F/TDMA Cellular Access and GSM

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Outlines

- Cellular access principles
- Channel reuse [1]
- Call blocking
- GSM channels

1. Figures pp. 8, 9, 10, 13, 15 are taken from X. Lagrange, IMT Atlantique.

Cellular access principles I

- Cellular access really took off with 2G in the 90's
- The considered service is "terrestrial mobile service" : "set of radiocommunications with mobile stations able to move in surface within the limits of a country or a continent"
- This definitions does not include : satellite communication systems, cordless telephony, WLANs, PANs, etc.

Cellular access principles II

Main characteristics of a cellular network :

- The territory is divided in cells
- Every cell is served by a base station (BS)
- The set of all cells form a single network : the division is not perceptible neither by a user of the fixed network nor by a mobile user
- Radio resources are reused in several cells
- The service is continuous over a large territory
- Small cells implies smaller transmit powers and higher network capacity

Cellular access principles III

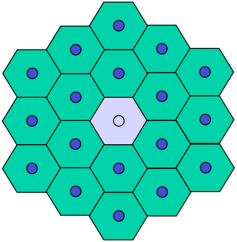
Main functions of a cellular network :

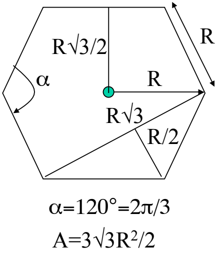
- Ensure the service coverage
- Ensure a sufficient capacity thanks to the reuse of radio resources
- Allow roaming, international roaming
- Allow handover, i.e., mobility while in communication

Channel reuse I

Hexagonal network :

- A traditional model for representing cells of a cellular network.
- The model is regular and homogeneous (in traffic and propagation).
- The model is useful for a first dimensioning or performance evaluation.
- Other models : Diamonds, circular (deterministic), Poisson (random)





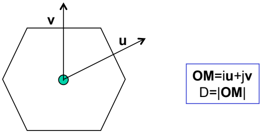
Channel reuse II

A cellular cluster :

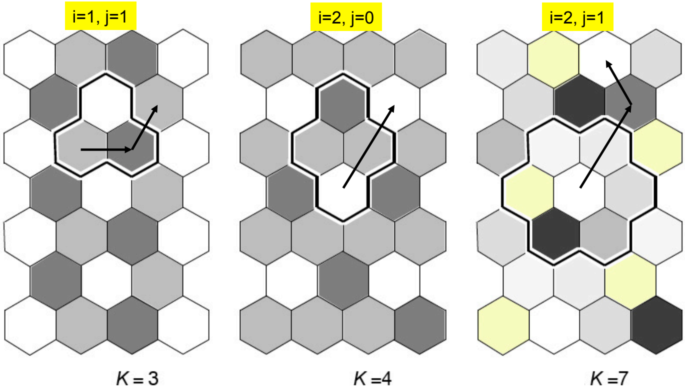
- A set of cells, in which every cell is assigned a unique set of frequency channels that is not assigned to any other cell in the cluster.
- We can show that optimal cluster sizes are regular. Let K be the cluster size (called *reuse factor* or simply *reuse*), then optimal cluster sizes are of the form :

$$K = i^2 + ij + j^2,\ \ i,j \in \mathbb{N} \quad (1)$$

- In a hexagonal network, the reuse distance is given by : $D = \sqrt{3K}R$, where R is the cell range and K is the reuse factor.
- Integers (i,j) can be interpreted as the coordinates of a closest co-channel cell to the cell $(0,0)$ in a frame $(\boldsymbol{u},\boldsymbol{v})$, with $\widehat{(\boldsymbol{u},\boldsymbol{v})} = \alpha/2$, and $||\boldsymbol{u}|| = ||\boldsymbol{v}|| = R\sqrt{3}$.

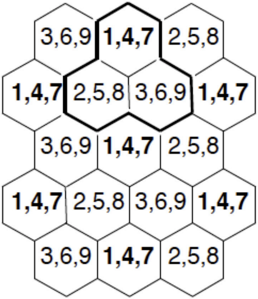


Channel reuse III

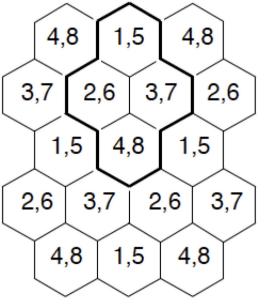


Channel reuse IV

Examples of clusters with set of frequency channels :



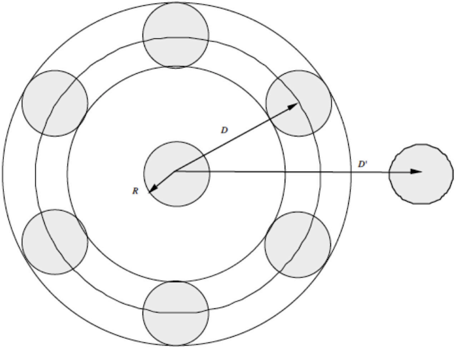
9 frequencies, K=3



8 frequencies, K=4

Channel reuse V

When cluster are regular, co-channel interferers are located on concentric rings :



For performance evaluation, it is common to consider only 2 rings of interferers. Other rings create negligible interference.

Channel reuse VI

Cluster size determination :

- Assume we want to achieve a minimal SIR γ^* on the downlink.
- If we ignore shadowing and fast fading, and if we consider only the first ring of interferers, we have in the worst case and approximately : $p_r = p_t K R^{-\alpha}$ (for the serving cell) and $p_r^j = p_t K D^{-\alpha}$ (for interferer j) such that :

$$\gamma = \frac{p_t K R^{-\alpha}}{\sum_j p_t K D^{-\alpha}} = \frac{1}{6}\left(\frac{R}{D}\right)^{-\alpha} \qquad (2)$$

From which we can deduce the minimum cluster size :

$$K \geq \frac{1}{3}(6\gamma^*)^{\frac{2}{\alpha}} \qquad (3)$$

- Remarks : 1) cluster size doesn't depend on the transmit power (this is because we have neglected noise) 2) higher is the quality of service requirement (γ^*) higher is K 3) higher is α, lower is K.

Channel reuse VII

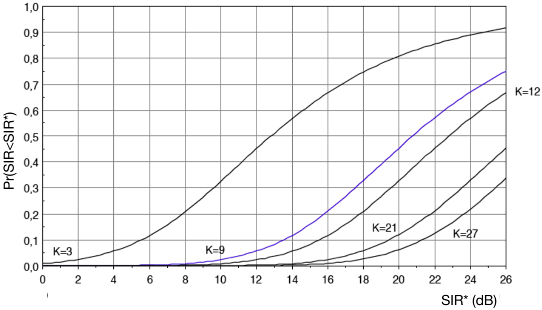
- Assume now that shadowing is taken into account.
- A classical and reasonable assumption : shadowing is drawn once for the duration of the communication, fast fading is taken into account in the target SIR.
- The SIR is now a r.v. and can be written :

$$\gamma = \frac{R^{-\alpha} a_s}{\sum_j D^{-\alpha} a_s^j}, \tag{4}$$

where a_s and a_s^j are the shadowing log-normal r.v. wrt the serving station and interferers respectively.

- The numerator is a log-normal r.v.
- The denominator is a sum of independent log-normal r.v. and can be approximated as a log-normal r.v. (using e.g. the Fenton-Wilkinson method).
- As a result, γ can be approximated by a log-normal r.v.

Channel reuse VIII

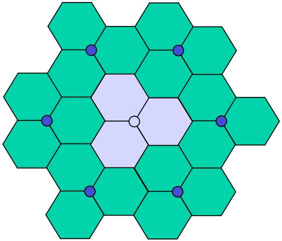


$\alpha = 3{,}5$ $\sigma = 6$ dB (tri-sectorization, best server, downlink)

Channel reuse IX

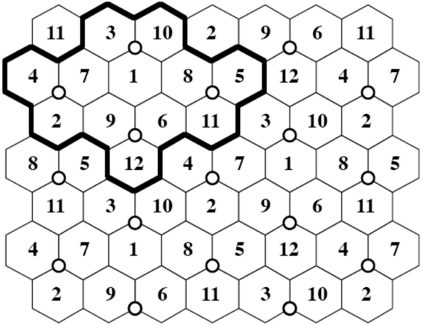
Sectorization :

- Directional antennas are often used in order to reduce the number of cell sites.
- 1 site = 1 Base Station = 3 (geographic and logical) cells
- The SIR is slightly reduced (at cell boundaries) for a given K but the number of sites is divided by 3. K is now a multiple of 3.



Channel reuse X

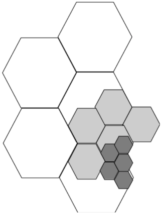
Example of frequency assignment with $K = 12$:



Channel reuse XI

Hierarchical network :

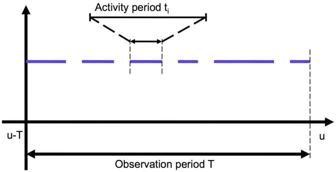
- Macro-cells : 1-30 km of radius, ensures coverage
- Micro-, pico-, small cells : 100-1000 m, for hot-spots
- Femto-cells : 10-50 m at home
- Out-of-band deployment : every layer is independent.
- In-band deployment : huge cross-layer interference, inter-cell interference coordination techniques are required (e.g. based on power control, time sharing, load balancing, etc.)

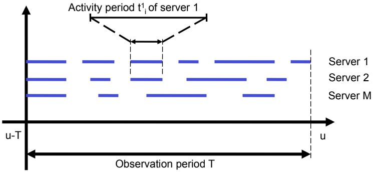


Call blocking I

Traffic of a circuit/server in a circuit-switched network :

- Proportion of time a circuit is active/occupied (same as *load* in queuing theory)
- On an observation period T, the traffic at time u is : $a(u, T) = \frac{1}{T}\sum_i t_i$, where t_i is the duration of the i-th activity period.
- Average traffic is $a(u) = \lim_{T\to\infty} a(u, T)$ and is expressed in Erlangs
- The traffic of a group of M circuits is the sum of all traffics : $A(u, T) = \frac{1}{T}\sum_j \sum_i t_i^j \leq M$, where t_i^j is the duration of the i-th activity period of circuit j.
- The traffic is *ergodic* if the average number of occupied circuits equals the probability for a circuit to be occupied.





Call blocking II

Loss process :

- Call arrivals are Poisson of parameter λ, i.e., a stationnary counting process N with independent increments such that for all $s, t \in \mathbb{R}$ and $k \in \mathbb{N}$:

$$\mathbb{P}[N(s+t) - N(s) = k] = \frac{(\lambda t)^k}{k!} e^{-\lambda t} \tag{5}$$

- Remarks : There are λ calls/s and inter-arrival time has an exponential distribution of parameter λ.
- Call duration is exponential with parameter μ. Let T be the service time, we have the pdf of T : $f_T(t) = \mu e^{-\mu t}$ and $E[T] = 1/\mu$.
- A new call finding all circuits occupied is rejected or *blocked*.

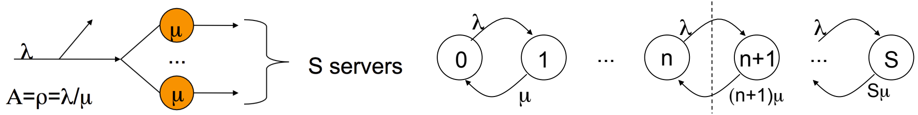
Call blocking III

Queueing model and Markov process :

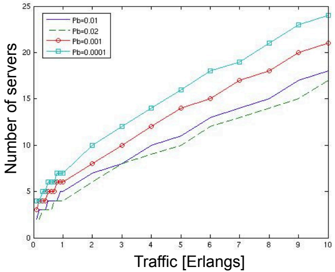
- We consider the Markov process $X(t) = \{n(t)\}_{t \geq 0}$, where $n(t)$ is the number of occupied circuits at t.
- Stationary probabilities verify : $\lambda \pi_n = (n+1)\mu \pi_{n+1}$ for $0 \leq n \leq S-1$ and $\sum_n \pi_n = 1$, which solves in $\pi_n = \frac{A^n}{n!}\pi_0$ and $\pi_0 = \left(\sum_{i=0}^{S} \frac{A^i}{i!}\right)^{-1}$.

Blocking probability is given by (Erlang B) :

$$P_b(S, A) = \frac{\frac{A^S}{S!}}{\sum_{i=0}^{S} \frac{A^i}{i!}} \tag{6}$$



Call blocking IV

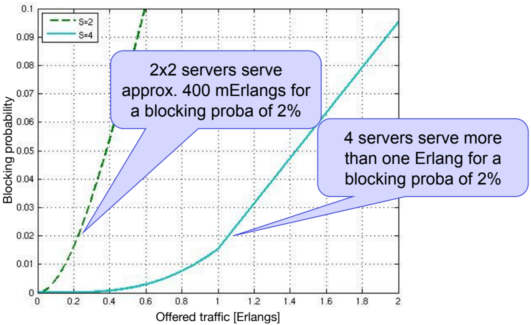


Some tricks :

- Recursive formula : $P_b(S+1, A) = \frac{AP_b(S,A)}{S+1+AP_b(S,A)}$
- Approximation : If $P_b(S, A) = 10^{-k}$, then $S \approx A + k\sqrt{A}$.
- Example : 10 calls per min, average call duration of 2 min, blocking probability of 1% give 30 circuits (the approximation gives 29).

Call blocking V

Trunck gain :



Call blocking VI

Spectrum Efficiency :

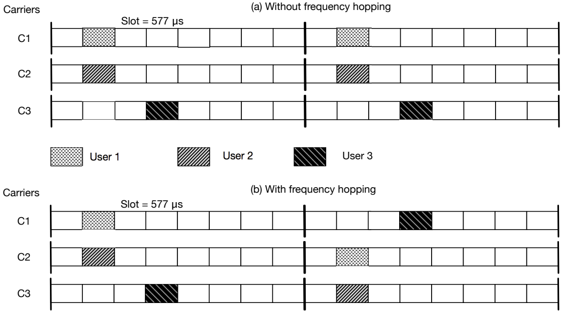
- Assume : W is the system bandwidth, W_c is the channel bandwidth, s is the number of slots per carrier, A is the cell area, $C = W/W_c$ is the number of carriers, $g_\epsilon(n)$ the number of Erlangs that can be offered when there are n circuits and the blocking probability is ϵ.
- There are $\frac{sC}{K}$ slots in a cell. The number of offered Erlangs per cell is $g_\epsilon(\frac{sC}{K})$.
- The spectrum efficiency, defined as the Erlang capacity per unit area per Hz is now given by :

$$\nu = \frac{g_\epsilon(\frac{sC}{K})}{AW} = \frac{g_\epsilon(\frac{s}{W_c}\frac{W}{K})}{AW} \tag{7}$$

- Example of numerical application with GSM : $s = 7$ (1 slot is reserved for signaling), $W = 5$ MHz, $W_c = 2 \times 200$ kHz, $\epsilon = 2$ %, $K = 9$, $R = 1$ km gives : $\nu = 1$ E/cell/MHz.
- Remarks : 1) $\frac{s}{W_c}$ only depends on the technology, 2) ν decreases with K but K should be chosen to meet SIR requirement, 3) $\nu(W)$ increases with W because of the trunck gain, 4) ν increases with $1/A$, this is *network densification*.

GSM channels I

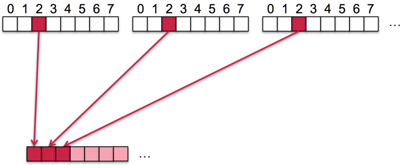
- Every carrier frequency is divided TDMA frames of 8 *slots*, every slot caries a *burst*. $T_{slot} = 0.5769$ ms, $T_{TDMA} = 4.6152$ ms.
- Every user uses one slot per TDMA frame.
- A *physical channel* is the periodic repetition of one slot on a given carrier.



GSM channels II

A N-slot multiframe :

- is a sequence of N concatenated slots.
- Between 2 slots of a multiframe there is a duration of T_{TDMA}, multiframe duration is thus $T_{N-TDMA} = N \times T_{TDMA}$ ms.
- Multiframe is a way of allocating less resource than 1 slot per frame and to define *logical channels*.
- In GSM, there are 26- and 51-multiframes ; there are also superframes (26 51-multiframes or equilavently 51 26-multiframes) and hyperframes (2048 superframes).



GSM channels III

Logical channels : They specify the type of carried information, e.g., system information, signaling, traffic, etc. They don't specify how information is carried (coding, data rate, etc.). They are offered by the MAC layer to the upper layer.

Type	Channels	Function
Broadcast Ch.	Frequency Correction Ch. (FCCH) DL Synchronization Ch. (SCH) DL Broadcast Control Ch. (BCCH) DL	Frequency synchronization Synchronization System Info
Common Control Ch.	Paging Ch. (PCH) DL Random Access Ch. (RACH) UL Access Grant Ch. (AGCH) DL Cell Broadcast Ch. (CBCH) DL	Incoming call Random access Resource allocation Short messages broadcast
Dedicated Control Ch.	Stand-Alone Dedicated Control Ch. (SDCCH) UL/DL Slow Associated Control Ch. (SACCH) UL/DL Fast Associated Control Ch. (FACCH) UL/DL	Signaling Physical control Handover
Traffic Ch.	Traffic Ch. (TCH) UL/DL	Voice

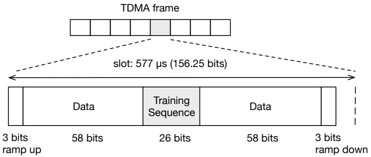
GSM channels IV

Notes :

- FCCH : perfect sinus used for frequency synchronization.
- SCH : fine time synchronization (μs), frame number, cell color code BSIC. First channel to be decoded by the MS. SCH detection ensures that the system is GSM.
- BCCH : informations related to cell selection process (2 Hz), location area (2 Hz), random access (4 Hz), control channel organization (1 Hz), neighbor cells (1 Hz), cell identity, BS frequencies. Note that frequency hopping is not possible on broadcast channels. There is no power control on the DL carrier frequency of the BCCH. Even if there is no traffic, dummy bursts are sent to maintain a constant transmit power.
- PCH : broadcast of user IDs for which there is an incoming call. Up to 4 MSs can be paged in every message.
- RACH : channel for slotted Aloha. Includes : service category and a random number to solve collisions/captures.
- AGCH : description of the dedicated signaling channel (frequency and slot, possibly hopping sequence) and timing advance.
- CBCH : broadcast of short messages to all users of the cell.

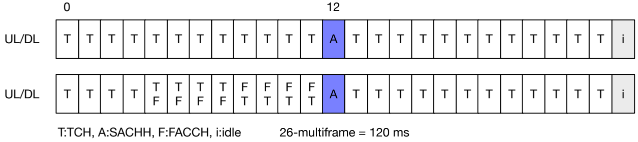
GSM channels V

- SDCCH : dedicated channel for signaling information. Data rate is only 800 bps.
- SACCH : every TCH or SDCCH is associated to a SACCH, which carries timing advance information, MS power control, radio quality indications, measurements. 380 bps.
- FACCH : used for handover execution. Some capacity is *stolen* to the TCH in order to have a fast signaling. Note that LAPDm is used above FACCH, SACCH, SDCCH.
- TCH : voice or data channel. Voice is carried at 13 kbps (full rate) or 5.6 kbps (half rate). Data is carried at 12 kbps max.

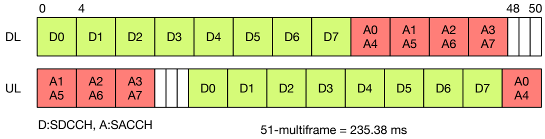


GSM channels VI

On a physical channel, one can have either a TCH and its SACCH or 8 SDCCH and their SACCH. Location in the multiframes :



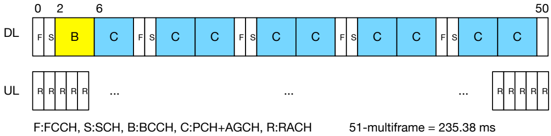
Note : in case of handover, some bits on traffic slots are preempted by the FACCH. The SACCH associated to the TCH is located on position 12.



Note : SDCCH Di is associated to SACCH Ai. Channels A0, A1, A2, A3 and A4, A5, A6, A7 alternate on even and odd multiframes.

GSM channels VII

On the slot 0 of the BCCH carrier frequency (maximal configuration) :



GSM channels VIII

Example of channel configuration :

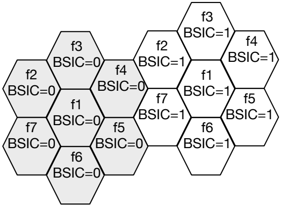
- Cell with 2 carrier frequencies, i.e., 16 physical channels (slots).
- 1 slot (slot 0) on the BCCH frequency (C0) for FCCH, SCH, BCCH, PCH, AGCH and RACH. 51-multiframe structure.
- 1 slot (slot 1) on the BCCH frequency (C0) for dedicated signaling SDCCH and associated SACCH. 51-multiframe structure.
- 14 slots for traffic (TCH) on carrier frequencies C0 and C1. 26-multiframe structure.

C1	TCH SACCH	TCH SACCH	TCH SACCH	TCH SACCH	TCH SACCH	TCH SACCH	TCH SACCH	TCH SACCH
C0	CCH	SDCCH SACCH	TCH SACCH	TCH SACCH	TCH SACCH	TCH SACCH	TCH SACCH	TCH SACCH

GSM channels IX

Cell color code BSIC (BS Identity Code) : used to differentiate several close-by BSs with the same BCCH frequency. In a small region the couple (BSIC, frequency) allows a unique identification of the cell. BSIC is made of :

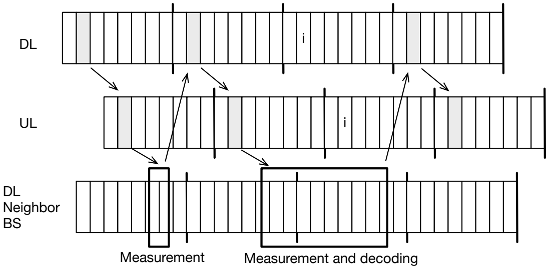
- 3 bits for identifying the PLMN (Public Land Mobile Network) ;
- 3 bits for identifying the BS inside the PLMN.



GSM channels X

Measurements in communication :

- MS can monitor neighboring BS between DL and UL slots (receive power measurements) ;
- MS can measure and decode the BCCH frequency of neighboring cells during the idle slot of the 26-multiframe.



Acronyms I

AGCH	Access Grant Channel
BCCH	Broadcast Control Channel
BS	Base Station
BSIC	Base Station Identity Code
CBCH	Cell Broadcast Channel
FACCH	Fast Associated Control Channel
FCCH	Frequency Correction Channel
FDMA	Frequency Division Multiple Access
GSM	Groupe Spécial Mobile
MAC	Medium Access Control
MS	Mobile Station
PAN	Personal Area Network
PCH	Paging Channel
PDF	Probability Density Function
PLMN	Public Land Mobile Network
PMR	Professional Mobile Radio
RACH	Random Access Channel
SACCH	Slow Associated Control Channel
SCH	Synchronization Channel
SDCCH	Stand-Alone Dedicated Control Channel
SINR	Signal to Interference plus Noise Ratio
SIR	Signal to Interference Ratio
TCH	Traffic Channel
TDMA	Time Division Multiple Access
WLAN	Wireless Local Area Network