Lecture #7

From “Wireless Communications and Networking” (Prentice Hall)

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Chapter 6 Multiple Access Techniques

Introduction

Radio cell: a geographical coverage area in which the services of mobile stations (MSs) are supported by a single base station (BS)

Forward link (downlink): BS $\rightarrow$ multiples MSs (one to many broadcasting)

Reverse link (uplink): MSs $\rightarrow$ BS (many to one multiple access)

Multiple access:

1. Multiple MSs want to access the common BS simultaneously
2. If two or more user signals arrive at the BS at the same time, there will be interferences, unless the signals are orthogonal
3. $x_i(t)$ and $x_j(t)$ are orthogonal in $[0, T]$ if

$$\int_0^T x_i(t)x_j(t)dt = 0 \qquad \text{for } i \neq j.$$

Question: How can we achieve the orthogonality?

1. Frequency division multiple access (FDMA)
2. Time-division multiple access (TDMA)
3. Code-division multiple access (CDMA)

6.1 Multiple Access Techniques for Mobile Communications

6.1.1 FDMA

1. The total bandwidth is divided into nonoverlapping frequency bands (channels)
2. Each user occupies a channel for the duration of the connection
   $\longrightarrow$ waste of resources
3. Narrowband transmission
4. Strict requirements on RF filters
5. Forward and reverse links use FDD

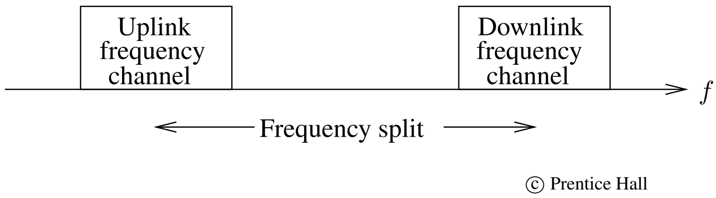


Figure 1: FDD for duplex operation

6.1.2 TDMA

1. Time is partitioned into frames
2. Each frame consists of N_{slot} data slots plus a header and a trailer
3. Each slot is for transmission of one information unit
4. A user continues to use the same slot in every frame during call connection $\longrightarrow$ waste of resources

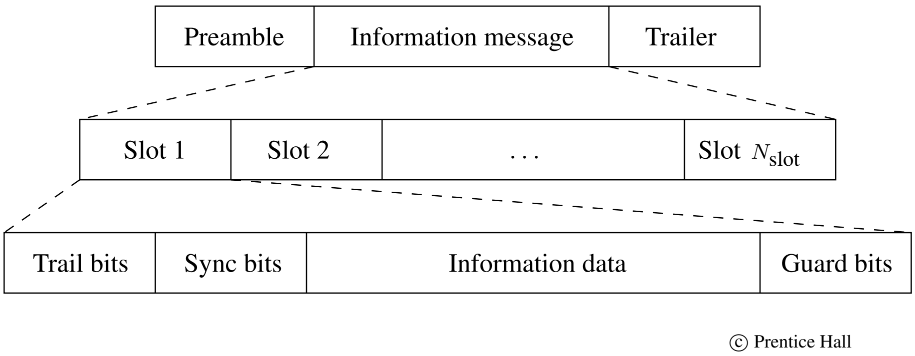


Figure 2: TDMA Frame Structure

5. TDMA: wideband TDMA (W-TDMA) and narrowband TDMA (N-TDMA)

   W-TDMA: Each user occupies the total frequency bandwidth during its slots

   N-TDMA: The total frequency spectrum is divided into frequency subbands (channels); within each frequency channel, TDMA is used. $\longrightarrow$ Both time and frequency are partitioned.

6. Forward and reverse links can use either FDD or TDD.

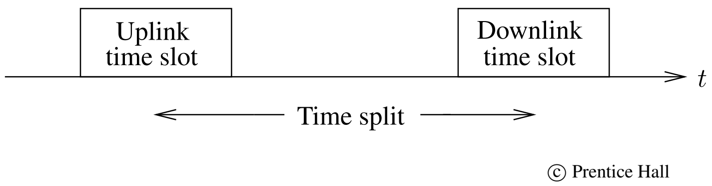
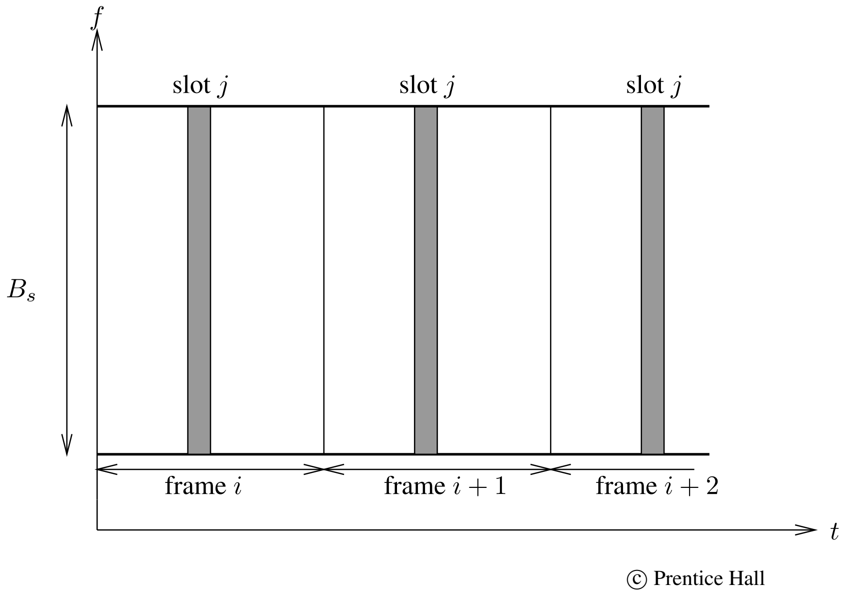
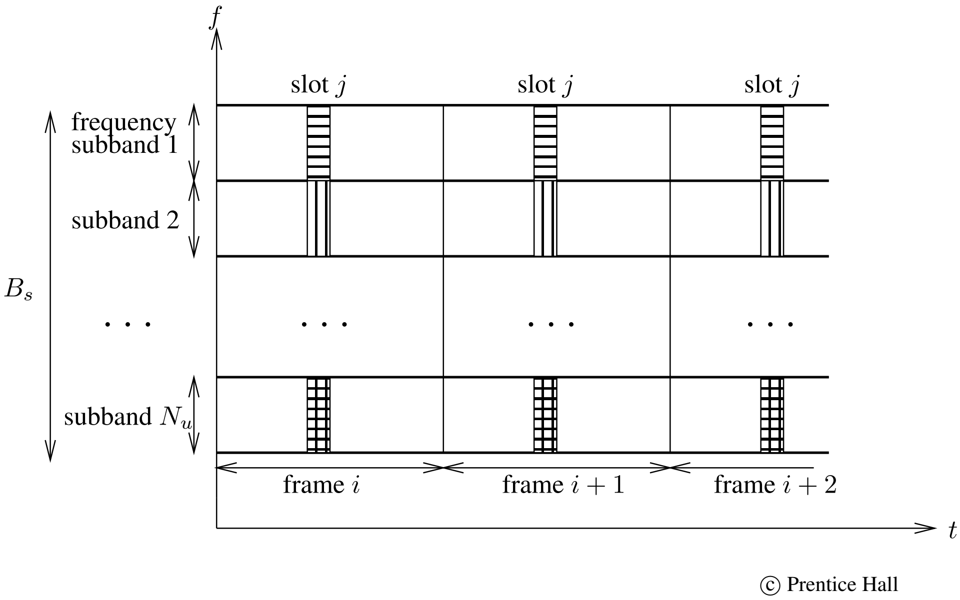


Figure 3: TDD for duplex operation

7. TDMA systems require strict time synchronization.



(a) Wideband TDMA



(b) Narrowband TDMA

Figure 4: Wideband TDMA and narrowband TDMA

6.1.3 CDMA

Spread spectrum: the spectrum of the baseband message signal is spread by a significant order of magnitude larger than the minimum required bandwidth

Direct-sequence (DS) CDMA: The spread spectrum is achieved by directly multiplying the baseband signal with a high-rate pseudorandom noise (PN) sequence, called the spreading sequence

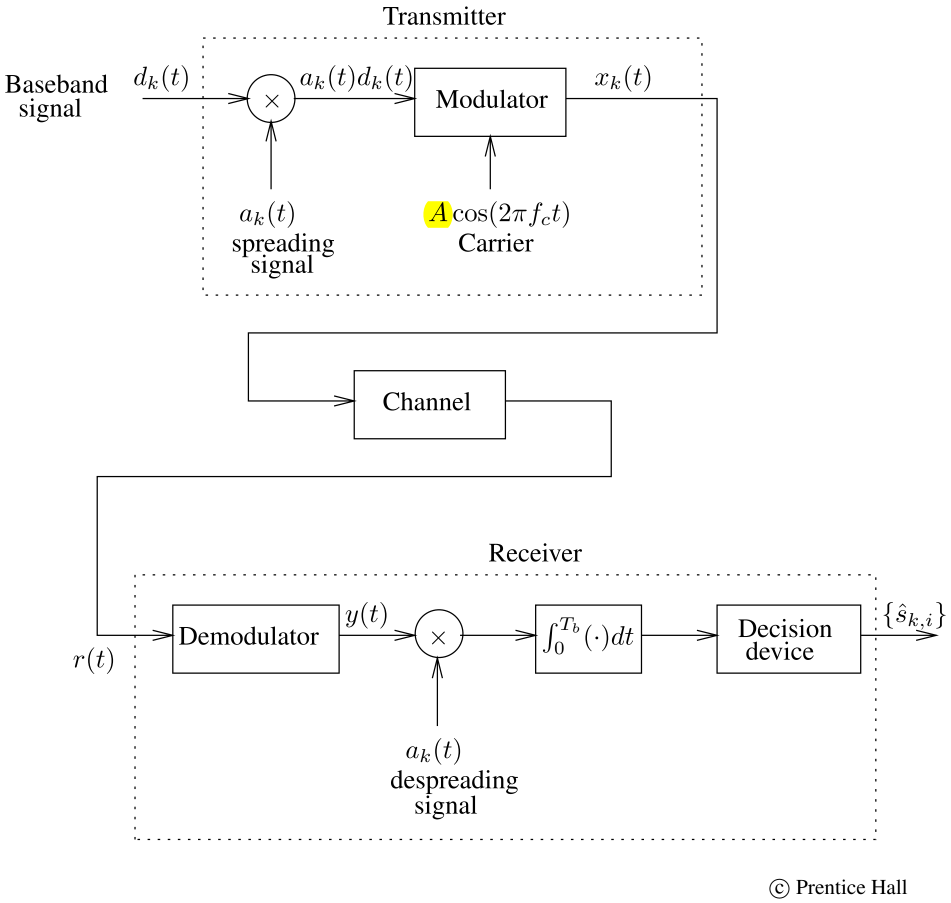


Figure 5: Function block diagram of user k transmitter and receiver in a DS-CDMA system

The information-carrying baseband signal $d_k(t)$ is

$$d_k(t) = \sum_i s_{k,i} \Pi(\frac{t - iT_b}{T_b})$$

where $s_{k,i} \in \{-1, +1\}$ is the ith binary information bit, T_b is the information bit interval, and $\Pi(t/T_b)$ is the rectangular pulse

$$\Pi(\frac{t}{T_b}) = \begin{cases} 1, & 0 \le t \le T_b \\ 0, & \text{otherwise.} \end{cases}$$

The spreading signal of the kth user is $a_k(t)$ and can be represented as

$$a_k(t) = \sum_l a_{k,l} P_{T_c}(t - lT_c)$$

where $a_{k,l} \in \{-1, +1\}$ is the lth chip of the binary PN sequence assigned to user k, $P_{T_c}(t)$ is the chip pulse waveform depending on baseband pulse shaping, and T_c is the chip interval.

For simplicity, we consider $P_{T_c}(t) = \Pi(t/T_c)$ and BPSK for the passband modulation.

Normally, $T_b/T_c = L$, where L is an integer.

Spreading: $d_k(t)a_k(t)$ with the same psd as that of $a_k(t) \Longrightarrow$ The bandwidth is increased by L times.

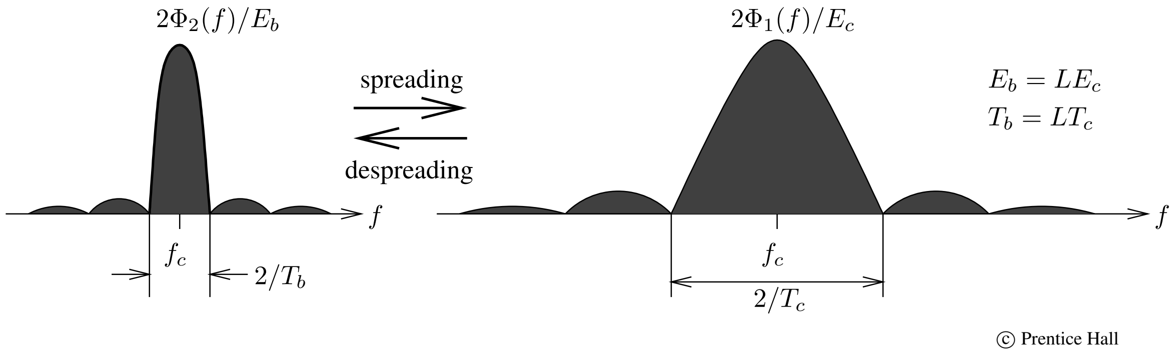


Figure 6: Illustration of signal power spectral density without and with spreading

Despreading: $[d_k(t)a_k(t)] \cdot a_k(t) = d_k(t) \cdot [a_k^2(t)] = d_k(t)$

Requirements:

1. The receiver should generate the same spreading waveform $a_k(t)$;
2. The locally generated $a_k(t)$ should accurately synchronized with that in the received signal $\longrightarrow$ PN code acquisition and tracking

Let K denote the number of mobile users in the cell. Assuming that all the K users in the cell are synchronized in time and have the same received signal power ($A_c^2/2$), $r(t)$ is given by

$$r(t) = \sum_{k=1}^{K} x_k(t) + I(t) + w(t)$$

where $I(t)$ is intercell interference and $w(t)$ is background white Gaussian noise with zero mean and two-sided psd $N_0/2$.

MAI (multiple access interference): intracell interference + intercell interference

$$\begin{aligned} r(t) &= A_c a_1(t) d_1(t) \cos(2\pi f_c t) \\ &\quad + \sum_{k=2}^{K} A_c a_k(t) d_k(t) \cos(2\pi f_c t) + I(t) + w(t). \end{aligned}$$

The demodulator translates the received signal centered at f_c to baseband centered at frequency zero. Its output, $y(t)$, can be written as

$$y(t) = \frac{A_c}{2} a_1(t) d_1(t) + \sum_{k=2}^{K} \frac{A_c}{2} a_k(t) d_k(t) + n(t)$$

where

$$n(t) \approx \frac{1}{T_c} \sum_l \{ \int_{lT_c}^{(l+1)T_c} [I(t) + w(t)] \cos(2\pi f_c t) dt \} \Pi(\frac{t - lT_c}{T_c})$$

is due to the intercell interference and additive background noise.

After despreading, we have

$$a_1(t)y(t) = \frac{A_c}{2} d_1(t) + \sum_{k=2}^{K} \frac{A_c}{2} a_1(t) a_k(t) d_k(t) + a_1(t) n(t).$$

To suppress the interference and noise, the next step in the receiver is to integrate the despread signal over each information symbol (bit) interval over which the desired signal component is a constant. The output of the integrator at the end of the ith symbol is

$$\int_{iT_b}^{(i+1)T_b} a_1(t)y(t)dt = \frac{A_cT_b}{2}\alpha_1 d_{1,i} + \frac{A_cT_b}{2}[\sum_{k=2}^{K}\alpha_k d_{k,i}] + n_i$$

where

$$\alpha_1 = \frac{1}{T_b}\int_{iT_b}^{(i+1)T_b}[a_1(t)]^2 dt = 1$$

is the autocorrelation of the spreading signal $a_1(t)$ over the symbol interval and

$$\alpha_k = \frac{1}{T_b}\int_{iT_b}^{(i+1)T_b} a_1(t)a_k(t)dt, \quad k = 2, 3, \ldots, K$$

is the crosscorelation between the spreading signals $a_1(t)$ and $a_k(t)$ over the symbol interval.

If all the spread signals $a_k(t)$, $k = 1, 2, \ldots, K$, are orthogonal in the symbol interval, then there is no intracell interference in the recovered baseband signal.

The effect of the intercell interference and background noise on the signal detection is given by the last term n_i, which is

$$n_i = \int_{iT_b}^{(i+1)T_b} a_1(t)n(t)dt.$$

In the frequency domain, the integrator is a lowpass filter with bandwidth approximately equal to $1/T_b$. The LPF lets the desired signal component $\frac{A_c}{2}d_1(t)$ go through without distortion and greatly reduces the interference and noise power. The despreading process significantly improves the signal-to-interference plus noise ratio (SINR) value.

The spread spectrum system performance is measured by the processing gain, G_p, defined as the SINR improvement achieved by despreading, i.e.,

$$G_p \triangleq \frac{\text{SINR after despreading}}{\text{SINR before despreading}} = \frac{W}{R_b} = \frac{T_b}{T_c} = L.$$

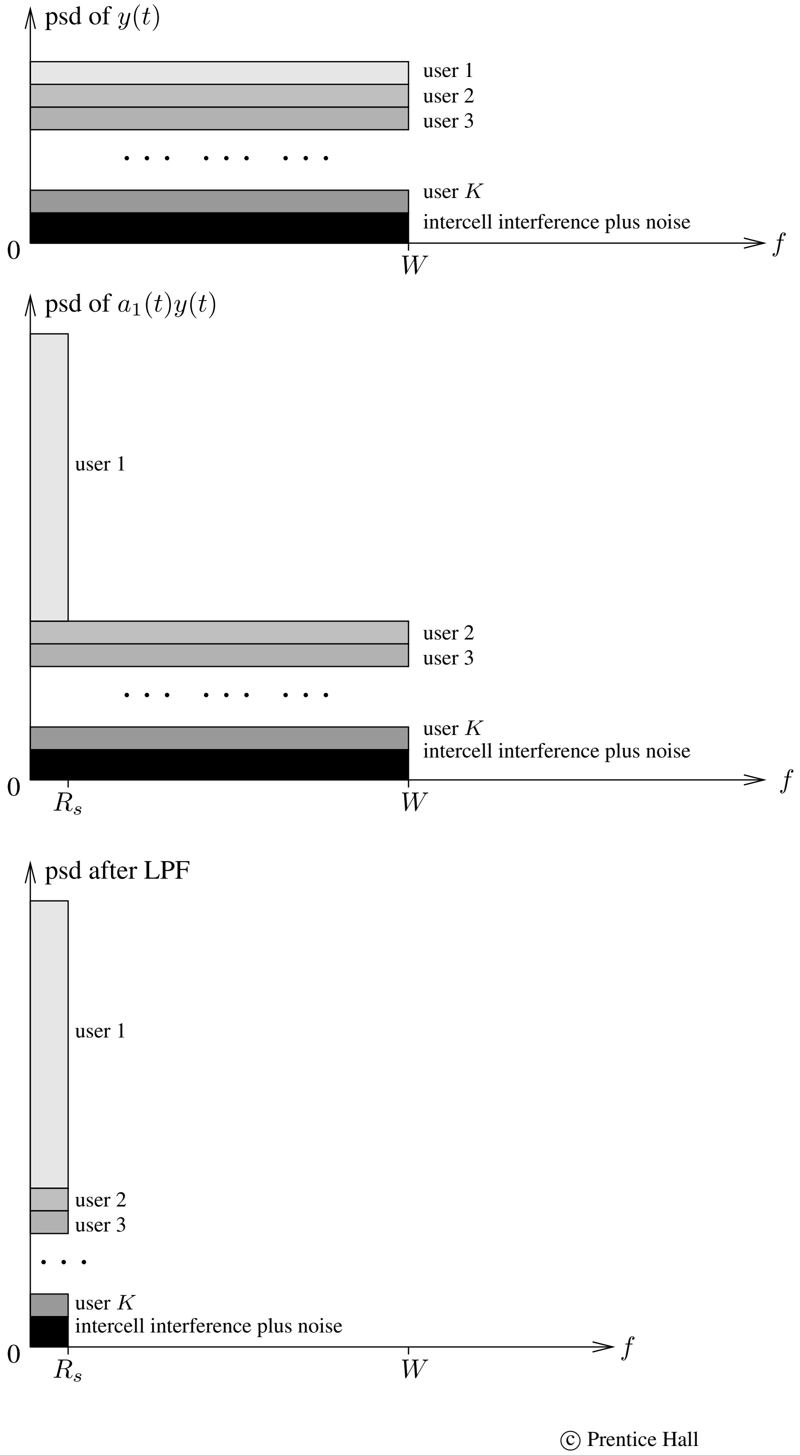


Figure 7: Illustration of signal power spectral density before and after despreading

Transmission performance:

- AWGN channel with two-sided noise psd $N_0/2$ in the absence of MAI

1. For the signal component $d_k(t)$, the effects of spreading and despreading cancel each other.
2. For the additive white Gaussian noise $n(t)$, because $a_k(t) = +1$ or -1 equally likely, $n(t)a_k(t)$ is still white Gaussian noise with the same statistics.

$\Longrightarrow$ The probability of transmission bit error is the same as that in the AWGN channel without spread spectrum. For example, if BPSK is used, the BER for the DS-CDMA user with coherent detection is

$$P_b = Q(\sqrt{\frac{2E_b}{N_0}}).$$

- AWGN channel with two-sided noise psd $N_0/2$ in the presence of MAI

1. MAI will increase transmission error rate if the spreading sequences are not orthogonal.
2. MAI can be approximated as a Gaussian process when the number of mobile users is large.
3. With a large spread spectrum bandwidth W, the psd of the interference is approximately uniform over the bandwidth.

$\Longrightarrow$ The effect of the MAI on the transmission performance can be treated in the same way as the additive white Gaussian noise and the BER is

$$P_b = Q(\sqrt{\frac{2E_b}{n_0 + N_0}})$$

where n_0 is the two-sided psd of the MAI over the spread spectrum bandwidth.

Advantages of CDMA:

1. universal frequency reuse
2. diversity and the use of Rake receiver $\longrightarrow$ better transmission accuracy
3. soft handoff
4. soft capacity
5. utilization of source activity factor
6. facilitating multimedia traffic

Drawbacks of CDMA:

1. strict power control required
2. data rate limitation especially with a large processing gain
3. high complexity of transceivers (high chip rate, spread waveform synchronization, Rake receiver, power control, etc.)

6.2 Spectral Efficiency

The overall spectral efficiency depends on

1. channel spacing in kHz
2. cell size in km^2
3. frequency reuse factor
4. multiple access scheme

$\Longrightarrow$ The spectral efficiency $\eta = \eta_{\text{sys}} \times \eta_{\text{access}}$

$$\eta \triangleq \frac{\text{Total number of channels available for data in system}}{\text{(system bandwidth)(total coverage area)}} \quad \text{Channel/MHz}/\mathrm{km}^2$$

where the total number of channels for data = total number of channels - total number of control channels, taking into account frequency reuse. Or,

$$\eta \triangleq \frac{\text{Total traffic carried by the system}}{\text{(system bandwidth)(total coverage area)}} \quad \text{Erlang/MHz}/\mathrm{km}^2.$$

Techniques used to enhance the spectrum utilization:

1. source coding (data compression to reduce the source rate)
2. bandwidth reduction (modulation, detection, channel coding)
3. channel assignment
4. choice of multiple access method

6.2.1 FDMA Systems

Spectral efficiency of FDMA (η_{FDMA})

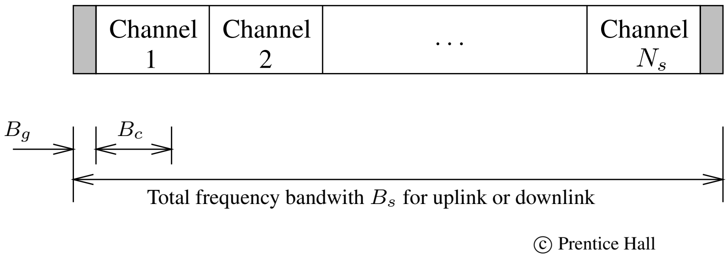


Figure 8: Channel spacing and guard bands in FDMA uplink or downlink

The number of channels, N_s, that can be simultaneously supported is

$$N_s = \frac{B_s - 2B_g}{B_c}.$$

Let N_{ctl} be the number of allocated control channels and N_{data} be the number of data channels in the system. Then the total number of available channels is

$$N_s = N_{data} + N_{ctl}.$$

The spectral efficiency of FDMA is defined as

$$\eta_{FDMA} = \frac{\text{bandwidth available for data}}{\text{system bandwidth}} = \frac{N_{data}B_c}{B_s} < 1.$$

Example 6.1 Spectral efficiency of FDMA
In the AMPS (Advanced Mobile Phone System) system, the system bandwidth is 12.5 MHz, the channel spacing is 30 kHz, and the edge guard spacing is 10 kHz. The number of channels allocated for control signaling is 21. Find

a) the number of channels available for message transmission, and

b) the spectral efficiency of FDMA.

Solution:
We have $B_s = 12.5$ MHz, $B_c = 30$ kHz, and $B_g = 10$ kHz. Therefore,

a) the number of available channels is

$$N_s = \frac{B_s - 2B_g}{B_c} = \frac{12.5 \times 1000 - 20}{30} = 416 \text{ channels, and}$$

b) the spectral efficiency of this FDMA system is

$$\eta_{FDMA} = \frac{30 \times (416 - 21)}{12.5 \times 1000} = 0.948.$$

□

System spectral efficiency η

The number of available channels per cluster is given by

$$N_{ch/cluster} = \frac{B_s - 2B_g}{B_c}.$$

The total number of channels available for data traffic per cluster is

$$N_{data/cluster} = N_{ch/cluster} - N_{ctl/cluster} = \frac{B_s - 2B_g}{B_c} - N_{ctl/cluster}$$

The total number of channels available for data traffic per cell is

$$N_{data/cell} = \frac{N_{data/cluster}}{N} = \frac{\frac{B_s-2B_g}{B_c} - N_{ctl/cluster}}{N}$$

which is also the cell capacity, N_c, defined as the maximum number of mobile stations that can be served at one time in each cell.

$\Longrightarrow$

$$\eta = \frac{\text{number of data channels per cluster}}{\text{system bandwidth times area of the cluster}} = \frac{N_{data/cluster}}{B_s \cdot (N \cdot A_{cell})}.$$

$\Longrightarrow$

$$\eta = \frac{1 - \frac{B_c}{B_s} \cdot (N_{ctl/cluster} + \frac{2B_g}{B_c})}{B_c \cdot N \cdot A_{cell}} \quad \text{channel/MHz/km}^2.$$

$\Longrightarrow$

$$\eta = \frac{1}{B_c \cdot N \cdot A_{cell}} - \frac{N_{ctl/cluster} + \frac{2B_g}{B_c}}{B_s \cdot N \cdot A_{cell}} \quad \text{channel/MHz/km}^2$$

where the second term on the right-hand side accounts for the overhead in FDMA and overhead for control message.

Let η_t be the trunk (system) efficiency. Trunk efficiency is defined as carried traffic intensity in Erlangs per channel, which is a value between 0 and 1, and is a function of channels per cell and the specified GoS parameters (such as call blocking rate in the Erlang-B system and average queueing delay in the Erlang-C system)

The total traffic carried in a cluster, in Erlang, is $\eta_t \times N_{data/cluster}$.

$$\eta = \frac{\eta_t \cdot N_{data/cluster}}{B_s \cdot N \cdot A_{cell}} \quad \text{Erlang/MHz/km}^2.$$

$\Longrightarrow$

$$\eta = \frac{\eta_t}{B_c \times N \cdot A_{cell}} - \frac{\eta_t \cdot (N_{ctl/cluster} + \frac{2B_g}{B_c})}{B_s \times N \cdot A_{cell}} \quad \text{Erlang/MHz/km}^2$$

where the second term on the right-hand side is due to the overhead in FDMA.

Example 6.2 System spectral efficiency in channel/MHz/km^2
Suppose a cellular system in which the one-way bandwidth of the system is 12.5 MHz, the channel spacing is 30 kHz, and the guard band at each boundary of the spectrum is 10 kHz. If i) the cell area is 6 km^2, ii) the frequency reuse factor (cluster size) is 7, and iii) 21 of the available channels are used to handle control signaling, calculate the following.

a) The total number of available channels per cluster;

b) The number of available data channels per cluster;

c) The number of available data channels per cell;

d) The system spectral efficiency in units of channel/MHz/km^2.

Solution:

We allocate all of the available frequencies to one cluster and these frequencies or channels are distributed evenly among the N cells in the cluster.

a) The total number of available channels in the cluster is

$$N_{ch/cluster} = \frac{B_s - 2B_g}{B_c} = \frac{12.5 - 2 \times 0.01}{0.03} = 416.$$

b) The number of available data channels per cluster is

$$N_{data/cluster} = N_{ch/cluster} - N_{ctl/cluster} = 416 - 21 = 395.$$

c) The number of available data channels per cell is

$$N_{data/cell} = N_{data/cluster}/N = 395/7 = 56.$$

d) The overall spectral efficiency of the system is

$$\eta = \frac{N_{data/cell}}{B_s \cdot A_{cell}} = \frac{56}{12.5 \times 6} = 0.747 \quad \text{channel/MHz/km}^2.$$

□

6.2.2 TDMA Systems

W-TDMA:

Let

$$\begin{aligned} \tau_p &= \text{the time duration for the preamble} \\ \tau_t &= \text{the time duration for the trailer} \\ T_f &= \text{the frame duration} \\ L_d &= \text{the number of information data symbols in each slot} \\ L_s &= \text{the total number of symbols in each slot.} \end{aligned}$$

Then, we have

$$\eta_{W-TDMA} = \frac{T_f - \tau_p - \tau_t}{T_f} \times \frac{L_d}{L_s}.$$

N-TDMA:

$$N_u = \frac{B_s - 2B_g}{B_c}.$$

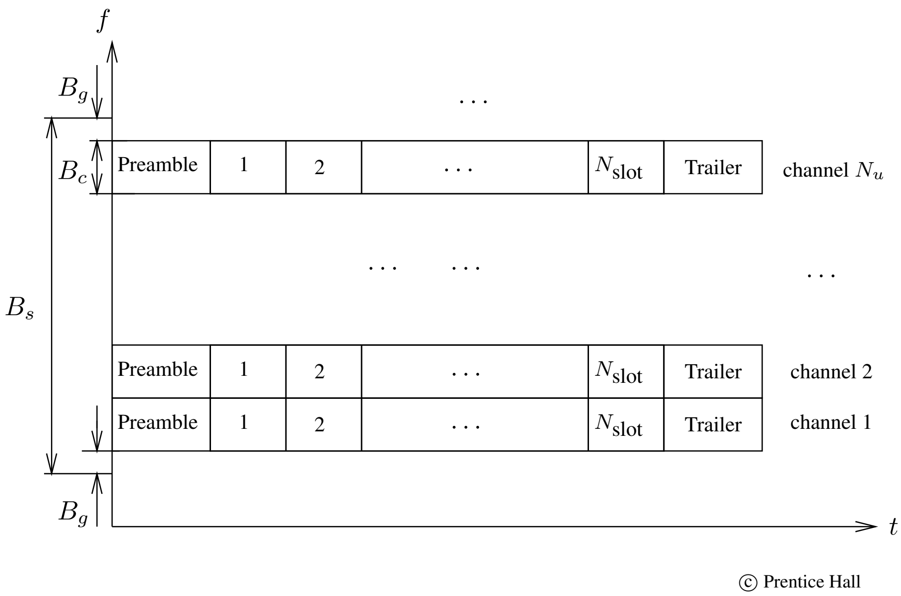


Figure 9: Narrowband TDMA format

The spectral efficiency of narrowband TDMA is then given by

$$\begin{aligned}\eta_{N-TDMA} &= \eta_{W-TDMA} \times \frac{B_c N_u}{B_s} \\ &= \frac{T_f - \tau_p - \tau_t}{T_f} \times \frac{L_d}{L_s} \times \frac{B_s - 2B_g}{B_s}.\end{aligned}$$

Cell capacity of TDMA Systems

The maximum number of simultaneous users that can be accommodated without frequency reuse is

$$N_s = N_u \cdot N_{\text{slot}}$$

where

$$N_u = \begin{cases} 1, & \text{for W-TDMA} \\ \frac{B_s - 2B_g}{B_c} > 1, & \text{for N-TDMA.} \end{cases}$$

With frequency reuse, all the N_s channels can be allocated to a single cell cluster. Then, the cell capacity, N_c, in a TDMA system with frequency reuse factor N is

$$N_c = \frac{N_u \cdot N_{\text{slot}}}{N}.$$

Taking into account of the source activity factor s_f, we have

$$N_c = \frac{N_u \cdot N_{\text{slot}}}{s_f \cdot N} \quad \text{user/cell.}$$

System spectral efficiency η

Let ϵ_{bw} denote the modulation efficiency (defined as maximum transmission rate in bits per second that the modulation can accommodate over one hertz bandwidth), R_b the bit rate of each mobile source. The effective number of users, $N_{\text{effective}}$, that can be supported per cell is

$$N_{\text{effective}} = \epsilon_{bw} \times \frac{B_s}{R_b \cdot N}.$$

Taking into account of the overhead necessary for TDMA, the effective number should be modified to

$$N_{\text{effective}} = \epsilon_{bw} \times \frac{T_f - \tau_p - \tau_t}{T_f} \times \frac{L_d}{L_s} \times \frac{B_s - 2B_g}{R_b \cdot N}$$

The overall spectral efficiency of the system in bit/unit time/unit bandwidth/cell, η, can be expressed as

$$\begin{aligned}\eta &= N_{\text{effective}} \times \frac{R_b}{B_s} \\ &= \epsilon_{bw} \times \frac{T_f - \tau_p - \tau_t}{T_f} \times \frac{L_d}{L_s} \times \frac{B_s - 2B_g}{B_s} \times \frac{1}{N} \ \text{bit/s/Hz/cell.}\end{aligned}$$

Example 6.3 Spectral efficiency of the IS-54 system
Consider IS-54 (updated as IS-136), which is a synchronous N-TDMA/FDD system that uses a one way bandwidth of 25 MHz for the forward (or reverse) channel. The system bandwidth is divided into radio channels of 30 kHz, each supporting transmission at rate 48.6 kbps. Guard bands with $B_g = 20$ kHz are used. A single radio channel supports 3 speech channels (each using 2 slots in a frame). The frame duration is 40 ms, consisting of 6 time slots. The slot duration is then 40/6 ($\simeq 6.667$) ms. Each slot consists of 324 bits, among which 260 bits are for information data and the remaining 64 bits are overhead for access control. If the frequency reuse factor is 7, find

a) the number of simultaneous users that can be accommodated in each cell cluster,

b) the cell capacity,

c) the spectral efficiency η_{N-TDMA} of TDMA, and

d) the overall spectral efficiency.

`48.6 kbps = 324 bits x 6/40ms`

Solution:

Given:

$$
\begin{aligned}
B_s &= 25\text{MHz} = 25000\text{kHz} \\
B_c &= 30\text{kHz} \\
B_g &= 20\text{kHz} \\
N_{\text{slot}} &= 3 \\
T_f &= 40\text{ms} \\
\tau_p &= 0\text{ms} \\
\tau_t &= 0\text{ms} \\
L_d &= 260\text{bits} \\
L_s &= 324\text{bits} \\
\epsilon_{bw} &= (324\text{bits} \times 6/40\text{ms})/30\text{kHz} = 1.62 \text{ bit/s/Hz} \\
s_f &= 1 \\
N &= 7
\end{aligned}
$$

a) The number of simultaneous users that can be accommodated is

$$N_u = \frac{B_s - 2B_g}{B_c} = \frac{25 \times 1000 - 2 \times 20}{30} = 832 \quad \text{user/cell cluster.}$$

b) The cell capacity of the synchronous TDMA system is

$$N_c = \frac{N_u N_{\text{slot}}}{s_f N} = \frac{832 \times 3}{1 \times 7} \simeq 356 \quad \text{user/cell.}$$

c) The spectral efficiency of the N-TDMA is

$$\eta_{N-TDMA} = \eta_{W-TDMA} \times \frac{B_c N_u}{B_s} = \frac{T_f - \tau_p - \tau_t}{T_f} \times \frac{L_d}{L_s} \times \frac{B_s - 2B_g}{B_s} \simeq 0.8.$$

d) The overall spectral efficiency is

$$
\begin{aligned}
\eta &= \epsilon_{bw} \times \frac{T_f - \tau_p - \tau_t}{T_f} \times \frac{L_d}{L_s} \times \frac{B_s - 2B_g}{B_s} \times \frac{1}{N} \\
&= 1.62 \times \frac{40 - 0 - 0}{40} \times \frac{260}{324} \times \frac{25000 - 2 \times 20}{25000} \times \frac{1}{7} \\
&\simeq 0.185 \quad \text{bit/s/Hz/cell.}
\end{aligned}
$$

□

6.2.3 DS-CDMA Systems

Cell capacity

Consider the uplink (from MSs to the BS) with accurate power control. The signal-to-interference ratio, S/I, is given by

$$\frac{S}{I} = \frac{R_b E_b}{B_s I_0} = \frac{1}{G_p}\frac{E_b}{I_0}.$$

$\Longrightarrow$

$$\frac{E_b}{I_0} = G_p \frac{S}{I}.$$

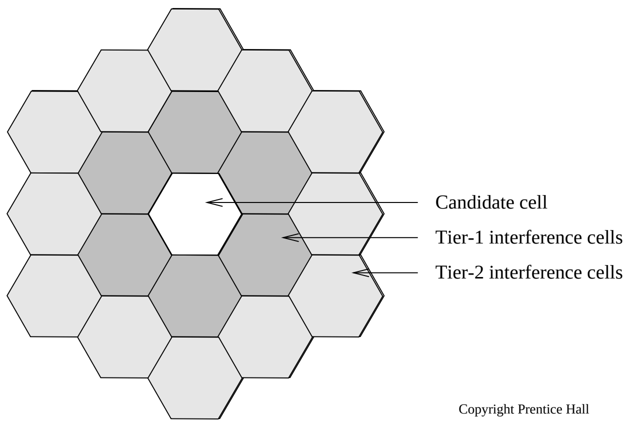


Figure 10: Interfering neighbors in hexagonal array

Let κ_f is the total intracell and intercell interference (on the average) normalized to the total intracell disturbance

$$\kappa_f = 1 + 6k_1 + 12k_2 + 18k_3 + \cdots$$

where k_i is normalized interference from a Tier-i interference cell, normalized with respect to the intracell interference within the target cell.

Then the total interference power, including both intracell and intercell interference, is

$$I = [(N_{MS} - 1)S] \cdot \kappa_f. \text{ + Pn}$$

The SINR can then be expressed as

$$\frac{S}{I} = \frac{1}{(N_{MS} - 1)\kappa_f + P_n/S}.$$

Define $\eta_f = 1/\kappa_f$ as the frequency reuse efficiency factor.

$$\frac{E_b}{I_0} = G_p \cdot \frac{S}{I} = \frac{G_p \cdot \eta_f}{(N_{MS} - 1) + \eta_f P_n/S}.$$

$\Longrightarrow$

$$N_{MS} = 1 + \eta_f \left[\frac{G_p}{E_b/I_0} - \frac{P_n}{S} \right].$$

Consider source activity factor (s_f), cell sectors (Q) with directive antennas, and imperfect power control (c_d):

Pn is background noise power at the receiver. It is not affected by source activity factor, cell sectors, and power control

$$\begin{aligned} & I && = [(N_{MS} - 1)S] \cdot \kappa_f + \text{Pn} \\ \xrightarrow{s_f} \; & I' && = s_f[(N_{MS} - 1)S \cdot \kappa_f] + P_n \\ \xrightarrow{Q} \; & I'' && = s_f[(N_{MS} - 1)S \cdot \kappa_f]/Q + P_n \end{aligned}$$

$\Longrightarrow$ The SINR is now S/I'', from which we get

$$N_{MS} = 1 + \frac{Q\eta_f}{s_f} \left[\frac{G_p}{E_b/I_0} - \frac{P_n}{S} \right].$$

With the capacity degradation factor c_d due to imperfect power control, we have

$$N_{MS} = 1 + \frac{c_d Q\eta_f}{s_f} \left[\frac{G_p}{E_b/I_0} - \frac{P_n}{S} \right]$$

From the required BER, we can obtain the required E_b/I_0 value, $(E_b/I_0)^*$, then the cell capacity is

$$N_c = 1 + \frac{c_d Q\eta_f}{s_f} \left[\frac{G_p}{(E_b/I_0)^*} - \frac{P_n}{S} \right].$$

System utilization

The system utilization is defined as the number of users, U_{MS}, that can be supported under the constraint that $E_b/I_0 \geq (E_b/I_0)^*$.

$$U_{MS} = 1 + \frac{c_d Q \eta_f}{s_f}\left[\frac{G_p}{E_b/I_0} - \frac{P_n}{S}\right], \quad \text{with } E_b/I_0 \geq (E_b/I_0)^*.$$

Spectral efficiency of DS-CDMA systems

$$\eta = \frac{U_{MS}}{N_c} = \frac{(E_b/I_0)^*}{E_b/I_0}$$

or

$$\eta = U_{MS} \times \frac{s_f R_b}{B_s} \text{ bit/s/Hz}$$

where R_b is the constant bit rate (in units of bit/s/user) when a user is in an *on* state and B_s is the one-way system bandwidth in Hz.

Example 6.4 Capacity and utilization of CDMA system
Consider a DS-CDMA system where the one-way system bandwidth is 25 MHz. Suppose the data rate per user is 8 kbps. Assume perfect power control, one sector antenna, and persistent transmissions.

a) Calculate the E_b/I_0 specification required to support a maximum number of 250 users/cell if the signal-to-background noise ratio is 26 dB and the frequency reuse efficiency is 0.9.

b) If the actual operating value of E_b/I_0 is 12 dB, calculate the system utilization for the parameter values specified in part a).

Solution:

a) With the assumptions given in the problem, the E_b/I_0 specification can be written as

$$(E_b/I_0)^* = \frac{\eta_f G_p}{N_c - 1 + \eta_f P_n/S}.$$

It is given that $S/P_n = 26$ dB or 400, $\eta_f = 0.9$, $G_p = B_s/R_b = 25 \times 1000/8 = 3125$, and $N_c = 250$. Substituting these values in the above equation for $(E_b/I_0)^*$ yields

$$(E_b/I_0)^* = \frac{0.9 \times 3125}{250 - 1 + 0.9/400} \simeq 11.25 \text{ or } 10.5 \text{ dB}.$$

b) The utilization can be expressed as

$$U_{MS} = 1 + \eta_f \cdot \left[\frac{G_p}{E_b/I_0} - \frac{P_n}{S}\right], \quad \text{with } E_b/I_0 \geq 10.5 \text{ dB}.$$

If the actual operating value of E_b/I_0 is 12 dB, or 15.85, then the system utilization is

$$U_{MS} = 1 + 0.9 \times \left[\frac{3125}{15.85} - 1/400\right] \simeq 178.$$

□

Example 6.5 Spectral Efficiency of DS-CDMA
Consider the CDMA system in Example 6.4, with the same assumptions about parameter values.

a) If the actual operating value of E_b/I_0 is 12 dB, find the spectral efficiency for this CDMA system.

b) Suppose the actual operating value of E_b/I_0 is now 11 dB, find the spectral efficiency.

c) Discuss the impact of operating at a lower value of E_b/I_0 in terms of spectral efficiency and system utilization. What would be the benefit, if any, to the service provider?

Solution

a) For $E_b/I_0 = 12$ dB, the number of users that can be supported was 178 (Example 6.4), and the system capacity is 250. Therefore, the spectral efficiency is

$$\eta = 178/250 = 71.2\%$$

or

$$\eta = 178 \times \frac{8}{25 \times 1000} = 0.005696 \text{ bit/s/Hz}.$$

b) If the value of E_b/I_0 is now 11 dB or 12.59, the system utilization is

$$U_{MS} = 1 + 0.9 \times \left[\frac{3125}{12.59} - \frac{1}{400}\right] \simeq 224.$$

Therefore, the spectral efficiency is

$$\eta = 224/250 = 89.6\%$$

or

$$\eta = 224 \times \frac{8}{25 \times 1000} = 0.007168 \text{ bit/s/Hz}.$$

c) A reduction in the operating value of E_b/I_0 from 12 dB to 11 dB is accompanied by an increase in spectral efficiency from 71.2% to 89.6%. With a 1-dB decrease in E_b/I_0, the system utilization is increased from 178 to 224 users. This is significant from the revenue point of view for the service provider.

With the system operating at $E_b/I_0 = 11$ dB, which is 0.5 dB above the QoS requirement, the resultant BER would be acceptable for the system users.

$\square$