2 = P(d_0) - 10n \log(d_2/d_0) = -3n$$

$$\hat{p}_3 = P(d_0) - 10n \log(d_3/d_0) = -10n$$

$$\hat{p}_4 = P(d_0) - 10n \log(d_4/d_0) = -14.77n$$

$$J(n) = \sum_{i=1}^{4} (p_i - \hat{p}_i)^2$$

$$= (0-0)^2 + (-30-(-3n))^2 + (-35-(-10n))^2 + (-70-(-14.77n))^2$$

$$= 327.15n^2 - 2387.6n + 6525$$

$$\frac{\partial J(n)}{\partial n} = 0 \quad \Rightarrow \quad \boxed{n = 4.4}$$

b) Find σ^2 / σ

$$\sigma^2 = \frac{\Sigma(4.4)}{4} = 38 \Rightarrow \boxed{\sigma = 6.17 \text{ dB}}$$

c) Find P_r at 2km

$$P_r(2\text{km}) = P(d_0) - 10n\log\left(\frac{2\text{km}}{d_0}\right)$$

$$= \boxed{-57.24 \text{ dBm}}$$

d) Predict likelihood of coverage @ 2km > -60 dBm

$$Q\left(\frac{-60-(-57.24)}{6.17}\right) = \underline{P(P_r(2\text{km}) > -60\text{dBm})}$$

$$\Rightarrow \boxed{67.4\%}$$

e) % age Useful area

From graph
$\hookrightarrow$ Find the useful area;

$$\boxed{U = 67.4\%}$$

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Mobile Communications

Excess Delay

reference

↳ Propagation Delay relative to the shortest path ; Suppose three signals are transmitted and reciever gets it with $t_i = i$;

$$y(n) = \alpha_0 x(n) + \alpha_1 x(n-1) + \alpha_2 (n-2)$$

↳ LCCD — Linear but not Time Invariant (LTV)

Linearity ~ Superposition Property

$$Y(z) = \alpha_0 X(z) + \alpha_1 X(z) z^{-1} + \alpha_2 X(z) z^{-2}$$

- α_i are random in nature as well
  ↳ taps

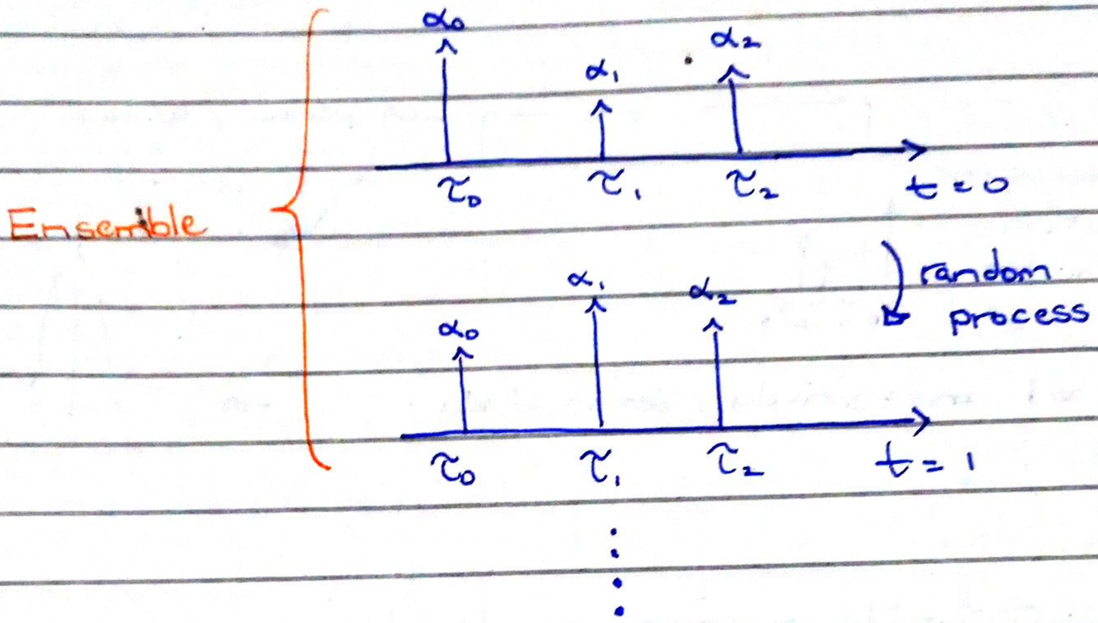
Channel is a Filter

$$x(t) \rightarrow h(t, \tau) \rightarrow y(t)$$

convolution

$$y(t) = \int_{-\infty}^{\infty} x(t-\tau) h(t, \tau) \, d\tau$$

↳ Impulse is important as an input as it contains all frequency components



Baseband Impulse Response

↳ original → passband : transmitted (modulated)

$$h(t,\tau) = \mathrm{Re}\{h_b(t,\tau)\, e^{j\omega_c t}\}$$

$$x(t) = \mathrm{Re}\{c(t)\, e^{j\omega_c t}\}$$

$$y(t) = \mathrm{Re}\{r(t)\, e^{j\omega_c t}\}$$

convolution of $h_b(t,\tau)$ and $c(t)$

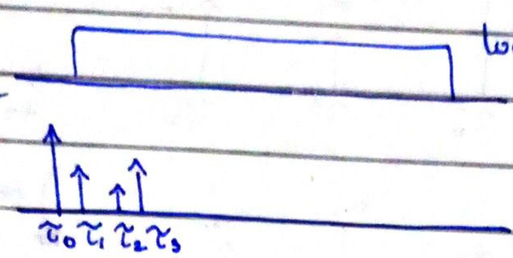
$$r(t) = \frac{1}{2}\int_{-\infty}^{\infty} c(t-\tau)\, h_b(t,\tau)\, d\tau$$

↳ ensures passband average power equals baseband average power

- Each path has amplitude $\alpha(t)$ and phase $\theta(t)$; propagation delay τ

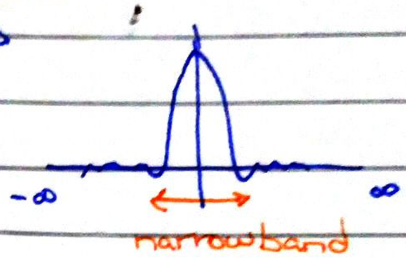
Narrowband Fading

overlap after convolution with random phases $[0, 2\pi)$



long period / width

Fourier



→ may add constructively / destructively

Ergodicity

└ ensemble average equals time average

mean of means

$\theta \in [0, 2\pi)$

↳ uniform distribution

↳ incorrect but good enough (isotropic scattering model)

ISI

└ inter symbol interference

└ delayed copies of same signal x_n could come when x_{n+1} is being resolved

in wideband

└ equalizers mitigate ISI

└ OFDM ~ solution

Solutions : Narrowband : MIMO

diversity gain

Wideband : OFDM

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Mobile Communication System

- Wideband and narrowband average powers are equal
- Channels are often described by their RMS delay spread

Moments of the PDP

$\mu = E[x]$ Mean

$\mapsto$ $E[x^2]$ Variance if $\mu = 0$

$\mapsto$ $E[x^3]$ Skewness

$\mapsto$ $E[x^4]$ Kurtosis

$$\sqrt{\sigma_\tau^2} = \sqrt{\overline{\tau}_2 - \overline{\tau}_1^{\,2}}$$

RMS Delay Spread

2nd moment

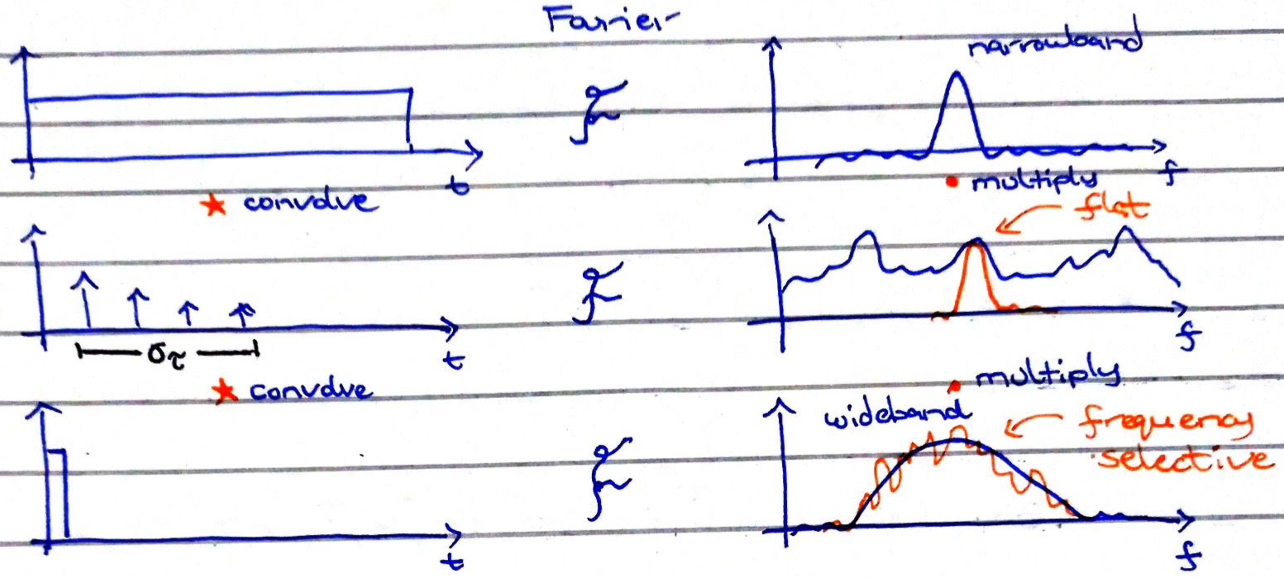
mean

$\sigma_\tau \ll$ Symbol Period $\rightarrow$ Narrowband

$\sigma_\tau \gg$ Symbol Period $\rightarrow$ Wideband

Recap			
CTFT	:	In (Cont.)	Out (Cont.)
DTFT	:	In (Discrete)	Out (Cont.)
DFT	:	In (Gen.)	Out (Cont. * ↑) or Discrete

↳



Coherence Bandwidth ⇝ of the Channel

(Bandwidth of Channel alone does not mean much)

Correlation

We want to find two points on our channel random process with max(correlation) ; given c(t) {message width} ≫ σ_τ , to minimize fading effects {experiences flat fading}

Normalized Covariance $\rho_{xy} = \dfrac{\mathbb{E}\left[(X-m_x)(Y-m_y)^*\right]}{\sigma_x \, \sigma_y}$ ↳ STD's

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Mobile Communication Systems

Wide Sense Stationary Uncorrelated Scattering (WSSUS)

- Assume path gains at different delays are uncorrelated
- Assume f response depends only on Δf
- Correlation, now, is of the entire process

Coherence Bandwidth

$\rho_{\Delta f} = X / 100$ » It quantifies the corelationship b/w two points
- If 30 kHz is 90 % ; CB ; then, all points separated by 30 kHz are 90 % correlated

- If $BW_{transmit} > 50\% \cdot B^{\text{coherence}}$, channel is frequency selective

- Equalizer → mitigates frequency distortions
  - → zero forces in time domain
  - Adaptive Tapped Delay Filter
    - → reverses effect of channel taps dynamically
    - → requires CSI – CSI is determined by using pilot signals

pilot symbols are at the ~~start of each~~ message

Correlation in Time ~ Same / Similar to f

→ Channel response changes as the vehicle moves

- Doppler Shift $f_d = f_0 \frac{v}{c} \cos\theta$

Fast Fading

if $\underbrace{T_s}_{\text{symbol time}} > \underbrace{T_c}_{\text{coherence time}}$

or, in terms of Doppler spread:

$$B_s < B_d = \frac{k}{T_c}$$

Mobile Communication System

Problem

→ Binary BPSK $R_b = 250$ kbps

a) Range of values for σ_τ such that Rx signal is flat?

$T_s = k / R_b$; where k is number of modulated bits

$= 4\ \mu s$

→ Rx signal is flat for $\boxed{\sigma_\tau < 0.4\ \mu s}$

b) Coherence Time

$f_0 = 5.8$ GHz ; $f_m = f_0 \dfrac{v}{c} = \boxed{259.3 \text{ Hz}}$

$T_c = \dfrac{0.423}{f_m} = \boxed{1.63 \text{ ms}}$

As $T_s \ll T_c$, $\boxed{\text{slow fading}}$

c) How many bits can be sent such that the channel appears static?

$$\frac{T_c}{T_s} \approx \boxed{407 \text{ bits}}$$

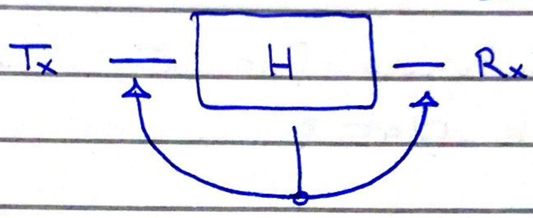
Small Scale Fading Distributions

$y = hx + n$

$\hookrightarrow$ with CSI

$|h|^2 x + h^* n$

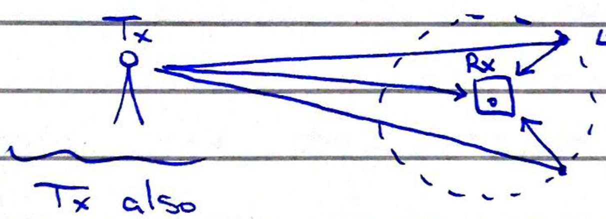
$h^* h x$



{ **Ring Models:**

1 ring model

scatterers.



if Tx also has scatterers

2 ring model

CLT $\rightarrow$ when number of samples $\rightarrow \infty$, the addition yields {underlying distribution approaches gaussian}

$\rightarrow Z = X + jY$ — Complex Gaussian

Mobile Communication Systems

Small Scale Fading Distribution

- $R = |\overline{X + jY}|$ ⇝ Gaussian as per CLT
  where $X \sim N(0, \sigma^2)$
  $Y \sim N(0, \sigma^2)$
  then, R has a Rayleigh distribution

$$\therefore \overbrace{X + Y}^{RV} \longrightarrow f_x \overset{\text{convolved}}{*} f_y$$

- Now, if theres a LoS component
  then,
  $R = \sqrt{(X + Re(A))^2 + (Y + Im(A))^2}$; A is the power of LoS component

if $|Z| \sim \text{Rayleigh}(\sigma^2)$
$|Z|^2 \sim \text{Exponential}(\sigma^2)$
elif $|Z| \sim \text{Rice}(\dots)$
$|Z|^2 \sim \text{Non central chi square}(\dots)$

Level Crossing Rate

Expected rate at which normalized fading crosses the threshold ρ with either +ive or -ive slope.

Rician shifts mean of Rayleigh ;

- Hence, LCR at same threshold is less for Rician

└ LCR can be used to estimate the velocity of the vehicle.

Average Fade Duration

└ duration fade is below the threshold

└ used / impacts interleaving depth

- Example

[1101 1011 0111 0110] ⟶

└ in stream

1	1	0	1
1	0	1	1
0	1	1	1
0	1	1	0

└▷ Read data out as columns

err

1100 $\boxed{1011}$ 0111 1110 ⟶ after interleaving

⟶ deep fade ⟶ removes the bits (err)

burst errors

- Followed by de-interleaving

- bursts can't be corrected ; hence, we spread out the errors. [n, m, k]

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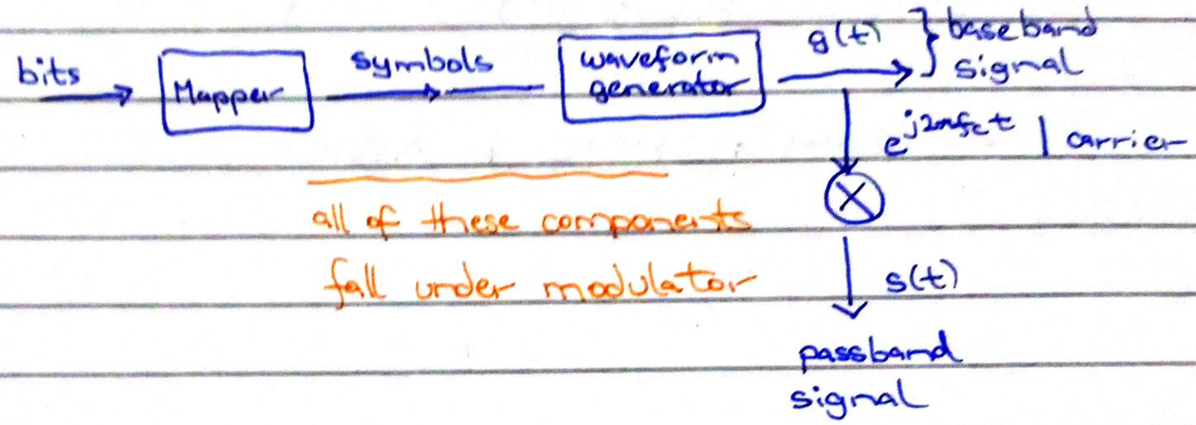
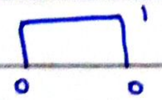
Mobile Communication Systems

Modulation



- Properties of a Good Modulator
  - Compact PSD
  - Low BER (Bit-error rate)
  - Friendly to Non-linear Amplifiers

- Mapper : N-coded bits $\longrightarrow$ $M = 2^N$ possible waveforms

Let $p(t) =$  $\rightarrow$ localized in time

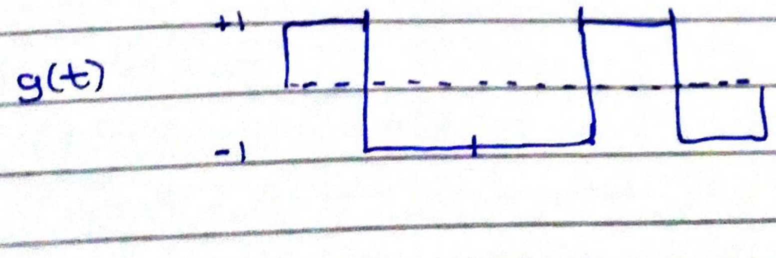
trade-off

does not remain localized in frequency

PSD should be compact

bits : 1 0 0 1 0

bpsk x_s : 1 -1 -1 1 -1



$$g(t) = x_0\, p(t) + x_1\, p(t - T_s) + \dots$$
$$= \sum_{n=0}^{N} x_n\, p(t - nT_s)$$

$$s(t) = \text{Re}\{ g(t)\, e^{j2\pi f_c t} \}$$

- QAM : PSK + ASK

→ Receiver Side

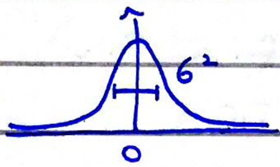
AWGN

$$r(t) = a(t)\, A \sum_n x_n\, p(t - nT_s) \cos(2\pi f_c t + \theta_c) + n(t)$$

Adds

AWGN → Gaussian → never repeats

affects all frequencies



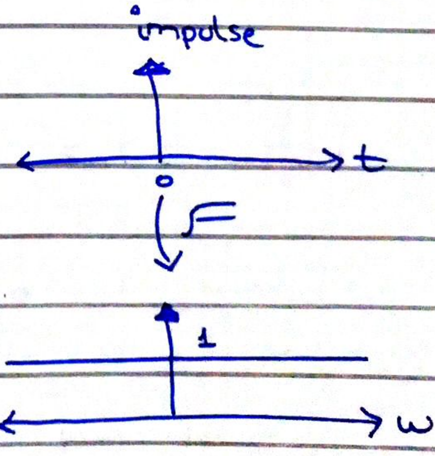
- PSD Analysis $\quad X \rightarrow \phi_{xx} \xrightarrow{F} S_{xx}(\omega)$

Auto correlation

$$\text{conv}(x, y)(t) = \int x(t) \cdot y(-t)$$
$$\text{corr}(x, y)(t) = \int x(t) \cdot y(t)$$

auto corr

$$\text{corr}(n(t), n(t)) = \delta(t)$$



- Next lecture

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Mobile Communication Systems

Demodulator

$$\underbrace{r(t) \Rightarrow \sqrt{\frac{2}{T_s}} \cos(2\pi f_c t)\, dt}_{\text{correlate}}$$

channel gains and Tx power

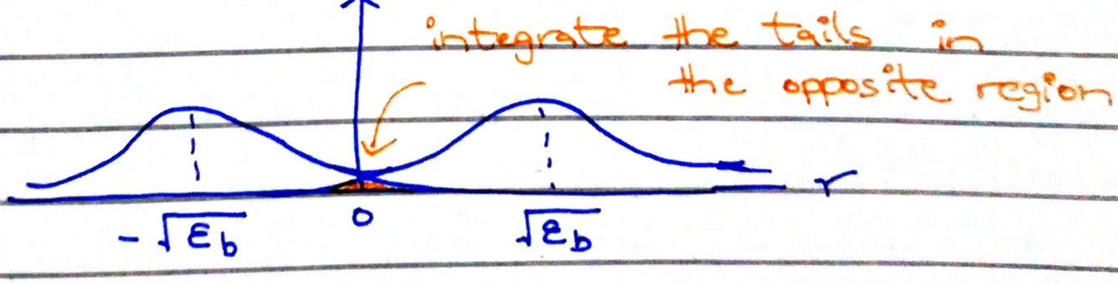
noise

$$R = \int_{(n-1)T_s}^{T_s} (\cdot)\, dt = x_n \sqrt{\mathcal{E}_b} + V_n$$

For BPSK $x_n \in \{1, -1\}$

if $x_n = 1 \gg R = \sqrt{\mathcal{E}_b} + V_n \sim f_{R|x_n=1}$

else if $x_n = -1 \gg R = -\sqrt{\mathcal{E}_b} + V_n \sim f_{R|x_n=-1}$



$$P(\text{error}) = Q\left(\frac{\sqrt{2\mathcal{E}_b}}{\sqrt{N_0}}\right) = Q\left(\sqrt{\frac{\mathcal{E}_b}{N_0/2}}\right)$$

$N_0/2$: noise power (variance)

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Mobile Communication Systems

Nyquist Pulses

Tx | bit stream → Mapper → Waveform Generator $\xrightarrow{g(t)}$ $\otimes$ $\xrightarrow{s(t)}$

Mapper: bpsk, QPSK etc.

Waveform Generator ← $p(t)$ — current focus

$\otimes$ ← $e^{j2\pi f_c t}$

$\alpha(t) A \sum x_n p(t - nT_s) + n(t)$

Rx | $r(t)$ → $\otimes$ → $\int_0^{T_s} (\cdot)\, dt$ → x_n'

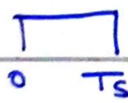
└→ correlation receiver

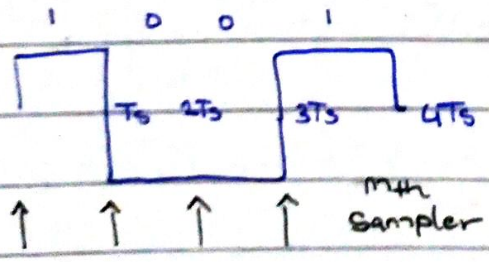
$\otimes$ ← $e^{j2\pi f_c t}$

$\int_0^{T_s} (\cdot)\, dt$: integrator

x_n' └→ recovered symbols

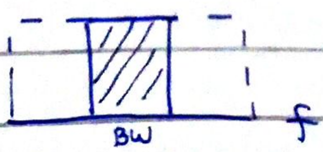
- Digital - "ver" of correlation receiver ~ matched receiver / filter

Let $p(t) =$  → but it is not localized in frequency

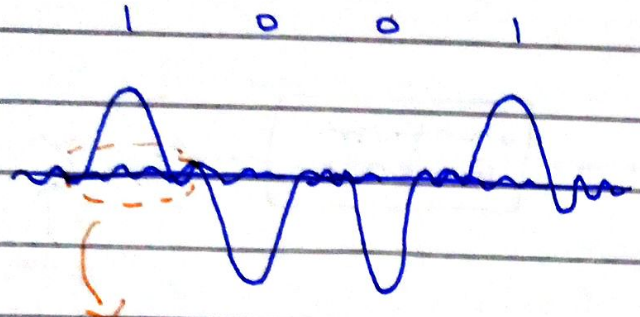


$R_m = \alpha x_m + n$

- Sinc → for localization in frequency



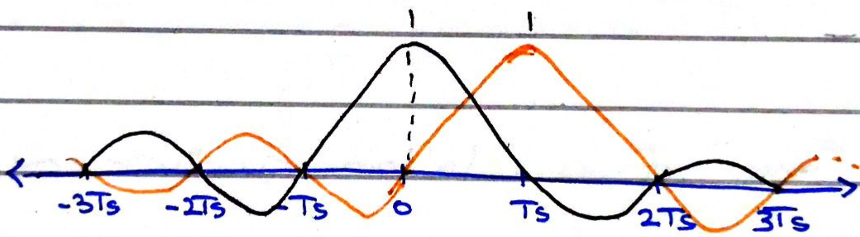
Let $p(t) = \text{sinc}(t)$



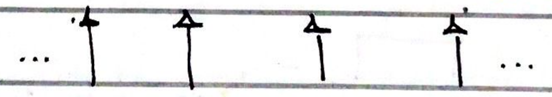
now, ISI is present ; $R_m \neq \alpha x_m + n$

now there are other symbols present

beauty of sinc ; zero crossings occur at regular intervals



at T_s (zero crossing), no ISI occurs ~



<u>Nyquist Condition</u>

ignore

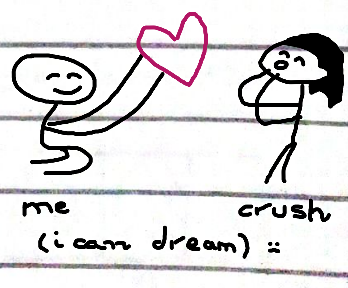
$$\tilde{p}(t) = p(t)\sum_n \delta(t - nT_s) = \delta(t)$$

or

$$\tilde{p}(t) \sum_{n=-\infty}^{+\infty} \delta(t - nT_s) = \delta(t)$$

ISI conditions

- Non-nyquist Pulses
- Non-ideal sampler
- Multipath fading



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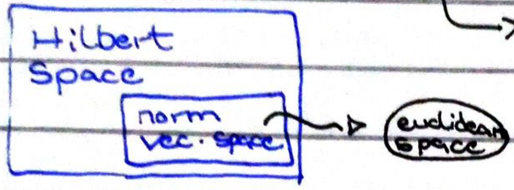
Mobile Communication Systems

Geometry of Signals

↳ geometrically compute the BER



$L_2 \rightsquigarrow |x_2 - x_1|^2 = \|x_2 - x_1\|$

$L_1 \rightsquigarrow |x_2 - x_1|$

$\mathbb{R}$ => basis function $\{1\}$

number line

$\mathbb{R}^2$ => basis $\left\{\begin{bmatrix}1\\0\end{bmatrix}, \begin{bmatrix}0\\1\end{bmatrix}\right\}$

↳ and so on

L_2 sqr. integrable func

$$\int_{-\infty}^{\infty} |f(x)|^2 \, dx < \infty$$

From fourier, sines and cosines linearly combined act as the basis of our L_2 sqr. integrable space.

inner product

$$\langle x, y \rangle = \int_{-\infty}^{\infty} x(t)y(t)\,dt$$

-> receiver just computes the inner product.

-> Draw a threshold line b/w two noiseless points for optimal decision boundary.

$P(\text{bit error}) = Q\left(\dfrac{d_{xy}}{\sqrt{2N_0}}\right) \rightarrow$ distance b/w two noiseless points

QPSK $\underbrace{M = 2^k}$; k is bits per symbol

when possible bits > 2 ; use union bound

$$\underbrace{P(\text{symbol error})}_{\text{upper bound}} = \frac{1}{M} \sum_{i}^{M} \sum_{\substack{j \\ i \neq j}}^{M} \cdot \left[\frac{d_{ij}}{\sqrt{2N_0}}\right]$$

$\triangleq$ cosine – in-phase

$\triangleq$ sine – quadrature

- PAPR : Peak to average Power Ratio

— OFFSET QPSK To counter pulse shaping effects

shift IP or I channel & Q channel to harbor a difference of half a time period

- higher the bits per symbol ; higher the data rate but lower the inter symbol distance { ergo, higher the BER for the same SNR }
- higher power increases the constellation circle's radius ; higher distance b/w symbols

Mobile Communication Systems

Gray Coding

└ Adjacent bits / symbol differ by only one bit

Matched Filter

└ $r(t) = s(t) + n(t)$; $n(t)$ is WGN with spectral height $N_0/2$

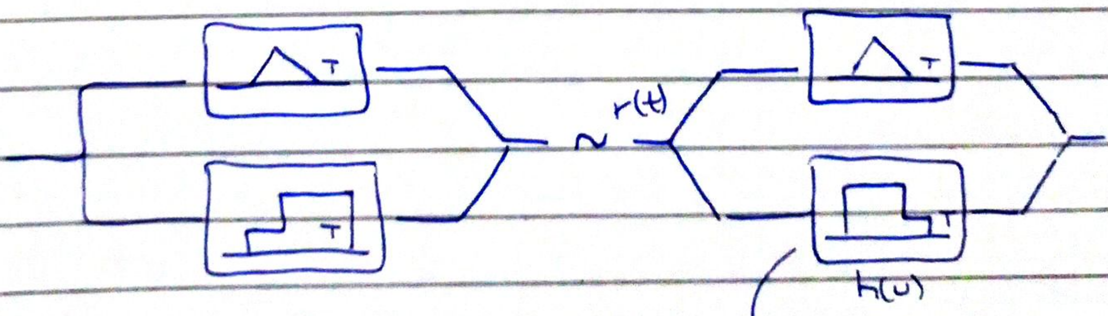
⟶ with $n(u)$ & $n(v)$ as noise {WGN}

$$E(n(u)\,n(v)) = \frac{N_0}{2}\,\delta(u-v)$$

Cauchy - Schwarz Inequality

$$\langle s, a \rangle^2 \le |s|^2 |a|^2$$

Receiver



flipped and shifted

gets converted to correlation after flipping $h(u)$; $h(-u)$

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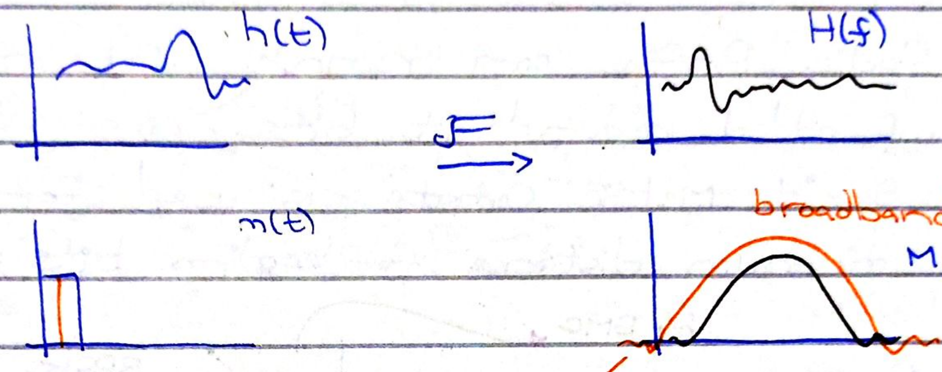
Mobile Communication Systems

OFDM — { multiplxing / modulation } both

Recap



OFDM tackles this by carving band into subbands

→ transmate at rate W/N across each independently

would need more taps, i.e., bigger filter to remove freq. selective effects

Näive Implementation

$$r(t) = \underbrace{\alpha}_{\text{fading}} \Big[\underbrace{a_k^{(0)} e^{j2\pi f_0 t} + a_k^{(1)} e^{j2\pi f_1 t} + \dots + a_k^{(N-1)} e^{j2\pi f_{N-1} t}}_{\text{block modulation}}\Big] \overbrace{p(t)}^{\text{pulse}} + \underbrace{n(t)}_{\text{noise}}$$

receiver block

$$\to \underbrace{a_k^{(0)} \int_0^T e^{j2\pi f_0 t} e^{-j2\pi f_0 t} dt}_{100\%\ \text{correlation}} + \underbrace{a_k^{(1)} \int_0^T e^{j2\pi f_1 t} e^{-j2\pi f_0 t} dt}_{\text{orthogality property} = 0} + \dots$$

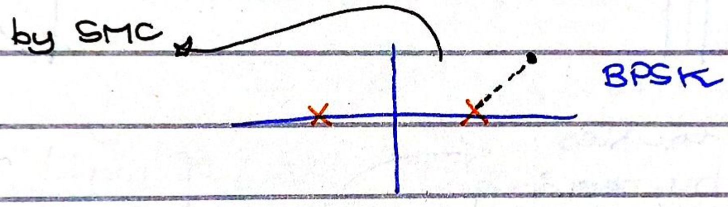
$$\to \alpha a_k^{(0)} + \underbrace{v}_{\text{noise}}$$

FFT is only applicable for powers of 2.

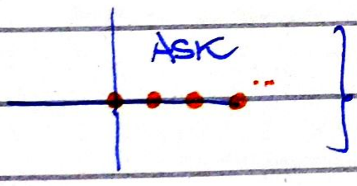
↳ Cooley Tuckey

└ can be used for modulation / demodulation

- Cyclic Prefix can remove ISI at the expense of added redundant bits.
- Serial Metric Compute is used for finding minimum distance for decoding bits ; e.g.



PSD ⇝ only an overview, sir said its too hard (hehe)



} just see from slides

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Mobile Communication Systems

Multiple Access

Recap : 1G — FDMA (30 kHz)

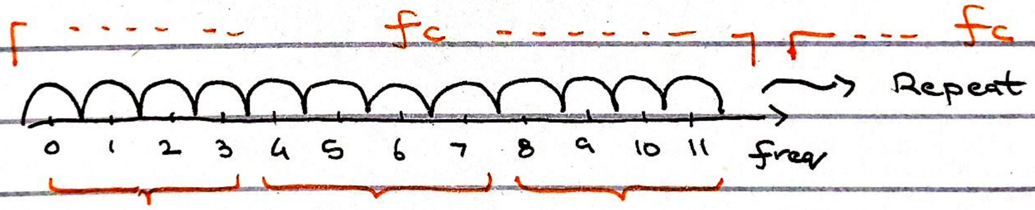
2G — TDMA + FDMA (200 kHz) { TDMA only possible if digital scheme

3G — CDMA (UMTS) (2 MHz)

4G — uplink SC-FDMA (20 – 40 MHz)
 — downlink OFDMA

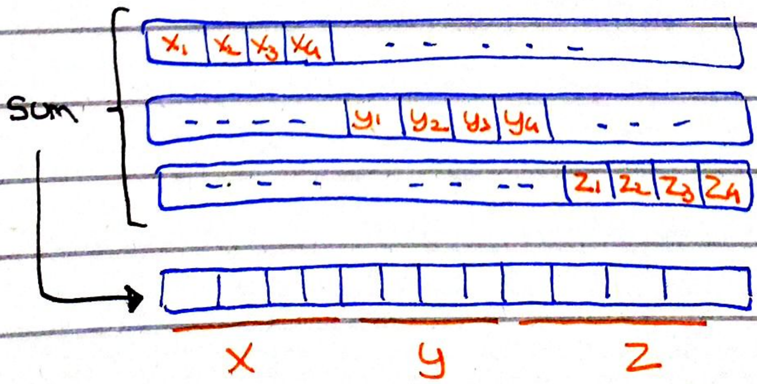
$M = 12$ sub-carriers $N = M/Q = 4$ sub-carrier/user

$Q = 3$ users



τ disjoint set (no overlap) τ_j $j=1$ τ_2 τ_3

Data blocks



where (- - -) are zero pads

Read em up

unicast | multicast | broadcast

OFDMA
is like broadcast

Single Carrier ~ No PAPR issues

SC - FDMA

└ multiplexing in the frequency domain