LTE – Long Term Evolution of mobile networks

Mobile Radio Channel, MIMO and Access Methods

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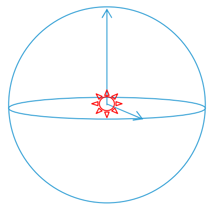
Fundamentals on

- Mobile channel characteristic
  - Attenuation models, shadowing
  - Multipath propagation and fading
  - Time dispersion and frequency dispersion
  - Fading statistical models and BER degradation
- Multi-antena systems
  - Diversity, directionality and spatial multiplexing
  - MIMO systems
- Multiple Access
  - Divison and assignments
  - Duplexing, multiplexing and multiple access
  - Space divison multiple access
  - Frequency, time and code division multiple access

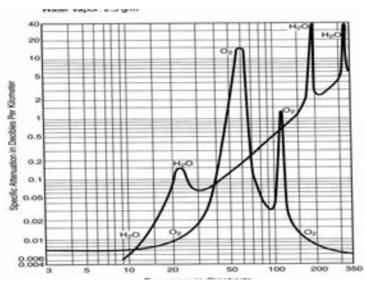
Radio signal attenuation

- **Free space propagation model conditions:**
  - **a free space beetween receiver and transmitter,**
  - **isotropic antena**
  - **received power:**

$$P_R = k_{fs} \cdot P_T \cdot \frac{1}{d^2}$$

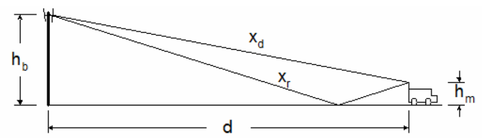


- **Attenuation (loss)** due to atmospheric gases:
  - **problems arrise at carrier frequency over 10GHz!**



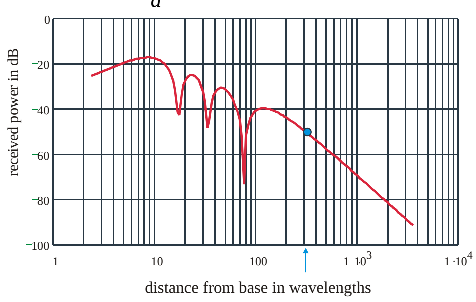
Plane earth model

- **A two-ray propagation model** parameters:
  - antena height: hb, hm
  - distance= ***d***
  - **direct wave** and **ground reflected wave** path distance: x_d, x_r
  - path length difference: $\Delta x = x_r - x_d$



- ***Simplified attenuation formula:***

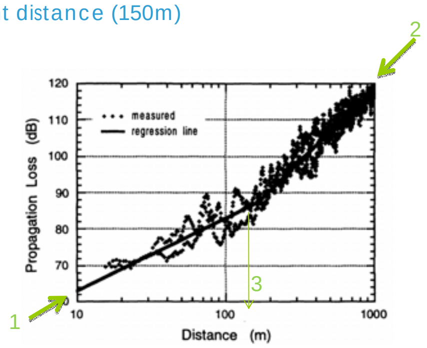
$$P_R = \frac{P_T}{d^2}(1 - \cos(\beta \cdot \Delta x))$$



- ***calculation results:***
  - ***example: h_b=20m, h_m=2m***
  - wavelength: $\lambda = c/f$,
  - ***Note at 2GHz: λ=15cm, $d_{min} > h_b > 100\lambda$***

Radio signal attenuation

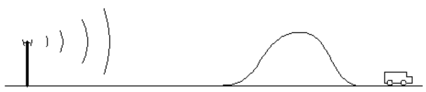
- microcell attenuation measurements and statistical model:
  1. regime #1: , short distance, free space loss model, ***n=2***
  2. regime #2: plane earth loss model, ***n=4***
  3. breakpoint distance (150m)

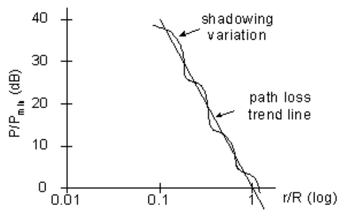


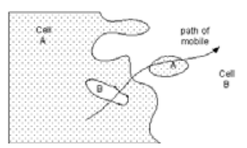
#2 received power approximation: $$P_R = k_{pe} \cdot P_T \cdot \frac{(h_b \cdot h_m)^2}{d^4}$$

Shadowing

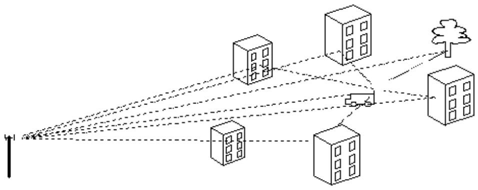
- Large obstacles on the direct path produces excess loss – s**hadowing**. Typical obstacles are hills, large buildings, foliage, etc.,
- Shadowing causes considerable variability about the mean power predicted by path loss, **the scale of significant variation is hundreds of wavelengths**.
- Shadowing loss is well described by a lognormal distribution with zero mean and typical variance betweeen 6 and 8 dB.
- Shadowing makes cell boundaries less well defined than simple path loss calculations suggest. It also produces difficulty in the handoff of a mobile from one base station to another.





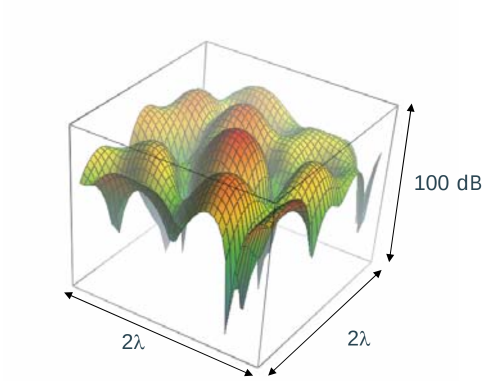


Multipath propagation



- Multipath propagation is the result of several reflections around the mobile: from buildings, hills, other vehicles, etc.
- Each path has its own delay and gain/phase shift.
- The receiver antenna picks up multiple reflections of the transmitted signal, with different phase and delay.
- They can interfere constructively or destructively, producing a random standing wave vith large amplitude variations.

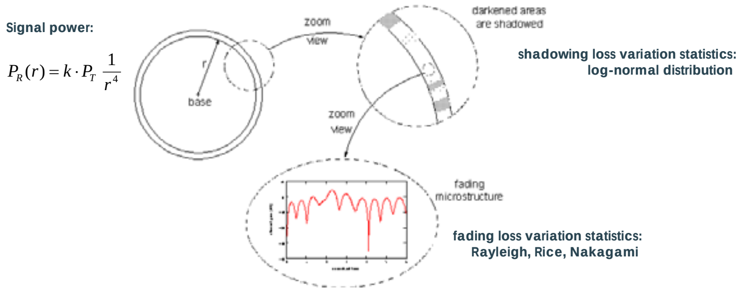
Fading



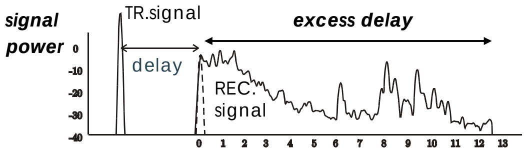
- A displacement of a fraction of a wavelength in any direction causes a large change in the aggregate gain !!
- Channel transfer characteristic is frequency selective with several strong attenuation bands – **fades**.
- Demo example: 15 rays under random angles

Mobile Channel attenuation

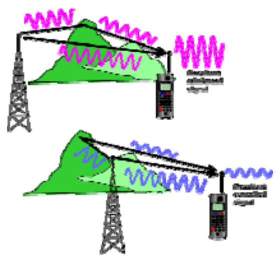
- as a set of **nested models**:
  - <u>**Path loss**</u> is due to a combination of inverse square law and destructive interference with ground reflected wave. The simplified model asserts that path loss depends only on distance from the base station, so that all points on a circle centred on the base have the same received power.
  - Shadowing produced by obstructions such as buildings, trees or small hills. The scale of significant variation is hundreds of wavelengths λ and the received power is more or less constant over a patch tens of wavelengths across.
  - Fading- the microstructure of signal level variation - is due to interference among the multiple paths, with significant variations over about λ/2.



Time dispersion



- Main channel parameters are derived from the multipath intensity (power delay) profile:
  - mean excess delay and maximum excess delay τ_{mean}, T_m
  - **coherence bandwidth**= approx. frequency range where the channel characteristic is flat: $B_c = 1/T_m$
- Type of fading depends on relative symbol time T_s
  - <u>**flat fading**</u> Narowband channel has a constant gain, but may be in fade. Symbol duration is longer than delay spread ***Ts*** >***Tm***. ISI is very small.
  - <u>**frequency selective fading**</u> Wideband channel has frequency selective attenuation. Symbol duration is smaller than delay spread ***Ts < Tm.*** Equalization is necessary to deal with intersymbol interference.

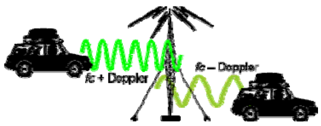


2-ray standing wave signal cancellation at:

$$\Delta x = \frac{\lambda}{2} + n \cdot \lambda$$

Frequency dispersion

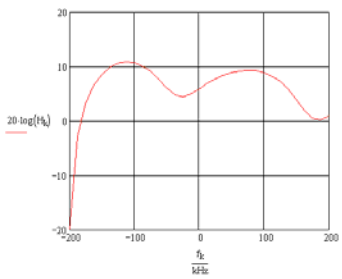
- Doppler shift
  - example at v=30m/s (108km/h) and f=1GHz → f_D=100Hz.
  - coherence time: $T_C=1/f_D$
  - channel characteristic is time invariant only for short intervals $\Delta t<T_C$
- Type of fading depends on channel bandwidth and symbol duration.
  - fast fading when $T_C<T_S$
    Channel impulse response is radiply changing within symbol duration.
  - slow fading when Doppler spread is smaller than signal bandwidth and consequently $T_C>T_S$
    Channel is static over one or several symbol durations.

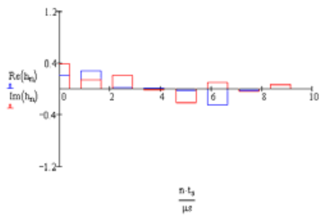


Doppler shift: $f_D = f_0 \cdot \frac{v}{c}$

Time-varying mobile channel

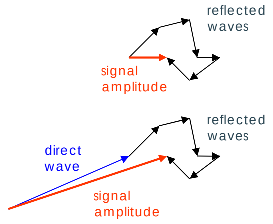
- If the mobile moves through the random field, then it experiences changes in signal level and phase. The rate of changes is proportional to the mobile speed !
- channel transfer function shows time-varying fades
- channel impulse response shows time-varying dispersion

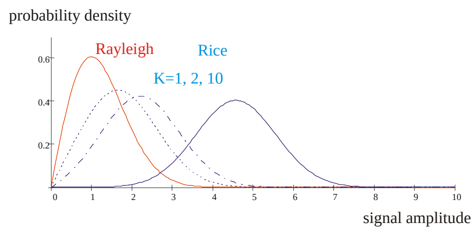




Fading channel models

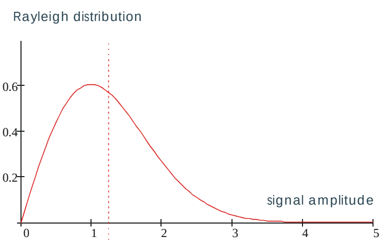
- Different situations call for a different amplitude density distribution models:
  - NLOS=no direct wave : **Rayleigh distribution**
  - LOS=direct wave, strong scaterers: **Rice** distribution
  - NLOS, small number of paths: **Nakagami** distribution
  - Rice and Nakagami distribution covers area beetween both situations LOS and no LOS.

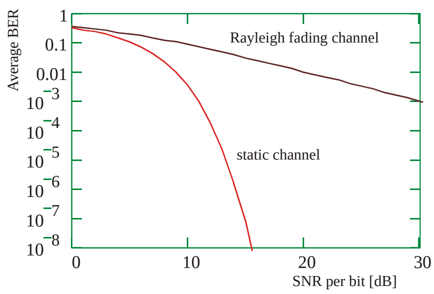




Rayleigh fading channel

- Rayleigh probability approx.:
  - 10dB fade – probability 10%
  - 20dB fade – probability 1%
  - 30dB fade – probability 0.1%
- Deep fade consequences ?
- BER(SNR) on static channel:
  - BER (SNR) decreases strongly nonlinear: SNR variation in positive direction gives less improvement than degradation in opposite direction.
- BER(SNR) on Rayleigh fading channel:
  - Average BER decreases lineary with SNR
  - Much higher average BER on fading channel is the result of deep fade.
  - Errors occur in burtst !





Mobile Channel

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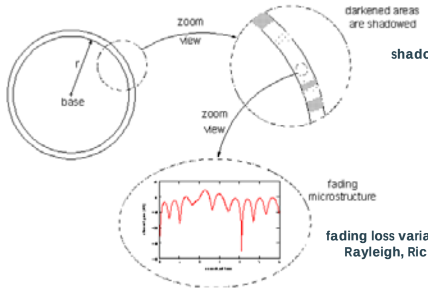
Signal power:

$$P_R(r) = k \cdot P_T \frac{1}{r^4}$$



shadowing loss variation statistics: log-normal distribution

fading loss variation statistics: Rayleigh, Rice, Nakagami

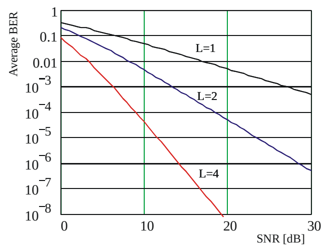
Diversity

- Diversity techniques reduces the effects of fading.
- Several replicas of the same information signal are supplied to the receiver over independently fading channels.
- The probabilty of all the signal componnents are fading simultaneosly is reduced !
- Conditions:
  - a copy of the same signal is received over more different paths,
  - each path fades differently,
  - some type of diversity combining of received signals is possible
- There are several ways to provide independently fading replicas of the same information signal:
  - frequency diversity: multiple different carriers
  - time diversity: multiple time slots,
  - space diversity or **antena diversity**
    - **receive diversity** : beamforming improves SNR
    - **transmit diversity**: space-time coding (Alamouti) reduces SNR variations

Space diversity

- By employing more than one antenna, we gain **diversity** - the likelihood that not all antennas will receive badly faded signals.
- Effective diversity relies on independence, or at least **weak correlation**, among the channel gains experienced by the various antennas.
- Increase in SNR due to **multiple receive antennas** is obtained with or without independence of the diversity channels. (doubling=3dB)

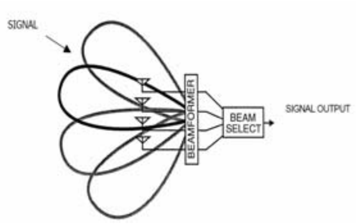
Simple diversity signal processing example: select line with largest power

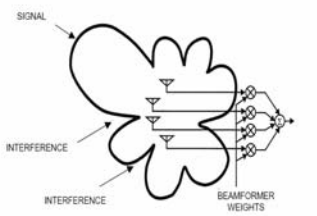


Diversity gain on Raylaigh fading channel

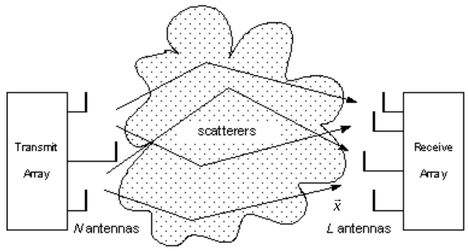
Beamforming and smart antenas

- Multiple antennas also provides **directional gain.**
- **Beamforming** is a signal processing technique for directional transmission and/or reception.
- **Directionality benefits:**
  - increase SNR and the cell range,
  - reduce flat fading,
  - suppress interference between users
- **Directive antena array types:**
  - **switch beam antenna array** provides high gain across a range of fixed arrival angles, can be also used to sectorize the directions
  - **adaptive antena arrays ("smart" antenas)** work by adapting the phase of each antenna element. Array size defines max.number of nulls in directional diagram.





MIMO spatial multiplexing



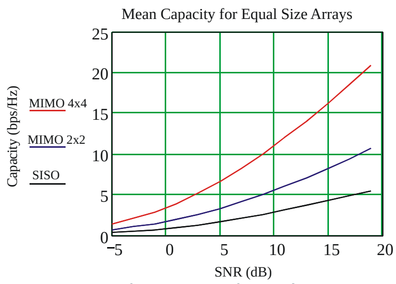
$$\mathbf{x} \qquad \mathbf{y} = \mathbf{H} \cdot \mathbf{x} + \mathbf{n}$$

- MIMO system uses spatial multiplexing: independent information streams are transmited in parallel through the spatial channels.
- A linear relationship between N-dimensional transmited signal and L-dimensional received signal is modelled by N*L complex path gains $h_{i,j}$ described by channel matrix ***H***.

MIMO capacity

- Capacity is greatest if the *NL* gains between antennas are statistically independent = uncorrelated.
- Effectively, these gains can set up min(*N*,*L*) parallel channels between the two antenna arrays.
- Under ideal conditions MIMO capacity is proportional to array size:

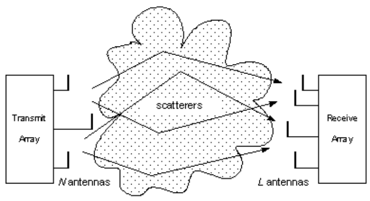
$$C_{MIMO} \le \min\{N, L\} \cdot C_{SISO}$$



- In realistic case, the gains are more or less correlated !
- Correllation between path gains reduces capacity!!
- There are also some practical limitations on mobile side: dimensions, signal processing complexity and power consumption.

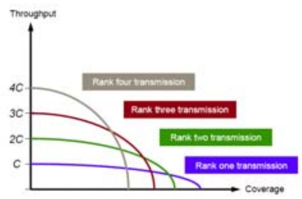
Capacity and/or Diversity ?

- DIVERSITY gain
  - The goal is a reliability improvement BER(SNR), and indirectly coverage increase
  - signals are carying **the same information** through different paths
- CAPACITY gain
  - is achieved by spatial multiplexing,
  - signals are carying **different information** through different paths,
- It is not possible to achieve both maxima at the same time !



MIMO coverage and throughput

- **A tradeoff is neccessary** to achieve both: good diversity gain and capacity improvement.
- Low SNR scenario: the goal is a reliability improvement
  - achieve higher diversity gain
  - result is higher SNR
  - SNR improvement will reduce BER and/or extend cell coverage
- High SNR scenario: the goal is a capacity improvement
  - share SNR (share transmitt power) by spatial multiplexing
  - Result si higher channel capacity

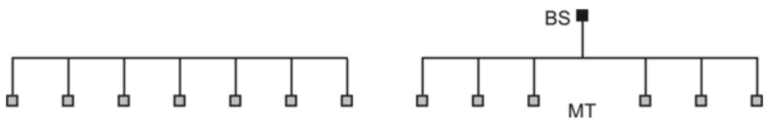


Resource division and assignment

- The radio electromagnetic spectrum is a limited natural resource. Use of radio frequency bands is regulated by governments. The managment process is known as **frequency allocation**. Radio spectrum is **divided** into frequency bands and **assigned** ($)to different major users - operators.
- Available band capacity is further divided according to different signal characteristics in **different signal domains**: **frequency** – FDMA, **time** - TDMA , or **code** - CDMA.
- The division results in a finite number of **communication channels** that are assigned to different users.
- **Assignments** may follow the principles of:
  - *(static)* **dedicated assignment**: permanent reservations, assured QoS, unefficient if assigned capacity is not utilized,
  - *(dynamic)* assignment with **random access**: efficient , simple protocols, unpredictable delays, best effort QoS depending on traffic loads.
  - *(dynamic)* **demand-based assignement**: temporary reservation acording to user need, negotiation process is controlled, different traffic-type requirements are taken into account, Qos is far superior than in random access.

Cell network topology

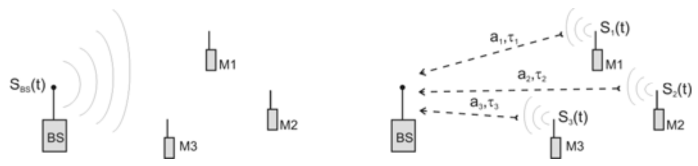
- A set of equivalent ranking devices on a common physical medium can be illustrated as linked in a bus topology (left)



- In cellular networks, the nodes are not equivalent in roles, and the communication between the base station (BS) and the mobile terminals (MT) takes place directionally (right):
  - The communication to mobile devices is called a **downlink,**
  - and the link to transfer information from mobile devices is known as an **uplink.**

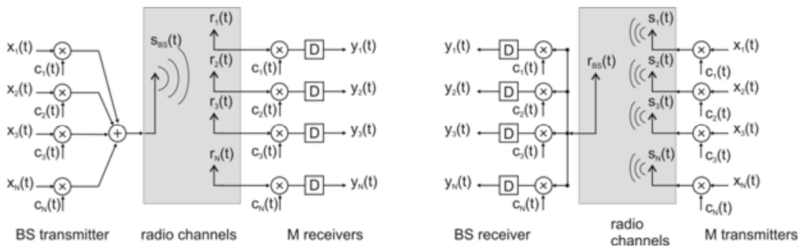
Duplexing, multiplexing and multiple access

- The bi-directional nature of communication requires the division of transmission capacity according to the direction of the information exchange: **duplexing**.



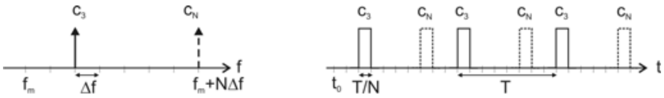
- The methods of separating users differ between the two transfer directions:
  - In the case of the downlink, we deal with **multiplexing**,
  - while in the case of the uplink, with **multiple access**.

Multiplexing < > multiple access



- LEFT : The base station simultaneously emits a common signal for all mobile stations (**broadcasting**). The method of signal combining is called **multiplexing**. With multiplexing, each signal is already available in the base station and has defined amplitudes and phases. Multiple signal summation takes place in the base station.
- RIGHT: Mobile terminals must communicate with the base station in a coordinated way, with minimum possible interference. Such an arrangement is known as **coordinated multiple access**. Signals are added together on the radio channel. The differences in amplitudes and phases between mobile terminal signals may cause interference.

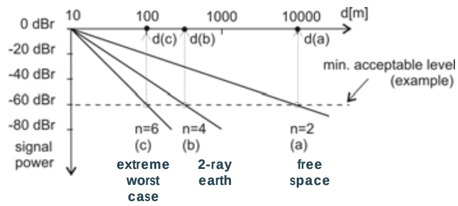
Signal multiplexing

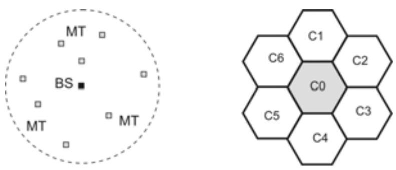


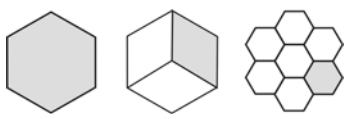
- **Signal-based divison** uses a set of basic signal shapes (carriers, timeslots, **codes**), which allow the desired signal to be recognized among the multitude of received signals. The most common signal shapes are:
  - **the harmonic signals**, which makes possible the division of medium capacity in the frequency domain (**FDM**),
  - **periodic pulse train**, which tmakes possible the division of medium capacity in time domain (**TDM**)
- The capacity of the medium can be divided without inter-channel interference, becouse both basic signal sets are orthogonal:
  - Frequency multiplexing is not sensitive to differences in delays becouse the base signals are mutually **uncorrelated**.
  - Time multiplexing base signals differ only in phase and consequently are correlated. Multiple access critically depends on proper synchronization.
- By selecting other signal shapes, we obtain different code division multiplexing methods (CDM), orthogonal (*Walsh-Hadamard*)and non-orthogonal (*Gold, Kasami* etc.). The application of a large number of non-orthogonal codes allows the dynamic division of the medium capacity.

Space division – Cell network

- Radio link range is limited by transmitter power, frequency, position and antenna type, and most of all by the terrain config.
- **The operating range of a transmitter is limited. This in turn allows the use of the same frequency band, by way of repetition, at different locations.**
- The capacity of a cellular network can be increased
  - By **sectoring** the cells: the spatial sectorization of the cell is achieved by three separate antennas and radio modules.
  - By **cell splitting** into several smaller cells requires the same number of new base stations In smaller cells, the base station transmitters operate at lower power levels, and the sum of the capacities of the split cell is larger than before the splitting.

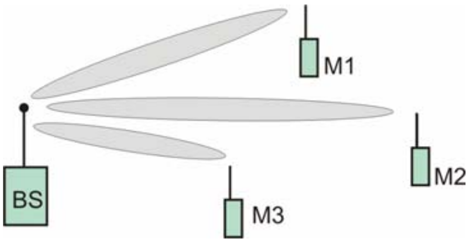




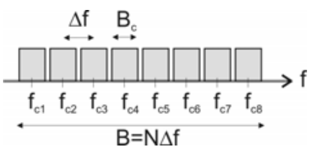


Space divison limitations

- **Spatial differentiability** of user signals is limited in mobile communications.
- The application of the space division multiple access (SDMA) technique **alone is not sufficient** in mobile radio communications. Space division technique is supplemented by other multiple access methods.
- **Space diversity** is utilized to increase transmission reliability.
- Under certain circumstances, MIMO systems increase **transmission capacity** significantly.



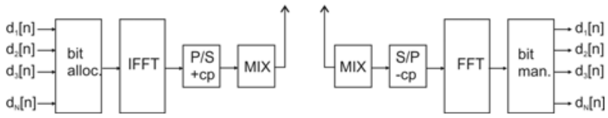
FDMA



- The available frequency band ***B*** is divided between a set of ***N*** radio channels. The channels are mutually separated by carrier frequencies which determine the centers of their frequency ranges,
- Due to a finite filter quality, the spacing between channels must exceed the channel bandwidth. The spacing between channels is a partial loss of medium capacity.
- In narrow-band channels, the effects of time dispersion due to signal propagation along different paths is practically negligible.
- advantage: simple implementation, natural choice in analog 1G systems,
- disadvantage: N conventional (analog) FDMA receives are required to receive signals from N bands!

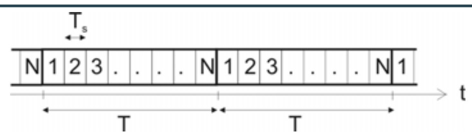
Modern FDMA implementation

- Signal processing is greatly simplified by setting the channel spacing equal to the symbol rate.
- The modulation and demodulation process is simply carried out by calculating the Discrete Fourier transform. FFT algorithm allows the use of a large number of channels, which also results in extended symbol time and therefore small inter-symbol interference (ISI).
  - LTE example: df=15kHz ->Ts=66.7us.



- A single device can transmitt on any combination of N channels simultaneously!
- Orthogonal FDMA (OFDMA) adapts to conditions in the mobile channel and allows optimum utilization of transmission capacity.

TDMA

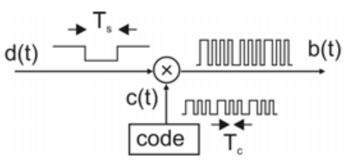


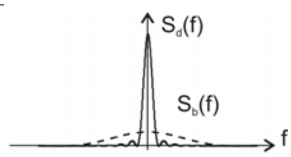
- The division of transmission capacity takes place as a periodic sequence of time slots.
- Within a time slot ***Ts*** , the transmission medium is reserved for only one of the ***N*** users, hence **the synchronization of all active devices is mandatory**.
- Within each time slot, a guard time is provided to allow the compensation of differences in delays between users.
- The time slot is divided into traffic data fields and different overhead fields provided for the synchronization and marking.
- the symbol time is more than N-times shorter than with FDMA and **elimination of inter-symbol interference is mandatory**
- The implementation of a TDMA GSM system in 2G was much more complex than the implementation of 1G FDMA system, in particular due to the need for synchronization and channel equalization.

DS-CDMA

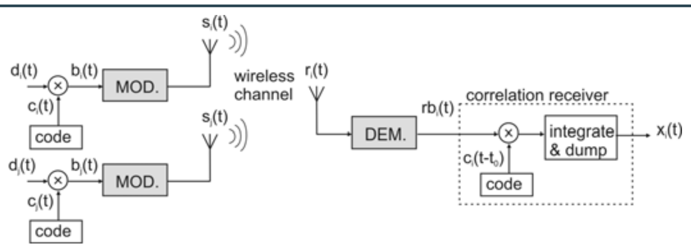
- CDMA uses spread spectrum communication. Several SS transmisson types are known:
  - direct sequence spread spectrum DSSS,
  - frequency-hopping spread spectrum FHSS,
  - time-hopping spread spectrum THSS
- The most common applied process is **CDMA with direct spreading**. The transmitters apply different binary pseudo-noise (PN) spreading sequences c(t). Data signal *d(t)* consists of a set of rectangular-shape binary symbols with symbol duration *Ts* , while (PN) sequence bipolar pulses have width *Tc* (chip time).
- The spread data signal *b(t)* frequency spectrum width is broader than the original signal by a spreading factor *Gs* :

$$G_S = \frac{T_S}{T_C}$$





CDMA channel separation



- CDMA signals are not separated in time domain or in frequency domain.
- The selection of the "proper" signal is carried out by the **correlation receiver**. The correlation receiver output signal is distorted due to radio channel **noise** as well as due to **interference** from other CDMA transmitters.
- Signals from different transmitters do not interfere only if the code sequences are non-correlated. The number of code sequences in orthogonal sets is equal to the spreading factor, hence OCDMA systems are limited to N channels, as in FDMA and TDMA systems.
- In cellular CDMA systems, non-orthogonal code sequences with small cross – correlation are applied where the number of sequences is much larger K>>N.

Multiple access evolution

- FDMA, TDMA and OCDMA do not differ in the number of available channels. CDMA system advantages become evident with non-orthogonal codes, which allow much larger number of channels than in TDMA or FDMA systems. The rate of interference increases linearly with the number of active channels, and therefore medium capacity sharing is dynamic.
- Modern FDMA with a large number of carriers perfectly adapts to conditions in the mobile channel. OFDMA offers optimum utilization of transmission capacity with high sharing flexibility.
- The development of 1G–3.5G mobile communications implies the evolution of multi-access techniques from FDMA and TDMA to CDMA . The last step in 3G is back again to frequency division concept: OFDMA and SC-FDMA.