$x(t) \longrightarrow \boxed{h(t)} \longrightarrow y(t) = x(t) * h(t)$; $h(t)$ wireless channel

$h(t) = \sum_{i=0}^{L-1} a_i\, \delta(t-\tau_i) \rightarrow$ due to scattering

$y(t) = Re\left\{ \sum_{i=0}^{L-1} s_b(t-\tau_i)\, a_i\, e^{j2\pi f_c \tau_i} \cdot e^{j2\pi f_c t} \right\}$

complex base band representation of $y(t)$

Narrow band assumption: $f_m < \frac{1}{\tau_i} \Rightarrow s_b(t-\tau_i) \approx s_b(t)$

$\Rightarrow y_b(t) = s_b(t) \cdot \sum_{i=0}^{L-1} a_i\, e^{-j2\pi f_c \tau_i}$ → complex fading coefficient (h)

fading: variation of power w.r.t time

$h = X + jY = a\, e^{j\phi}$

$X, Y \sim \mathcal{N}(0, 1/2)$; $f_A(a) = 2a\, e^{-a^2}$; $\phi \sim unif(-\pi, \pi)$

- To get knowledge of 'h' it must be measured atleast once every coherence time
- measuring/estimating h is called channel estimation
- Estimation is done using pilot symbol transmission

$T_c <$ channel estimation time ← fast fading

$T_c >$ channel estimation time ← slow fading

generally $\sigma_\tau << T_c$

$T_c \uparrow$		
	flat fading slow fading	Freq. selective fading slow fading
	flat fading fast fading	Freq. selective fading fast fading
		$\rightarrow \sigma_\tau$

CDMA multiuser down link:

$0, 1, \dots K \rightarrow$ users

$s_0, s_1, \dots s_K \rightarrow$ Information symbols

$c_0, c_1, \dots c_K \rightarrow$ codes of users

Tx signal: $x(m) = \sum_{i=0}^{K} s_i c_i(m)$

Rx signal: $y(m) = \sum_{i=0}^{L-1} h_o(i)\, x(m-i) + n(m)$

at user 0: $r(0) = \frac{1}{N} \sum_{m=0}^{N} y(m)\, c_0(m)$

$\Rightarrow r(0) =$ Signal + Multi path interference + Multi user interference + noise

$r = \sum_m w^* r(m) \rightarrow$ Rake receiver

$\rightarrow SINR = \dfrac{N P_o \|h_o\|^2}{\sum_{i=0}^{K} \|h_o\|^2 P_i - P_o \sum_{i=1}^{L-1} \frac{|h_i|^4}{\|h_o\|^2} + \sigma_n^2}$

for uplink also

wireline	wireless
SNR: $\frac{P^2}{\sigma_n^2}$	$\frac{P^2 a^2}{\sigma_n^2}$; a - random variable
BER $= Q(\sqrt{SNR})$ $\approx e^{-SNR}$	avg. BER $= \frac{1}{2}\left(1 - \sqrt{\frac{SNR}{SNR+2}}\right)$ $\approx \frac{1}{2\,SNR}$

Deep fade → Noise power > signal power

$\mathbb{P}(\text{deep fade}) \approx \frac{1}{SNR}$

TDMA → $u_1\, u_2\, u_3 \rightarrow t$ used in 2G GSM

FDMA → $u_1\, u_2\, u_3 \rightarrow f$ used in 1G

CDMA – used in 3G

$u_0 \rightarrow a_0 [1\,1\,1\,1]_{c_0}$

$u_1 \rightarrow a_1 [1\,-1\,1\,-1]$; 4 chips ← c_1

Tx, Rx, c_0 → user 0, c_1 → user 1

Correlation (dot product)

Code → collection of chips

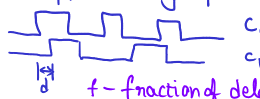
$N \rightarrow$ # chips in a code ; Time duration of chip $(T_c) = \frac{T}{N}$

(or) spread factor $\Rightarrow$ B.W $= N \times f$ → spread spectrum

– # orthogonal codes possible of length N are N

Asynchronous CDMA:

- happens during uplink



f - fraction of delay

$f \sim unif(0,1)$, $1-f \sim unif(0,1)$

$r_{01}^a = f\, r_{01}(-1) + (1-f)\, r_{01}(0)$

$SINR = \dfrac{\|h_o\|^2 P_o N}{\frac{2}{3} \sum_{i=0}^{K} \|h_i\|^2 P_k - \frac{2}{3} P_o \sum_{d=0}^{L-1} \frac{|h_o(d)|^4}{\|h\|^2} + \sigma_n^2}$

- Codes are generated using Linear Shift Feedback Registers (LSFR)
  - # 1's are 1 more than 0's ; correlation (dot product) $= \begin{cases} 1 & \text{if shift} = 0 \\ -\frac{1}{N} & \text{else} \end{cases}$
  - $\frac{1}{2^{i+1}}$ runs of length 2^i
- Random spread sequence: 1. Each $c(i)$ is ± 1 w.p $1/2$
  2. $c(i)$, $c(j)$ are independent
  3. $c_0(i)$, $c_1(i)$ are independent

  $\mathbb{E}[c_0(i)] = 0$, $\mathbb{E}[r_{00}(K)] = 0$, $\mathbb{E}[r_0(K)] = 0$

  $\mathbb{E}[r_{00}^2(K)] = \frac{1}{N}$, $\mathbb{E}[r_0^2(K)] = \frac{1}{N}$

  $r_{ij}(K) = \frac{1}{N} \sum_m c_i(m)\, c_j(m+K)$

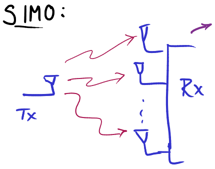
Near - far problem of CDMA

$SINR = \dfrac{P_o}{\frac{P_1}{N} + \frac{\sigma_n^2}{N}}$

$P_r \propto \frac{1}{d^2}$; u_0, u_1

Power transmitted by user must be regulated.

SIMO:



→ Improves BER

h_i – fading coefficient of link i

$\bar{y} = \bar{h} x + \bar{n}_{L\times 1}$; $\mathbb{E}[|n_i|^2] = \sigma_n^2$

Signal detection: linear combination of y_i's (Beam forming)

$\hat{x} = w^T \bar{y}$; $w^* = \frac{h}{\|h\|} \rightarrow$ Maximal Ratio Combiner (MRC) (or) Spacial Matched filter

$SNR = \frac{\|h\|^2 \cdot P}{\sigma_n^2}$

avg. BER $\approx \frac{1}{2^L} \cdot \frac{1}{(SNR)^L} \cdot {}^{2L-1}C_L \;\propto\; \frac{1}{(SNR)^L}$

$\mathbb{P}(\text{deep fade}) \propto \frac{1}{(SNR)^L}$

Diversity order $= -\lim_{SNR \to \infty} \frac{\log(BER)}{\log(SNR)}$ → L SIMO system ; → ∞ for wireline

Multi user CDMA:

$x(n) = a_0 c_0(n) + a_1 c_1(n)$

$y(n) = x(n) + w(n)$

at user 0

$r_0 = \frac{1}{N} \sum_n y(n)\, c_0(n)$

$= \underbrace{\frac{1}{N} \sum_n a_0 c_0^2(n)}_{\text{desired signal}} + \underbrace{\frac{1}{N} \sum_n a_1 c_0(n) c_1(n)}_{\text{Interference}} + \underbrace{\frac{1}{N} \sum_n w(n) c_0(n)}_{\text{noise}}$; $(r_{01}(0))$

$\Rightarrow SNR = \dfrac{P_0}{\frac{P_1}{N} + \frac{\sigma_w^2}{N}} = N\left(\dfrac{P_0}{P_1 + \sigma_w^2}\right)$; Spread gain

Multiple Input Multiple output (MIMO)

t – Tx antenna ; r – Rx antenna ; $r \le t$ generally

- Spatial multiplexing

  $\bar{y}_{r\times 1} = H_{r\times t}\, \bar{x}_{t\times 1} + \bar{n}_{r\times 1}$

- Total rt channel coefficients
- Noise: $\mathbb{E}[|n_i|^2] = \sigma_n^2$, $\mathbb{E}[n_i n_j^*] = 0$

Receiver:

$\bar{y} = H\bar{x} + \bar{n}$; $\hat{x} = H^{-1} y - H^{-1} n$ (H is not a square matrix)

$\Rightarrow \hat{x} = (H^T H)^{-1} H^T \bar{y}$ → MMSE estimator of $\|y - Hx\|^2$

Pseudo inverse ; Zero forcing receiver

$(r-t+1)$ diversity ; amplifies noise if h is small ($\frac{n}{h}$ term)

Linear estimator: $\hat{x} = \bar{c}^T \bar{y}$

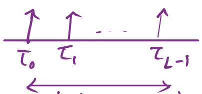
minimize $\mathbb{E}[\|\hat{x} - x\|^2]$ over $\bar{c}$

$c^* = R_{yy}^{-1} R_{yx}$; $\mathbb{E}[\bar{x}\bar{y}^T] = R_{xy} = R_{yx}^T$

$= P_d H^T (P_d H H^T + \sigma_n^2 I)^{-1} \bar{y}$

at low SNR: $(H^T H)^{-1} H \bar{y}$ (Zero forcing) ; at high SNR: $\frac{P_d}{\sigma_n^2} H^T \bar{y}$ (matched filter)

$|h(\tau)|^2 = \sum_{i=0}^{L-1} |a_i|^2\, \delta(\tau - \tau_i)$



τ_0 τ_1 … τ_{L-1} ; delay spread

max delay spread $= \tau_{L-1} - \tau_0$

RMS delay spread (σ_τ) ; weighted power

$\sigma_\tau = \sqrt{\dfrac{\sum_{i=0}^{L-1} |a_i|^2 (\tau - \bar{\tau}_i)^2}{\sum_i |a_i|^2}}$; $\bar{\tau} = \dfrac{\sum_i |a_i|^2 \tau_i}{\sum_i |a_i|^2}$ → Total power

- avg. Power $= \mathbb{E}[|h(\tau)|^2] = \bar{\phi}(\tau)$

$f(\tau) = \dfrac{\bar{\phi}(\tau)}{\int_0^\infty \bar{\phi}(\tau)\, d\tau}$; $\bar{\tau} = \int_0^\infty \tau f(\tau)\, d\tau$; $\sigma_\tau^2 = \int_0^\infty (\tau - \bar{\tau})^2 f(\tau)\, d\tau$

Delay spread $\approx$ 1-3 μs outdoor

$\approx$ 10-50 ns indoor

Advantages of CDMA

→ Jammer margin

disruptive user with high power P_I cause interference $\frac{P_I}{N}$ (supress Jammer power)

→ Graceful degradation

$SNR = \dfrac{P_0}{\frac{P_1}{N} + \frac{P_2}{N} + \dots + \frac{\sigma_n^2}{N}}$

→ Interference by new user is distributed among other users

→ Universal frequency reuse

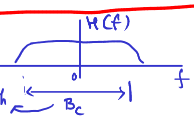
- Same frequencies can be used in all cells
- Interference due to adjacent cells is $\frac{P_I}{N}$

→ Multipath diversity

$y(m) = h(0)\, x(m) + h(1)\, x(m-1) + \dots + h(L-1)\, x(m-L+1)$; $x(m) = s_0 c_0(m)$

ISI ⇒ freq. selective

$H(f) = \mathcal{F}(h(t)) \longrightarrow$



coherence bandwidth ; B_c

$B_c \approx \frac{1}{2\sigma_\tau}$; B_s – symbol Bandwidth

$B_s > B_c \Rightarrow$ frequency selective distortion

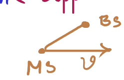
⇕

$\sigma_\tau >> T_{symbol} \Rightarrow$ Inter symbol Interference (ISI)

$(2B_c << B_s)$

Change in frequency due to motion ← doppler effect

$h_b(t) = \sum_{i=0}^{L-1} a_i\, e^{-j2\pi f_c \tau_i}\, e^{j2\pi f_d t}$



time varying channel ; time varying phase ; $\tau_i(t) = \tau_i - \frac{v \cos\theta}{c} t$

$f_d = f_c \frac{v \cos\theta}{c}$

mobility → doppler → Time selective channel.

Coherence Time $T_c = \frac{1}{4 f_d}$ (approx time channel is constant)

Doppler spread $B_d = 2 f_d$; $T_c \approx$ ms

$r(0) = \frac{1}{N} \sum_m y(m)\, c_0(m) = s_0 h(0) + \tilde{n}(0)$

⋮

$r(K) = \frac{1}{N} \sum_m y(m)\, c_0(m-K) = s_0 h(K) + \tilde{n}(K)$

$\Rightarrow \bar{r} = \bar{h} s_0 + \bar{n}$ (receiver diversity)

- By combining $r = \sum \bar{w}^* \cdot \bar{r}$ → RAKE receiver

for maximizing SNR we get $\bar{w}^* = \frac{\bar{h}}{\|h\|}$

$SNR = \frac{\|h\|^2 P_0}{\sigma_n^2} \cdot N$; $BER \sim \frac{1}{(SNR)^L}$

RAKE reciver extracts multipath diversity by coherent combination of multipath components

Singular Value Decomposition (SVD) of H

$H = U\Sigma V^T;\quad UU^T = I,\quad VV^T = I$

$\Sigma = \begin{bmatrix}\sigma_1 & & 0\\ & \sigma_2 & \\ 0 & & \ddots\ \sigma_t\end{bmatrix}\qquad \sigma_1 > \sigma_2 > \dots > \sigma_t$

$\bar{y} = H\bar{x} + \bar{n} = U\Sigma V^T\bar{x} + \bar{n}$

$\Rightarrow \underset{t\times 1}{\tilde{y}} = U^T\bar{y} = \Sigma V^T x + U^T\bar{n} = \Sigma\,\underset{\tilde{x}}{\tilde{x}} + \tilde{n}$

Decoupling / Parallelization of MIMO channels

$\sigma_{\tilde{n}}^2 = E[\tilde{n}\tilde{n}^T] = \sigma_n^2$

$\Rightarrow$ SNR of i^{th} stream $= \dfrac{P_i\sigma_i^2}{\sigma_n^2}$

Total capacity $= \sum_{i=1}^{t}\log_2\left(1 + \dfrac{P_i\sigma_i^2}{\sigma_n^2}\right)$

MIMO Beam forming

- use directional antennas

$\bar{y} = U\Sigma V^T\bar{x} + \bar{n};\quad V^T v_1 = \begin{bmatrix}1\\0\\ \vdots\\0\end{bmatrix}$

$\bar{x} = v_1\tilde{x}_1 \rightarrow$ (MRT)

Maximal Ratio Transmission

$\bar{y} = \sigma_1\tilde{x}_1\bar{u}_1 + \bar{n}$

$\bar{u}_1 \rightarrow$ dominant direction

$\bar{u}_1^T\bar{y} = \sigma_1\tilde{x}_1 + \tilde{n}_1 \Rightarrow \text{SNR} = \dfrac{\sigma_1^2 P}{\sigma_n^2}$

- MRT is capacity optimal at low SNR
- Achieves complete diversity order

Advantage:

Simple Tx and Rx scheme for MIMO

MIMO-OFDM

Freq. selective MIMO channel modelled as

$\underset{n\times 1}{\bar{y}}(k) = \sum_{l=0}^{L-1} H(l)\,\bar{x}(k-l) + \bar{n}(k)$

we need to perform IFFT at each Tx antenna.

$\tilde{Y}(0) = \tilde{H}(0)\,\tilde{X}(0)$

$\vdots$

$\tilde{Y}(k) = \tilde{H}(k)\,\tilde{X}(k)$

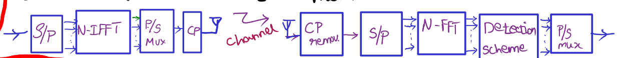
$\tilde{H}(0), \tilde{H}(1) \dots \tilde{H}(k) \rightarrow$ flat fading channels

$\tilde{H}(0)$: FFT of $H(0)$

- Each $\tilde{Y}(0)\dots\tilde{Y}(N-1)$ can be processed by simple MIMO Z Forcing (or) MIMO MMSE reciver for detection.

$\hat{X}(k) = (\tilde{H}(k))^{-1}\,\tilde{Y}(k)\quad;\quad \hat{X}(k) = P_d\left(P_d\tilde{H}^T(k)\tilde{H}(k) + \sigma_n^2 I\right)^{-1}\tilde{H}^T\tilde{Y}(k)$

Schematic of OFDM with cyclic Prefix

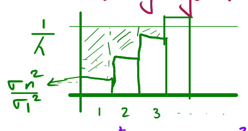


Optimal MIMO power allocation:

$\max_{P_1\dots P_t} \sum_{i=1}^{t}\log\left(1 + \dfrac{P_i\sigma_i^2}{\sigma_n^2}\right)$

s.t. $\sum_{i=1}^{t} P_i \le P$

- Water filling algorithm $\frac{1}{\lambda} = ?$



$P_1 \ge P_2 \ge P_3 \dots$

$P_i = \left(\frac{1}{\lambda} - \frac{\sigma_n^2}{\sigma_i^2}\right)^+$

$P = \sum_{i=1}^{t}\left(\frac{1}{\lambda} - \frac{\sigma_n^2}{\sigma_i^2}\right)^+$

Asymptotic capacity:

$C_a = \log_2\left|I + \frac{1}{\sigma_n^2} H R_x H^T\right|;$

$R_x = \frac{P_t}{t}\ ,\quad t >> r\ ,\quad HH^T \rightarrow tI$

$\Rightarrow C_a = r\log_2\left(1 + \frac{P_t}{\sigma_n^2}\right)$

$= \min(r, t)\log_2\left(1 + \frac{P_t}{\sigma_n^2}\right)$

$C_a \uparrow$ as $r\uparrow \Rightarrow$ MIMO increases capacity

Alamouti code: → for 2Tx, 1Rx system

- Orthogonal space Time Block code (OSTBC)
- Achives diversity without channel state Information (CSI)

1^{st} Instance

$y(1) = [h_1\ h_2]\begin{bmatrix}x_1\\x_2\end{bmatrix} + n(1)$

2^{nd} Instance

$y(2) = [h_1\ h_2]\begin{bmatrix}-x_2^*\\x_1^*\end{bmatrix} + n(2)$

At Rx:

$\begin{bmatrix}y(1)\\y^*(2)\end{bmatrix} = \begin{bmatrix}h_1 & h_2\\ h_2^* & -h_1^*\end{bmatrix}\begin{bmatrix}x_1\\x_2\end{bmatrix} + \begin{bmatrix}n(1)\\n^*(2)\end{bmatrix} \rightarrow 2\times2$ MIMO

$\quad c_1\quad c_2$

$\bar{w}_1^T\bar{y} = \|h\|x_1 + \tilde{n}_1 \Rightarrow \text{SNR} = \dfrac{\|h\|^2 P_1}{\sigma_n^2};\quad w_1 = \dfrac{c_1}{\|c_1\|}$

$\bar{w}_2^T\bar{y} = \|h\|x_2 + \tilde{n}_2 \Rightarrow \text{SNR} = \dfrac{\|h\|^2 P_2}{\sigma_n^2};\quad w_2 = \dfrac{c_2}{\|c_2\|}$

c_1, c_2 are orthogonal

space ↓ $\begin{matrix}x_1 & -x_2^*\\ x_2 & x_1^*\end{matrix}$ → time

Transmits 2 symbols / 2 time slots

⇒ Rate = 1 (full rate)

Non linear MIMO reciver

V-BLAST (vertical Bell Labs space Time)

- Employs Successive Interference cancellation (SIC)

$\bar{y} = H\bar{x} + \bar{n} = \bar{h}_1 x_1 + \bar{h}_2 x_2 + \dots + \bar{h}_t x_t + \bar{n}$

$\hat{y}_1 = \bar{q}_1^T\bar{y} = x_1 + \tilde{n};\quad Q = \begin{bmatrix}\bar{q}_1\\ \bar{q}_2\\ \vdots\\ \bar{q}_t\end{bmatrix}\ \&\ QH = I$

$\hat{y}_2 = \bar{y} - \bar{h}_1 x_1 = \bar{h}_2 x_2 + \dots + \bar{h}_t x_t + \bar{n} \rightarrow r\times t-1$ MIMO

— repeat the process for $x_2\dots$

Advantages:

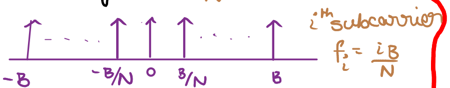
- Diversity order progresively increases
- Streams decoded later have higher diversity
- for last symbol r^{th} order diversity.

B - Bandwidth available for communication

$T = \frac{1}{B} \rightarrow$ symbol duration

If we tx 1 symbol for every T sec Then symbol rate $= 1/T = B$

Multi carrier system: N - subcarriers



i^{th} subcarrier $f_i = \frac{iB}{N}$

$X_i \rightarrow$ data transmitted on i^{th} sub carrier

Tx signal: $S(t) = \sum_{i=1}^{N} x_i\, e^{j2\pi i\frac{B}{N}t}$

$S_i(t) \rightarrow$ duration $\frac{N}{B}$

If no noise

Rx signal: $y(t) = \sum_{i=1}^{N} x_i\, e^{j2\pi i\frac{B}{N}t}$

By coherent demodulation $\hat{x}_i = \frac{B}{N}\int y(t)\cdot e^{j2\pi i\frac{B}{N}t}\,dt$ (duration of detection) $= x_i$

- This scheme is called Multi carrier Modulation (MCM)
- Symbol rate $= \dfrac{N}{N/B} = B$ (same as single carrier)

B = 1024 KHz → Single carrier → $B > B_c$ (~200 - 300 KHz) ↳ (ISI, freq. selective)

→ Multicarrier → $\frac{B}{N} << B_c \Rightarrow$ Flat fading (No ISI)

Bottle neck:

- Implementing N modulators and demodulators

Orthogonal Frequency Division Multiplexing (OFDM)

- Sample $s(t)$ with $T_s = \frac{1}{B}$

u^{th} Sample: $s(uT_s) = \sum_{i=0}^{N-1} x_i\, e^{j\frac{2\pi}{N}iu}$

IDFT of $[x(0)\,x(1)\dots x(N-1)]$

- Implementing this have lower complexity than Correlators

$y(0) = h(0)x(0) + h(1)\tilde{x}(N-1) + \dots + h(N-1)\tilde{x}(N-L+1)$ (Prev symbol)

Cyclic prefix: To avoid ISI and make channel multiple flat fading channels

By cyclic prefix: → has only samples of x ↗ Circular convol.

$y(0) = h(0)x(0) + h(1)x(N-1) + \dots + h(L-1)x(N-L+1)$

⇒ $Y(k) = H(k)\cdot X(k)$ → Flat fading for k^{th} sub carrier

∴ Wide band Frequency selective channel became group of narrow band flat fading channels

Sample detection: By Zero forcing $\hat{x}(k) = \frac{1}{H(k)}Y(k)$

By matched filter: $H^*(k)\,Y(k) = |H(k)|^2 x(k) + N'(k)$

By MMSE: $\hat{x}_{MMSE}(k) = \dfrac{H^*(k)}{|H(k)|^2 + \sigma_n^2}\,Y(k)$

- Max length of cyclic prefix = L-1

⇒ Loss of efficiency $= \dfrac{L-1}{N+L-1} \xrightarrow{N\to\infty} 0$

$N\uparrow \Rightarrow$ symbol duration $\uparrow \Rightarrow$ increases decoding time

Intutively: $N_{cp}T_s \ge T_d \Rightarrow N_{cp} \ge \frac{1}{2}\frac{B}{B_c}$

Standard: CP 12.5% symbol time

$N >> N_{cp} >> \frac{B}{B_c} \Rightarrow B_c >> \frac{B}{N}$ for flat fading

---

Effect of frequency offset in OFDM:

- This leads to loss of orthogonality among subcarriers thus causing Inter carrier Interference (ICI)

Let Δf - frq. offset, $\epsilon = \frac{\Delta f}{B/N} \rightarrow$ Normalized freq. offset

l^{th} coefficient if $\epsilon \ne 0$

$Y_l = \frac{1}{N}\sum_n y_n\, e^{-j2\pi n l/N}$

$= \underbrace{\frac{1}{N}\sum_n x_k H_k\, e^{\frac{j2\pi n\epsilon}{N}}}_{k=l} + \overbrace{\frac{1}{N}\sum_n\sum_{k\ne l} x_k H_k\, e^{\frac{j2\pi n}{N}(k-l+\epsilon)}}^{ICI} + \tilde{w}_l$

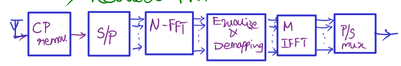
$\text{SINR} = \dfrac{P|H|^2(\text{sinc}\,\epsilon)^2}{0.822P\,|H|^2(\sin\pi\epsilon)^2 + \sigma_n^2}$ for $N\to\infty$

Soft handover → change of code in CDMA

Hard handover → change in frequency

Single Carrier FDM access (SCFDMA):

↳ Reduces PAPR



Sub carrier mapping: M < N

1. Interleave

$x(1), 0, 0, 0, x(2), 0, 0, 0, x(3)\dots$

2. Zero padding → SFDMA

$x(1), x(2), x(3), 0, 0\dots$

Wireless channel modelling:

Large scale propagation models → mean signal strength at Rx

a) Free space model

$P_r(d) = \dfrac{P_t G_t G_r \lambda^2}{4\pi\, d^2\, L};\quad P \propto \frac{1}{d^2}$ Path loss exponent

b) Ground reflection → $P \propto \frac{1}{d^4}$

c) Okumura model

- more practical, widely used in urban
- Predicts median loss
- valid range 1050 - 1920 MHz, can be extrapolated

d) Hata model

- another popular model for urban

e) Log normal shadowing

Link budget:

+	Transmit power	P_t
+	Gain	G_t
−	Median loss propagation	L^{50}
−	Margin	M_{dB}
+	Mobile Rx Gain	G_r
−	cable loss	L_r
−	Reciver (noise + Interference)	N+I
=	Required SNR	SNR_{req}