chap. 6

Multiple Access Techniques: FDMA, TDMA, CDMA; System capacity comparisons.

I. "channel": a system resource allocated to a given mobile user enabling that user to communicate with the network with tolerable interference from other users.

channel $\xrightarrow{\text{imply}}$ orthogonal to one another.

(e.g.) Frequency channels
time slots within Freq. Bands
distinct codes

FDMA, TDMA, CDMA multiple access techniques utilize FDMA.

(1) FDMA used for

① Broadcast Radio & TV (one-way, all recipients share the same channel)

ⓐ each station assign a given channel with sufficient guard band.

ⓑ The stations far apart geographically can reuse the same channel.

② 1G analog mobile system (AMPs $\Longrightarrow$ FDMA/FDD)

869-894 MHz (D.L.)
824-849 MHz (U.L.)

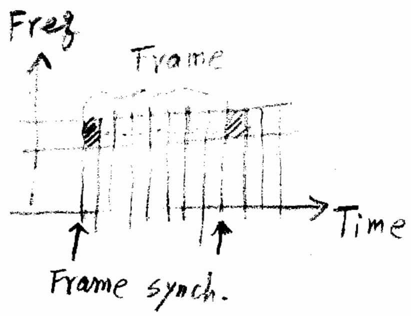
25 MHz band broken into 832 30kHz-channels.

I. TDMA

(1). FD/TDMA only apply to Digital system

(2). 2G TDMA systems $\xrightarrow{\text{imply}}$ circuit-switched systems (For Voice call)

(3) Frame synchronization needed



(4) 3G TDMA sys.

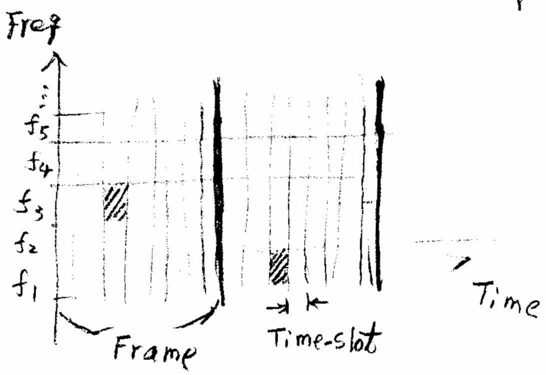
① For Data Transmission

② use Packet-swithed Technology
(This Technology used for the Internet)

(5) Consider GSM system

① one slot/frame/user

② Hop among the different Freq. channel to reduce the deep fading
(i.e., Freq. diversity concept)



Freq. Hopping scheme

③ Europe sys. allocate two 25 MHz bands

890 − 915 MHz
935 − 960 MHz

Also PCS band 2 GHz band

$$\frac{25\text{ MHz}}{200\text{ KHz}} = 125 \text{ Frames}$$

↑ GSM Bandwidth

$$125 \text{ Frames} - \underset{\uparrow\ \text{Guard band}}{1 \text{ Frame}} = \underset{\uparrow\ \text{Freq. assignments}}{124 \text{ Frame}}$$

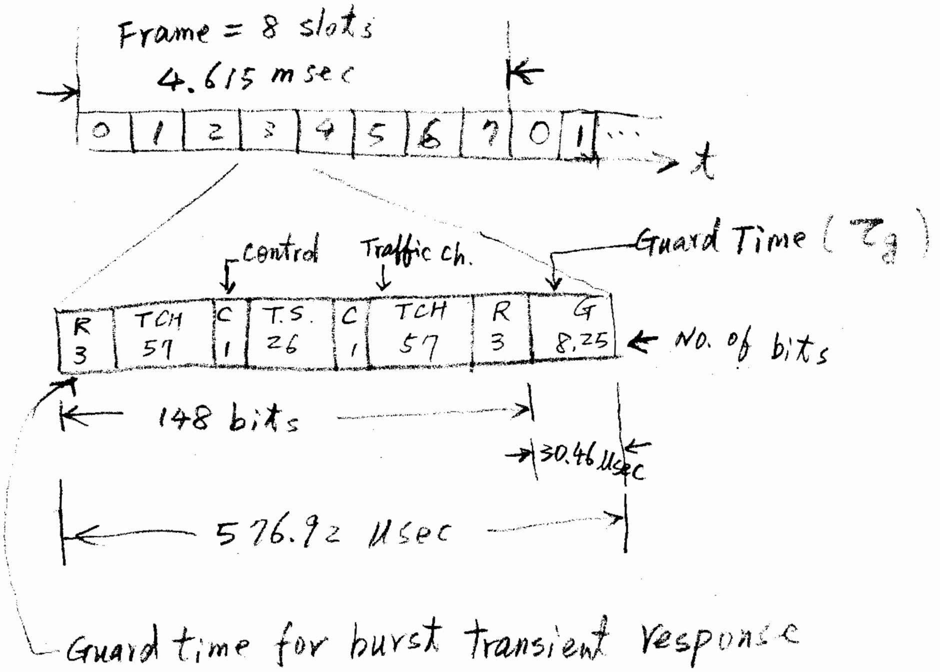
④ GMSK modulation

⑤ 1 frame = 8 slots

$\parallel$

4.615 ms

$8 \left(\text{slots}/\text{Frame}\right) \times 124 \left(\text{Frame}\right) = 992 \text{ ch.}/\text{GSM}$



$(3+57+1+26+1+57+3+8.25)\ \text{bits}/\text{Ts} \times 8\ \text{Ts}/\text{Frame} = 1250\ \text{bits}/\text{Frame}$

$0.57692\ \text{ms}/\text{Ts} \times 8\ \text{Ts}/\text{Frame} = 4.615\ \text{ms}/\text{Frame}$

$$\frac{1250\ \text{bits}/\text{Frame}}{4.615\ \text{ms}/\text{Frame}} = 207.8\ \text{kbit}/\text{sec}$$

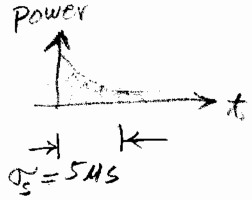
↑ Raw bit rate (Transmission rate)

Guard Time determination

$$\tau_g = \frac{8.25\ \text{bit}}{207.8\ \text{kbit}/\text{s}} \simeq 39\ \mu\text{s}_{\#}$$ (Is this a good design ?)

EX: Mobile radio in Free space travel ≃ $0.304\ m/ns$ ($\simeq 1\ ft/ns$)

(1) The delay spread of a typical urban mobile radio channel ≃ $5\ \mu s$
($3-5\ \mu s$)



(2) The mobile moving coverage ≃ 10KM

$$\tau_{g(max)} = \underbrace{\frac{10\ KM}{0.304\ m/ns}}_{\text{propagation delay}} + \underbrace{5\ \mu s}_{\text{delay spread}}$$

$$\simeq 33\ \mu s + 5\ \mu s = 38\ \mu s \ *$$

(3) For GSM system

$$\tau_g = \frac{8.25\ bits}{207.8\ kbit/s} \simeq 39\ \mu s,$$

It is suitable in GSM system planning.

From cellular planning $\tau_{g(max)} \simeq 38\ \mu s$

IF Cell size (↓) ⇒ propagation delay (↓)

⇒ guard time (↓), if delay spread is a constant *

GSM (conti)

⑥ In GSM detail in chap. 8, (user data channels occupy 24 slots of every 26 frames, the other two time-slot are used to carry control information)

The user data rate is

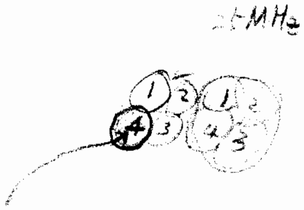
$$\frac{114\ \text{bit/Frame}}{4.615\ \text{ms/Frame}} \times \frac{24\ \text{data ch/slot, multi frame}}{26\ \text{total slot/multiframe}} = 22.8\ \text{kbps}$$

↑ user data rate

⑦ GSM SIR = 6.5 dB, because

(i) 0.3 GMSK modulation

(ii) Freq. hopping



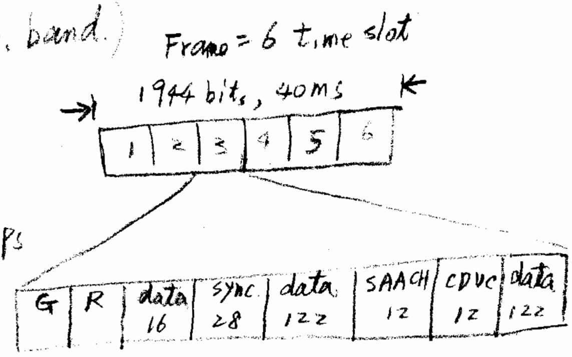
⑧ reuse factor = 4

⑨ $$\frac{124\ \text{Freq assignment} \times 8\ \text{ch./Freq assignment}}{4\ \text{reuse factor}} = 248\ \text{ch./cell}$$

↑ GSM sys. capacity.

(6). Consider IS-136 (D-AMPS)

① $\frac{25\ \text{MHz}}{30\ \text{kHz}} = 832$ (30kHz Freq. band.)



IS-136 reverse-link Frame Structure

② DQPSK.

③ Transmission rate $\frac{1944\ \text{bit/Frame}}{40\ \text{ms/Frame}} = 48.6\ \text{kbps}$

④ data rate/slot = 16+122+122 = 260 bit/slot

Full-rate user

$260\ \text{bit/slot} \times 2\ \text{slot/Frame} = 520\ \text{bit/Frame}$

$$\frac{520\ \text{bit/Frame}}{40\ \text{ms/Frame}} = 13\ \text{kbps}$$

↑ Full-rate user data rate

Full-rate user ⇒ allocate 2 time slot/Frame

half-rate user ⇒ 1 〃 〃

Ⅲ. CDMA

(1) Base on spread-spectrum technology for military communication sys.

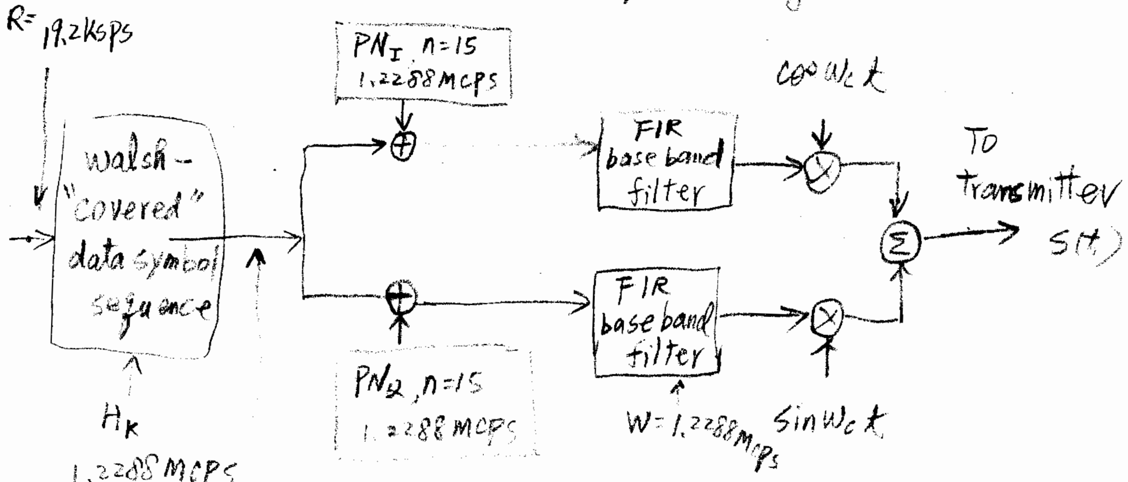
(2) Each user has a distinct orthogonal code.

① code $\underline{\underline{i}}$ has a specified sequance of l bits

$\bar{C}_i = \{ x_{ik} \}$, $k = 1, \cdots, l$, and $x_{ik} = \pm 1$

$$\bar{C}_i \cdot \bar{C}_j = \sum_k x_{ik} x_{jk} = 0, \quad j \neq i$$

② channel must be synchronized



CDMA system transmitter

③ spreading gain $= \dfrac{W}{R}$
(Processing gain)

For IS-95
$$\frac{W}{R} = \frac{1.2288 \text{ mcps}}{19.2 \text{ ksps}} = 64$$
↑ Processing gain

④ PN (pseudo-noise) sequence means

the sequence is deterministic, since it is generated using a linear shift register.

⑤ PN sequence properties

(i) $P_r\{0\} = \frac{1}{2}(1 - \frac{1}{P})$ where $P = 2^{\overset{\text{register}}{\overset{\swarrow}{n}}} - 1$

$P_r\{1\} = \frac{1}{2}(1 + \frac{1}{P})$

For $n \geq 10$, $P_r\{0\} \simeq P_r\{1\} \simeq \frac{1}{2}$.

(ii). The relative frequency of occurrence of any sequence (run) of 0s & 1s bits long is

$$\frac{1}{2^\ell}, \quad \ell \leq n-1.$$

Ex. $\frac{1}{2}$ of all run lengths are of length $1 \Leftarrow (\frac{1}{2^1}) = \frac{1}{2}$

$\frac{1}{4}$ - - - $2 \Leftarrow (\frac{1}{2^2}) = \frac{1}{4}$

$\frac{1}{8}$ - - - $3 \Leftarrow (\frac{1}{2^3}) = \frac{1}{8}$

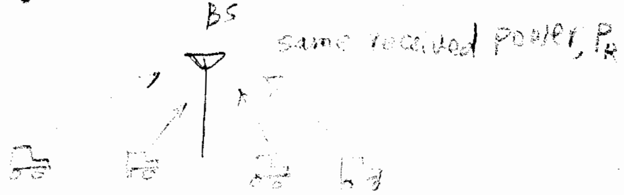
(iii) Assume aligned or synchronized.

$$\frac{1}{P}\sum_{k=1}^{P} x_{ik}\, x_{i,k+\ell} = \begin{cases} -\frac{1}{P} & ; \ \ell > 0 \\ 1 & ; \ \ell = 0 \end{cases}$$

We know $SIR \propto \frac{1}{P}$; $P = 2^n - 1$

$$n\uparrow \Rightarrow P\uparrow \Rightarrow SIR\uparrow \Rightarrow \underset{\substack{\uparrow \\ \text{chip}}}{T_c} \text{ length} \downarrow \Rightarrow BW\uparrow$$

IV. CDMA capacity: Single-Cell case



Spreading Gain

$$\frac{E_b}{I_0} = \frac{P_R/R}{(K-1)P_R/W} = \frac{\underset{\uparrow}{(W/R)}}{(K-1)}$$

with K users

For large number of users transmitting at its own PN code, the interfering behavior like <u>White Gaussian Noise</u>.

For single-Cell case, the number of users that may be accommodated in a cell

$$K = \frac{(W/R)}{(E_b/I_0)} + 1$$

Ex: Given $\frac{E_b}{I_0} = 5$ (or 7 dB), $R = 10$ kbps, $W = 1.25$ MHz

$K = 26$ users/cell for 1.25 MHz

$$K = 26 \text{ users/cell} \times \frac{25 \text{ MHz/sys}}{1.25 \text{ MHz/cell}} = 520 \text{ users/sys.}$$ (25 MHz spectrum)

V. An aside: probability of bit error considerations

Summarizing some pertinent comparative performance results

(1). For AWGN channel

bit energy

$$\text{BPSK} \quad P_e = \frac{1}{2}\,\text{erfc}\sqrt{\frac{E_b}{N_0}}$$

bit error prob.

Gaussian noise

complementary error function

where $$\text{erfc}(x) \equiv \frac{2}{\sqrt{\pi}}\int_x^{\infty} e^{-y^2}\,dy \simeq \frac{e^{-x^2}}{x\sqrt{\pi}}, \quad x > 3.$$

so, $$P_e \simeq \frac{1}{2}\,\frac{e^{-E_b/N_0}}{\sqrt{\pi}\sqrt{E_b/N_0}} \;\Longrightarrow\; \underline{P_e \propto e^{-E_b/N_0}}$$

Ex: Given $P_e = 10^{-5}$ with <u>No coding scheme</u>

BPSK $\frac{E_b}{N_0} = 9.6$ dB

coherent FSK $\frac{E_b}{N_0} = 12.6$ dB

Non-coherent FSK $\frac{E_b}{N_0} = 13.3$ dB

DPSK (DQPSK) $\frac{E_b}{N_0} = 10.5$ dB

Given $P_e = 10^{-5}$ with <u>coding scheme</u> ($\frac{1}{2}$ convolutional coding)

BPSK $\frac{E_b}{N_0} = 4 \sim 6$ dB

(2) For a fading environment

$$\text{BPSK} \quad P_e = \frac{1}{4(E_b/N_o)} \longrightarrow \boxed{P_e \propto \frac{1}{E_b/N_o}}$$

$$\frac{E_b}{N_o} = 10\,dB \quad P_e \simeq 0.025$$

Diversity recoup some of this servere performance deterioration due to fading

Ex:

$$\frac{E_b}{N_o} = 10\,dB \quad P_e \simeq 0.005$$

- * MIMO (multipule-input multiple-output) systems combined with space-time coding has proposed for use with the 3G CDMA mobile system

Trade off between <u>diversity Gain</u> and multiplexing <u>Gain</u> in MIMO sys.

- * RAKE receiver combines these seperate multipath signals, resulting in substantial diversity improvement.

- * Dual diversity reception of convolutionally coded CDMA signals using a RAKE receiver requires $\frac{E_b}{I_o} = 5$ (or 7 dB) for $P_e = 10^{-3}$.

CDMA sys. allowable users/cell depends on

① Bit error probability [$E_b/I_o = 5$ (or 7dB) through this chapter.]

② coding/diversity scheme

VI. CDMA capacity calculations

consider ① the interference from throughout the system region

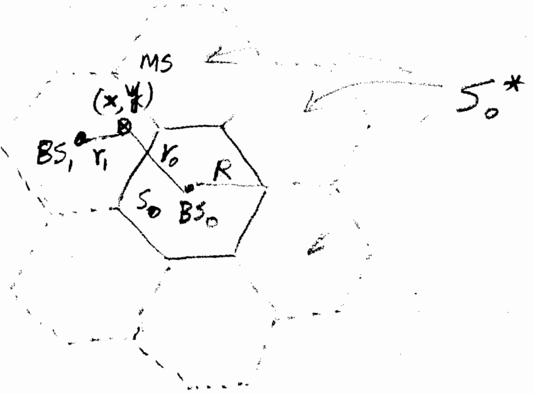
② power control

③ shadow fading

uplink analysis (consider propagation loss & shadow-fading parameters are the same from cell to cell)

(1) S_0 is the cell at its center.

S_0^* are all cell outside the S_0 cell.



Uniform traffic density

user/cell

$$\rho = k \Big/ (3\sqrt{3}/2)R^2 = \frac{2k}{3\sqrt{3}R^2}$$

⬡ $= 2.6R^2$

(2) The received power

path loss exponent

Gaussian-distributed shadow-fading r.v.

$$P_R = P_T \cdot r^{-n} \cdot 10^{z/10}$$ (ignoring the small-scale fading)

a distance from the mobile to its base station

The mobile transmitted power

(3). The interfering mobile located at (x, y), at a distance r_1 from its BS_1 in cell 1.

The mobile's Transmitted power

$$P_{T_1} = P_R \cdot r_1^n \cdot 10^{-z_1/10}$$

(4). The interfering power received at BS_0

$$P_{T_1} r_0^{-n} 10^{z_0/10} = P_R \left(\frac{r_1}{r_0}\right)^n \cdot 10^{(z_0 - z_1)/10}$$

(5) The number of mobiles in a differential area $dA(x,y)$ centered at point (x,y)

$$\rho \cdot dA(x,y) = \frac{2k \cdot dA(x,y)}{3\sqrt{3}\,R^2}$$

(6) The Total average interference power at BS_0 due to mobiles outside cell S_0.

$$I_{S_0^*} = \frac{2k}{3\sqrt{3}\,R^2} P_R \cdot E\left\{ \iint_{S_0^*} \left[\left(\frac{r_1}{r_0}\right)^n \cdot 10^{(z_1-z_0)/10}\right] dA(x,y) \right\}$$

$$= \frac{2K}{3\sqrt{3}\,R^2} P_R \cdot \underbrace{E\left\{10^{(z_0-z_1)/10}\right\}}_{\text{average over shadow-fading}} \cdot \underbrace{\iint_{S_0^*} \left(\frac{r_1(x,y)}{r_0(x,y)}\right)^n dA(x,y)}_{\text{geometric integration}}$$

For $n=4$.

$$I_{S_0^*} = 0.44 \cdot P_R \cdot \underset{\uparrow\ \text{significant term}}{E\left\{10^{(z_0-z_1)/10}\right\}}$$

① Assume the shadow-fading r.v. measured at each BS is the sum of two r.v.s

ⓐ one common to both shadow-fading terms, represent the effect of shadow fading in the vicinity of the transmitting mobiles at (x,y)

ⓑ The second rv represents random power variations encountered along the propagation path & is independent along the two paths from (x,y) to BS_0 & BS_1.

$$z_i = \underset{\uparrow\ \text{the vicinity fading}}{a h} + \underset{\uparrow\ \text{indep. fading}}{b h_i}\ ; \quad i=0,1 \qquad a^2+b^2=1$$

② the first & second moments for z_i

$$E\{z_i\} = 0 = E\{\hat{n}\} = E\{\hat{n}_i\}$$

$$E\{z_i^2\} = \sigma^2 = E\{\hat{n}^2\} = E\{\hat{n}_i^2\}$$

$$E\{\hat{n}\,\hat{n}_i\} = 0 = E\{\hat{n}_0\,\hat{n}_1\}$$

③ $(z_0 - z_1) = b(\hat{n}_0 - \hat{n}_1)$ is a gaussian rv with zero mean and variance $2b^2\sigma^2$

④ In order to calculate $I_{S_0^*}$

Define the variable transformation

$$e^y \equiv 10^{(z_0-z_1)/10}$$

$$\ln e^y = \ln\left[10^{(z_0-z_1)/10}\right]$$

$$y = \log_e 10 \cdot \log_{10}\left[10^{(z_0-z_1)/10}\right]$$

$$y = \log_e 10 \times 10^{(z_0-z_1)/10}$$

$y = 0.23\,(z_0 - z_1)$ is also gaussian with zero mean

Variance $\sigma_y^2 = (0.23)^2 \cdot 2b^2\sigma^2 = 0.053\,\sigma^2$, if $b^2 = \frac{1}{2}$

⑤ $$E\{10^{(z_0-z_1)/10}\} = E\{e^y\} = \int_{-\infty}^{\infty} e^y \frac{e^{-y^2/2\sigma_y^2}}{\sqrt{2\pi\sigma_y^2}}\,dy = e^{\sigma_y^2/2}$$

Assume $\sigma = 8$ dB, $\sigma^2 = 64$

$E\{e^y\} = e^{\sigma_y^2/2} = 5.42$ (This is quite a large number)

$$I_{S_0^*} = P_R \cdot K \cdot 0.44 \cdot 5.42 = 2.38\,P_R\,k$$

⑥ $\left.\begin{array}{l}\text{in-cell interference power } (K-1)P_R \\ \quad + \\ \text{Interference power from outside a cell}\end{array}\right\}$ The Total interference power, I.

For $n=4$ & $\sigma = 8\,dB$.

$$I = P_R(3.38K-1) \Rightarrow I_0 = (3.38K-1)P_R/W$$

$$\frac{E_b}{I_0} = (P_R/R)\left[\frac{W}{(3.38K-1)P_R}\right] = \frac{(W/R)}{(3.38K-1)}$$

Ex: $W = 1.25\,MHz$ $\quad E_b/I_0 = 5$ (or 7 dB)

$R = 10\,kbps$

$K = 7$ or 8 users/cell $\quad$ (a considerable reduction in capacity from the value of 26 users/cell for single cell)

However, 3 improvements in sys. capacity are

(1) soft handoff for 2 BSs $\Rightarrow$ user capacity increase $\frac{3.38}{1.77} = 1.91$
with 1dB power control loss user capacity $\simeq 1.25$

(2) sectorization $\Rightarrow$ 120° sectorization with 1dB antenna gain reduction
the user capacity improvement $\simeq 1.25$ to 2.4

(3) voice silence detection $\Rightarrow$ average speed 0.4 of the time
the user capacity improvement $\simeq 2.5$

<u>Notes</u>: In an ideal situation, in principle each Multiple Access Technique (FDMA, TDMA, CDMA) can deliver equal capacity

$$\underset{\substack{\uparrow \\ \text{users}}}{K_{FDMA}} = K_{TDMA} = K_{CDMA}$$

$\#$