Multiple Access Techniques for Wireless Communication

FDMA

TDMA

CDMA

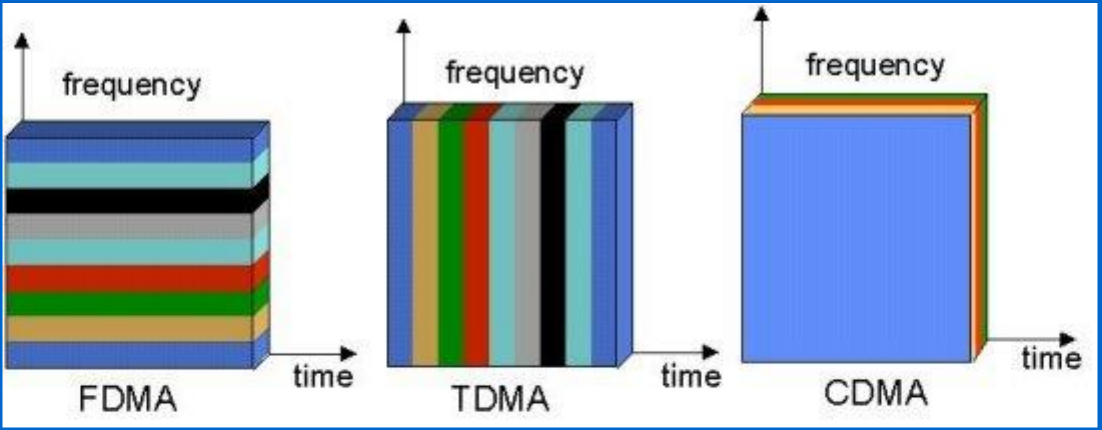
SDMA

PDMA

Introduction

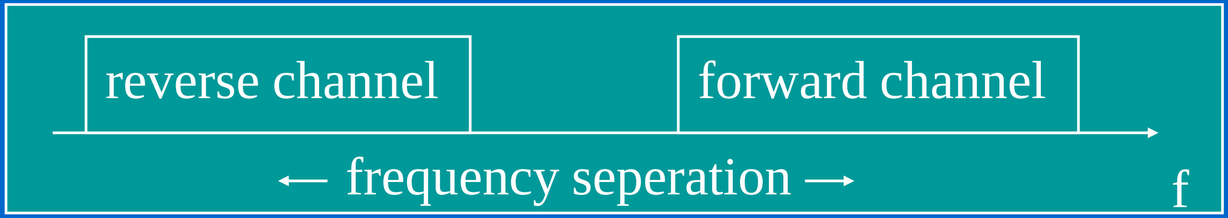
- many users at same time
- share a finite amount of radio spectrum
- high performance
- duplexing generally required
- frequency domain
- time domain

Introduction



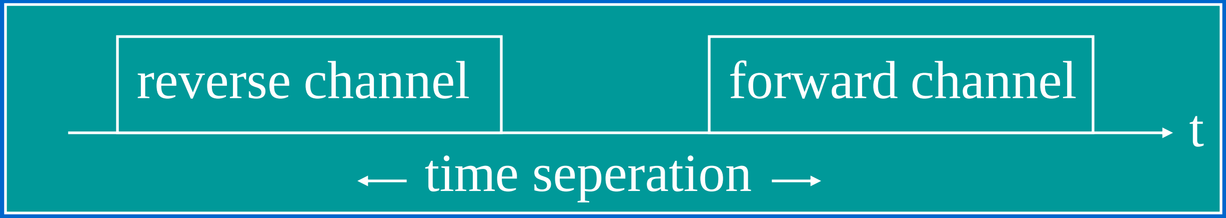
Frequency division duplexing (FDD)

- two bands of frequencies for every user
- forward band
- reverse band
- duplexer needed
- frequency seperation between forward band and reverse band is constant



Time division duplexing (TDD)

- uses time for forward and reverse link
- multiple users share a single radio channel
- forward time slot
- reverse time slot
- no duplexer is required



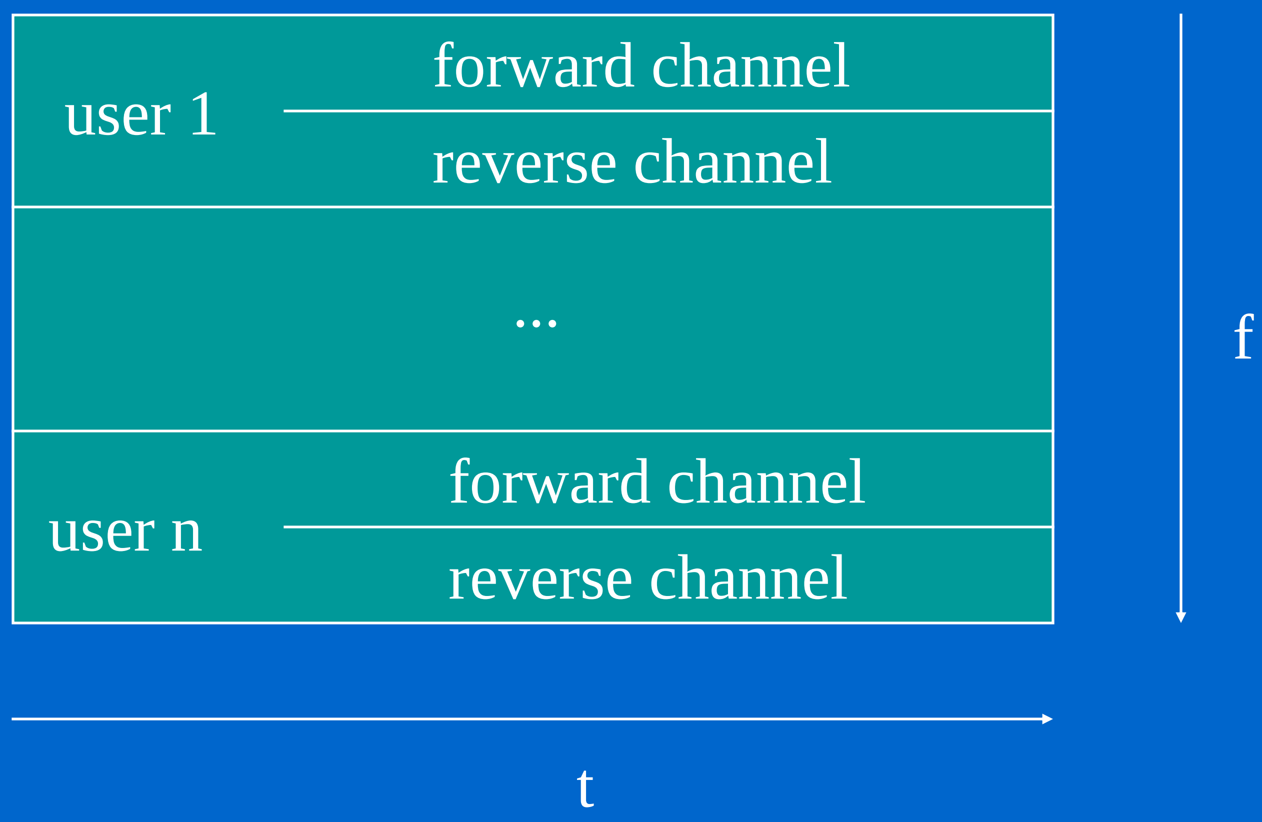
Multiple Access Techniques

- Frequency division multiple access (FDMA)
- Time division multiple access (TDMA)
- Code division multiple access (CDMA)
- Space division multiple access (SDMA)
- grouped as:
- narrowband systems
- wideband systems

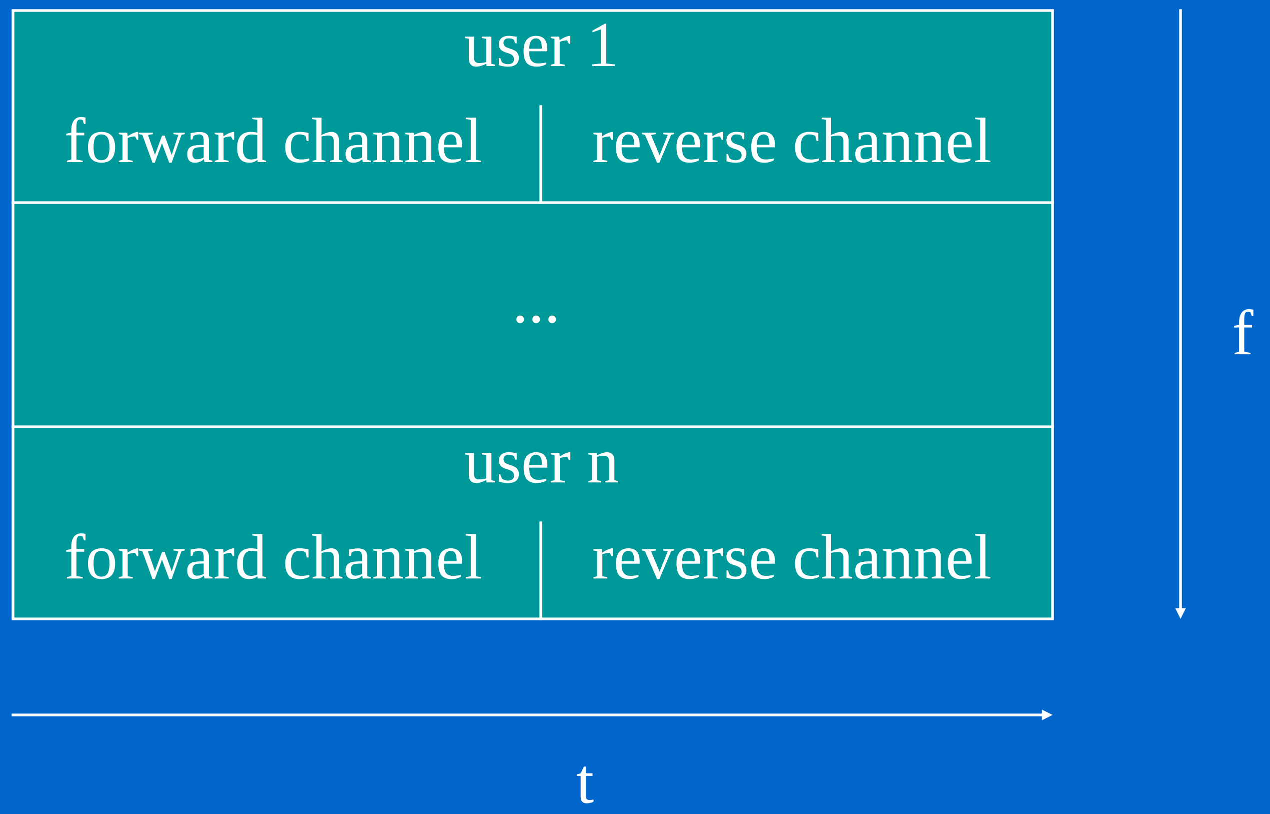
Narrowband systems

- large number of narrowband channels
- usually FDD
- Narrowband FDMA
- Narrowband TDMA
- FDMA/FDD
- FDMA/TDD
- TDMA/FDD
- TDMA/TDD

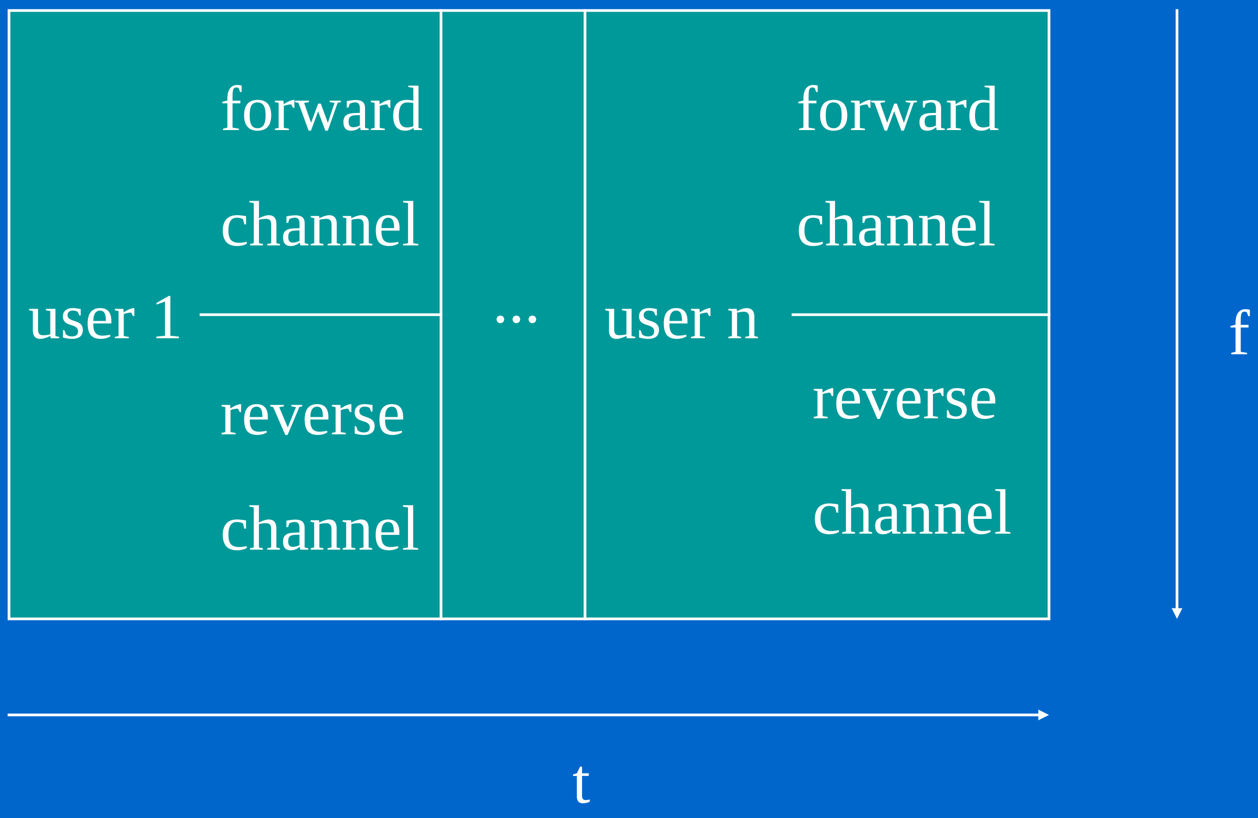
Logical separation FDMA/FDD



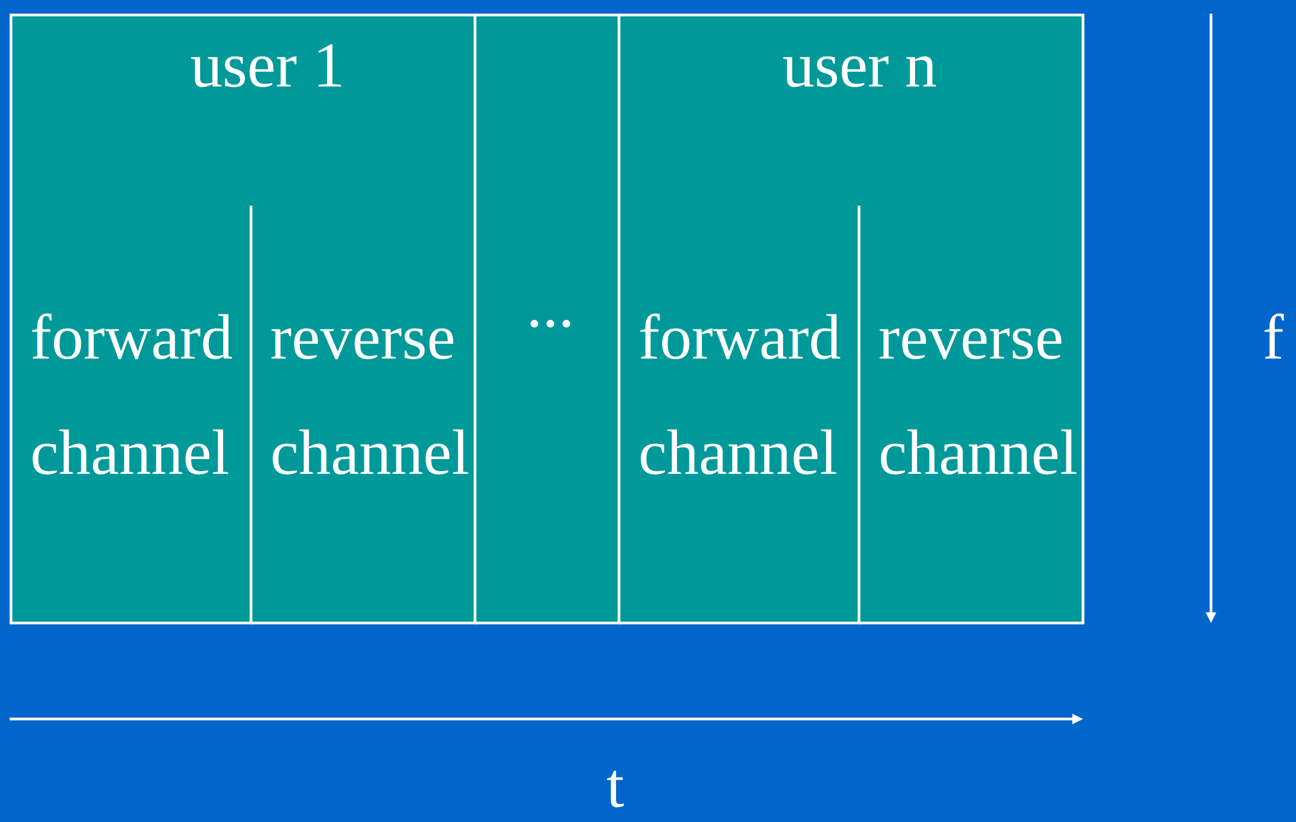
Logical separation FDMA/TDD



Logical separation TDMA/FDD



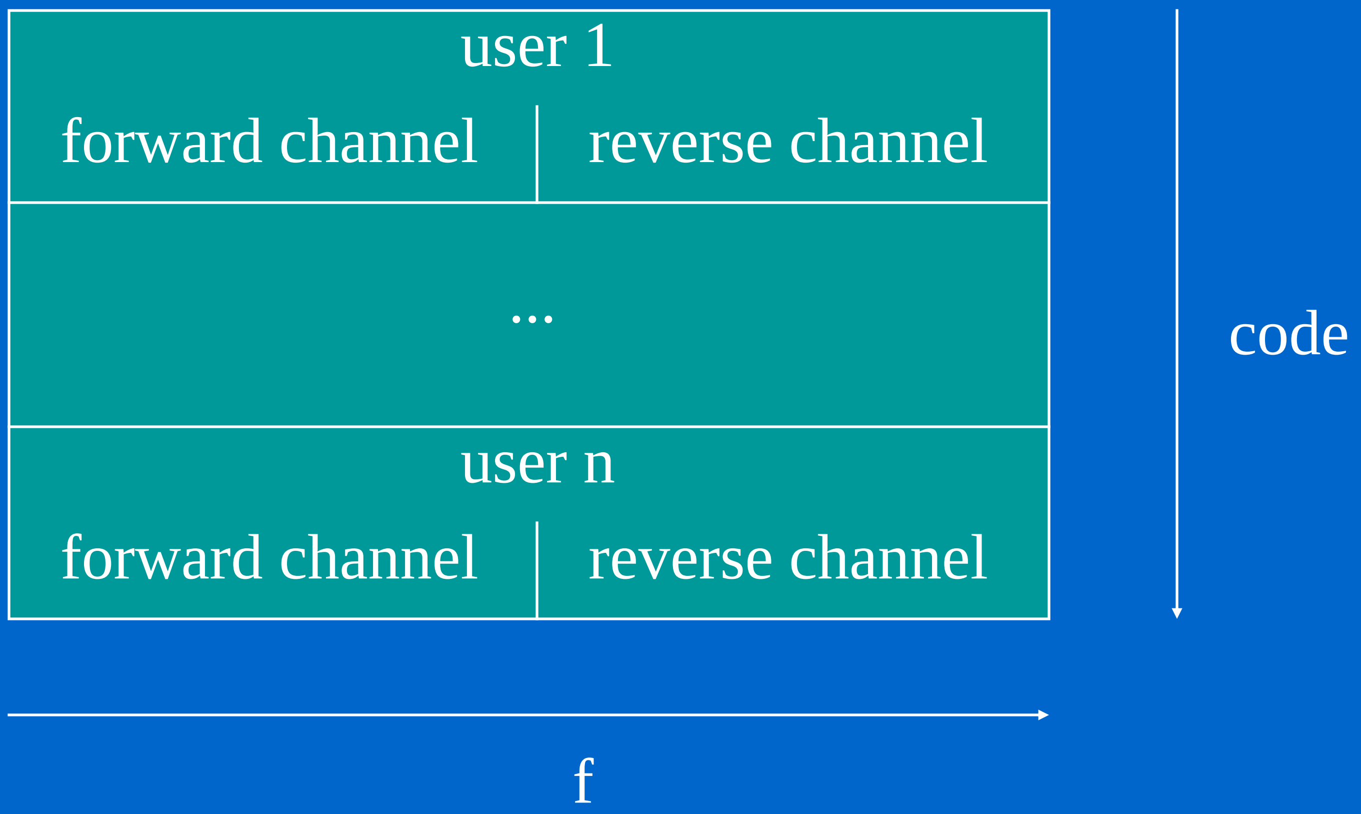
Logical separation TDMA/TDD



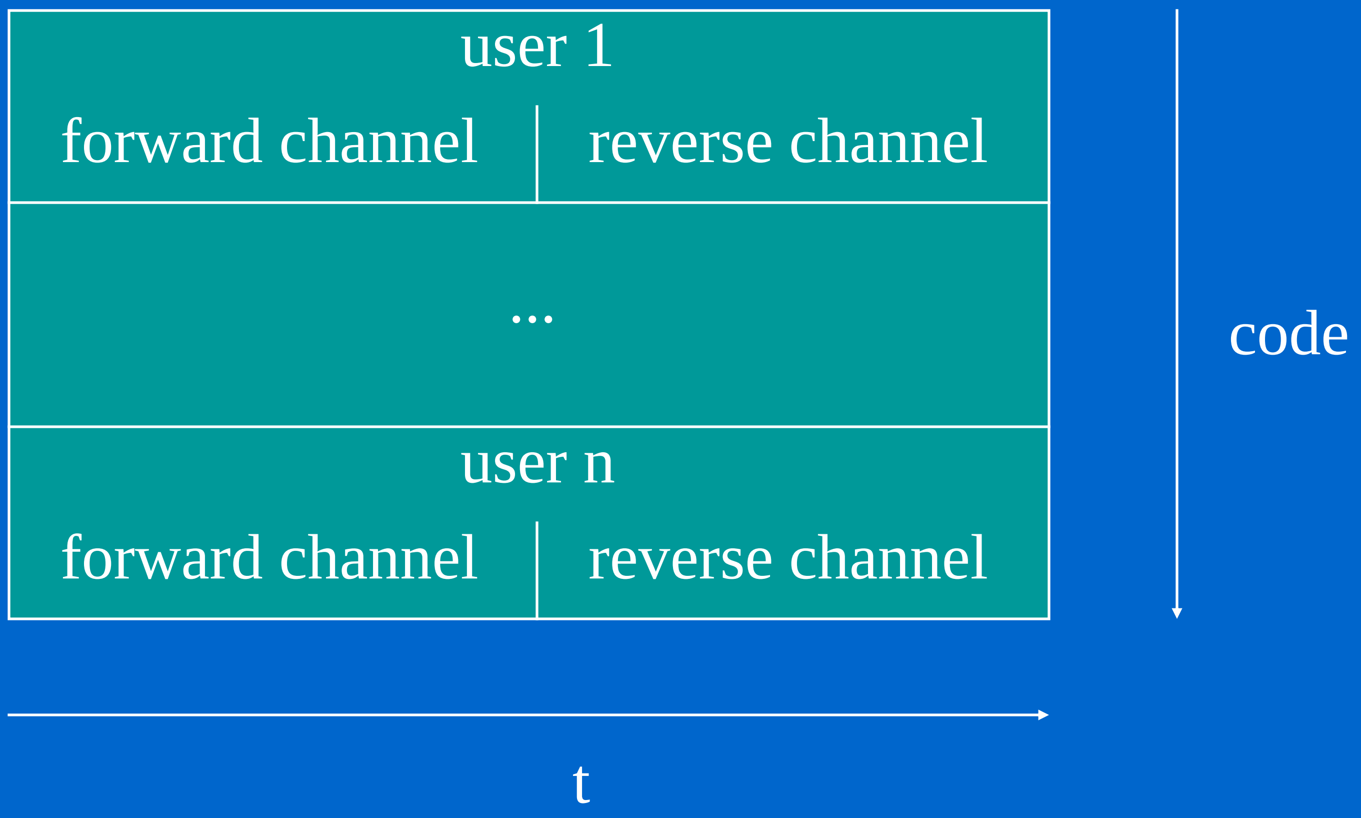
Wideband systems

- large number of transmitters on one channel
- TDMA techniques
- CDMA techniques
- FDD or TDD multiplexing techniques
- TDMA/FDD
- TDMA/TDD
- CDMA/FDD
- CDMA/TDD

Logical separation CDMA/FDD



Logical separation CDMA/TDD



Multiple Access Techniques in use

Cellular System	Multiple Access Technique
Advanced Mobile Phone System (AMPS)	FDMA/FDD
Global System for Mobile (GSM)	TDMA/FDD
US Digital Cellular (USDC)	TDMA/FDD
Digital European Cordless Telephone (DECT)	FDMA/TDD
US Narrowband Spread Spectrum (IS-95)	CDMA/FDD

Frequency division multiple access FDMA

- one phone circuit per channel
- idle time causes wasting of resources
- simultaneously and continuously transmitting
- usually implemented in narrowband systems
- for example: in AMPS is a FDMA bandwidth of 30 kHz implemented

FDMA compared to TDMA

- fewer bits for synchronization
- fewer bits for framing
- higher cell site system costs
- higher costs for duplexer used in base station and subscriber units
- FDMA requires RF filtering to minimize adjacent channel interference

Nonlinear Effects in FDMA

- many channels - same antenna
- for maximum power efficiency operate near saturation
- near saturation power amplifiers are nonlinear
- nonlinearities causes signal spreading
- intermodulation frequencies

Nonlinear Effects in FDMA

- IM are undesired harmonics
- interference with other channels in the FDMA system
- decreases user C/I - decreases performance
- interference outside the mobile radio band: adjacent-channel interference
- RF filters needed - higher costs

Number of channels in a FDMA system

$$N = \frac{B_t - B_{guard}}{B_c}$$

- N … number of channels
- B_t … total spectrum allocation
- B_{guard} … guard band
- B_c … channel bandwidth

Example: Advanced Mobile Phone System

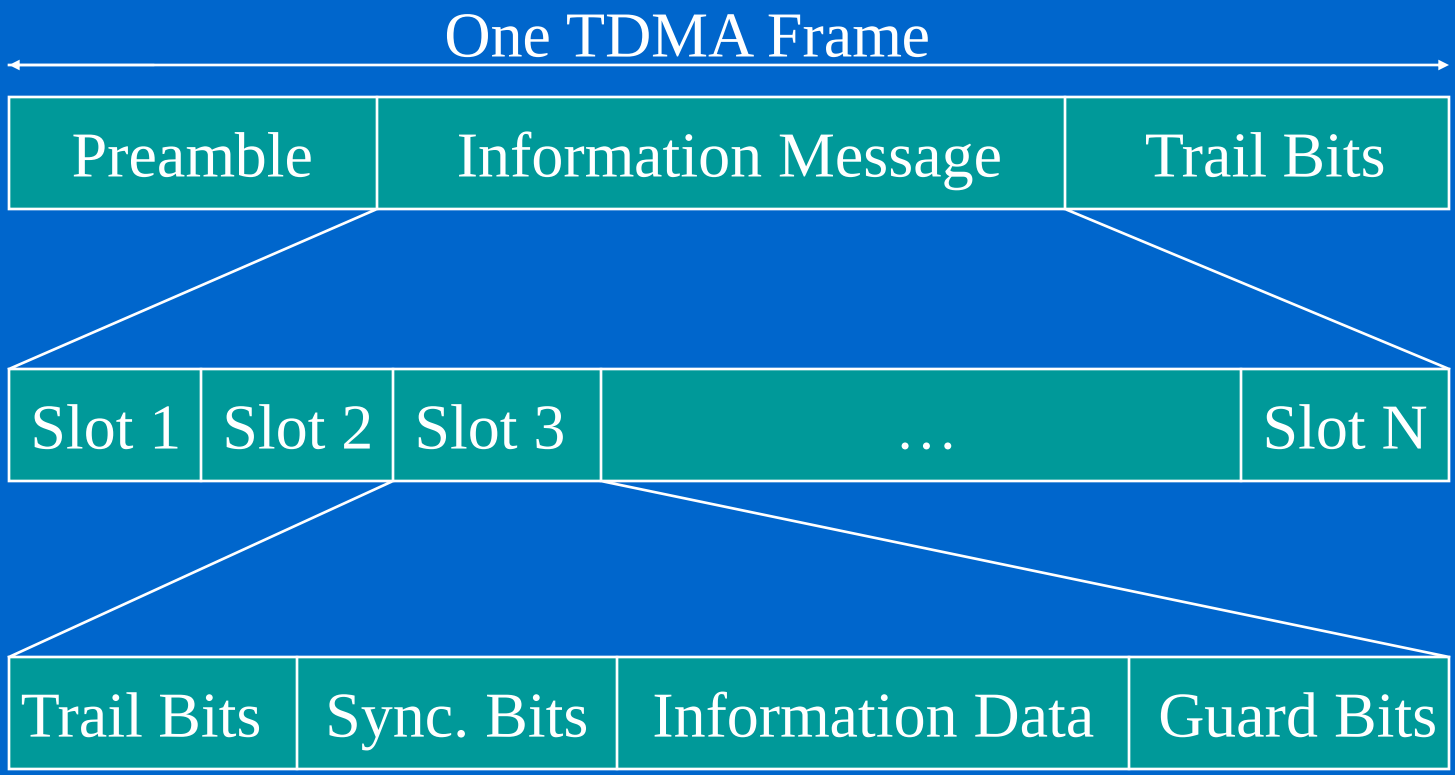
- AMPS
- FDMA/FDD
- analog cellular system
- 12.5 MHz per simplex band - B_t
- B_{guard} = 10 kHz ; B_c = 30 kHz

$$N = \frac{12.5E6 - 2*(10E3)}{30E3} = 416 \text{ channels}$$

Time Division Multiple Access

- time slots
- one user per slot
- buffer and burst method
- noncontinuous transmission
- digital data
- digital modulation

Repeating Frame Structure



The frame is cyclically repeated over time.

Features of TDMA

- a single carrier frequency for several users
- transmission in bursts
- low battery consumption
- handoff process much simpler
- FDD : switch instead of duplexer
- very high transmission rate
- high synchronization overhead
- guard slots necessary

Number of channels in a TDMA system

$$N = \frac{m*(B_{tot} - 2*B_{guard})}{B_c}$$

- N … number of channels
- m … number of TDMA users per radio channel
- B_{tot} … total spectrum allocation
- B_{guard} … Guard Band
- B_c … channel bandwidth

Example: Global System for Mobile (GSM)

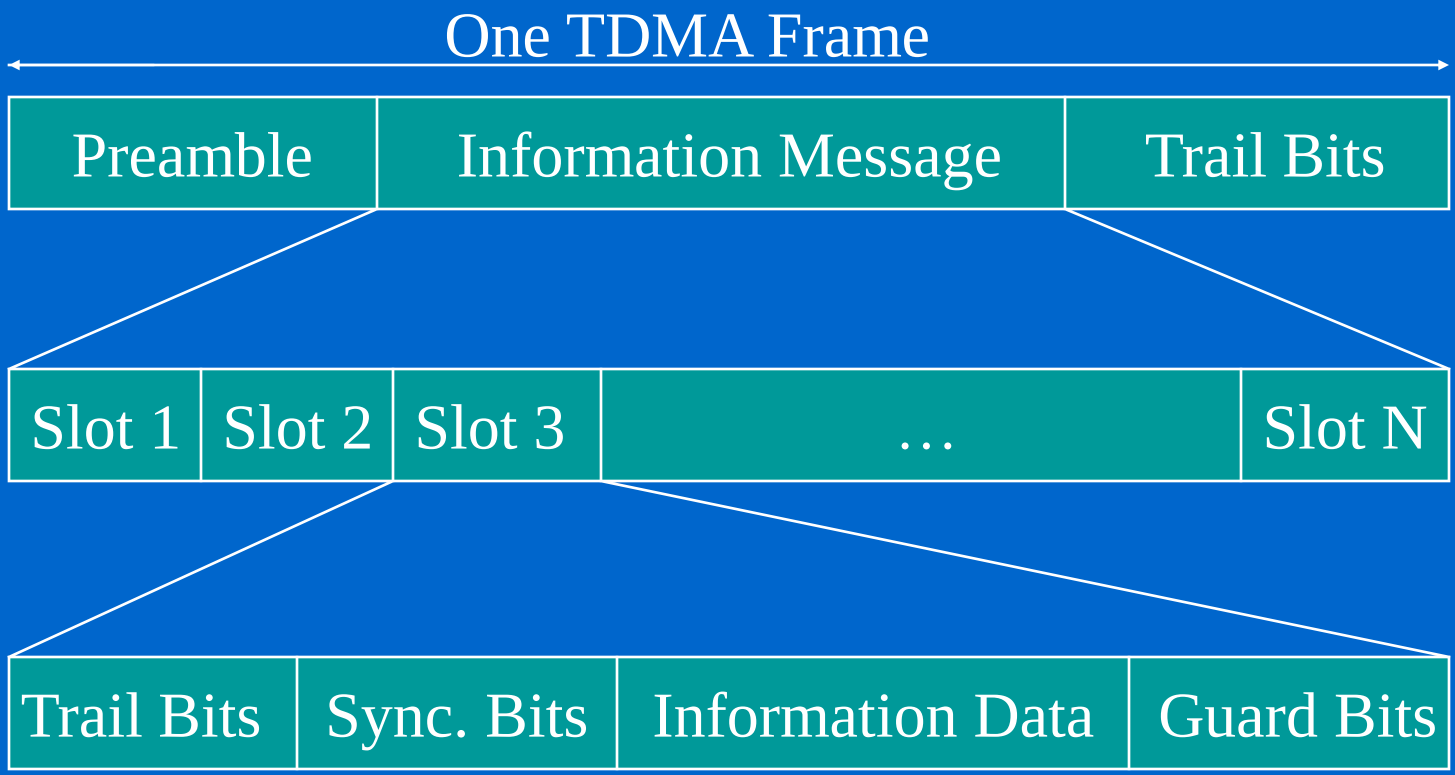
- TDMA/FDD
- forward link at B_{tot} = 25 MHz
- radio channels of B_c = 200 kHz
- if m = 8 speech channels supported, and
- if no guard band is assumed :

$$N = \frac{8*25E6}{200E3} = 1000 \text{ simultaneous users}$$

Efficiency of TDMA

- percentage of transmitted data that contain information
- frame efficiency η_f
- usually end user efficiency < η_f , because of source and channel coding
- How to get η_f ?

Repeating Frame Structure



The frame is cyclically repeated over time.

Efficiency of TDMA

$$b_{OH} = N_r * b_r + N_t * b_p + N_t * b_g + N_r * b_g$$

- b_{OH} … number of overhead bits
- N_r … number of reference bursts per frame
- b_r … reference bits per reference burst
- N_t … number of traffic bursts per frame
- b_p … overhead bits per preamble in each slot
- b_g … equivalent bits in each guard time interval

Efficiency of TDMA

$$b_T = T_f * R$$

- b_T … total number of bits per frame
- T_f … frame duration
- R … channel bit rate

Efficiency of TDMA

$$\eta_f = (1 - b_{OH}/b_T) * 100\%$$

- η_f … frame efficiency
- b_{OH} … number of overhead bits per frame
- b_T … total number of bits per frame

SPREAD SPECTRUM MULTIPLE ACCESS (SSMA)

- Transmission Bandwidth much greater than RF bandwidth
- PN sequences are used for spreading
- Provides immunity to multipath interference
- Bandwidth efficient in a multiuser environment
- Two types: FHMA and DSSS

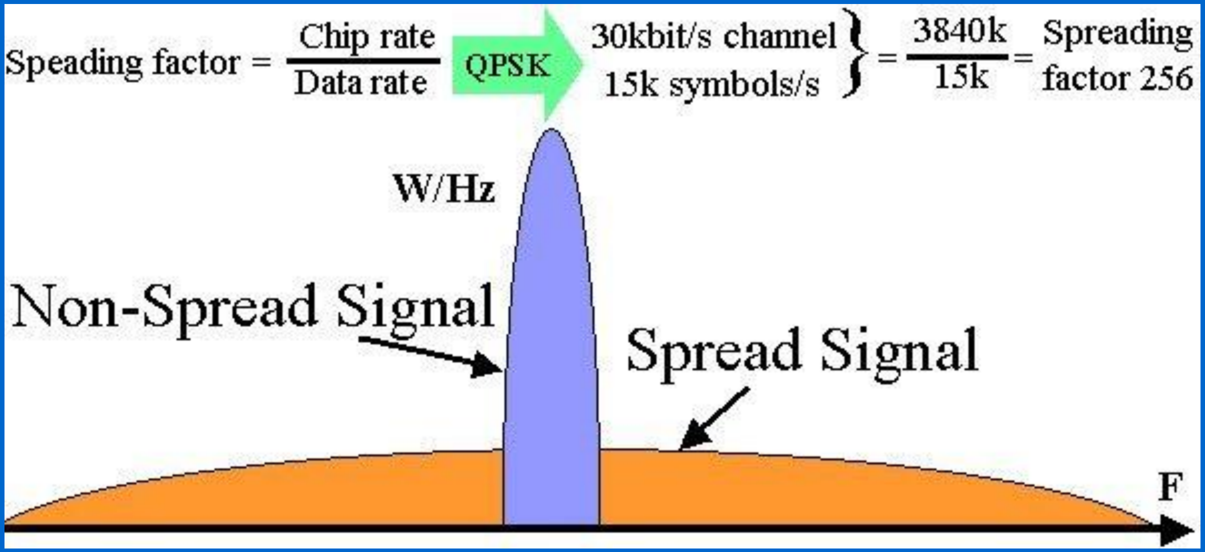
Frequency Hopping Multiple Access (FHMA)

- Carrier frequencies are varied in a pseudorandom fashion in a wideband channel
- FM/FSK is used
- Provides Security
- Immune to fading
- Fast Hopping: Rate of change of $f_c > f_s$
- Slow Hopping: Rate of change of $f_c < f_s$

Code Division Multiple Access (CDMA)

- Narrowband signal multiplied by large bandwidth PN sequence
- All users use the same carrier frequency and may transmit simultaneously
- Near-Far problem if undesired user has a high detected power as compared to desired user
- Power control is used to combat the near –far problem
- TDD/FDD can be used

CDMA


Speading factor =
Chip rate
Data rate
QPSK
30kbit/s channel
15k symbols/s
=
3840k
15k
=
Spreading
factor 256
W/Hz
Non-Spread Signal
Spread Signal
F

CDMA

- CDMA uses unique spreading codes to spread the baseband data before transmission.
- The signal is transmitted in a channel, which is below noise level.
- The receiver then uses a correlator to despread the wanted signal, which is passed through a narrow bandpass filter. Unwanted signals will not be despread and will not pass through the filter.
- Codes take the form of a carefully designed one/zero sequence produced at a much higher rate than that of the baseband data.
- The rate of a spreading code is referred to as chip rate rather than bit rate.

CDMA

- Unlike FDMA or TDMA, CDMA has a soft capacity
- Multipath Fading is reduced
- Very high channel data rates
- Rake receivers are used
- Soft handoff is used
- If spreading sequences are not exactly orthogonal, jamming occurs

CDMA CODES

- CDMA codes are not only required to provide call security, but create a uniqueness to enable call identification.
- Codes should not correlate to other codes or time shifted version of itself.
- Spreading codes are noise like pseudo-random codes, Gold codes, Walsh codes etc.

Hybrid Spread Spectrum Techniques

- Hybrid FDMA/CDMA
- Hybrid DS/FHMA
- Time-Division CDMA (TD-CDMA)
- Time-Division Frequency Hopping (TDFH)

WCDMA

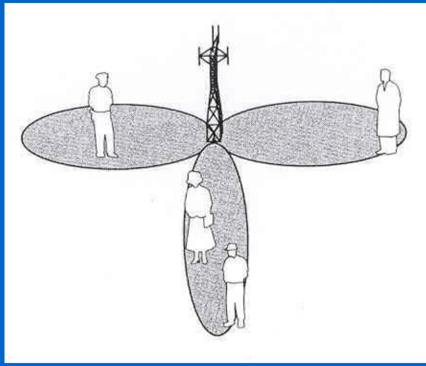
- WCDMA uses Direct Sequence spreading, where spreading process is done by directly combining the baseband information to high chip rate binary code.
- The Spreading Factor is the ratio of the chips (UMTS = 3.84Mchips/s) to baseband information rate.
- Spreading factors vary from 4 to 512 in FDD UMTS.
- Spreading process gain can be expressed in dBs (Spreading factor 128 = 21dB gain).

Space Division Multiple Access

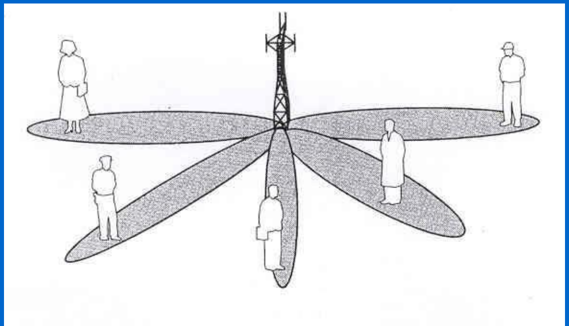
- Controls radiated energy for each user in space using spot beam antennas
- base station tracks user when moving
- covers areas with same frequency in a TDMA or CDMA systems
- cover areas with different frequencies in FDMA systems

Space Division Multiple Access

- primitive applications are "Sectorized antennas"



- in future, adaptive antennas simultaneously steer energy in the direction of many users at once



Reverse link (MS to BS) problems

- In forward link, BS has complete control of power of all transmitted signals
- In reverse link, different propagation paths from each user to base station
- dynamic control of transmitting power from each user to the base station required
- Transmit power limited by battery consumption of subscriber units
- possible solution is a filter for each user

Solution by SDMA systems

- adaptive antennas promise to mitigate reverse link problems
- In the limiting case of infinitesimal beamwidth and infinitely fast tracking ability, optimal SDMA is used, thereby providing a unique channel that is free from interference
- all users communicate at same time using the same channel
- Can track multipath components for each user and combine them in an optimal manner

Disadvantage of SDMA

- perfect adaptive antenna system requires infinitely large antenna
- Reasonably sized antenna arrays can be used

Packet Radio Multiple Access (PDMA)

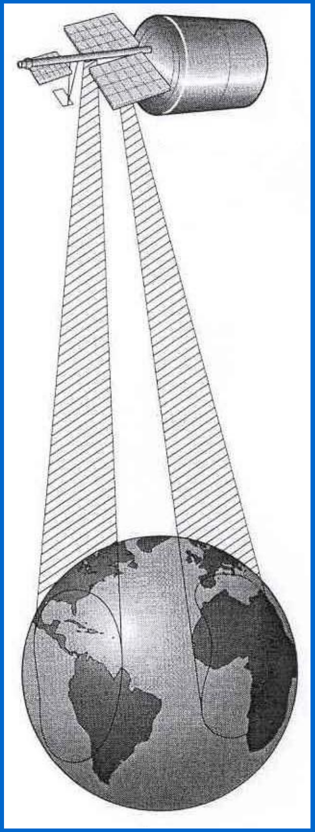
- Many subscribers access a single channel in an uncoordinated manner
- Burst data transmission
- Collisions are detected at BS and ACK or NACK signal is broadcast
- Perfect feedback
- Traffic delay is high due to collisions
- Easy to implement, but has low spectral efficiency and may induce delays

PDMA

- Contention techniques are used
- ALOHA protocols allow each subscriber to transmit whenever they have data to send
- If a collision occurs, packet is retransmitted after a delay
- Large number of users can be served with no overhead
- Performance evaluation in terms of Throughput and average delay

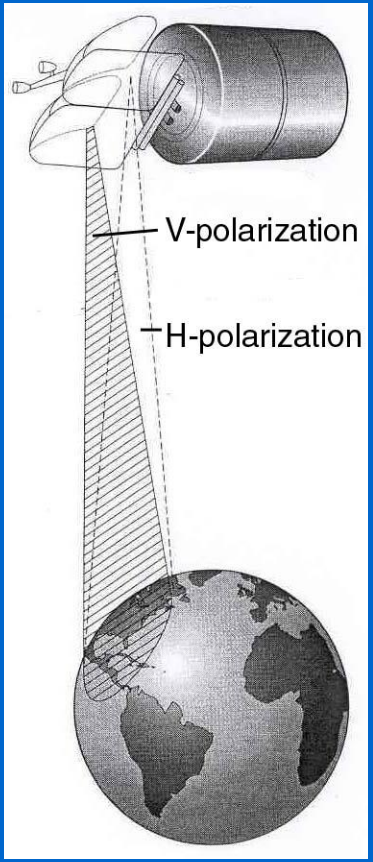
SDMA and PDMA in satellites

- INTELSAT IVA
- SDMA dual-beam receive antenna
- simultaneously access from two different regions of the earth



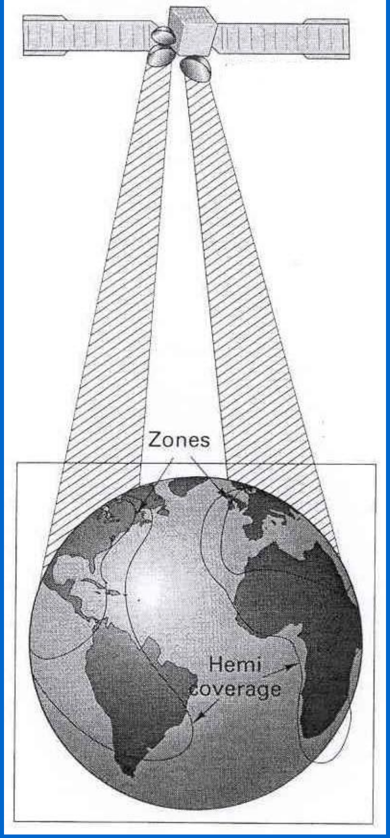
SDMA and PDMA in satellites

- COMSTAR 1
- PDMA
- separate antennas
- simultaneously access from same region



SDMA and PDMA in satellites

- INTELSAT V
- PDMA and SDMA
- two hemispheric coverages by SDMA
- two smaller beam zones by PDMA
- orthogonal polarization



Capacity of Cellular Systems

- channel capacity: maximum number of users in a fixed frequency band
- radio capacity : value for spectrum efficiency
- reverse channel interference
- forward channel interference
- How to determine the radio capacity?

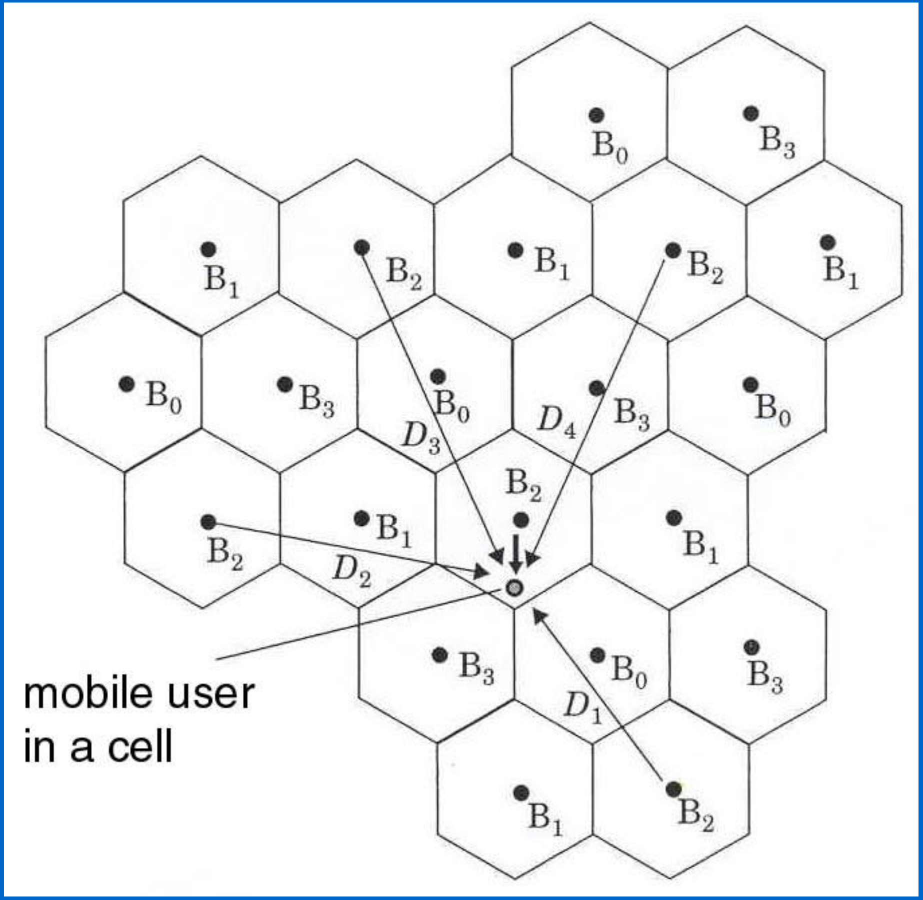
Co-Channel Reuse Ratio Q

$$Q = D/R$$

- Q … co-channel reuse ratio
- D … distance between two co-channel cells
- R … cell radius

Forward channel interference

- cluster size of 4
- D_0 … distance serving station to user
- D_K … distance co-channel base station to user



Carrier-to-interference ratio C/I

- M closest co-channels cells cause first order interference

$$\frac{C}{I} = \frac{D_0^{-n_0}}{\sum_{k=1}^{M} D_K^{-n_k}}$$

- n_0 … path loss exponent in the desired cell
- n_k … path loss exponent to the interfering base station

Carrier-to-interference ratio C/I

- Assumption:
- just the 6 closest stations interfere
- all these stations have the same distance D
- all have similar path loss exponents to n_0

$$\frac{C}{I} = \frac{D_0^{-n}}{6 * D^{-n}}$$

Worst Case Performance

- maximum interference at $D_0 = R$
- $(C/I)_{min}$ for acceptable signal quality
- following equation must hold:

$$1/6 * (R/D)^{-n} \geqq (C/I)_{min}$$

Co-Channel reuse ratio Q

$$Q = D/R = (6*(C/I)_{min})^{1/n}$$

- D … distance of the 6 closest interfering base stations
- R … cell radius
- $(C/I)_{min}$ … minimum carrier-to-interference ratio
- n … path loss exponent

Radio Capacity m

$$m = \frac{B_t}{B_c * N} \text{ radio channels/cell}$$

- Bt … total allocated spectrum for the system
- Bc … channel bandwidth
- N … number of cells in a complete frequency reuse cluster

Radio Capacity m

- N is related to the co-channel factor Q by:

$$Q = (3*N)^{1/2}$$

$$m = \frac{B_t}{B_c * (Q^2/3)} = \frac{B_t}{B_c * \left(\frac{6}{3^{n/2}} * \left(\frac{C}{I}\right)_{min}\right)^{2/n}}$$

Radio Capacity m for n = 4

$$m = \frac{B_t}{B_c * \sqrt{2/3 * (C/I)_{min}}}$$

- m … number of radio channels per cell
- $(C/I)_{min}$ lower in digital systems compared to analog systems
- lower $(C/I)_{min}$ imply more capacity
- exact values in real world conditions measured

Compare different Systems

- each digital wireless standard has different $(C/I)_{min}$
- to compare them an equivalent (C/I) needed
- keep total spectrum allocation B_t and number of rario channels per cell m constant to get $(C/I)_{eq}$:

Compare different Systems

$$\left(\frac{C}{I}\right)_{eq} = \left(\frac{C}{I}\right)_{min} * \left(\frac{B_c}{B_c'}\right)^2$$

- B_c … bandwidth of a particular system
- $(C/I)_{min}$ … tolerable value for the same system
- B_c' … channel bandwidth for a different system
- $(C/I)_{eq}$ … minimum C/I value for the different system

C/I in digital cellular systems

$$\frac{C}{I} = \frac{E_b * R_b}{I} = \frac{E_c * R_c}{I}$$

- R_b … channel bit rate
- E_b … energy per bit
- R_c … rate of the channel code
- E_c … energy per code symbol

C/I in digital cellular systems

- combine last two equations:

$$\frac{(C/I)}{(C/I)_{eq}} = \frac{(E_c * R_c)/I}{(E_c' * R_c')/I'} = \left(\frac{B_c'}{B_c}\right)^2$$

- The sign ' marks compared system parameters

C/I in digital cellular systems

- Relationship between R_c and B_c is always linear ($R_c/R_c' = B_c/B_c'$)
- assume that level I is the same for two different systems (I' = I) :

$$\frac{E_c}{E_c'} = \left(\frac{B_c'}{B_c}\right)^3$$

Compare C/I between FDMA and TDMA

- Assume that multichannel FDMA system occupies same spectrum as a TDMA system
- FDMA : $C = E_b * R_b$; $I = I_0 * B_c$
- TDMA : $C' = E_b * R_b'$; $I' = I_0 * B_c'$
- E_b … Energy per bit
- I_0 … interference power per Hertz
- R_b … channel bit rate
- B_c … channel bandwidth

Example

- A FDMA system has 3 channels , each with a bandwidth of 10kHz and a transmission rate of 10 kbps.
- A TDMA system has 3 time slots, a channel bandwidth of 30kHz and a transmission rate of 30 kbps.
- What’s the received carrier-to-interference ratio for a user ?

Example

- In TDMA system C'/I' be measured in 333.3 ms per second - one time slot

$$C' = E_b R_b' = 1/3 \cdot (E_b \cdot 10E4 \text{ bits}) = 3 \cdot R_b \cdot E_b = 3 \cdot C$$

$$I' = I_0 \cdot B_c' = I_0 \cdot 30\text{kHz} = 3 \cdot I$$

- In this example FDMA and TDMA have the same radio capacity (C/I leads to m)

Example

- Peak power of TDMA is 10logk higher then in FDMA (k … time slots)
- in practice TDMA have a 3-6 times better capacity

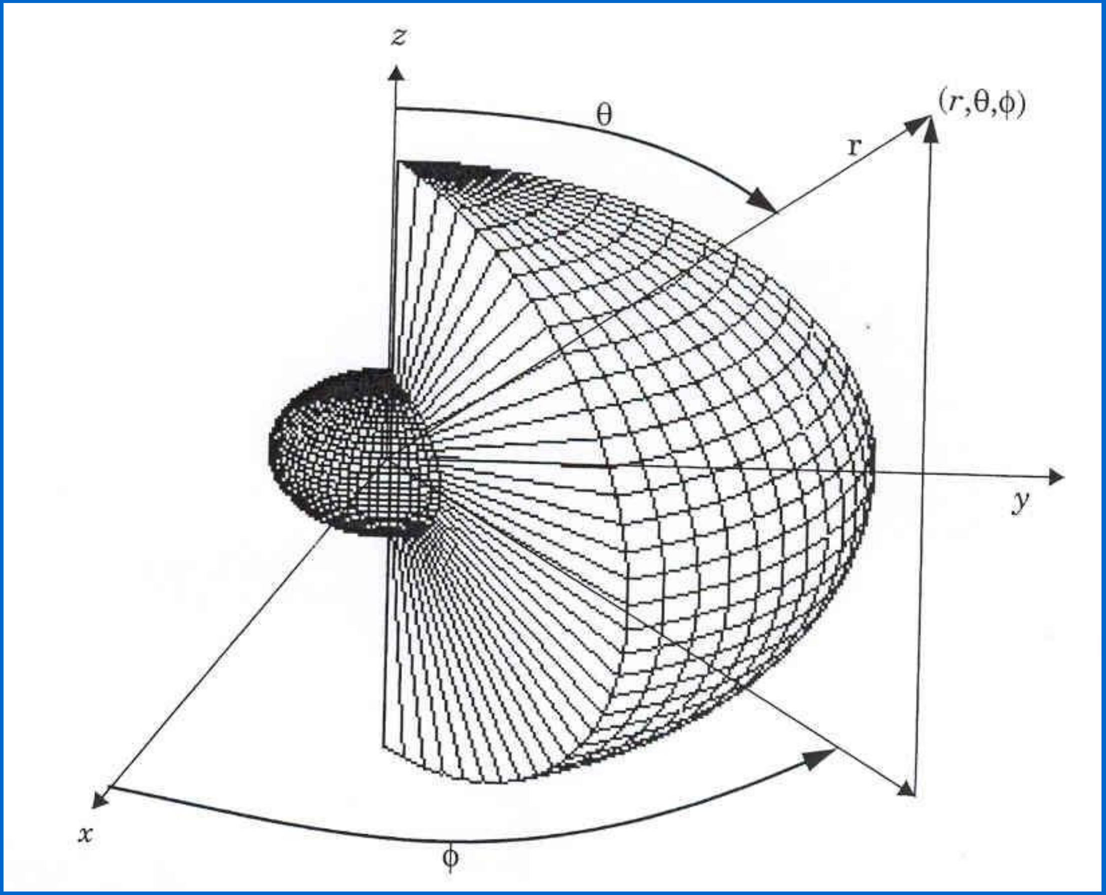
Capacity of SDMA systems

- one beam each user
- base station tracks each user as it moves
- adaptive antennas most powerful form
- beam pattern G(♐) has maximum gain in the direction of desired user
- beam is formed by N-element adaptive array antenna

Capacity of SDMA systems

- G(♐) steered in the horizontal ♐ -plane through 360°
- G(♐) has no variation in the elevation plane to account which are near to and far from the base station
- following picture shows a 60 degree beamwidth with a -6 dB sideslope level

Capacity of SDMA systems



Capacity of SDMA systems

- reverse link received signal power, from desired mobiles, is $P_{r;0}$
- interfering users i = 1,…,k-1 have received power $P_{r;I}$
- average total interference power I seen by a single desired user:

Capacity of SDMA

$$I = E \{ \overset{K-1}{\underset{i=1}{\text{💧}}} G(\text{☞}_i)\, P_{r;I} \}$$

- ☞i … direction of the i-th user in the horizontal plane
- E … expectation operator

Capacity of SDMA systems

- in case of perfect power control (received power from each user is the same) :

$$P_{r;I} = P_c$$

- Average interference power seen by user 0:

$$I = P_c \, E \left\{ \sum_{i=1}^{K-1} G(\theta_i) \right\}$$

Capacity of SDMA systems

- users independently and identically distributed throughout the cell:

$$I = P_c *(k -1) * 1/D$$

- D … directivity of the antenna - given by max(G(☞))
- D typ. 3dB …10dB

Capacity of SDMA systems

- Average bit error rate P_b for user 0:

$$P_b = Q\left(\sqrt{\frac{3\,D\,N}{K-1}}\right)$$

- D … directivity of the antenna
- Q(x) … standard Q-function
- N … spreading factor
- K … number of users in a cell

Capacity of SDMA systems