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# RF Fundamentals
# &
# Cellular OFDM Technology

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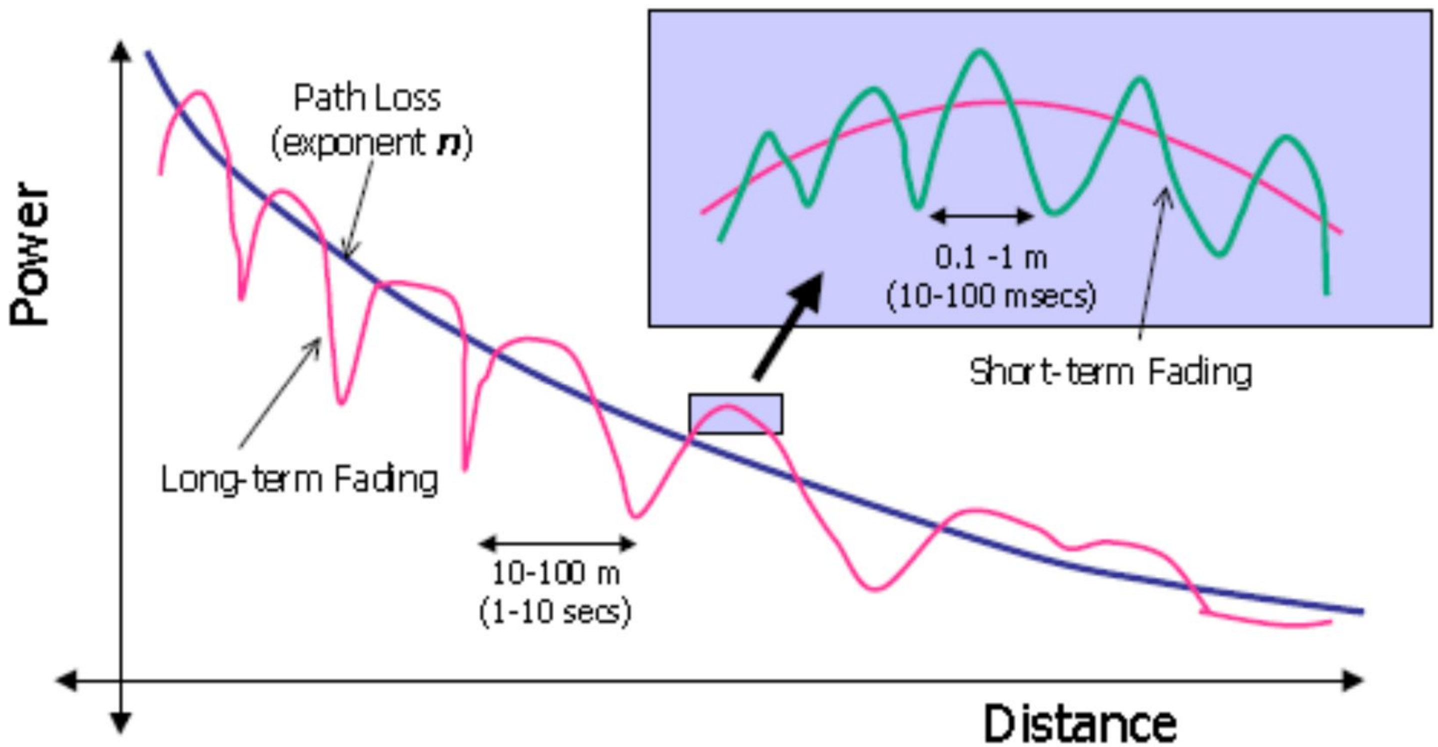
# Contents

# A1. Basics of Terrestrial Radio propagation



# A2. Path Loss -- Long Term Losses

- **Free-space Propagation (*n*=2)** → Received Power

$P_T$ – Power at Tx port of Isotropic Antenna in Watts

Power density at distance $d = P_T / 4\pi d^2$ Watts/m$^2$

$G_T$ – Directivity or Gain in a particular direction

Effective Isotropically Radiated Power (EIRP) $= P_T G_T$

Received power extracted by Rx is proportional to the effective area $A_R$ of the Rx antenna

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

# Aside1: Effective Area of Rx Antenna

From EM Theory, the effective area $A_R$ of the Rx antenna is related to the Rx antenna directivity $G_R$ as follows

$$A_R = \frac{G_R}{(4\pi / \lambda^2)} \text{ m}^2$$

where $\lambda$ is the wavelength of carrier

Example 1: For parabolic dish antenna of diameter D

$A_R = \frac{\pi D^2}{4}\eta$, where illumination efficiency $0.5 \le \eta \le 0.6$

Therefore, the directivity (gain) for the antenna is

$$G_R = \eta\left(\frac{\pi D}{\lambda}\right)^2$$

# Aside 2: Beam-width of Antenna

- **3dB Beam-width** → e.g., Parabolic dish antenna

For a parabolic antenna, the width in degrees at which the gain $G_T$ (or $G_R$) reduces to half of it's value is approximately given by

$$\Theta_T \approx \frac{70\lambda}{D} \text{ degrees}$$

*Note*: Therefore, $G_T \propto (1/\Theta_T)^2$;

If $D$ doubles, then $\Theta_T$ halves, and $G_T$ increases 4-fold

# Received Power

- **Free-space Propagation ($n$=2) → Received Power**

Substitution of $A_R = \left(\frac{\lambda^2}{4\pi}\right) G_R$ gives Rx power

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

Taking 1milliwatt = 0dBm, this can be expressed in a convenient Log (dBm) scale as

$$P_R(\text{dBm}) = P_T(\text{dBm}) + G_T(\text{dBi}) + G_R(\text{dBi}) - L_d(\text{dB})$$

where

$$L_d = 10\log_{10}((4\pi d/\lambda)^n)\text{ dB}$$ -- in free space, $n$=2

# Factors affecting Rx Power

In the presence of large-scale scatterers (buildings, usually) a random variation is expected (also called long-term fading)

$$P_R(\text{dBm}) = P_T(\text{dBm}) + G_T + G_R - L_d - L_{shadow} - L_{cable}$$

where $L_{shadow}$ (in dB) is an random-variable with pdf $N(0,\sigma)$, and standard-deviation $\sigma$ is in dB scale -- log-normal distribution;

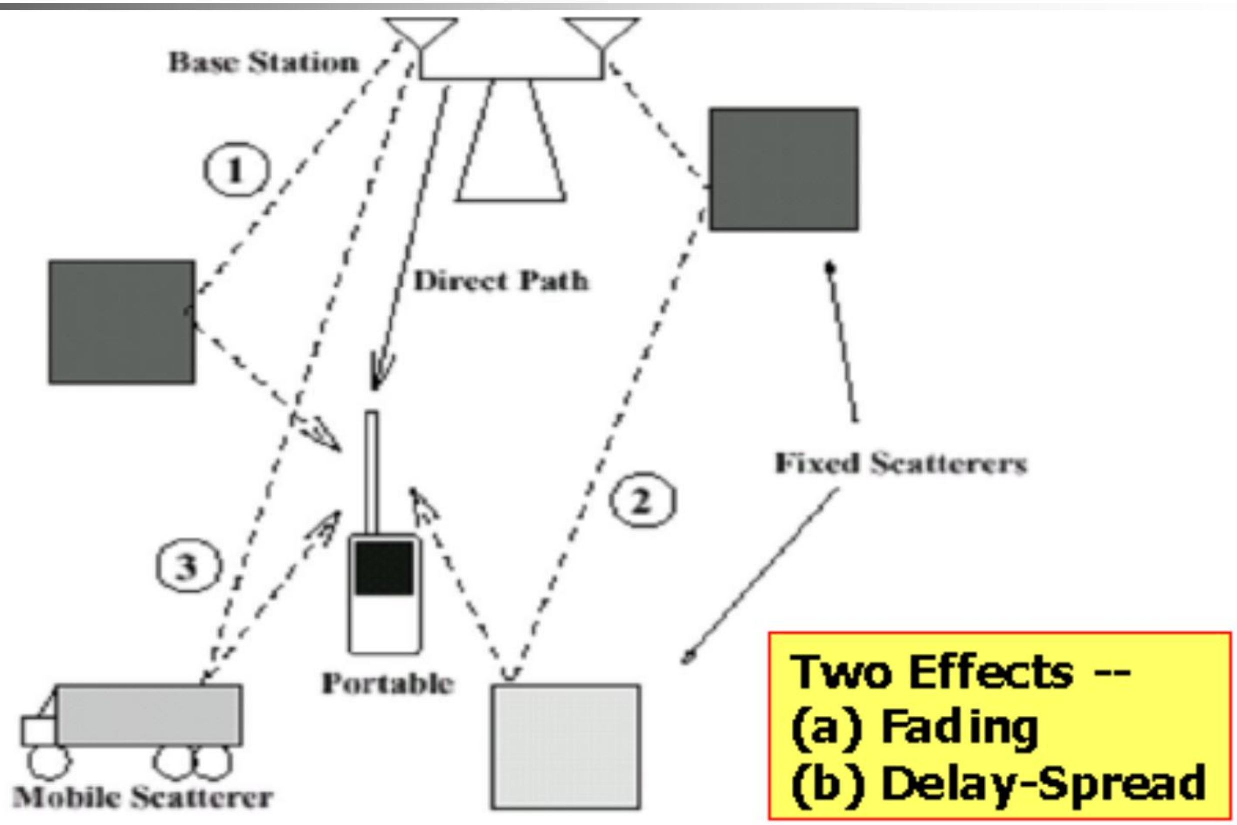
$L_{cable}$ (in dB) is the RF cable loss (specified in dB/meter).

Shadow-loss, Cable-loss, and antenna mis-alignment is sometimes clubbed into a single "Installation margin" term (in dB)

- What about short-term fading?

$$P_R(\text{dBm}) = P_T(\text{dBm}) + G_T + G_R - L_d - L_{shadow} - L_{cable} - L_{fading}(\text{dB})$$

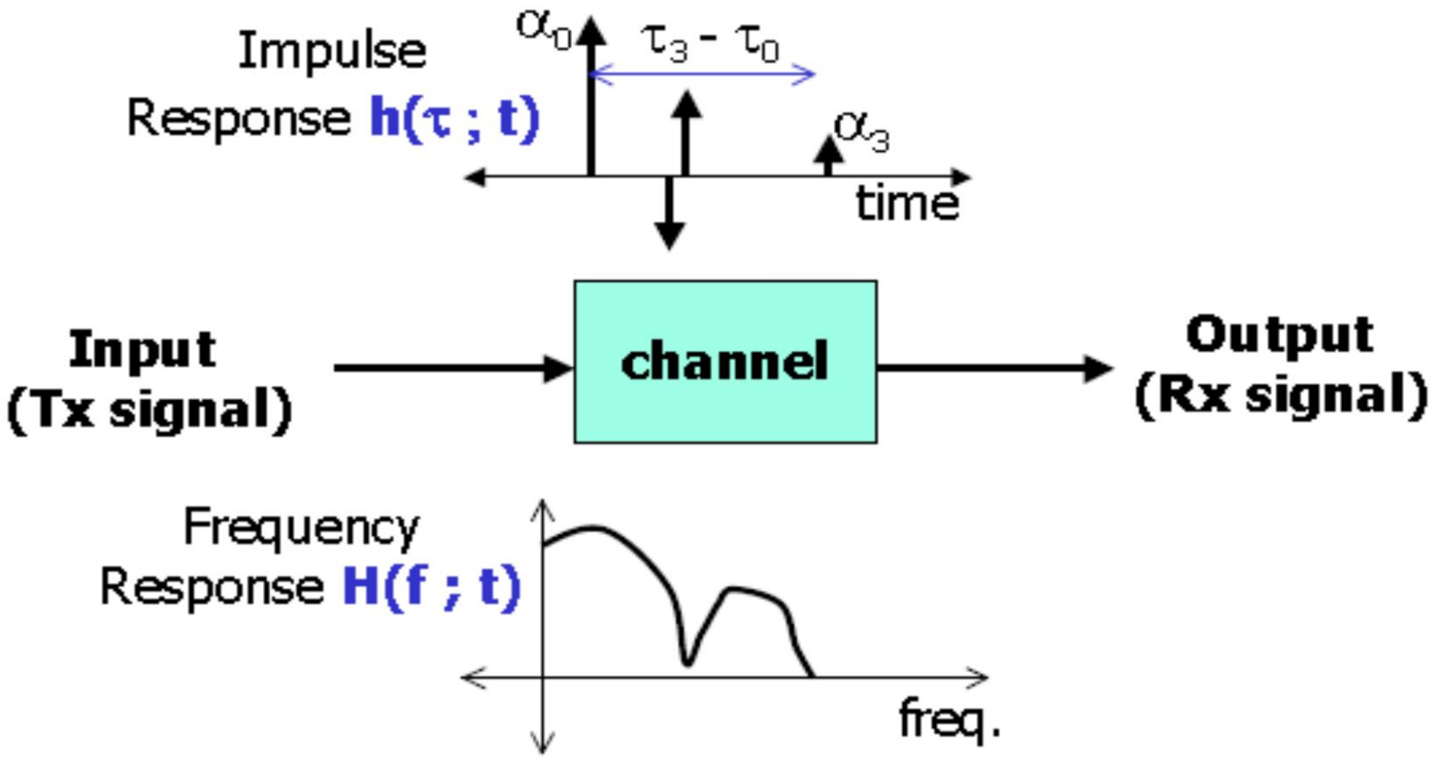
# Short-term Fading – Multipath Propagation




$$r(t) = \alpha_0\, s(t-\tau_0) + \alpha_1\, s(t-\tau_1) + \alpha_2\, s(t-\tau_2) + \alpha_3\, s(t-\tau_3)$$

# Multi-path Propagation -- contd.

$$r(t) = \alpha_0\, s(t-\tau_0) + \alpha_1\, s(t-\tau_1) + \alpha_2\, s(t-\tau_2) + \alpha_3\, s(t-\tau_3)$$



# How much Rx Power is required?

Minimum $P_R$ (dBm) required depends on SNR needed for a target BER!

This required SNR (specified in dB) is a function of:

(a) Receiver Sensitivity $\Rightarrow f$(bandwidth, RF design, Baseband algorithms, architechture, implementation)

(b) Digital Modulation and Coding used for getting the target BER

- Key Question: How to relate $P_R$ and SNR?
- Answer: Understand receiver noise power!

# A3. Rx Noise Figure

Thermal noise (passives) dominates over shot noise (actives);

at temperature $T$ Kelvins, for bandwidth $\Delta f$ Hz,

Noise Power $= N_o \Delta f = kT\,\Delta f \quad k = 1.38 \times 10^{-23}$ (Boltzmann const.)

Example 2: Room temp $T = 300^\circ$K and $\Delta f = 1$MHz

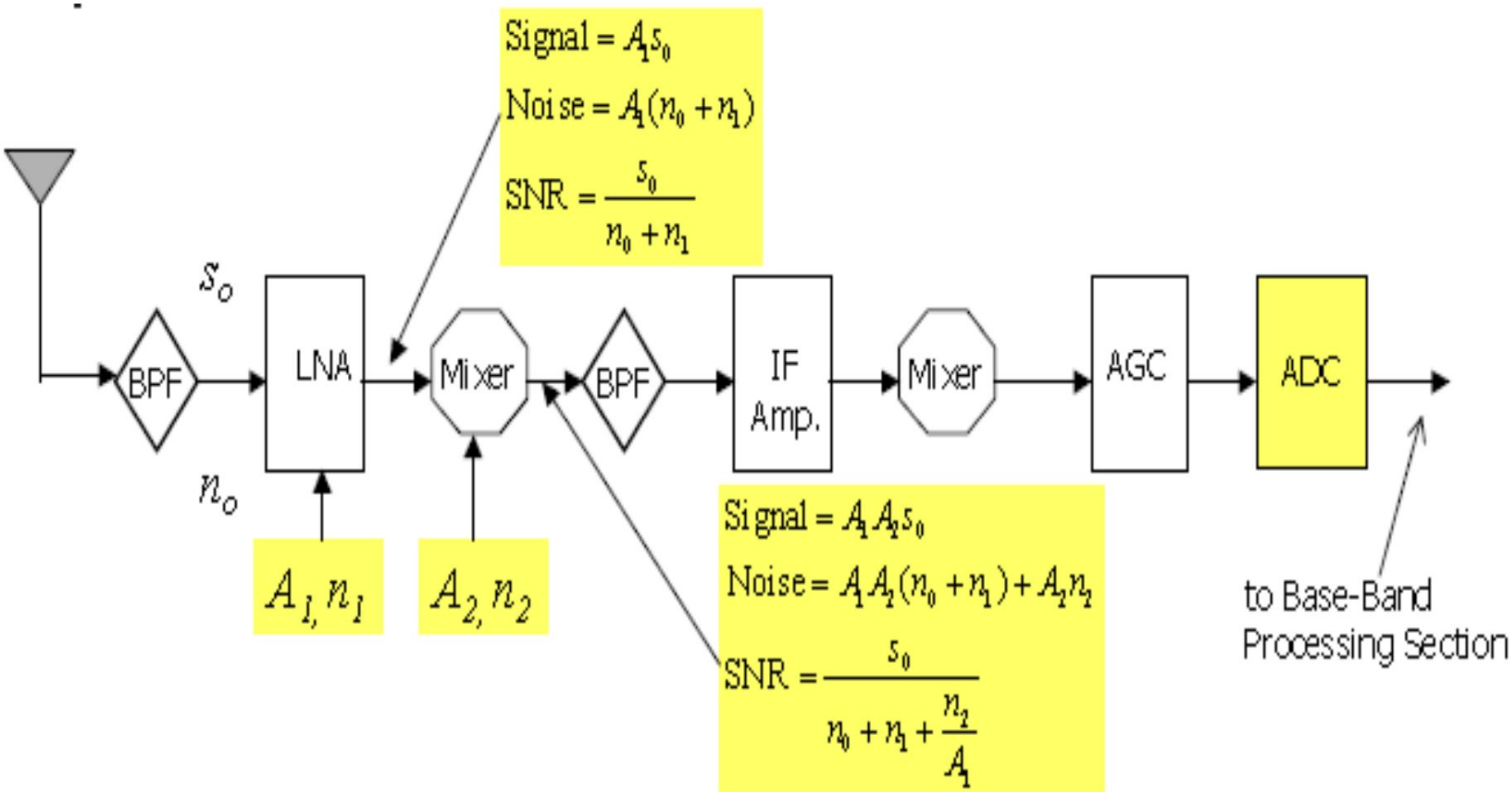
Noise spectral density $N_o = kT = -174$ dBm;

Noise power $kT\,\Delta f = -174 + 60 = -114$ dBm;

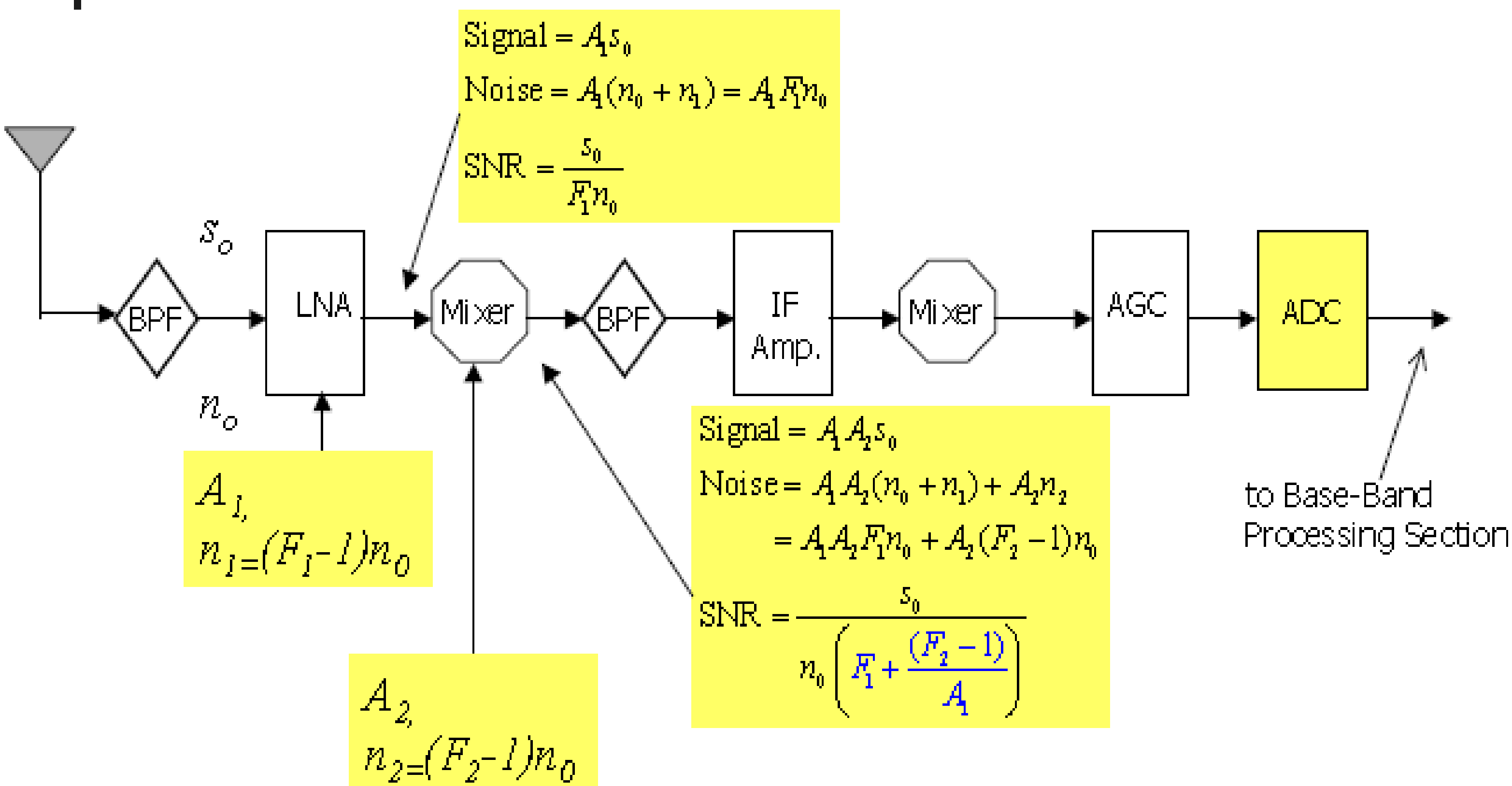
If Rx signal power $P_R = -90$ dBm (say), then SNR = 24 dB

- Why first-stage (usually LNA) noise dominates?

# Typical Rx Chain



# Receiver Noise Figure




**Thus, even 2nd stage contributes very little to overall Rx noise figure!**

# Rx Sensitivity –
## Impact of Noise Figure and Modulation used

Example 2 (contd.): Room temp $T$=300°K and $\Delta f = 1\text{MHz}$

Noise power $kT\,\Delta f = -174 + 60 = -114\ \text{dBm}$;

a) If Rx noise figure $F = 6$ dB $\Rightarrow$ noise floor rises to $-108$ dBm

(for RF-BB combo chip, $F$ could reflect base-band accuracy as well!)

b) Let QPSK be used. For BER=$10^{-3}$, QPSK requires in AWGN channels (and in the absence of FEC), an SNR=6.7dB

$\Rightarrow$ minimum signal strength required is -108+6.7= -101.3 dBm

- With diversity reception, turbo-coding, etc., required SNR for QPSK to (get same BER) would further reduce

# A4. Link Budget -- GSM Example

Example 2 : Communication link budget for GSM uplink

Given $P_T$= 100milliwatts, $G_T$=2dBi, $G_R$=15dBi, cable loss of 2dB, and no (zero) allowance for shadow loss or fading loss, compute the maximum link distance possible (in meters) for a GSM phone with a 5dB noise figure operating in the 800MHz band.

GSM uses 200KHz channelisation (bandwidth), and requires a SNR=7dB to achieve the target BER=$10^{-3}$. Assume free-space propagation on the uplink (i.e., exponent $n$=2), & $T$=300°K.

Recall: $P_R(\text{dBm}) \;=\; P_T(\text{dBm}) + G_T + G_R - L_d' - L_{cable}$

which conveniently $= P_T + G_T + G_R - L_{1m} - L_d - L_{cable}$

where at 1m, $L_{1m} \;=\; 10\log_{10}\left(\frac{4\pi}{\lambda}\right)^2$, and $L_d \;=\; 10\log_{10} d^n$

# GSM Link Budget -- assumptions

- **In noise limited coverage, link budget is easier to understand**
  - Example: Frequency planned systems
  - GSM can deploy reuse 1/7, 1/4 or even 1/3

- **Typical link-budget for GSM will include**
  - Noise figure for BS/UE (corresponding to UL or DL)
  - Fade Margin – for mobile users
  - Indoor Penetration Loss – for indoor/pedestrian users
  - These will be added to Ld
    - Safe to add interference margin also for reuse 1/3, but frequency hopping and other interference averaging schemes are used to make the CCI (nearly) vanish!

# Summary for Part A

- A1. Terrestrial Wireless Propagation
- A2. Path Loss – Long Term, Short Term
- A3. Noise Figure of Receiver
- A4. Example: GSM Link Budget
- Points to ponder:
  - What happens when the coverage and capacity are co-channel interference (cross-talk) limited?
    - Example: All DS-CDMA and OFDM-Cellular systems using reuse 1/1
    - Sensitivity is defined by SIR (or SINR) and not merely by SNR
  - What about sensitivity of SDR and Cognitive radios?

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# Access Systems Overview – WAN,MAN, and LAN Systems (not shown: PAN, HAN, VAN )

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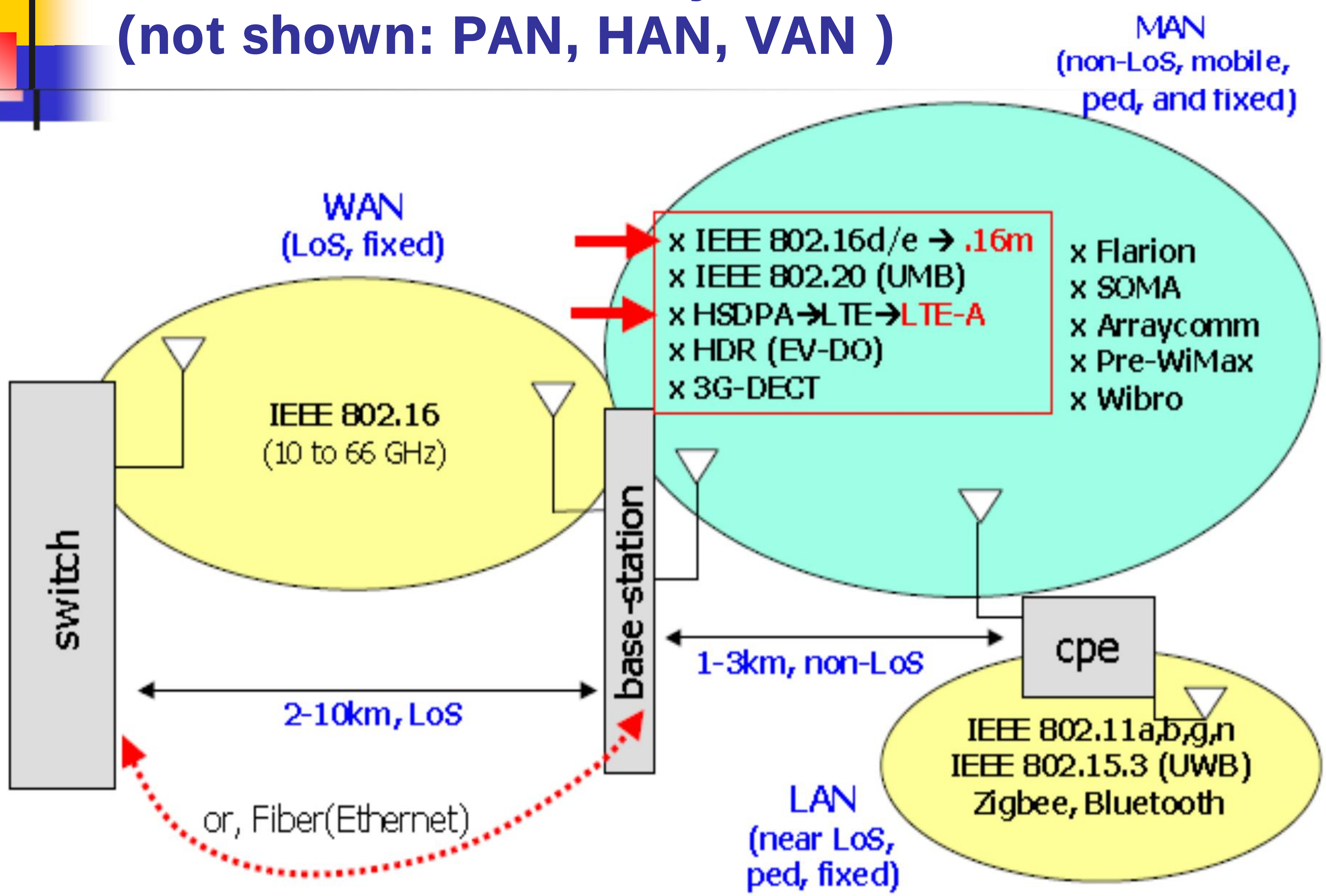
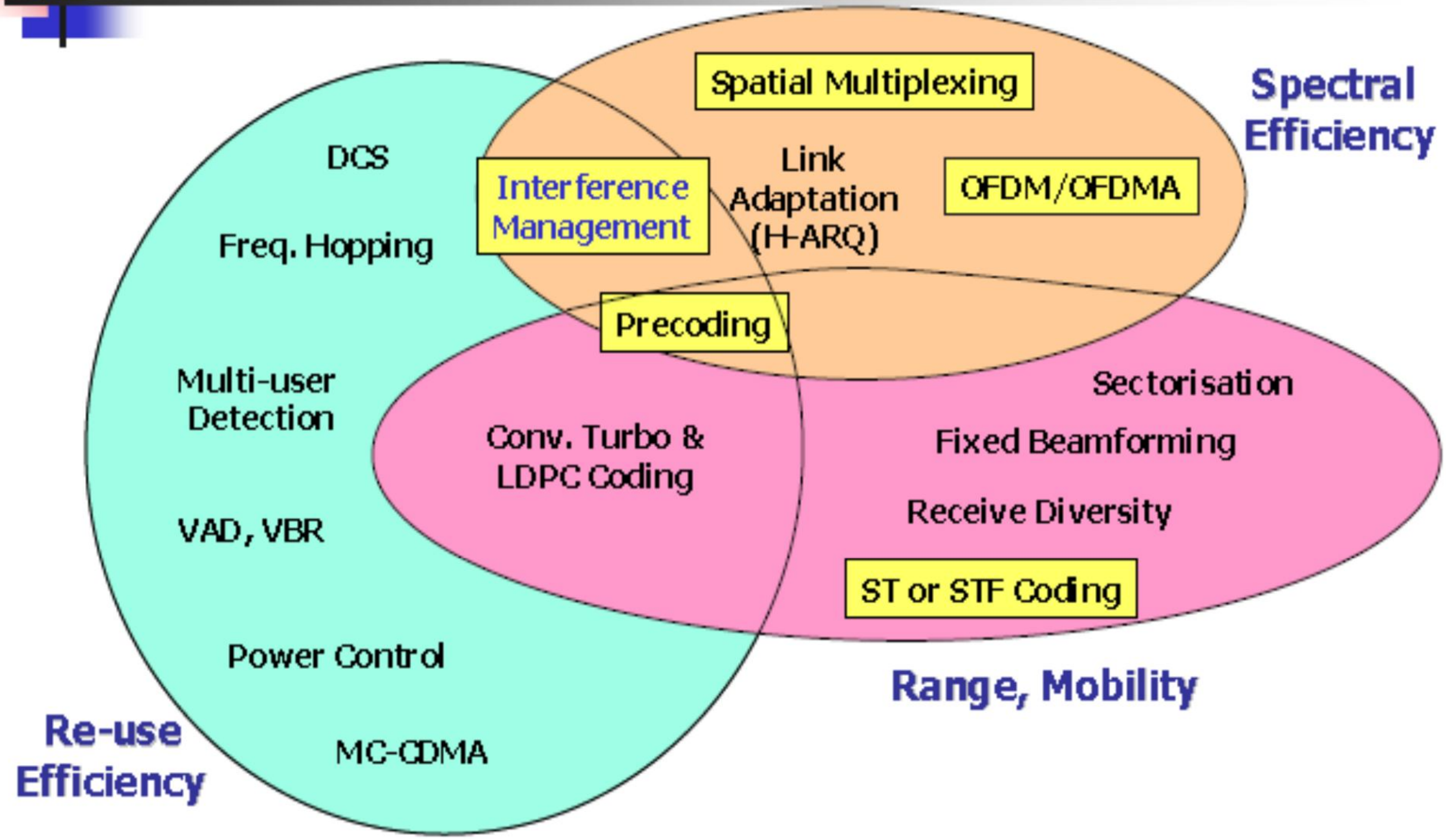


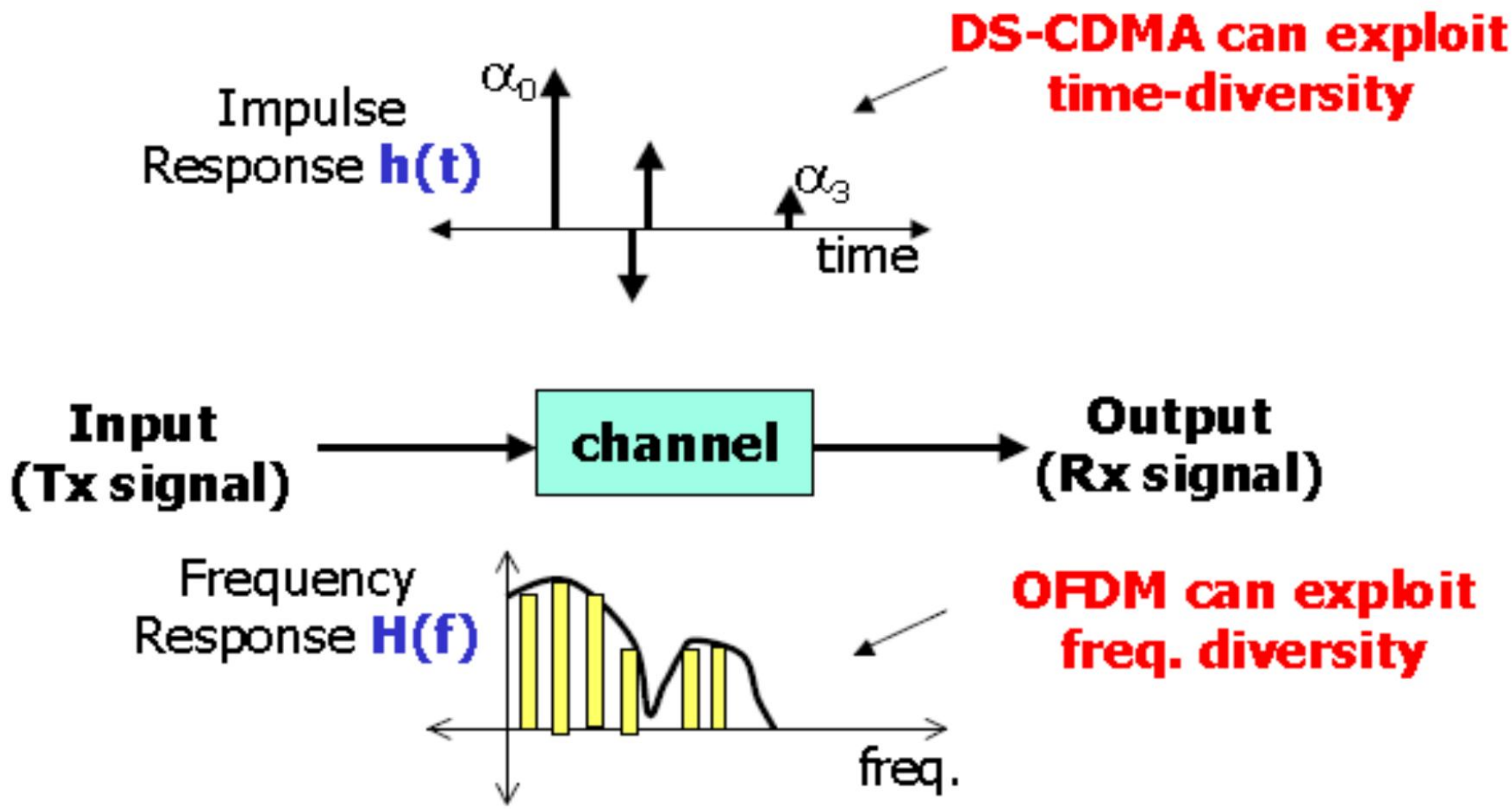
# Key Advances in Air-Interface



# Why OFDMA for Broadband Access?

- Why not CDMA or TDMA?
  - DS-CDMA cannot support high bit rates efficiently
  - TDMA (or any other single-carrier Tx) requires higher peak power
- **Advantages of OFDM/OFDMA**
  - **Closed-loop modes in multi-user OFDM/OFDMA can more effectively "ride the wave" →multi-user diversity**
  - **Greater flexibility in resource allocation**
- However, what about
  - PAPR, especially on the uplink?
  - Protection from co-channel interference?

# DS-CDMA versus OFDM



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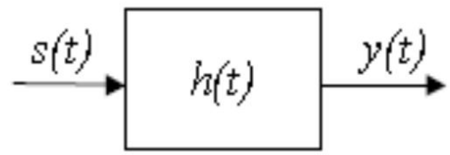
# B1. OFDM Fundamentals

# Continuous Time Signals and Systems

$$\text{Signal}: s(t) \rightarrow \text{bounded, with energy } E_s = \int_{-\infty}^{\infty} s^2(t)\,dt$$

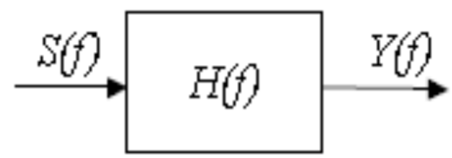
$$\text{System (Channel)}: h(t) \rightarrow \text{Stable, LTI (or LTV)}$$




$$\text{Linear Convolution}: s(t) * h(t) = \int_{-\infty}^{\infty} s(\tau)h(t-\tau)\,d\tau = y(t)$$

Continuous-time Fourier Transform:

$$S(f) = \int_{-\infty}^{\infty} s(t)e^{-j2\pi f t}\,dt, \text{ and similarly } H(f) \leftrightarrow h(t)$$




$$\text{then, } s(t) * h(t) \leftrightarrow S(f)H(f) = Y(f)$$

# Discrete Time Signals and Systems

Discrete - time signal $s(nT_s) \Leftrightarrow s[n]$: can be infinite or finite duration;

in the infinite duration case, signal can be either periodic or random.

For $s[n]$ of finite duration (say $L$), discrete - time FT (DTFT) pair

$$S(e^{j\omega}) = \sum_{n=1}^{L} s[n] e^{-j\omega n} \quad \text{and} \quad s[n] = \frac{1}{2\pi} \int_{-\pi}^{+\pi} S(e^{j\omega}) e^{j\omega n} d\omega$$

Linear Convolution remains valid for the DTFT

Discrete Fourier Transform (DFT):

If $s[n]$ is a finite sequence of length $L \le N$, then it is computationally beneficial to define only a finite, periodic basis set $\{e^{j\frac{2\pi}{N}kn}\}$ such that

$$S[k] = \sum_{n=0}^{N-1} s[n] e^{-j\frac{2\pi}{N}kn}, \text{ and similarly } s[n] = \frac{1}{N} \sum_{n=0}^{N-1} S[k] e^{j\frac{2\pi}{N}nk}$$

Enables FFT based efficient implementation

# Matrix Notation for DFT

$x[n] \leftrightarrow X[k]$ can also be written as

$$\mathbf{X} = \mathbf{F}\mathbf{x}$$

where $\mathbf{X}$ & $\mathbf{x}$ are $N \times 1$ vectors and

$$\mathbf{F} = \left[ W^0 \quad W^1 \quad W^2 \quad ☹ \quad W^{N-1} \right]$$ with the

$N \times 1$ orthogonal column vector $W^1$ given by

$$W^1 = [1 \quad e^{-j\frac{2\pi}{N}.1} \quad e^{-j\frac{2\pi}{N}.2} \quad ☹ \quad e^{-j\frac{2\pi}{N}.(N-1)}]^T$$

# DFT and Circular Convolution

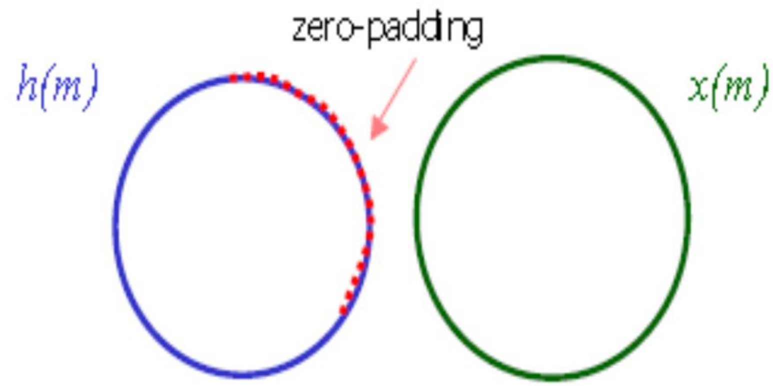
Similarly, the DFT for a system (FIR channel) $h[n] \leftrightarrow H[k], \{n, k \in 0, 1, \ldots, N-1\}$

1. Here, $H[k] = H(e^{j\omega}), \omega = \frac{2\pi}{N}k$, where around the UC we evaluate at $k = 0, 1, \ldots, N-1$

2. Now, what does "frequency domain" $Y[k] = H[k]X[k]$ represent in "time-domain"?

$H[k]X[k] \leftrightarrow h[n] \otimes x[n]$, where $\otimes$ represents "circular" convolution;

i.e., $y[n] = \sum_{m=0}^{N-1} x[m]h[(n-m)_{\bmod N}]$



# Linear vs Circular Convolution

If FFT engines are cheap, then for finite duration sequences:

(a) Implement filtering, i.e., $h[n] * x[n]$ using $h[n] \otimes x[n]$ $\rightarrow$ by zero-padding
(this is to use CC to implement LC -- Refer: any DSP book!)

(b) In OFDM, impact of channel distortion, i.e., $h[n] * x[n]$, is mitigated by adding a cyclic prefix to $x[n]$, and transform this to $h[n] \otimes \tilde{x}[n]$

# OFDM Principle – DFT Perspective

Recall that $x[n] \leftrightarrow X[k]$ can also be written as $\mathbf{X} = \mathbf{F}\mathbf{x}$,

and it can be seen easily that $\mathbf{F}\mathbf{F}^{H} = \mathbf{I}_{N \times N} = \mathbf{F}^{H}\mathbf{F}$.

$$\mathbf{X} \xrightarrow{\mathbf{F}^{H}} \mathbf{x} \xrightarrow{+CP} \tilde{\mathbf{x}} \xrightarrow{h[n]\otimes\tilde{x}[n]} \tilde{\mathbf{y}} \xrightarrow{-CP} \mathbf{y} \xrightarrow{\mathbf{F}} \mathbf{Y}$$

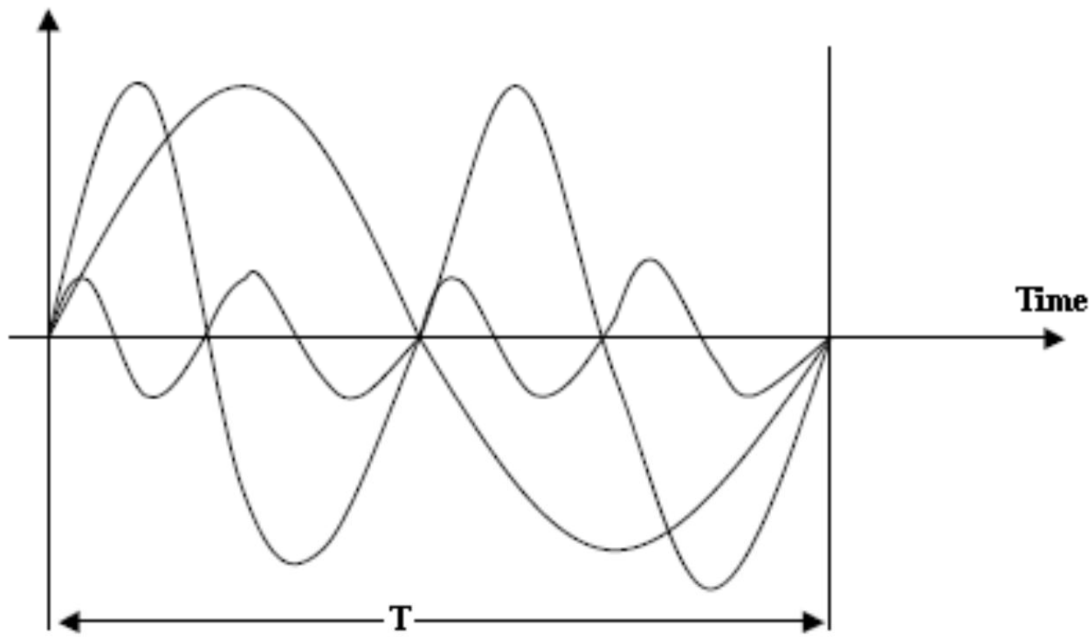
and it can be shown that $Y[k] = H[k]\,X[k], k = 0,1,\ldots,N-1$.

In other words,

(a) $\mathbf{F}^{H} \rightarrow$ is a bank of orthogonal Tx filters (eigen filters)

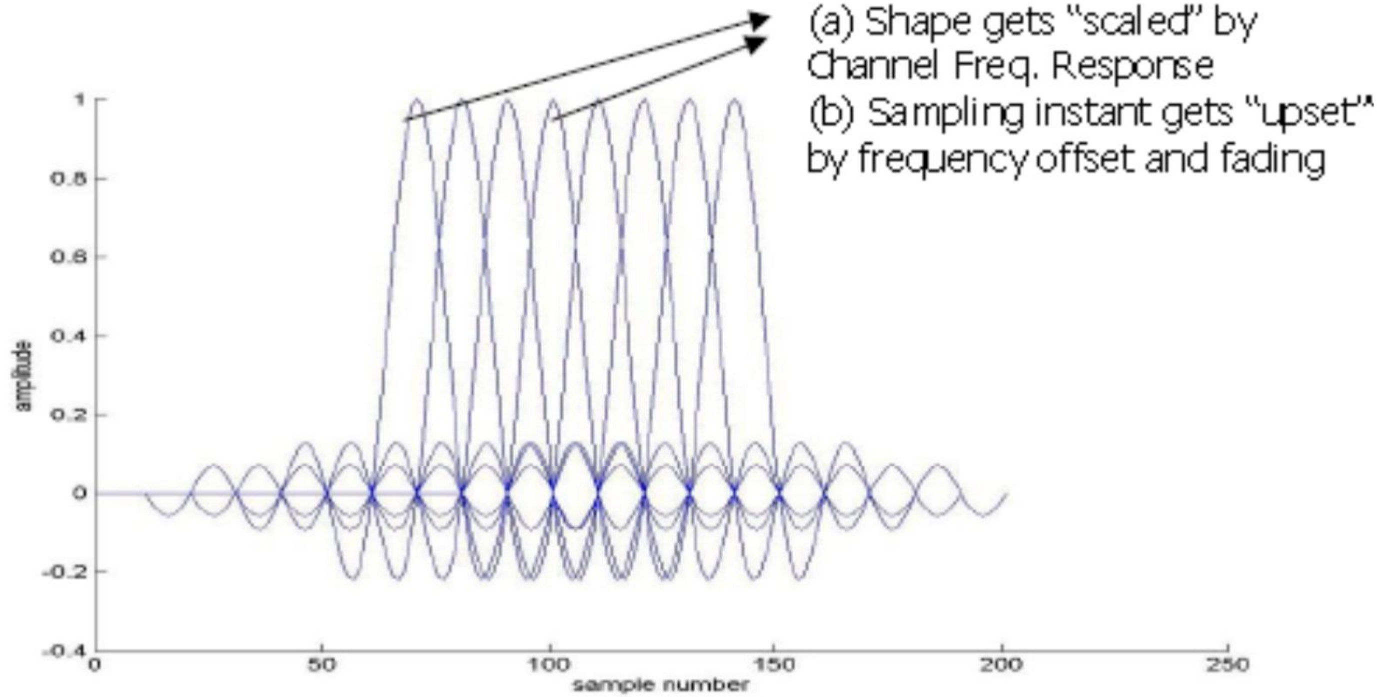
(b) $\mathbf{F} \rightarrow$ is a bank of orthogonal Rx filters (**matched filter bank**)

# **Condition for Orthogonality** (in **t** domain)




T="useful" symbol period

# **Sync Basis Functions** (in **f** domain)

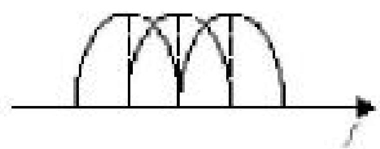



$$\text{Worstcase ICI power } \sigma^2_{ICI} = E(d^2[n]) \sum_{i=-N/2}^{N/2-1} | Sinc(i + \frac{\partial f}{\Delta f}) |$$

# FDM vs OFDM

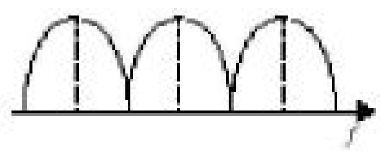
- **Courtesy**: any text-book on modern digital communications

OFDM spectrum



vs.

conventional
FDM spectrum



# Tx Waveform (Magnitude) over an OFDM Symbol

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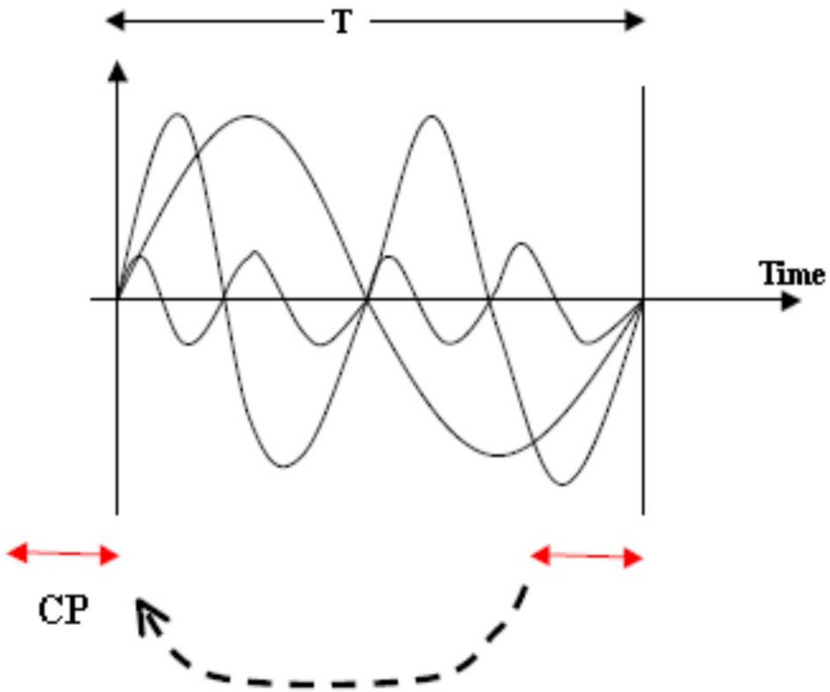
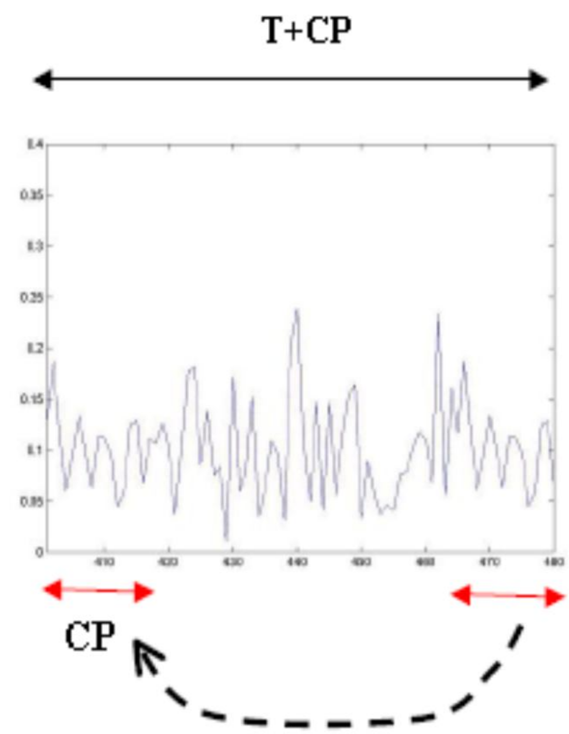
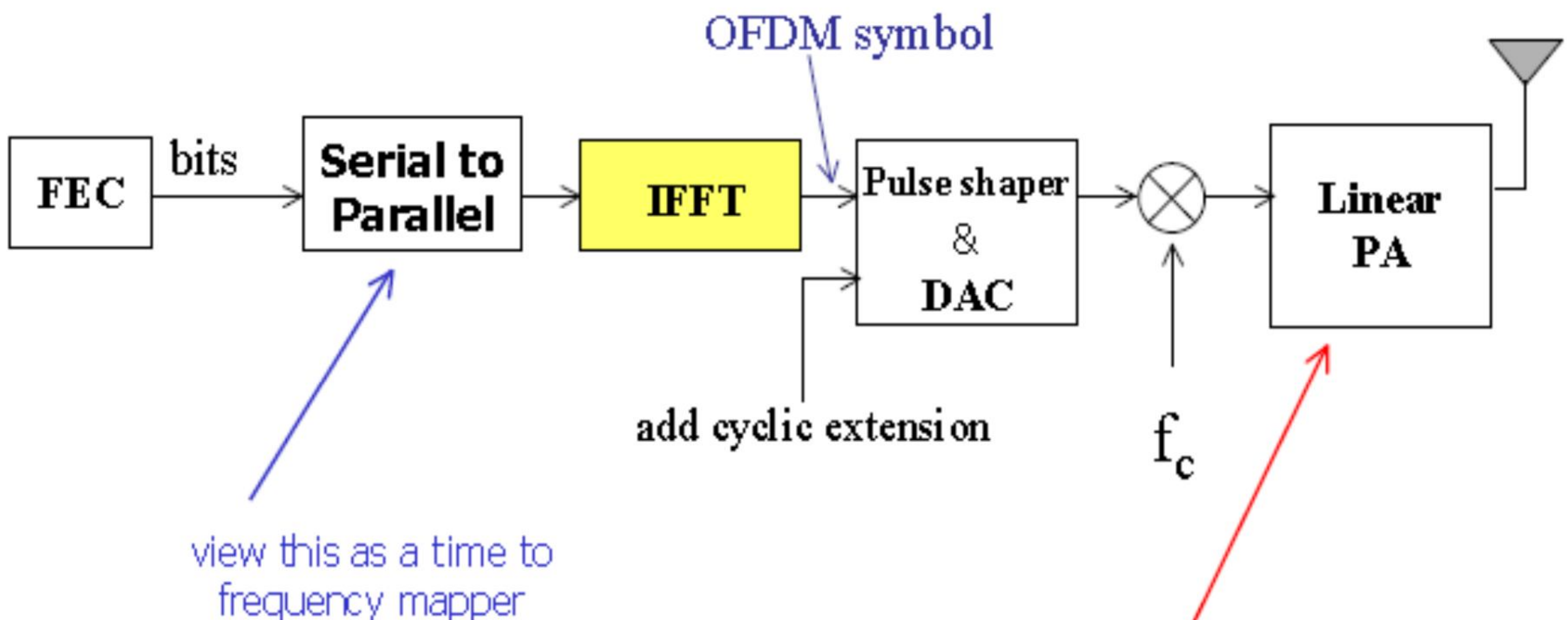


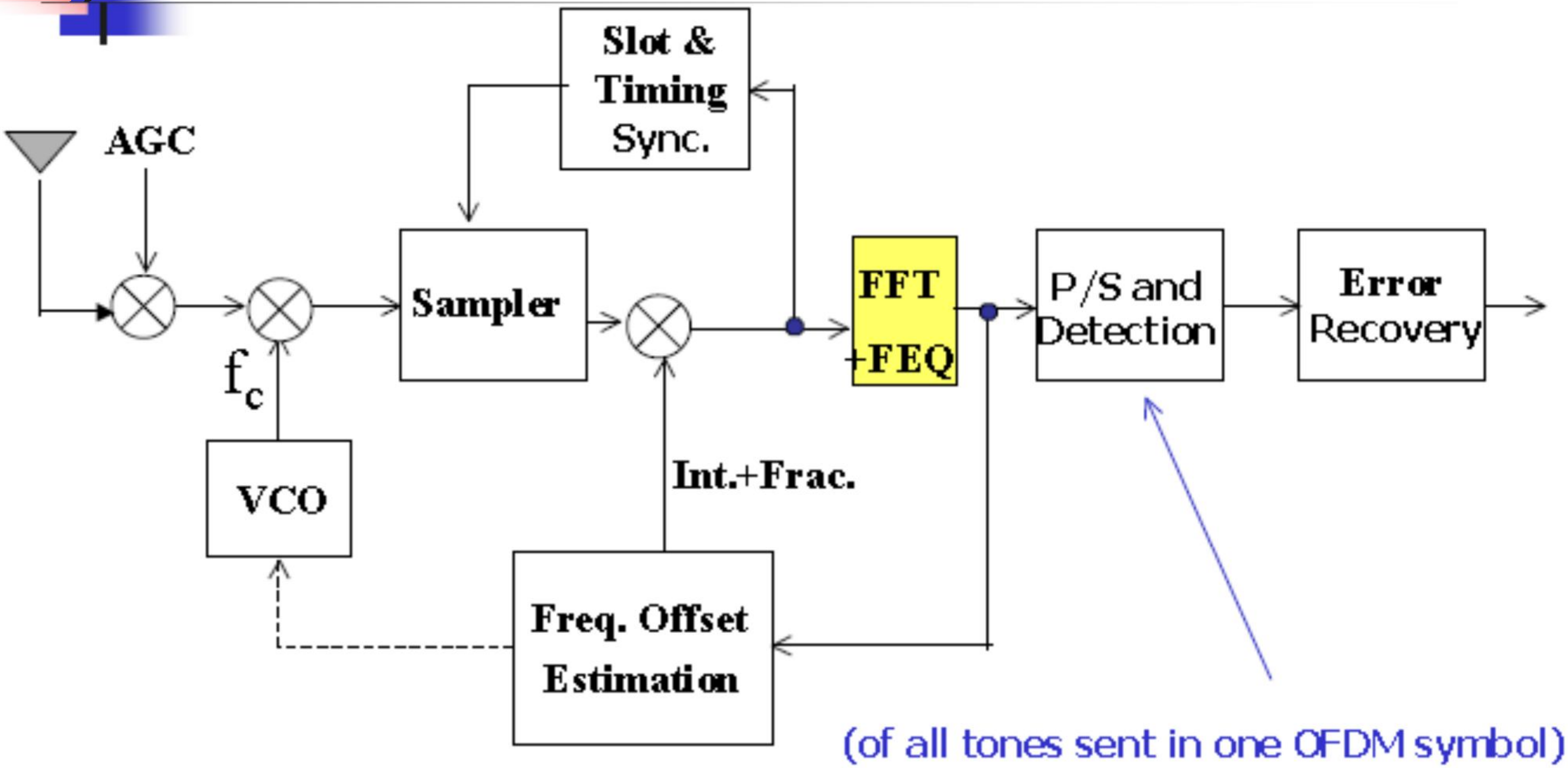



# Generic OFDM Transmitter




Complexity (cost) is transferred back from the digital to the analog domain!

# Generic OFDM Receiver



# B2. Other Block Modulation Schemes

# Block Tx flavours

- Multi-Carrier with
  - **Cyclic Prefix → OFDM**
  - **Zero-Padding**
- Single-Carrier with
  - **Cyclic Prefix**
  - **Zero-Padding**
  - **Unique-Word**
- Generalised Multicarrier
  - **Including FDOSS, DFT-spread OFDMA, etc.**
  - CP-less OFDM
  - **Offset QAM OFDM**

# Single Carrier & Generalised Multi-Carrier (GMC)

- Single Carrier with CP offers
  - Low PAPR
  - Freq. Diversity **(since each QAM symbol "sees" the entire BW)**
  - Ability for multiplexing **(of different user streams on down-link)**
  - However, not suitable for up-link
    - (a) high peak power requirement (lower link margin)
    - (b) multiplexing requires CP between every user burst ( inefficient)
- Generalised Multi-carrier modulation for the Uplink
    - Provides narrow-banding => higher link margin!
    - Provides freq. domain multiplexing – spectrally efficient
  - F-DOSS – Freq. Domain Orthogonal Spread Spectrum
    - **Chang & Chen, IEEE Comm. Letters, Nov.2000**
  - Interleaved OFDMA (I-OFDMA) or DFT spread OFDMA
    - **3GPP LTE has adopted this for UL**
    - Confusingly enough, LTE calls it "Single-carrier FDMA (SC-FDMA)"

# Conventional OFDM
(FDE is optional)

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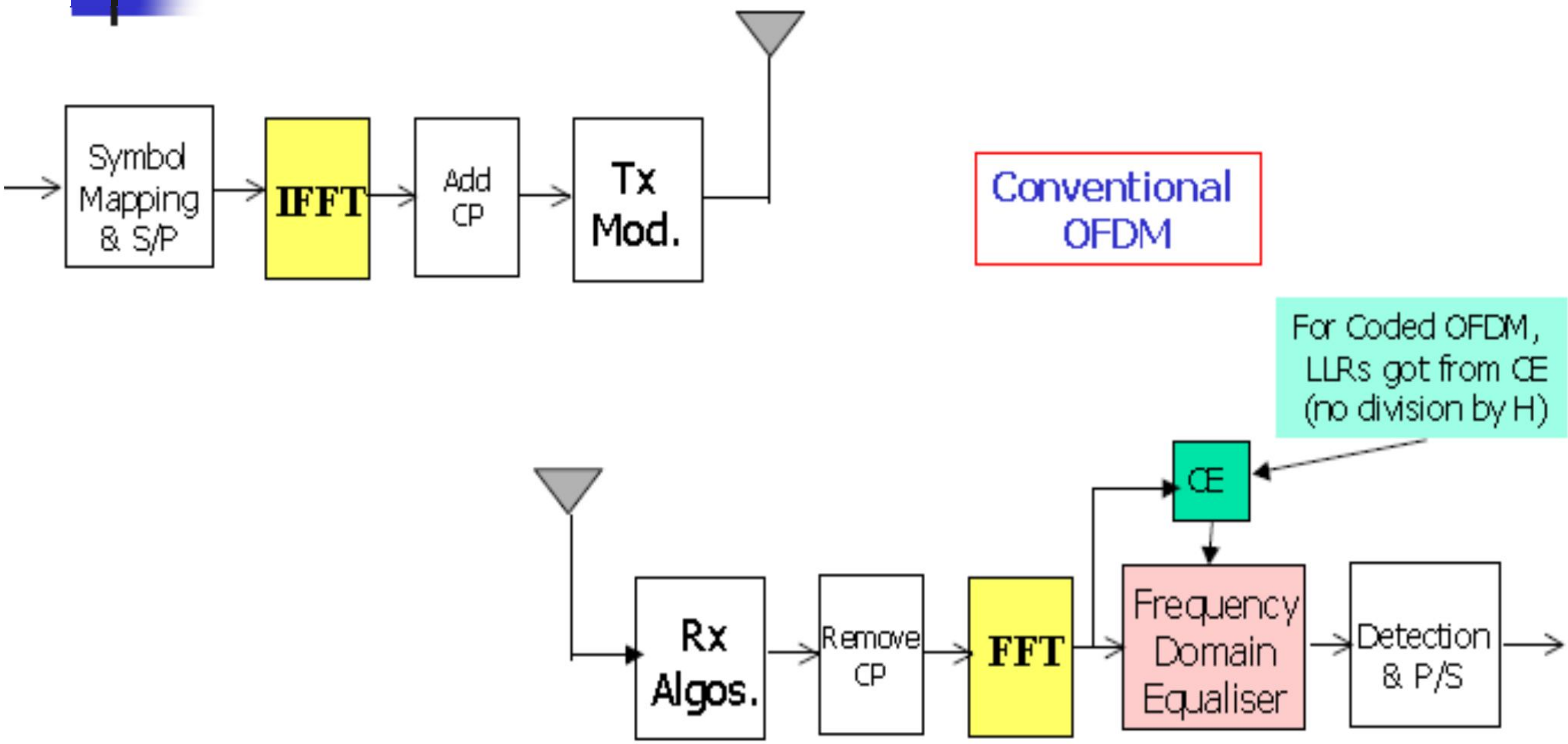

# Single Carrier Trasmission
(FDE is mandatory!)

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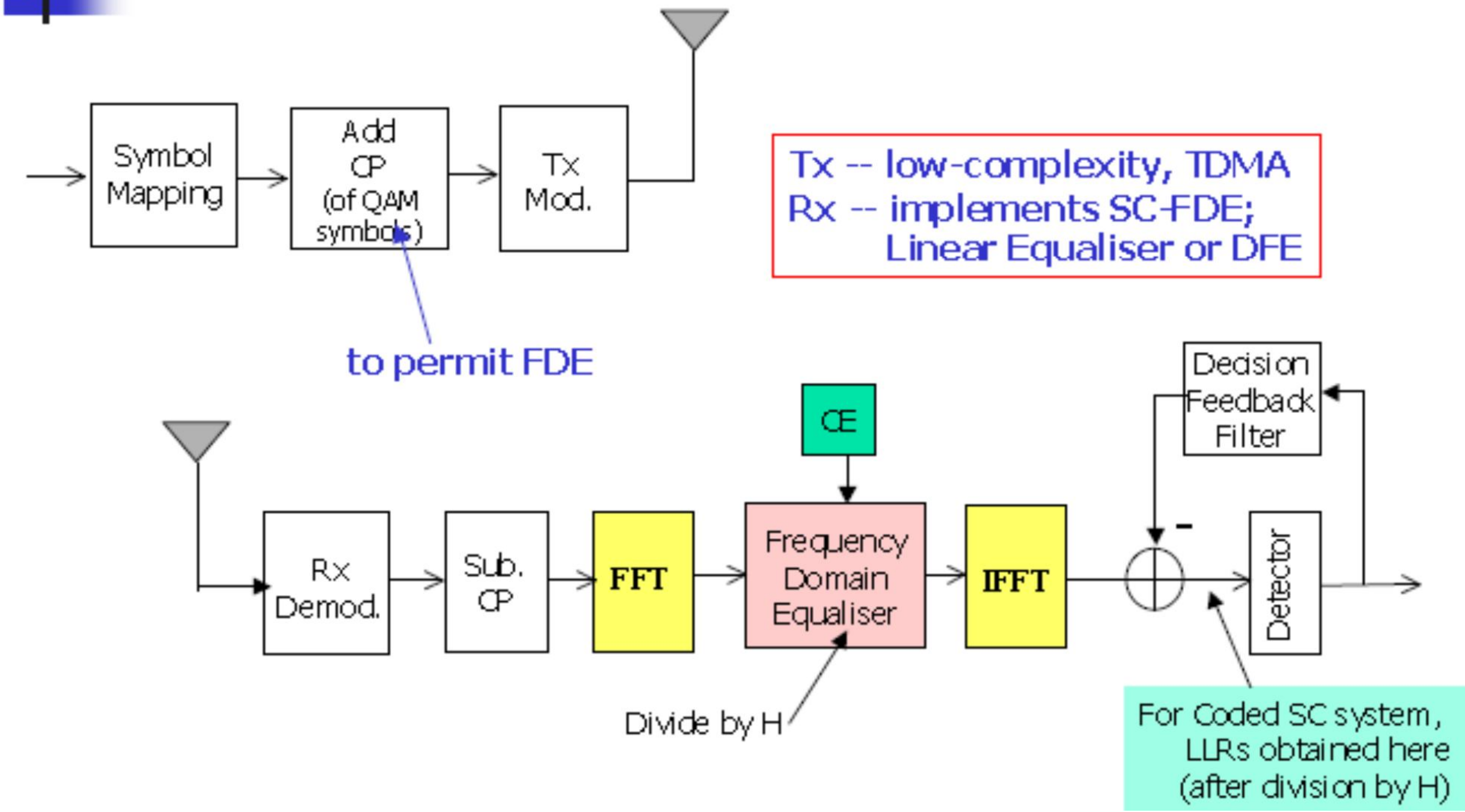
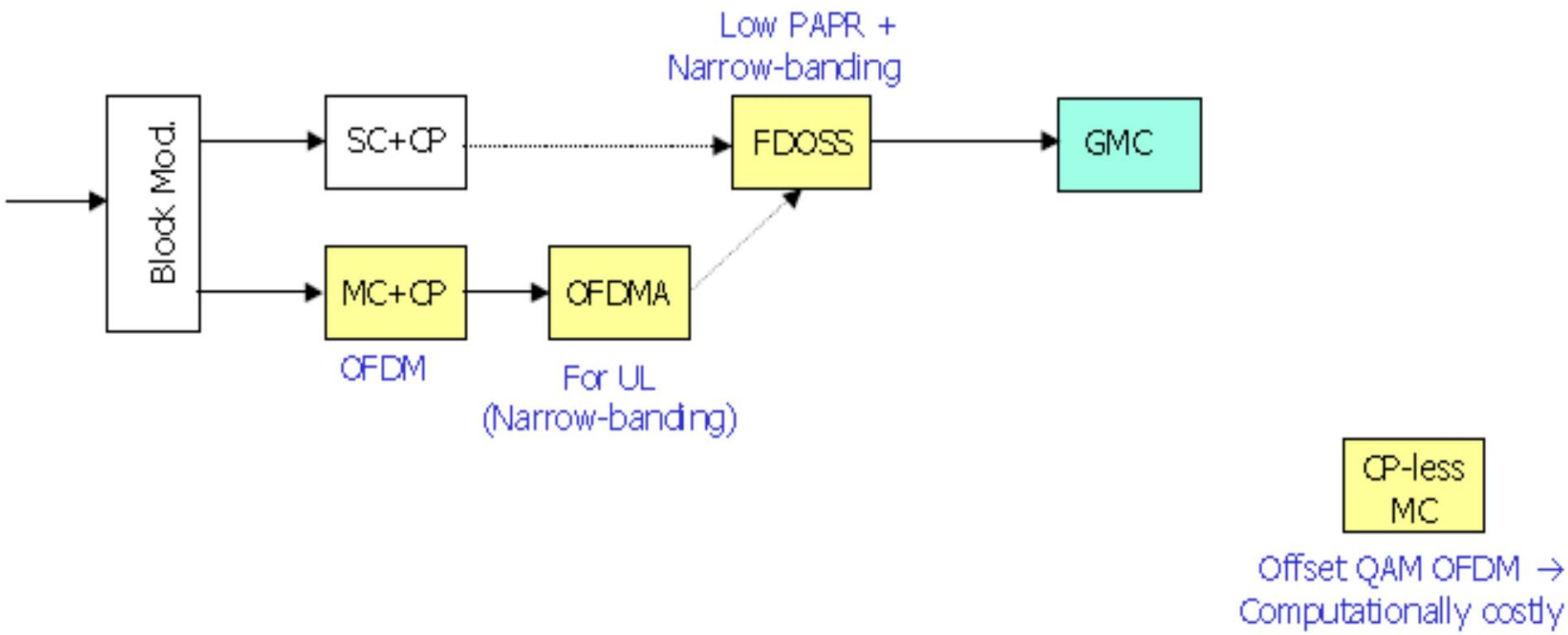
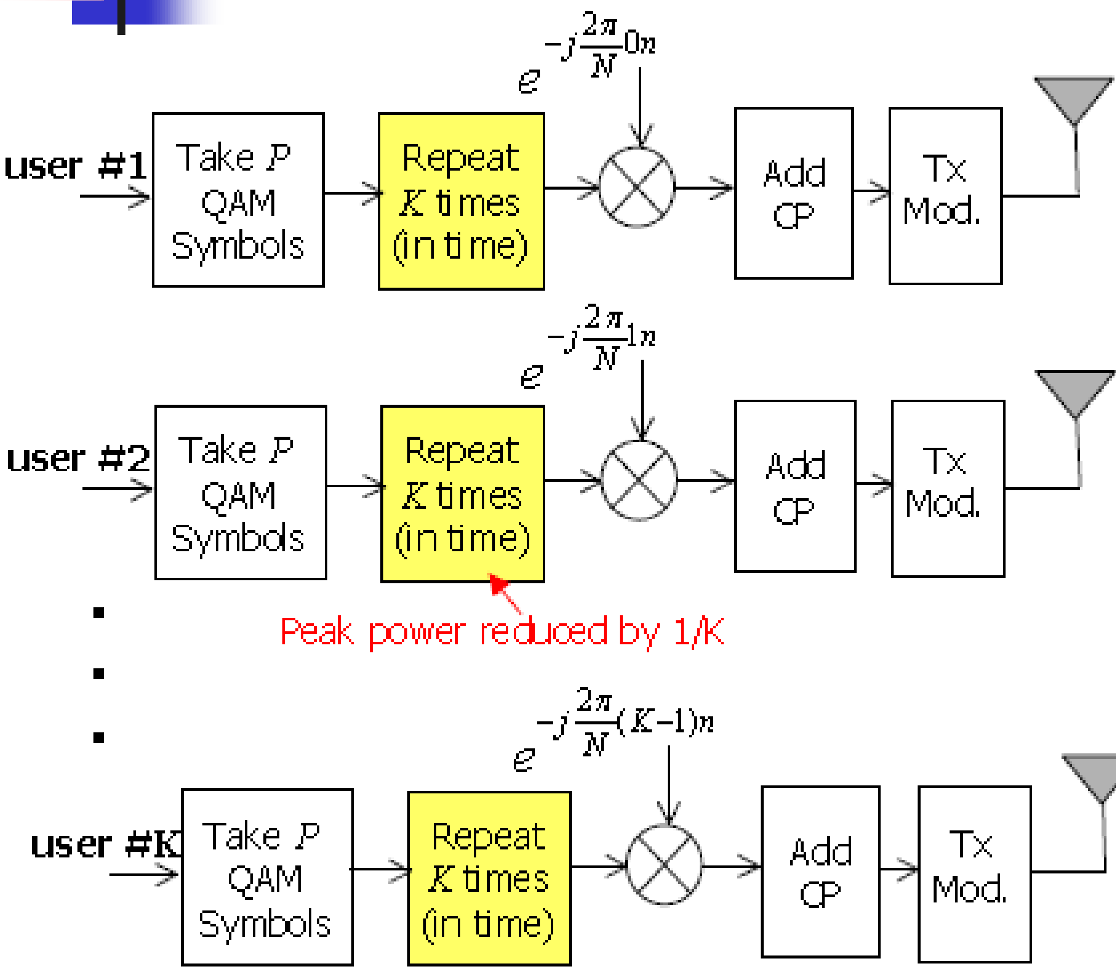


# Block Modulation -- “Evolution” to GMC




- **GMC offers more flexibility in tone allocation than FDOSS**

# Generalised MC with CP – **F-DOSS, IFDMA**




Let $KP=N$, where $N$ is FFT size,
$K$ – No. of uplink users
$P$ – No. of subcarriers per user

**Assumptions:**
All $K$ users are freq. synchronised (within 1% in 802.16e)
All $K$ users are ranged (well within CP length)

To mimic FDOSS

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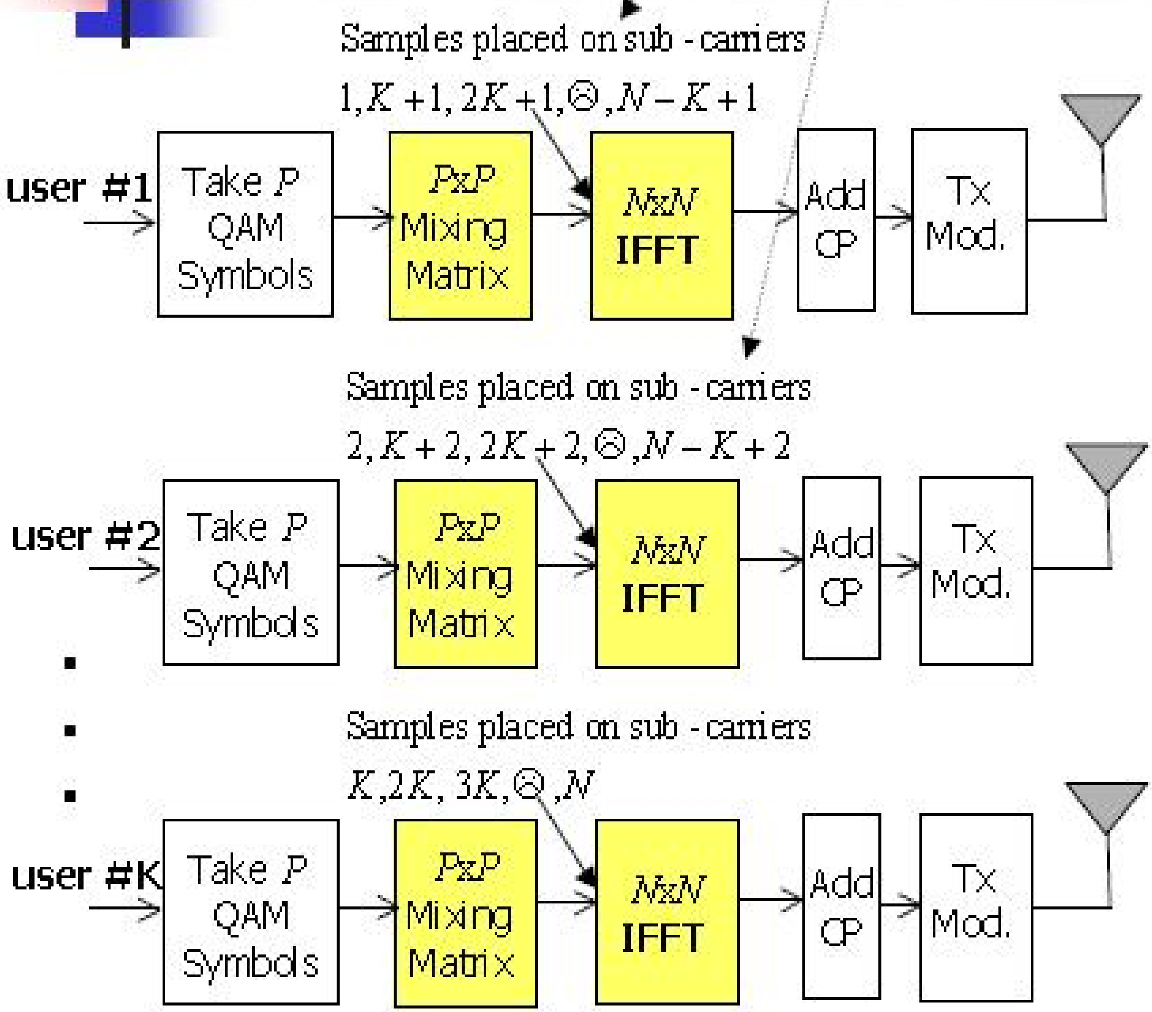
## Generalised MC – DFT-spread OFDMA (SC-FDMA)

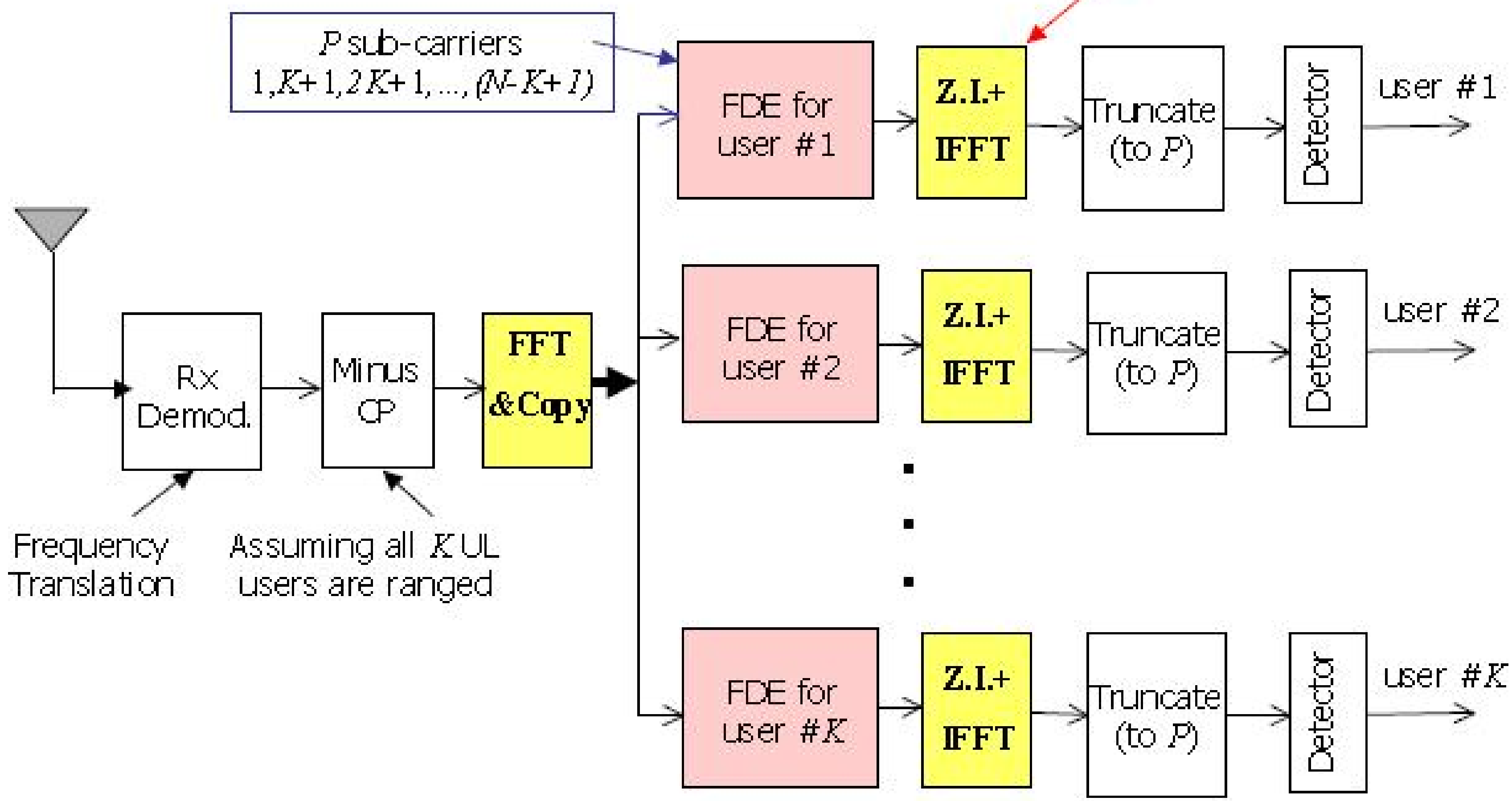



Let $KP=N$, where $N$ is FFT size,
$K$ – No. of uplink users
$P$ – No. of subcarriers per user

Mixing Matrix can simply be a $P$ point DFT matrix!

# F-DOSS: FDE at Base Station

Z.I.– Interleave with *K-1* zeroes to suppress noise



# I-FDMA to DFT-spread OFDMA -- Motivation

- **F-DOSS & I-FDMA** offer
  - Low PAPR (∴ better link margin compared to OFDMA)
  - Low Computational complexity
  - But, flexibility is limited
  - since each user stream goes thro uniformly spaced (*K*-spaced) subcarriers also called "frequency comb"
- **DFT spread OFDMA**
  - Some PAPR increase+ increase in computational complexity
  - But, ensures more flexibility
    - User stream can occupy any P out of N sub-carriers (like OFDMA)
    - Question: Does this "ensure" better CCI averaging in reuse-1 systems?

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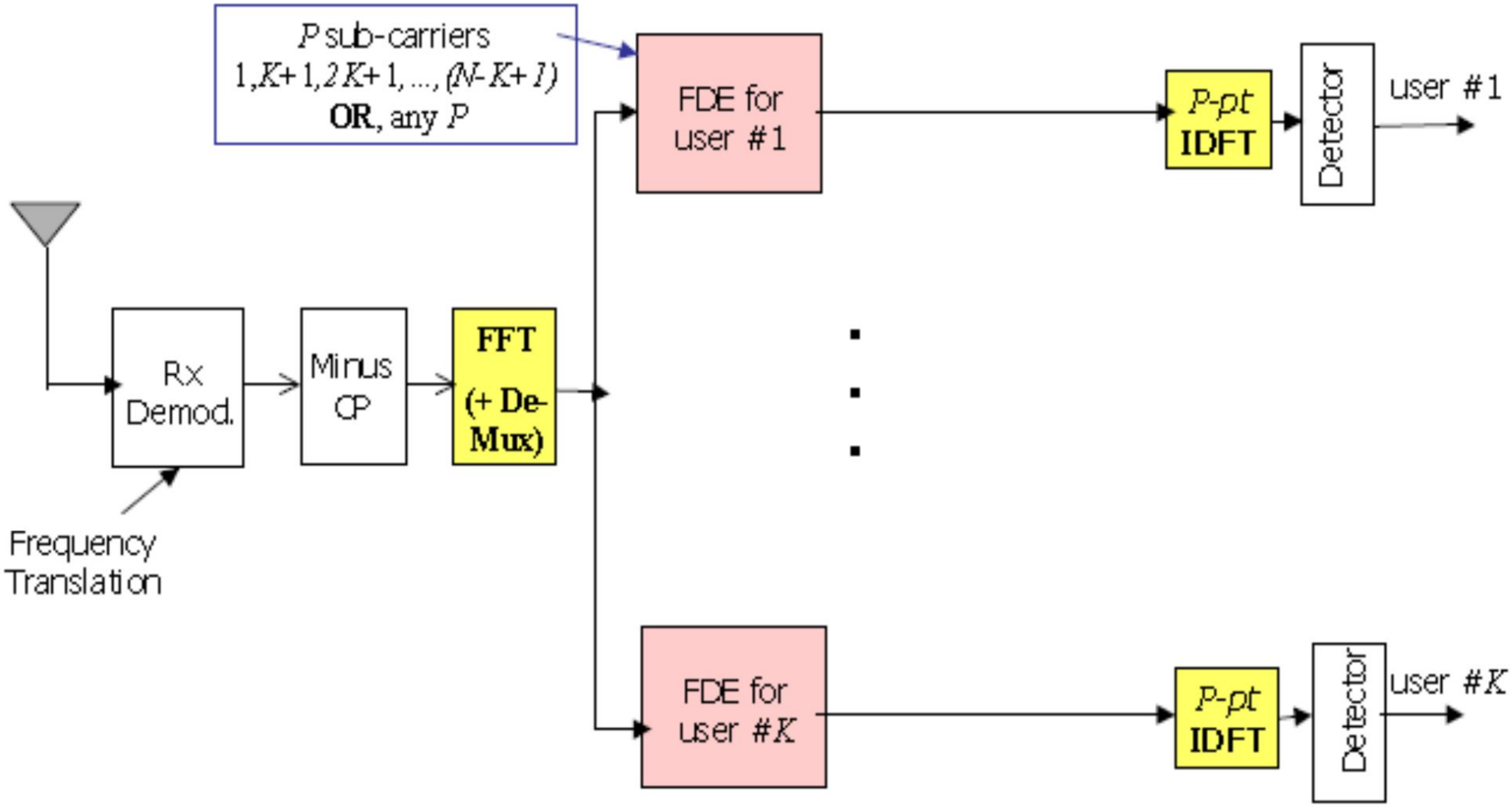
# **I-OFDMA:** FDE at Base Station



# Some key issue in SC-FDMA vs OFDMA

- **In coded GMC (SC-FDMA) and single-carrier systems**
  - Freq. domain equalisation is a must !
  - Noise enhancement could affect LLRs required for FEQ
- **In GMC techniques**
  - CE requires "lumped" pilots
  - While OFDM/OFDMA can use "embedded" pilots
- **How to track fast-fading channels ?**

- **What about Spatial Muxing on UL?**
  - Is ML receiver possible at low cost?

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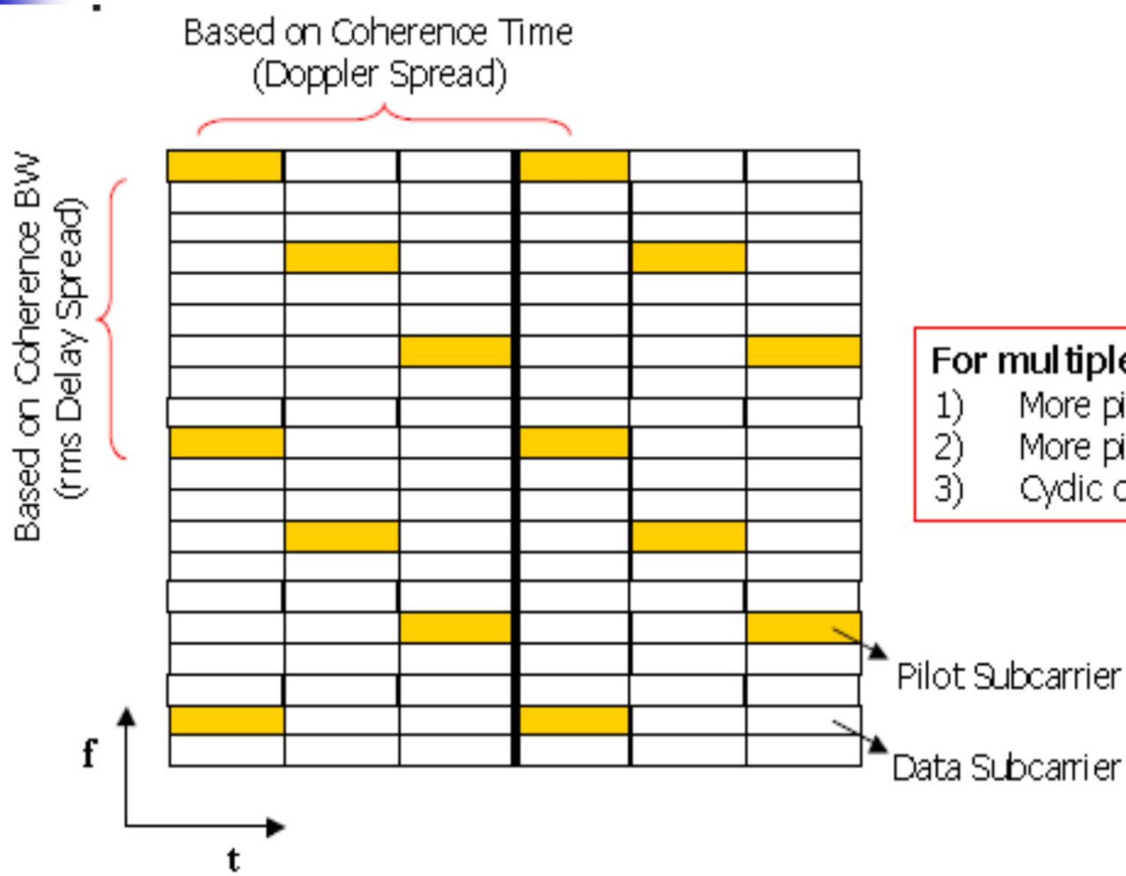
# B3. Case-study: Channel Estimation in WiMaX Downlink

# Pilot Subcarrier Placement




**For multiple Tx Antennas, either:**

1) More pilots by orthogonal allocation
2) More pilots by puncturing data
3) Cyclic delay diversity (delay by CP)

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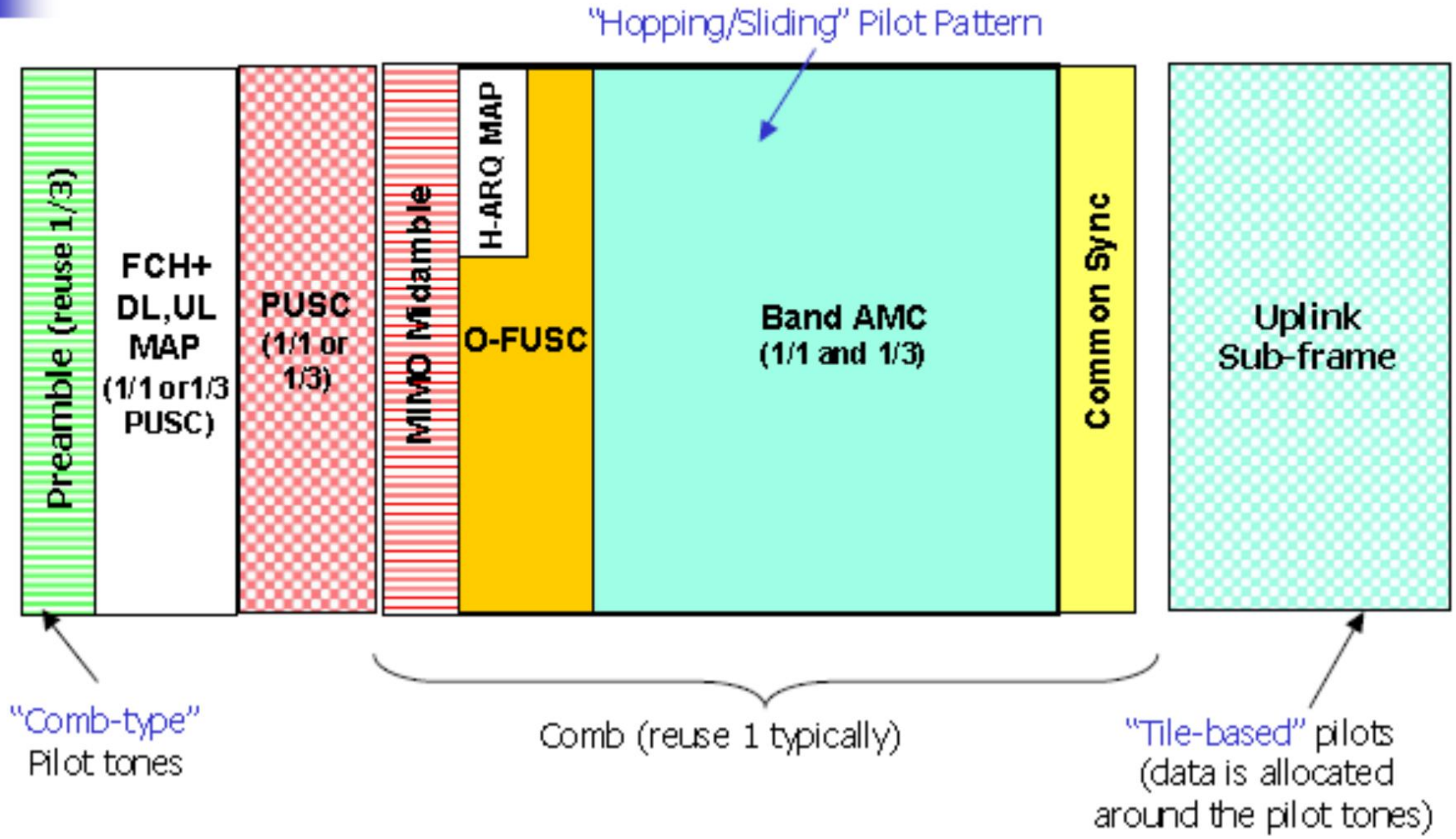
# 802.16e – Pilot Allocation Example



# ML and LS -- CFR Estimation

$\mathbf{Y}[k] = \mathbf{X}[k]\mathbf{H}[k] + \mathbf{W}[k]$, where $\mathbf{H}[k]$ is CFR

Dropping notation $k$ and if only $P$ pilots are available

$\mathbf{Y}_p = \mathbf{X}_{p\times p}\mathbf{H}_p + \mathbf{W}_p$, where noise $\mathbf{W}_p$ is AWGN

*ML Criterion*: $\min_{\hat{\mathbf{H}}_P} p(\mathbf{Y}_p - \hat{\mathbf{Y}}_P \mid \mathbf{X}_{p\times p})$, where $\hat{\mathbf{Y}}_P = \mathbf{X}_{p\times p}\hat{\mathbf{H}}_P$

Assuming (or approximating) $\mathbf{W}_p$ as white, ML reduces to LS problem

*LS Criterion*: $\min_{\hat{\mathbf{H}}_P} (\mathbf{Y}_p - \hat{\mathbf{Y}}_P)^H (\mathbf{Y}_p - \hat{\mathbf{Y}}_P)$, where $^H$ denotes Hermitian

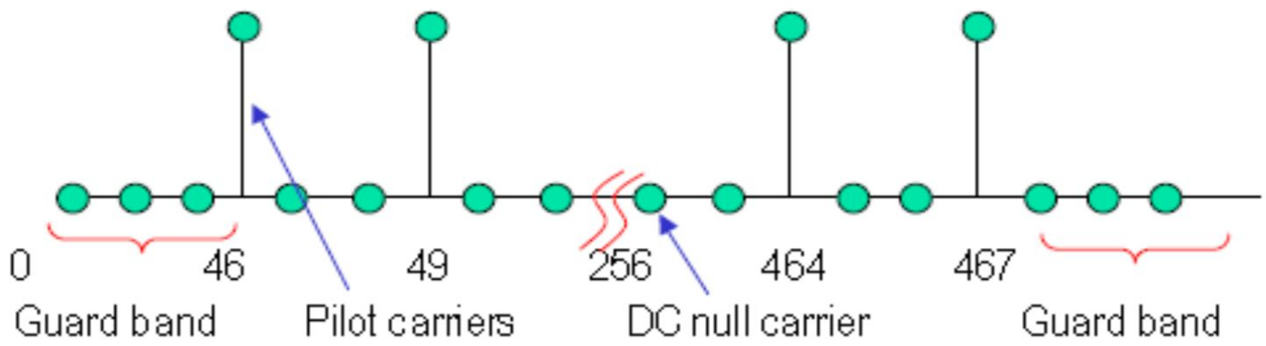
# **LS Estimation** – contd.

The LS problem $\min_{\hat{\mathbf{H}}_P} (\mathbf{Y}_P - \hat{\mathbf{Y}}_P)^H (\mathbf{Y}_P - \hat{\mathbf{Y}}_P)$ yields the well known LS/ML solution :

$$\hat{\mathbf{H}}_{LS,P} = \underbrace{(\mathbf{X}_P^H \mathbf{X}_P)^{-1} \mathbf{X}_P^H}_{\text{Pseudo-Inverse of } \mathbf{X}_P} \mathbf{Y}_P \Rightarrow \frac{Y[n]}{X[n]}, n \in P$$

For the other $N - P$ data subcarrier locations, linear/spline or other interpolation techniques are used to determine $\hat{\mathbf{H}}$

# **PUSC Example --** Preamble and Pilot Patterns (N=512)



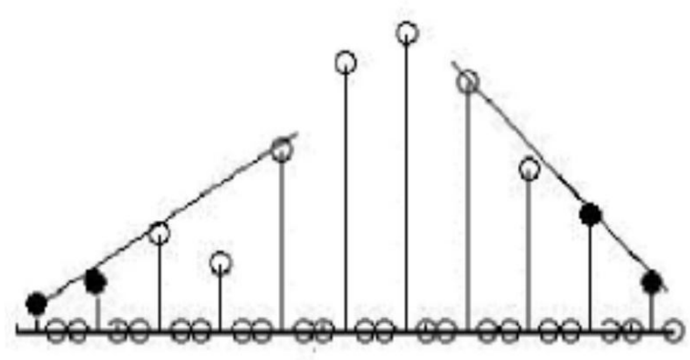

**"Well known" Channel Estimation Schemes (freq. / time):**

1) LS + Linear Interpolation
2) 2D-MMSE
3) LS + FFT based Interpolation

# CE Example: Preamble of 802.16d/e

## FFT Based Interpolation – with Windowing

- **Initially make an LS estimate on pilot tones**
- **Extrapolate LS estimate into guard bands by fitting a line through estimates near the edge**



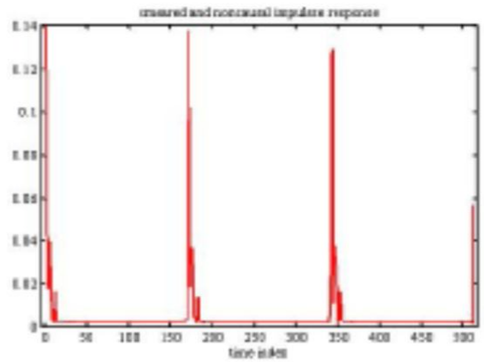
$$W[n] = \beta - (1-\beta)\,Cos\left(2\pi \frac{n}{N-1}\right), n = 0,1,\ldots N-1,$$

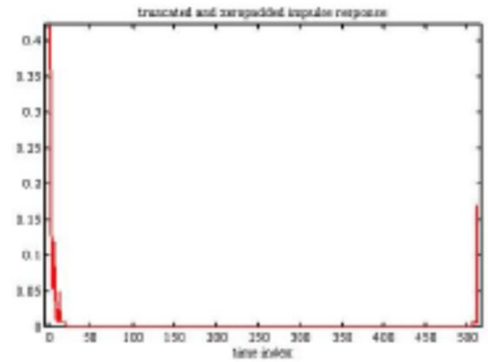
and Hamming window parameter $0 \le \beta \le 1$

**To reduce TD leakage -- apply a window function (say, Hamming window) before taking IFFT**

# **FFT Based Interpolation** – contd.1

- **We get a smeared and non-causal impulse response**





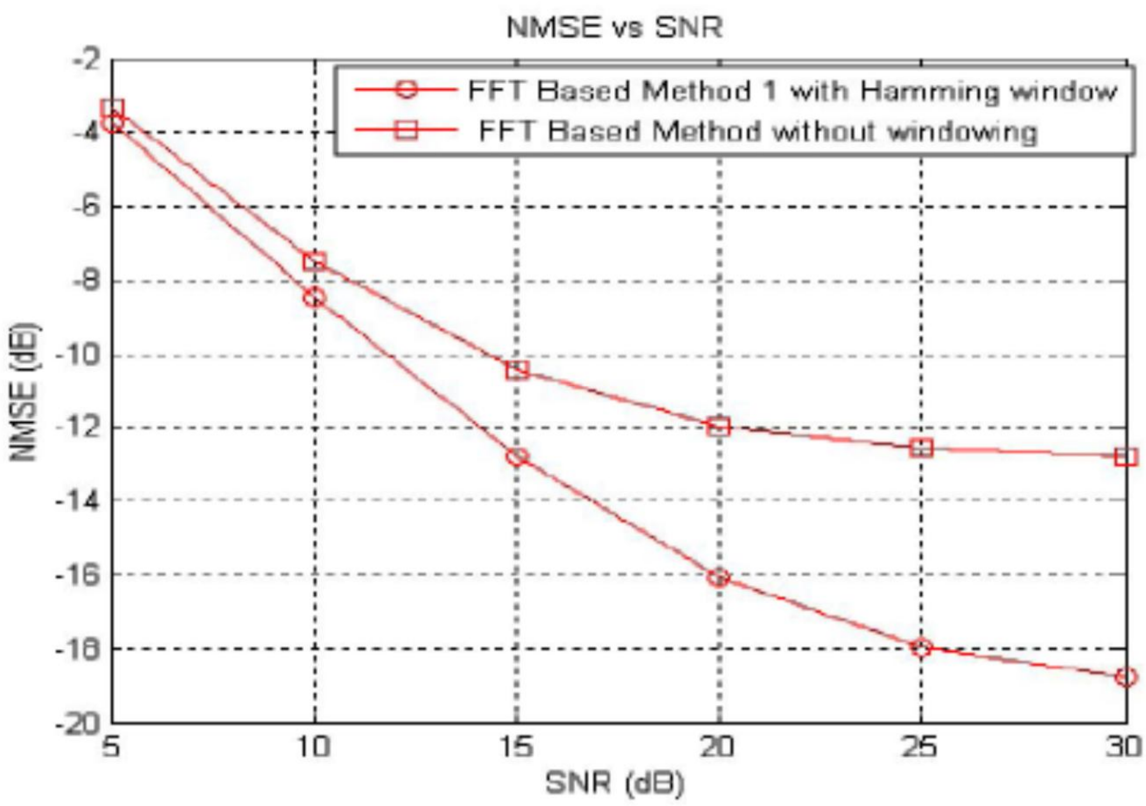
- **Keep first *L* samples and last $L_1$ samples and fill remaining samples with zero**

  - **Select *L* based on the maximum tap delay (or pdp) of channel**

  - **Choice of $L_1$ depends on the tap weight of first tap**

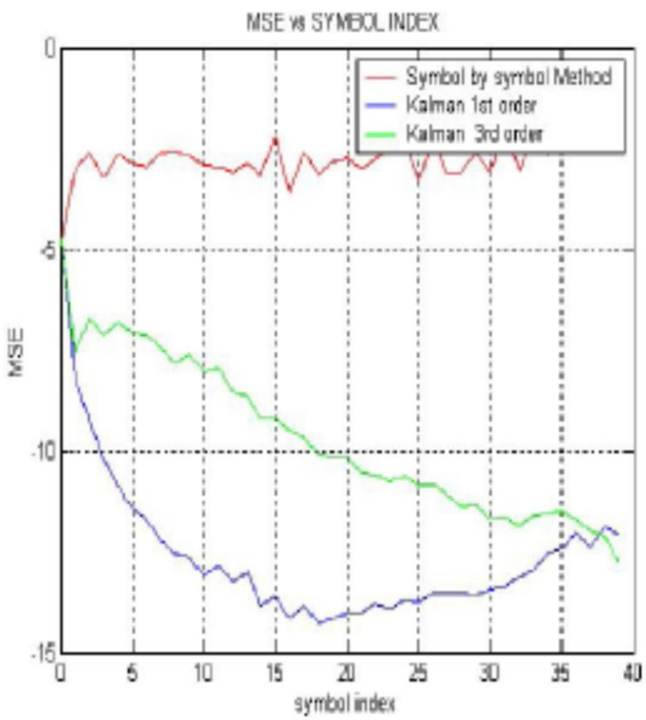
- **Take FFT and unwindow it to get the final estimate $\hat{H}[n]$**

# NMSE with and without windowing
-- in FFT based Interpolation

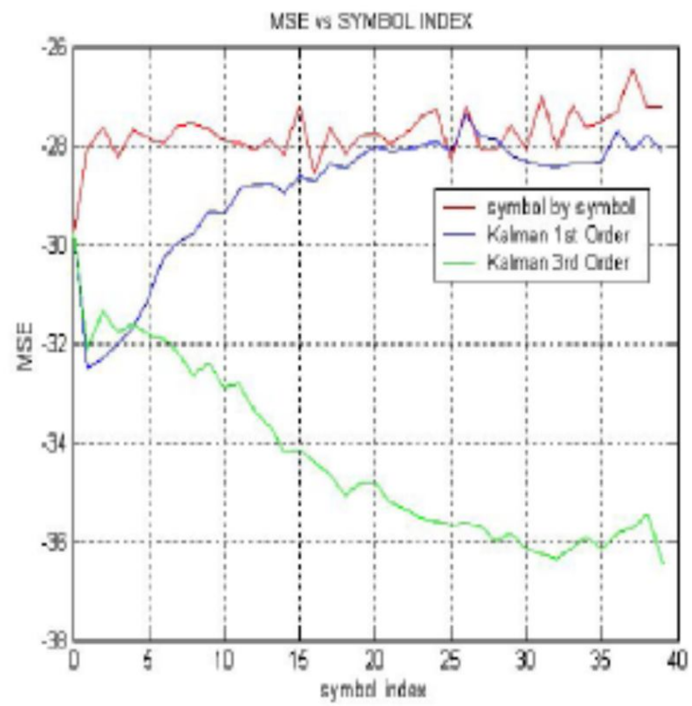


# NMSE vs Symbol Index with 1st order and 3rd order AR Model -- for **10Hz** Doppler

SNR = 0dB




SNR = 25 dB



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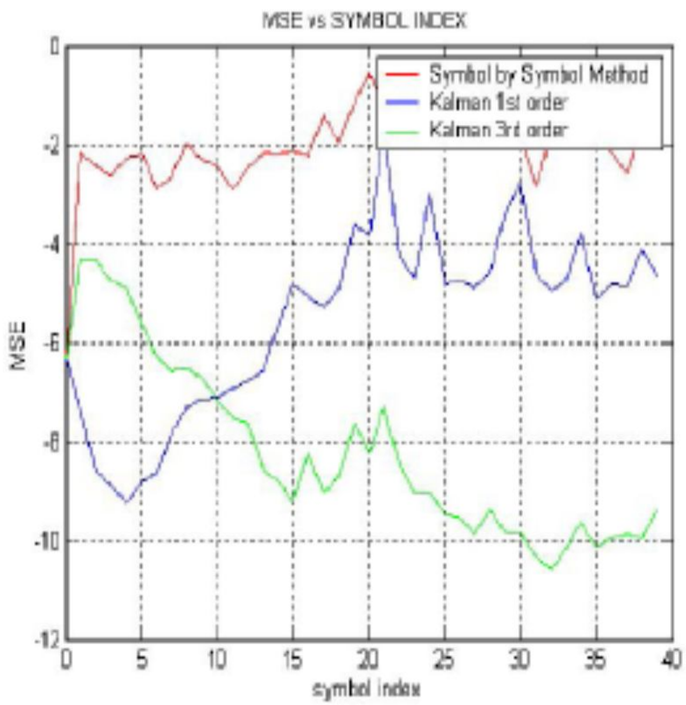
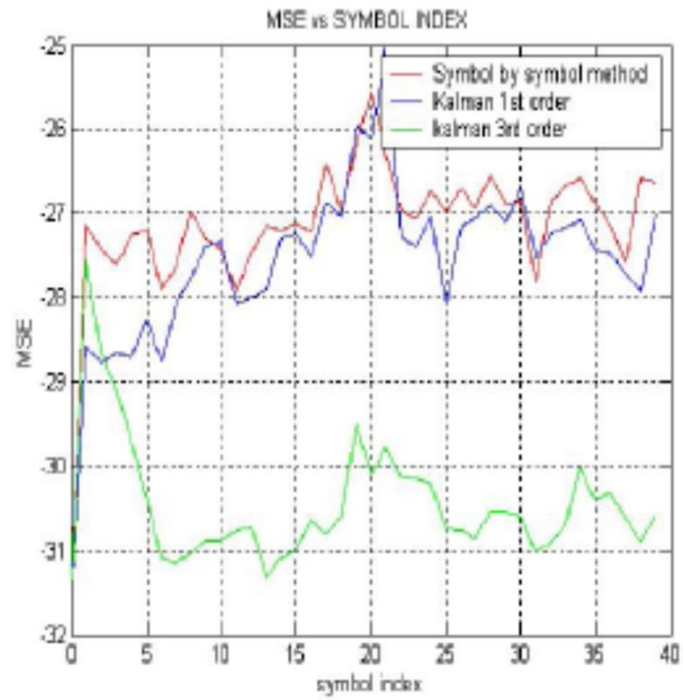
# NMSE vs Symbol Index with 1st order and 3rd order AR model -- for **70Hz** Doppler

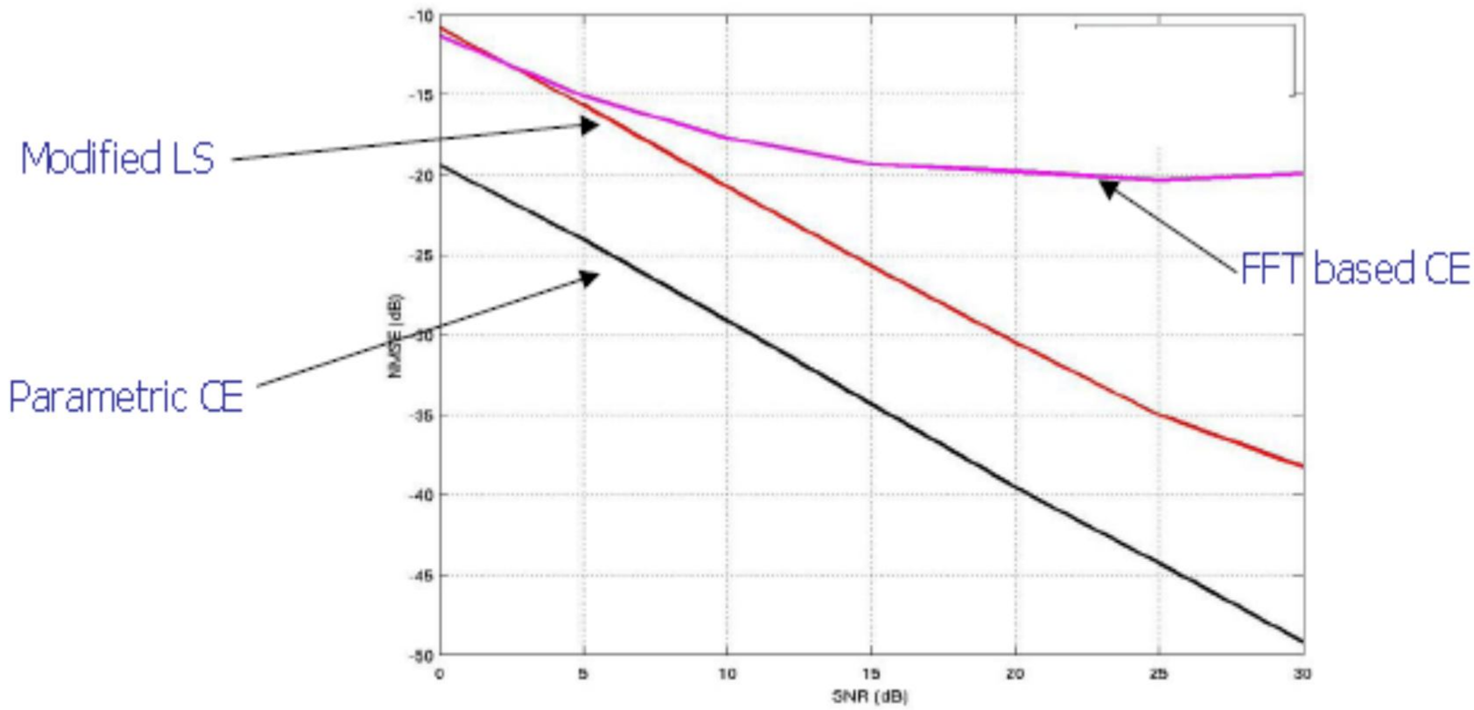
SNR = 0dB




SNR = 25 dB



# Channel Estimation – Ridiculous to the Sublime



# B4. Key Issues in Cellular OFDM/OFDMA

# Sources of Distortion in OFDM/OFDMA

- **Impact of the following on measurement model**
  - Additive, band-limited noise
  - RF distortion (I-Q imbalance, clipping, IM, etc)
  - Frequency offset
  - Timing error
  - In Mobile Broadband Cellular OFDM/OFDMA, we have
    - Delay spread
    - accentuated due to large band-width
    - Doppler spread
    - due to mobility
    - Co-channel interference
    - due to cellular nature

# Interference Management is the Key!

- Co-channel interference (CCI) in OFDM needs to be managed at
  - Antenna level (using multiple antennas)
  - Channel processing level (interference aware CE)
  - Detection level (interference nullers/combiners)
  - Decoding level (CCI aware decoders)
  - MAC level
  - Scheduler level
  - Co-operative communications

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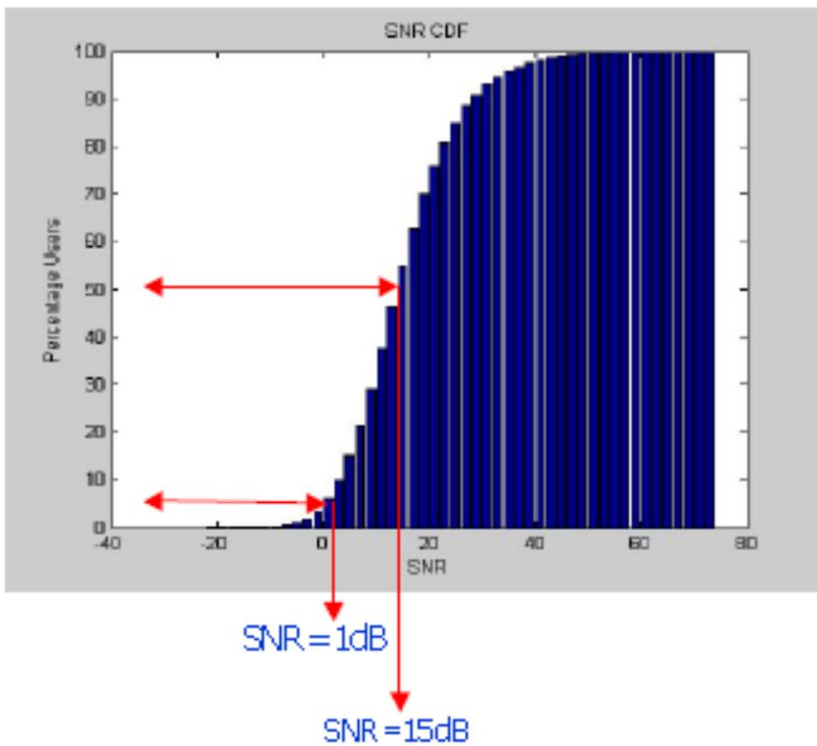
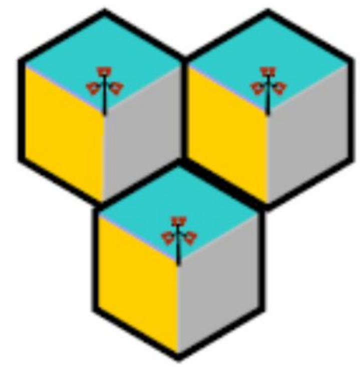
# CDF of SNR for Reuse-1/3 Cellular



**Reuse 1/3**

-- 75% of users have SNR>10dB
-- Only 3% gave SNR < 0dB
-- Highest SNR can be ~ 35dB
-- Similar to single-cell deployment

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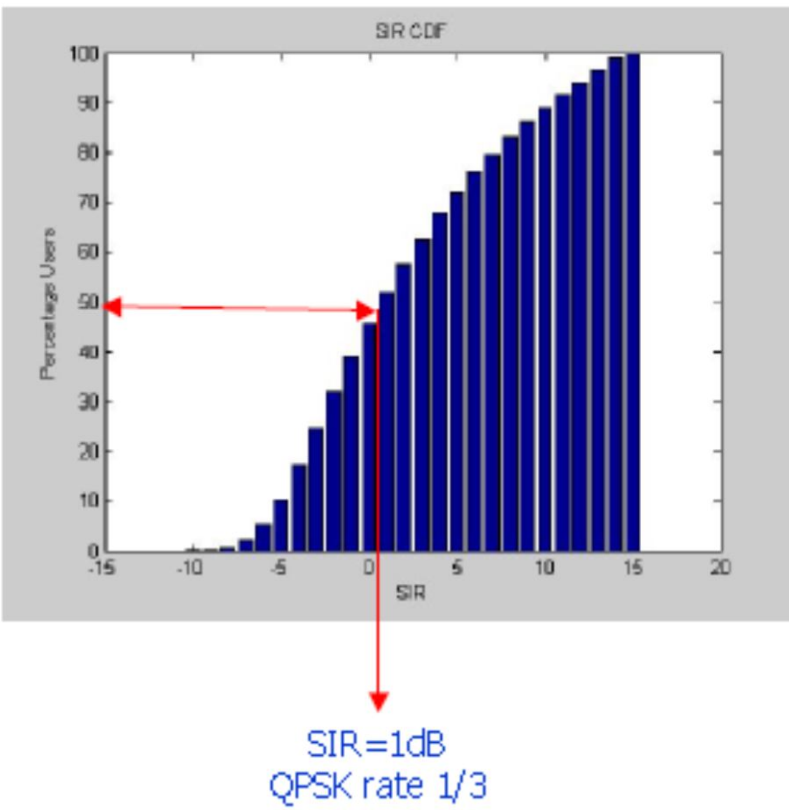
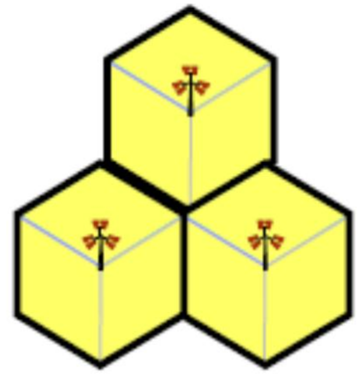
# CDF of SIR for Reuse-1/1 Cellular



**Reuse 1/1**

Nearly 50% of users have SIR < 0dB
Highest SIR is only 15dB
About 35% of users see one strong CCI

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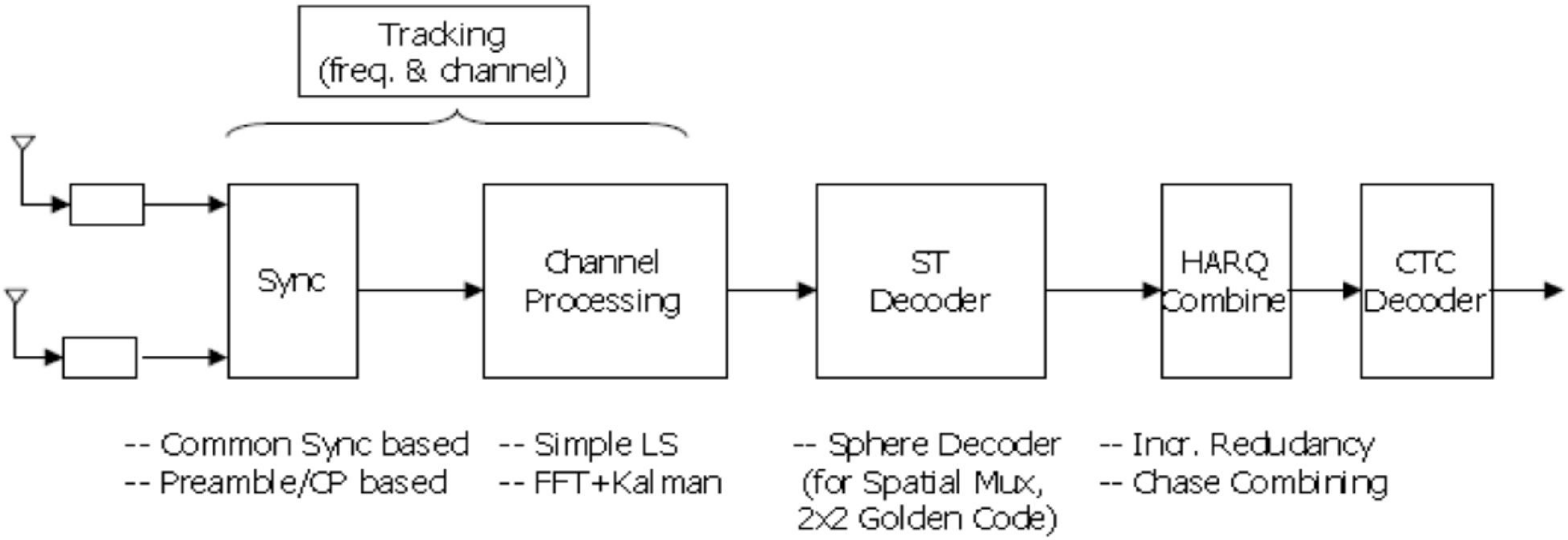
# **Downlink Rx** (Mobile Station)




CCI in Reuse-1 OFDMA can affect
all these algorithms severely!

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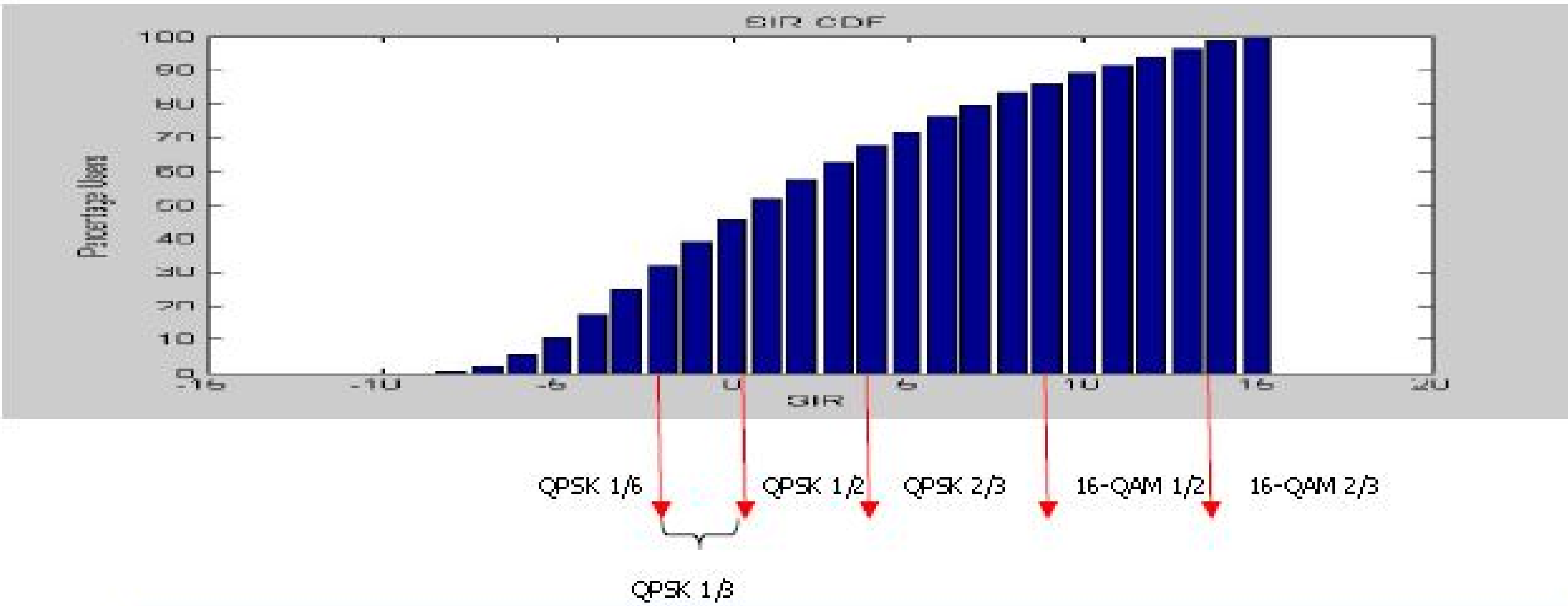
# Impact on System Capacity

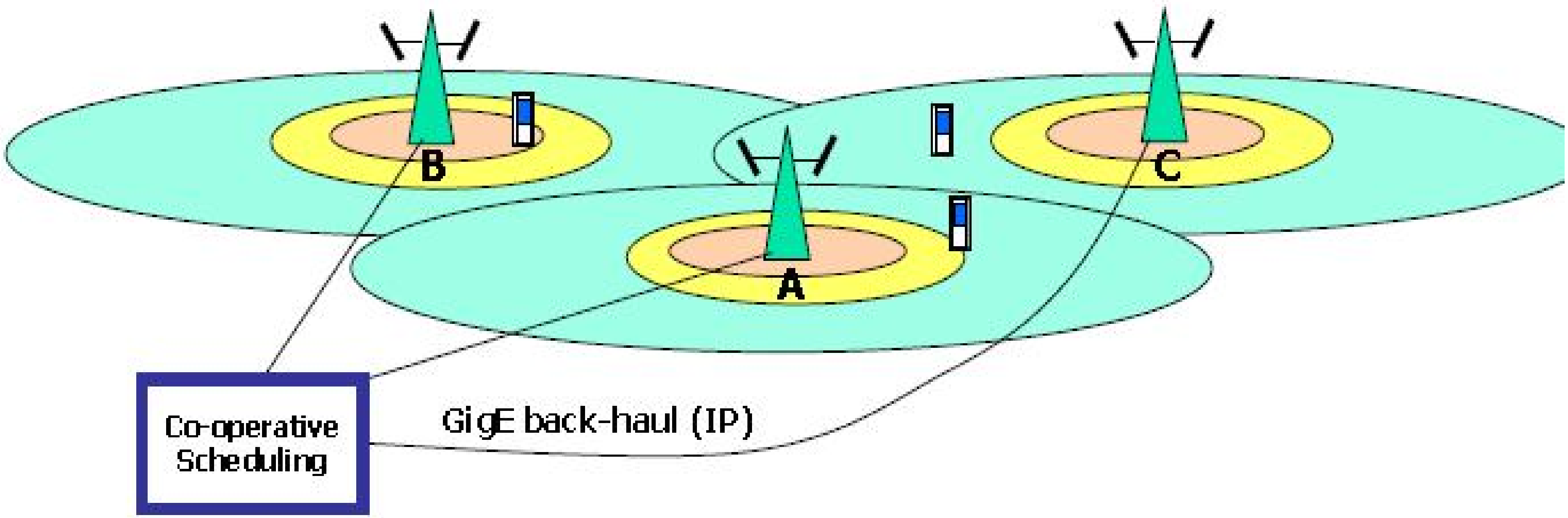



0x5%+1/3x15%+2/3x20%+1x20%+4/3x20%+2x15%+8/3x5% = 1.07 bits/sec/Hz;
(this should be typical with non-ideal channel estimation etc.)

Wimax Document (Feb'06) claims for DL 2x2 1.8-2.0, and UL 2x2* 0.7-1.0 ; (17+2 in 10MHz)
* -- when 2 users co-operate in Spatial Muxing on UL

# Broadband Wireless Research – **Multi-cell R&D**

- Interference Management is possible using BS co-operation
- Exploit IP back-haul to BS; Semi-centralised "upper MAC"



# B5. Example – Link Budget for 802.16d/e

# (to be developed "live")

# Summary of Part B

- **OFDM Fundamentals and Overview of Cellular OFDM**
  - B1. What and Why of OFDM
  - B2. Other Block Modulation Schemes
  - B3. Case Study: Channel Estimation in WiMaX DL
  - B4. Key Issues in Cellular OFDM/OFDMA
  - B5. Example: Communication Link Budget – 802.16d/e

- **What is IMT-advanced going to be?**
  - Spectrum identified in WRC-2007
  - IMT-A to be ratified by middle of 2010

# Some Learnings about 802.16m & LTE-A

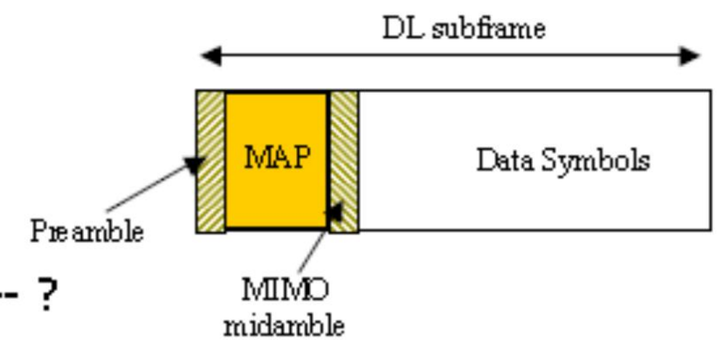
- Air interface –
  - Downlink : OFDM/OFDMA, TDD and FDD
  - Uplink : OFDMA and SC-FDMA ?
  - "Mandatory" : Packet Switching, Turbo/LDPC with HARQ, 2x2
  - Baseline, Mobility support, do better than IMT-A requirements
  - Multiple antenna techniques include:
    - Virtual antenna and/or STBC, STFC
    - Single user (SU) Spatial Mux and DL, Multi user (MU) SM on UL
    - Precoding (Open-loop, Closed-loop, SU, MU)
    - Co-operative MIMO
    - Relaying
  - "Optional" : Co-operative Relaying, Ad-hoc modes, >4 Tx Ants per sector at BS, >2 Tx Ants at MS
- Fundamental air-interface issues are currently being discussed

# Issues in/with BWA Standards (LTE & WiMaX)

- Pilot sub-carriers can be
  - Localised or Distributed
  - At cell-edge, 'pilots-on-pilots' OR 'pilots-on-data'

- Data sub-carriers can be
  - No power control; e.g., MAP symbols
  - With power control → fractional freq. reuse (FFR)

- What will preamble enable?
  - Easy synchronisation – Y
  - Better coverage -- ?
  - MIMO training -- ?
  - Interference measurements -- ?



# User Requirements – Indian Perspective

- Based on the unified views expressed by the various cellular operators of India
  - Broadband Wireless Consortium of India (**BWCI**)
  - A strategic initiative of Centre of Excellence in Wireless Technology(**CEWiT**)
- BWCI has enunciated the service and technology requirements for India which IMT-A should address
  - please also see http://www.cewit.org.in/docms/ibwsi.pdf
- Requirements reflect the fact that wireless access will the only way by which broadband can reach 100million+ Indian users!

# Indian Scenario – contd.

- Serve about 900 subscribers/cell/per operator that covers different market segments
- Cell radius varying between 100m and 20 Km
- Provide broadband services with limited spectrum per operator
  - FDD 10+10=20MHz per operator
  - TDD with 20MHz per operator (with sync between operators)
- Nearly 85% of the subscribers will be nomadic and indoors
- Need a minimum useful capacity per cell (per op.) of about 100 Mbps DL and 40 Mbps UL

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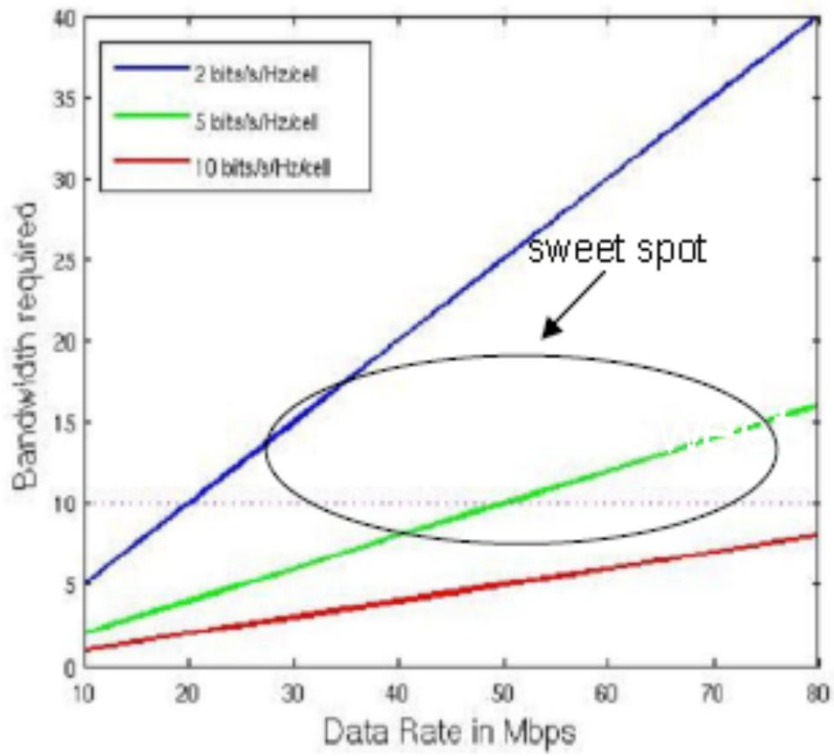
## Usage and Capacity




Example: With a FDD bandwidth of 10+10 MHz, spectral efficiency required is:

DL → 100/10 = 10 bits/sec/Hz/cell

UL → 40/10 = 4 bits/sec/Hz/cell

} Avg. ~ 7 to 8 bits/sec/Hz/cell

# Reading Material

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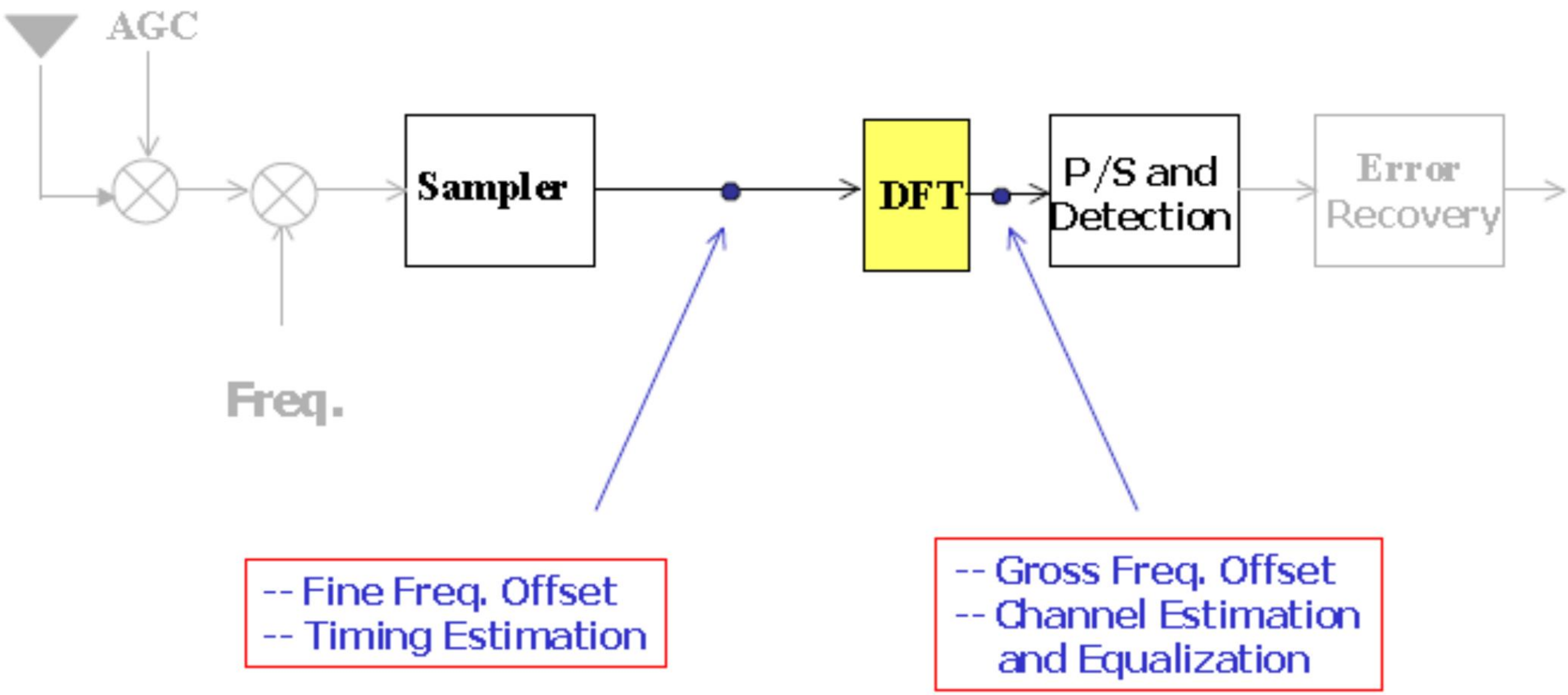
**www.ee.iitm.ac.in/~giri**

# OFDM Receiver Algorithms -- **Recap**



# Impact of Large Freq. Offset (Δf)

$$\hat{d}_{k,i} = H_{k,i} d_{k,i} + n_{k,i}$$

$$\hat{d}_{k,i} = e^{j2\pi k \Delta f T_s} H_i d_{k,i} \frac{\sin(\pi \Delta f T)}{N \sin(\pi \Delta f T / N)} e^{j\pi \Delta f T (N-1)/N} + I_{k,i} + n_{k,i}$$

# Residual Carrier Frequency offset

- Preamble can be used to estimate and compensate for the carrier freq offset during the initial synchronization procedure
- If the residual freq offset is assumed to be much smaller compared to subcarrier spacing,then at $i^{th}$ subcarrier

$$\hat{d}_{k,i} \approx e^{j2\pi k\Delta f T_s} H_{k,i} d_{k,i} + n_{k,i}$$

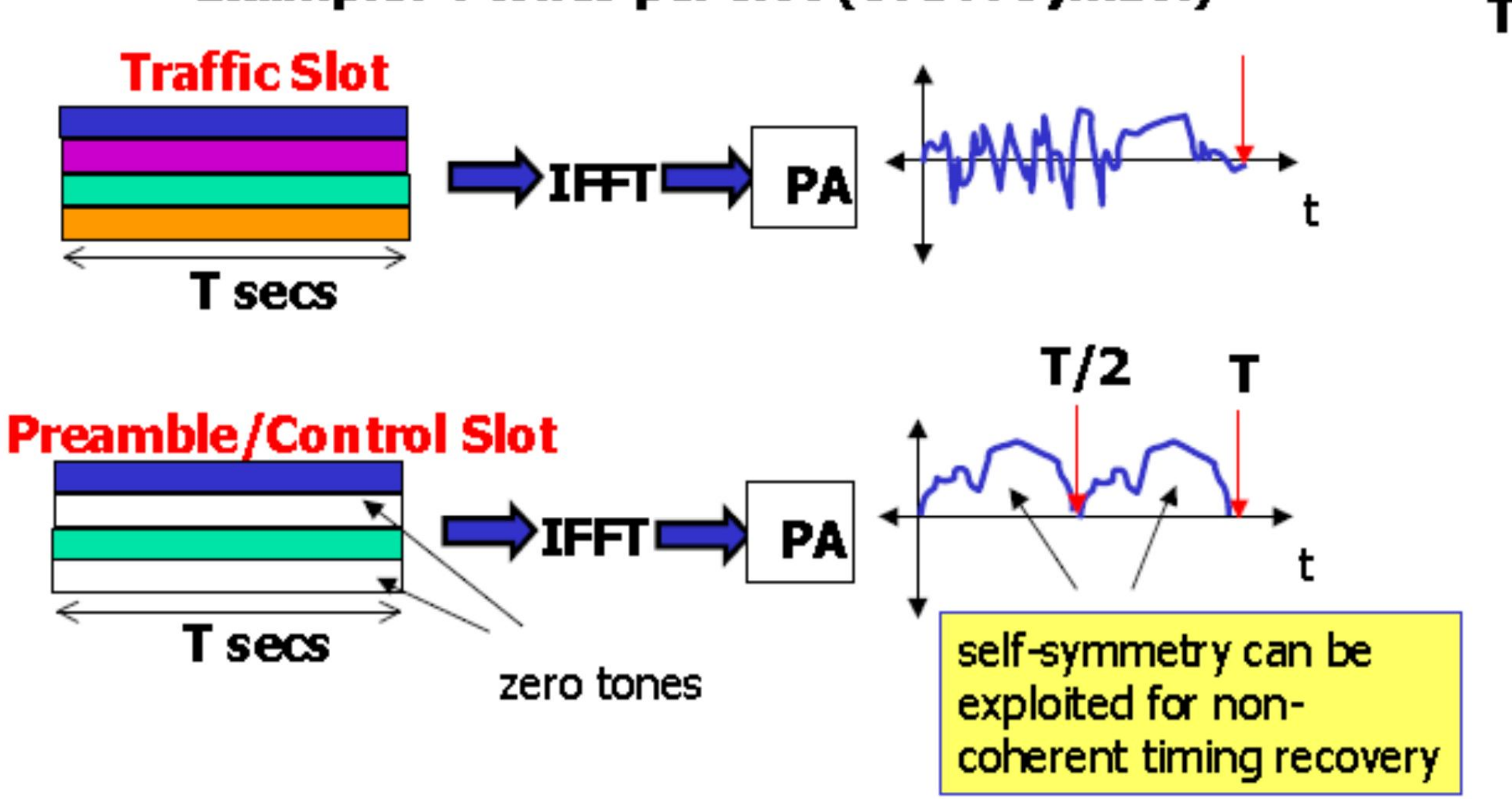
- **Constant phase shift in all sub carriers**
- **This offset is tracked using known pilot symbols in every OFDM symbol**

# Frequency Offset

- **Carrier recovery and tracking critical for OFDM**
  - Offsets can be comparable to sub-carrier spacing in OFDM
  - Non-coherent detectors possible with differential coding
- **Residual freq. offset causes**
  - constellation rotation in TDMA
  - loss of correlation strength over integration window in CDMA (thereby admitting more CCI or noise)
  - increased inter-channel interference (ICI) in OFDM
- **OFDM can easily compensate for gross freq. offsets** (offsets which are an integral multiple of sub-carrier width)

# Slot and Timing Synchronization in OFDM

**Example: 4 tones per slot (OFDM symbol)**



# Impact of Sampling Clock Offset

- Sampling frequency offset induces time-variant timing offset
  - **Varies slowly across several frames, usually**
  - **Let $\tau_k$ be the timing offset of $k^{th}$ OFDM symbol**
  - **The induced phase rotation is proportional to the sub-carrier index "$i$"**
    - **When the timing offset exceeds the sampling interval, the FFT window needs to be shifted.**
    - **Known pilot symbols in every OFDM symbol are again used to track this offset**

$$\hat{d}_{k,i} \approx e^{j2\pi i \tau_k / N} H_{k,i} d_{k,i} + n_{k,i}$$

# Timing Synchronisation

- **Timing recovery (at symbol level) is easily achieved in OFDM systems**
  - Can easily overcome distortions from delay spread
  - Can employ non-coherent timing recovery techniques by introducing self-similarity
    - => very robust to uncompensated frequency offsets
  - If cyclic prefix is larger than the rms delay spread, range of (equally good) timing phases become available
    - => robust to estimation errors

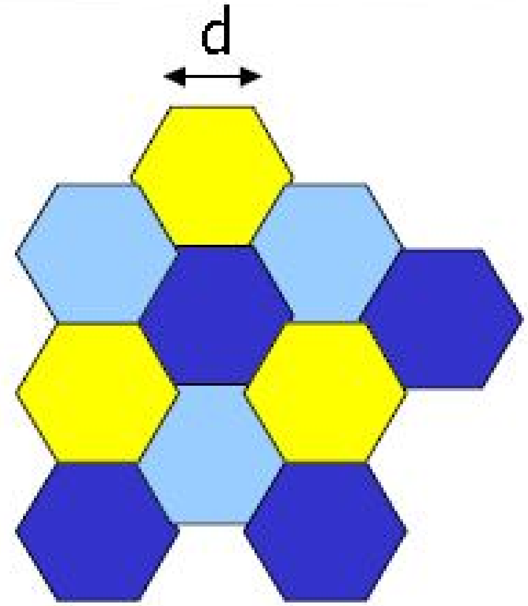
# Comparing Complexity
(of TDMA, DS-CDMA, & OFDM Transceivers)

| | TDMA | CDMA | OFDM |
|---|---|---|---|
| Timing Sync. | Easy, but requires overhead (sync.) bits | Difficult, and requires sync. channel (code) | Very elegant, requiring no extra overhead |
| Freq. Sync. | Easy, but requires overhead (sync.) bits | More difficult than TDMA | Gross Sync. Easy<br>Fine Sync. is Difficult |
| Timing Tracking | Modest Complexity | Complexity is high in Asynchronous W-CDMA | Usually not required within a burst/packet |
| Freq. Tracking | Easy, decision-directed techniques can be used | Modest Complexity (using dedicated correlator) | Modest complexity |
| Channel Equalisation | Modest to High Complexity (depending on bit-rate and extent of delay-spread) | RAKE Combining in CDMA usually more complex than equalisation in TDMA | FDE is arguably easy – but careful choice essential |
| Analog Front-end (AGC, PA, VCO, etc) | Very simple (especially for CPM signals) | Fairly Complex (power control loop) | Complexity or cost is very high (PA back-off is necessary) |

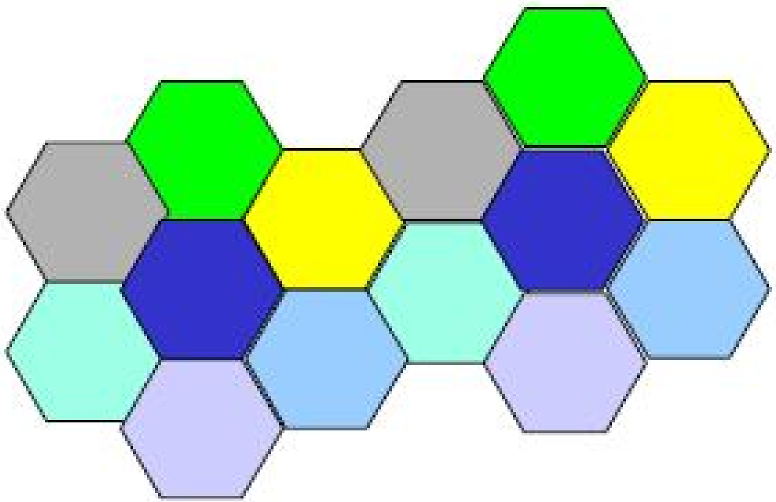
# Comparing Performance
## (of TDMA, DS-CDMA, & OFDM Transceivers)

| | TDMA | CDMA | OFDM |
|---|---|---|---|
| Fade Margin (for mobile apps.) | Required for mobile applications | Modest requirement (RAKE gain vs power-control problems) | Required for mobile applications |
| Range | Very easy to increase cell sizes | Range increase by reducing allowed noise rise (capacity) | Difficult to support large cells (PA , AGC limitations) |
| Re-use & Capacity | Modest (in TDMA) and High in MC-TDMA | Modest | Re-use planning is not crucial, but will help |
| FEC Requirements | FEC optional for voice | FEC is usually inherent (to increase code decorrelation) | FEC is vital even for fixed wireless access |
| Variable Bit-rate Support | Low to modest support | Very elegant methods to support VBR & VAD | Powerful methods to support VBR (for fixed access) |
| Spectral Efficiency | Modest | Poor to Low | Very High **(& Higher Peak Bit-rates)** |

# Cellular Fundamentals




7-cell Re-use

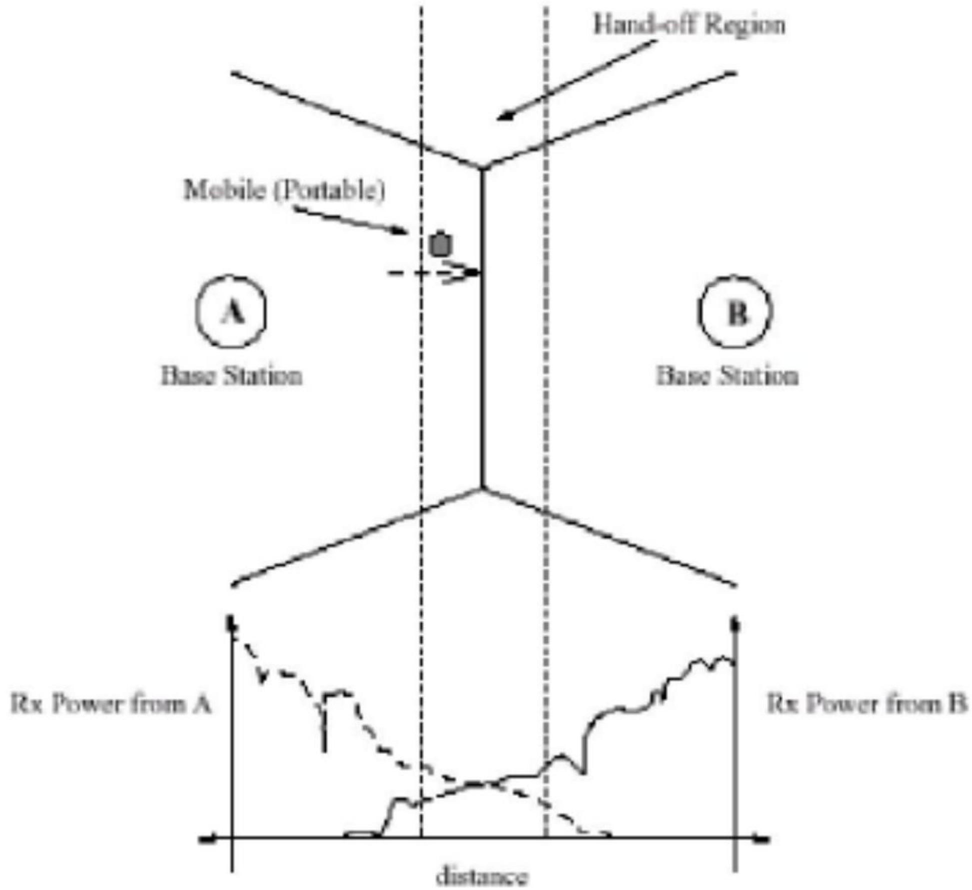


3-cell Re-use

Most Common : 7-cell, 4, 3, and 1-cell re-use
Re-use Distance: sqrt(7d), sqrt(4d), d, 0

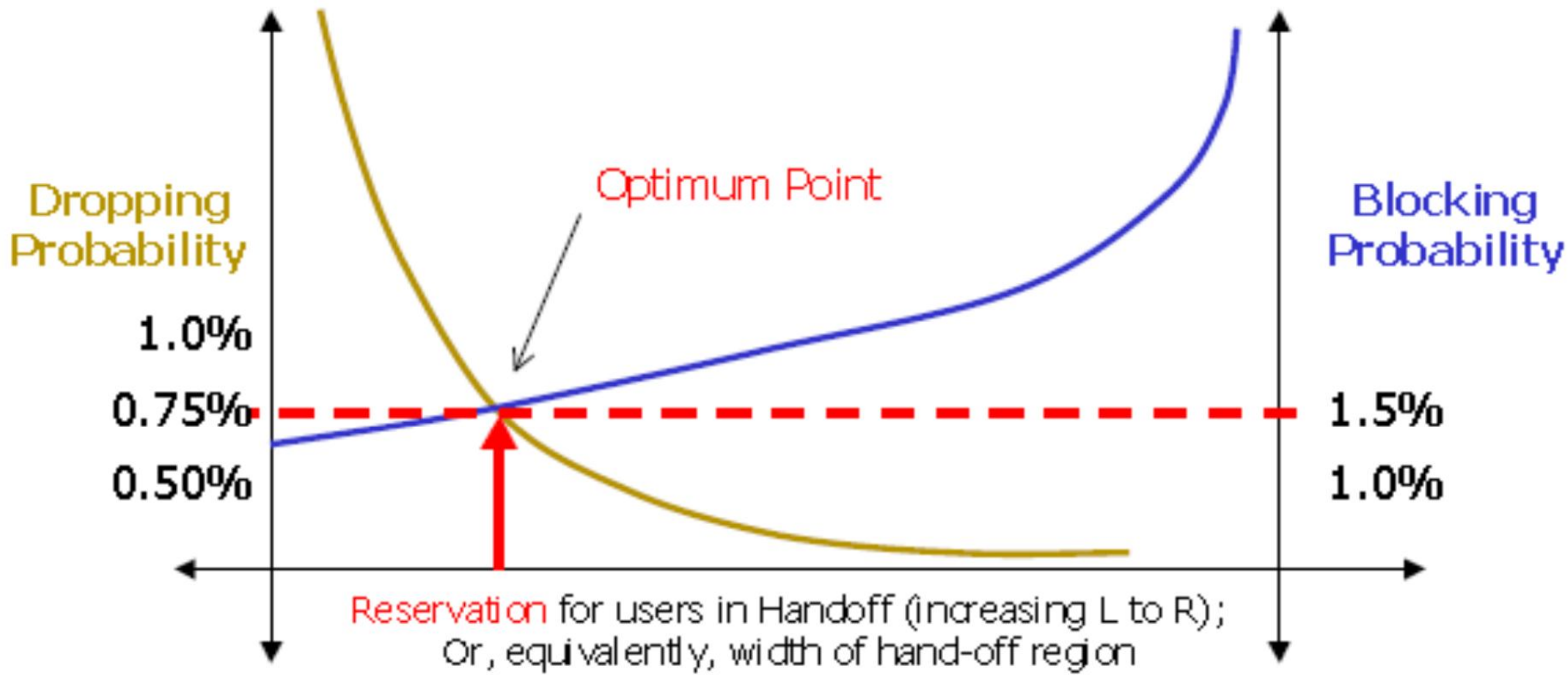
DS-CDMA:
Universal Reuse

# Handoff between Cells

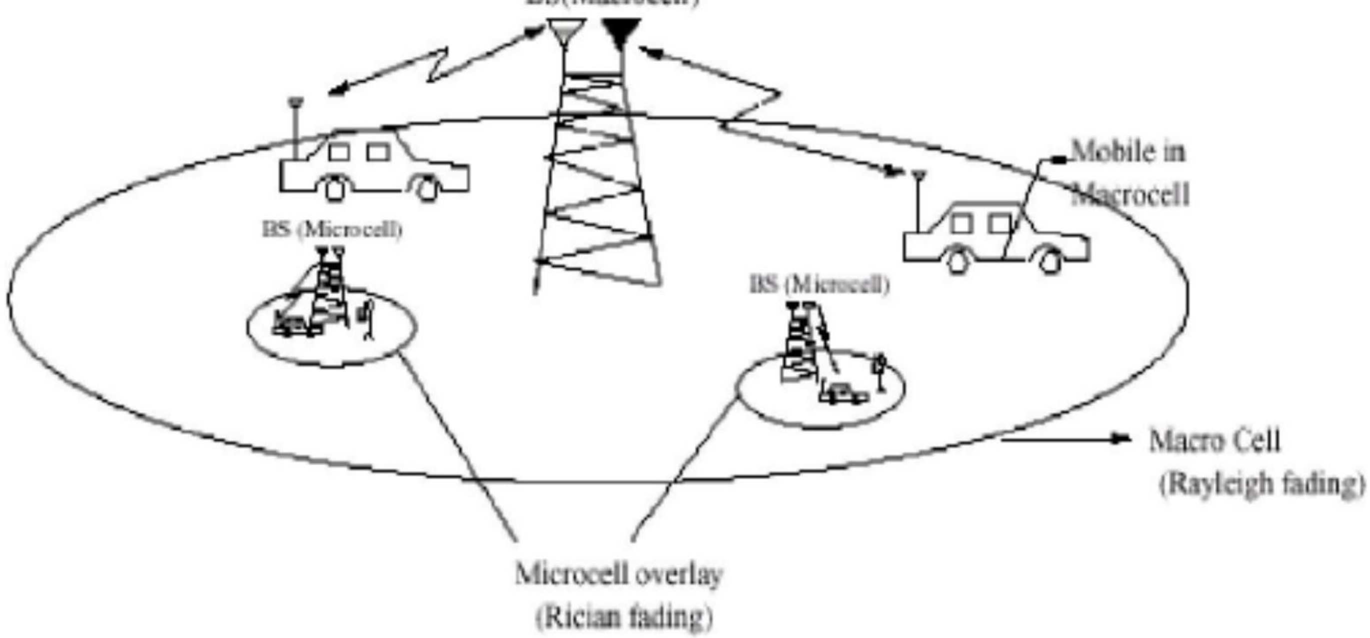


# Handoff between Cells -- contd.

- Many techniques have been proposed to optimize the trade off between dropping and blocking probabilities



# Overlay of Micro on Macro Cells




- Overlays could increase capacity;

  Alternatively, repeaters can increase coverage

## Spectral Efficiency of 2G Standards

| | Name | Bandwidth | Bit-rate | Efficiency |
|---|---|---|---|---|
| macro | IS – 136 | 30 KHz. | 48.6 Kbps | 1.62 |
| macro | GSM | 200 KHz. | 270.8 Kbps | 1.35 |
| macro | IS – 95 | 1.25 MHz. | 9.6 Kbps | 0.007 **x N users** |
| micro | CT2 | 100 KHz. | 72 Kbps | 0.72 |
| micro | DECT | 1.728 MHz. | 1.152 Mbps | 0.66 |
| | PHS | 300 KHz. | 384 Kbps | 1.28 |

☆ **IEEE 802.11b -- 1/22 to 11/22 = 0.045 to 0.50; 802.11a -- 54/20=2.70 bits/s/Hz**

Multi-antenna techniques can yield much higher spectral efficiencies

# A (the?) Golden Rule

- What is a fair yard-stick to compare various wireless communication standards ?
- Number of bits/sec/Hz per-cell site for a given QoS
  - "Cherry-picking" of good users should be avoided
  - Careful system-level simulation studies are required
- It is also essential to bring in cost (per connection)

# Factors Affecting Golden Rule

- **Co-channel Interference**
  - in TDMA/FDMA -- this determines the re-use distance, and thereby, system capacity
  - in CDMA -- this determines the number of users that can be supported by a single base-station
- **Control Overheads**
  - gross bit-rate versus actual pay-load
  - more control overhead could give more deployment flexibility and/or more services

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# TDMA, CDMA, and OFDM based Standards

- **Time Division Multiple Access (TDMA) is the most prevalent wireless access system to date**
  - GSM, ANSI-136, EDGE, DECT, PHS, Tetra
- **Direct Sequence Code Division Multiple Access (DSCDMA) became commercial only in the mid 90's**
  - IS-95(A,B,HDR,1x…),cdma-2000(3GPP2), W-CDMA (3GPP)
- **Orthogonal Frequency Division Multiplexing (OFDM) is new kid to the wireless block**
  - IEEE 802.11g,n, UWB
  - IEEE 802.16d/e, IEEE 802.20
  - 3GPP LTE, 3GPP2 Rev.C, 802.16n, Advanced IMT-2000,….