Cellular Technologies

1/ List the functionalities of

1. Radio access network: **(reseau d'accès) wireless interface between the mobile and the base station**
2. Core network: **(reseau coeur) interconnected network that offers service such as: user authentication, policy rule charging functionality, routing of the packet inside the network, etc**
3. Backbone network: **(réseau d'infrastructure) High data rate network to interconnect the base stations using wired connections such as coaxial cables, optical fibers or microwave communication (faisceaux Hertzriens)**

2/ Explain and indicate the channels that are involved in the:

1. Cell selection: **choice of the cell with the best received signal for a non-communicating user**
2. Handover: **The handover corresponds to the transfer of a moving user that is in communication from one cell to another.**
   a. Hard Handover: **The user is connected to one cell at a given time: 2G, 4G, 5G, 3G (TDD)**
   b. Soft Handover: **The user is connected to two cells at the same time: 3G (FDD)**
3. Roaming: **the possibility to communication with an international operator in a foreign country. There are agreements between operators for charging the services.**

3/ What is the difference between multiplexing and duplexing?

- **Multiplexing: authorize multiple users access to the shared resources. Radio resources can be frequency, time/frequency, codes, etc**
- **Duplexing: is how to separate the uplink from the downlink**

4/ What is the difference between baseband signal and modulated signal?
What is the difference between carrier frequency and the bandwidth?

All the practical signals are in the baseband: It means the most significant frequencies are between 0 and a range of frequency bounded by B. For example, the piano music, the human voice are signals with limited bandwidth between 0 and 5 KHz.

In Telecommunications, we use digital information communication. The first step consists of giving a binary representation to the information. Next, the bits are modulated using a QAM modulation such as,

$$x(t) = \sum_k (A_k cos(2\pi f_0 t) - B_k sin(2\pi f_0 t))\, rect(t - kT, T)$$

Over each period of T, we have in-phase and Q-phase components. The values of A_k and B_k change each period T depending on the values of the bits.

We call in-phase (resp. Q-phase) baseband signal the signal with changing amplitude A_k (resp. B_k) each period T. In the frequency domain, the Fourier transform is proportional to |sinc(fT)|. All the significant frequencies are in the principal lobe around -1/T and 1/T. The secondary lobes are neglected.

If we look at the Fourier Transform of the signal x(t), the amplitude of the Fourier Transform is proportional to $|\mathrm{sinc}((f-f_0)\,T)|$. This corresponds to a sinc translated around the frequency f_0 known as carrier frequency. The width of the principal lobe is 2/T and it is known as bandwidth.

5/ Terminology and standard parameters:
Complete the table with the missing fields

	2G	3G	4G	5G
Stations	BTS	Node B	eNB	g-NB eg-NB
Equipment	Mobile	UE	UE	UE
Radio Access Network	GERAN	UTRAN	EUTRAN	New Radio (5GRAN)
Core Network	NSS Network subsystem	PC Packet Core	EPC Enhanced Packet Core	New Core
Backbone Network	Cable coaxial; Optical Fiber, Microwave transmission (Faisceaux Hertziens)			
Frequency	900 MHz	1800-2100 MHz	2.6 GHz	3.5 GHz
Radio resource	Time-frequency slot	Channelization code + scrambling code	12 Carrier frequencies + 7 time slots	12 Carrier frequencies + 7 time slots
Handover	Hard	Soft with FDD Hard with TDD	Hard	Hard
Switching	Circuit	Packet / Circuit	Packet	Packet
Voice service	Circuit switching	Circuit switching	VoIP (IP-Multimedia Subsystem) Switch to 3G	VoIP
Bandwidth per comm.	200 kHz	5 MHz	180 kHz	180, 360, 720 kHz
Slot per communication	4.615/8 ms	2/3 ms	2 x 0.5 ms	2 x (0.5, 0.25, 0.125) ms
Frame duration	26 Frames 120 ms	10 ms	10 ms	10, 5, 2.5, 1.25 ms

Number of slots	8 slots per frame = 4.615 ms	15 slots	20 slots (same allocation on 2 consecutive slots)	20 slots (same allocation on 2 consecutive slots)
Duplexing	FDD	FDD or TDD	FDD or TDD	TDD FDD
Multiplexing	T-FDMA	CDMA	OFDMA Spatial multiplexing	OFDMA Spatial multiplexing
User data rate	100 kb/s (EDGE)	4 Mb/s	30 Mb/s	100 Mb/s
End to end Latency	500 ms	100 ms	50 ms	1 ms

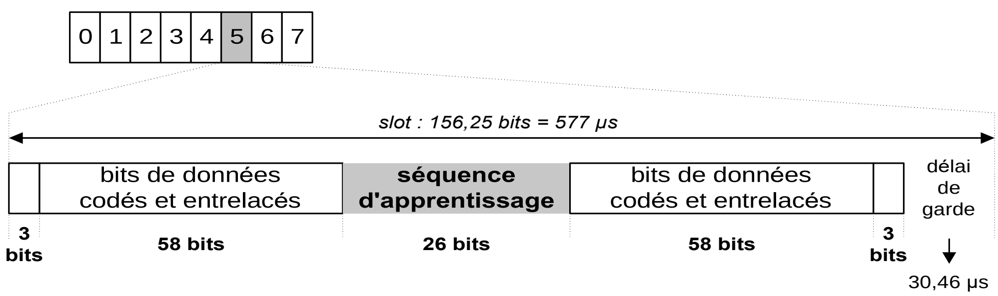
6/ Compared the time duration required to download the following applications:

In all cases, the download time = Typical size/ Data Rate

Activity	Typical Size	4G (30 Mb/s) Download Time	3G (4 Mb/s) Download Time	EDGE (0.1 Mb/s) Download Time
Accessing typical web page	2 MB	0.5 seconds	4 seconds	3 minutes
Sending an e-mail without attachments	10 KB	<0.1 seconds	<0.1 seconds	1 second
Downloading high-quality photograph	2 MB	0.5 seconds	4 seconds	3 minutes
Downloading a music track (MP3)	5 MB	3 seconds	10 seconds	7 minutes
Downloading an application	30 MB	8 seconds	1 minute	40 minutes

7/ Time advance in cellular networks:

We recall the structure the slot in GSM:



In 2G network, a mobile is situated at the edge of a rural cell with radius R = 2 km. The length of the LOS path to reach the BS is 2 km and the most significant NLOS can go up to 10 km.
To establish a communication, the network attributes to this mobile the time-frequency slot number 5.

Explain what the time advance concept is. Indicate the starting time t_0 at the mobile side in the LOS and NLOS case.

In cellular network, the signal arrives from the mobile to the station after a certain delay. The electromagnetic wave travels at the light speed of c = $3x10^8$ m/s.
The delay is distance/speed.

The mobile should take this delay into account and start transmitting before the beginning of slot 5. This is called as time advance.

For LOS case: delay = $2x10^3/3x10^8$ = 0.0666 μs
For NLOS case: delay = $10x10^3/3x10^8$ = 0.33 μs

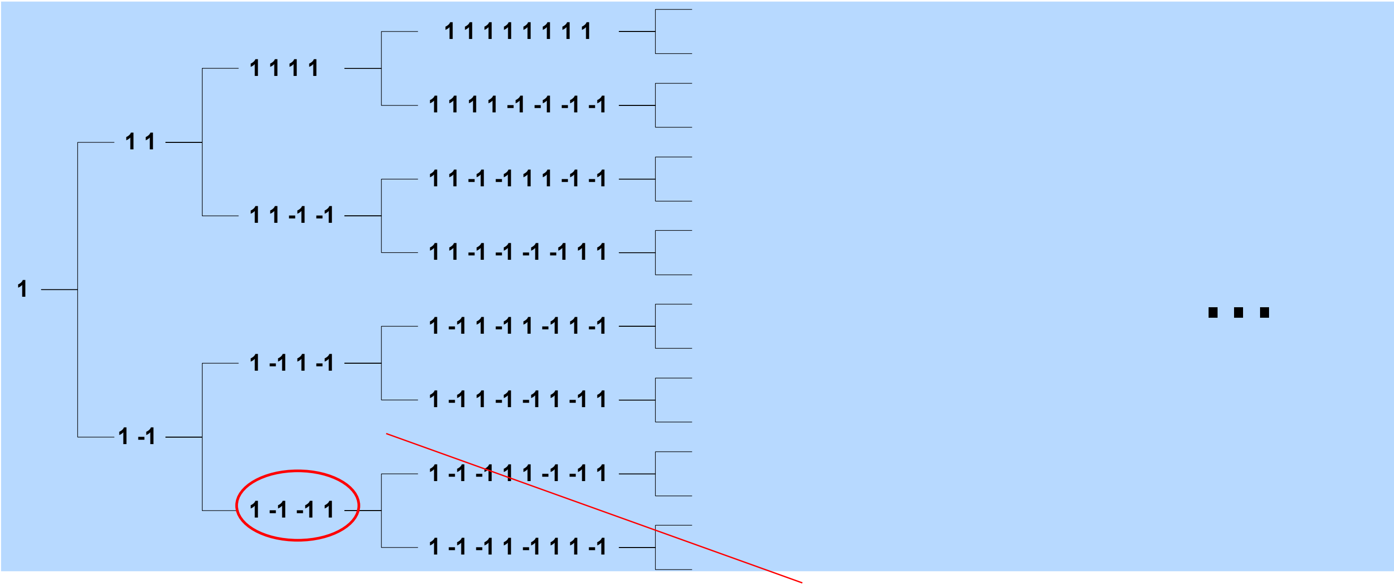
8/ Explain what the roles of the Channelization code and the scrambling code in 3G are.

In 3G, we need the QAM symbols are multiplied by 2 codes:
The channelization codes are generated using the Hadamard Tree to separate two users. The codes are orthogonal, and this will guarantee that there is no interference between users in each cell.

The same channelization codes are used in all the cell. Two users belonging to two different cells use the same channelization code. To decrease the interference, scrambling codes are used. The scrambling codes are uncorrelated codes and are affected to distinct cells.

9/ We consider a 3G network in which a user with high QoS transmits with a SF of 4. All the other UEs transmit with a SF of 128. Plot the Hadamard tree and compute the number of simultaneous users.

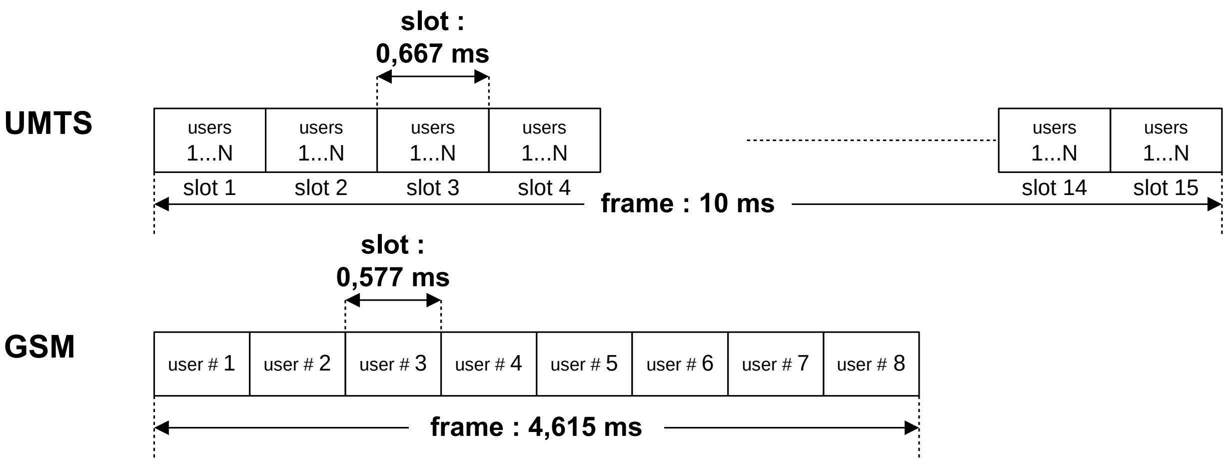
Note that when a code with SF 4 is affected to privileged user, he has a high data rate. We assume that in the Hadamard Tree the last branch with SF 4 is attributed to this code. All the children-branches of this code with SF 4 cannot be any more attributed to other users as the codes become not orthogonal.
If all other users use a code with SF = 128, we need to count how many children the 3 remaining codes with SF=4 have. We can count $2^7/2^2$ = 32 children for each code of SF = 4.
The total will be 3*32 + 1 = 96 + 1 = 97 distinct codes.



10/ 3G spreading factor and code allocation:

A bandwidth of 5 MHz is allocated to a 3G network operating in FDD mode. A QPSK constellation is used.
In UMTS, a roll-off coefficient of 0.22 is used. The chirp rate is fixed to 3.84 Mchirp/s.

The structure of 3G frame is illustrated below:



1. Find the bandwidth that is occupied by the CDMA signals.
2. Compute the QPSK symbol duration and indicate how many symbols are sent within the slot duration.
3. Find user data rate when no correcting code is used.
4. Find the data rate when a convolutional code with rate 1/2 is used.

Uplink: In HSUPA, it is possible to allocate multiple SF codes to a single user.

5. Complete the table to find the data bit rates per user when a code rate of ½ is used.

Channel bit rates	Number of allocated spreading codes	Spreading factors SF
15 – 960 kbps	1	SF = 256 – 4
1.92 Mbps	**2**	SF = 4
3.84 Mbps	**2**	SF = 2
5.76 Mbps	4	2 × {SF = 4} + 2 × {SF = 2} The codes span two different bandwidth of 5 MHz each

Uplink: In HSDPA, the SF is fixed to 16 and it is possible to allocate multiple spreading code to a single user.

6. Complete the table to find the channel bit rates per user.

Channel bit rates QPSK	Channel bit rates 16 QAM	Spreading codes	Number of allocated spreading codes
6 kbps – 1.872 Mbps	2x (6 kbps – 1.872) Mbps	512 - 4	1
480 kbps	**960 kbps**	16	1
960 kbps	**1.92 Mbps**	16	2
…	**…**	…	…
7.2 Mbps	**14.4 Mbps**	16	15

1. A primer on the roll-off coefficient:

To send a symbol information in digital communication, a reshaping filter is used to give a form for symbol in such a way that this information symbol lasts during a time duration T. The corresponding signal occupies on the spectrum a bandwidth,

$$B = \frac{1+\beta}{T}$$

β is the roll-off coefficient such that $0 < \beta \leq 1$.

As the spectrum is limited, the lowest β is, the lowest the spectrum occupancy will be.

$\beta = 1$: if we consider a rectangular form, meaning that the form attributed to the symbol is rectangle. The bandwidth is in this case:

$$B = \frac{2}{T}$$

This is so far the worst case.

To guarantee the orthogonality between users, the symbol information is multiplied by channelization code generated using Hadamard Tree. Each symbol information contains SF chirps. The chirp designs an element of the information and has a constant duration T_c.
The constant time duration is the time of the chirp.

In the UMTS case, $\beta = 0.22$. The bandwidth occupied is,

$$B = \frac{1.22}{T_c} = 1.22\ R_c$$

with R_c being the chirp rate = 3.84 Mb/s. The real bandwidth occupied is 4.684 MHz with is each lower than 5 MHz. The border of the bandwidth should be kept empty to avoid disturbing adjacent technologies on neighboring bandwidth.

2/ The data rate will depend on SF.
We assume that all users use a code with SF. Each information symbol contains SF chirps.
The information symbol duration T= SFxT_c

In UMTS, the slot duration is 0.666 ms.

1 symbol is sent during SFxT_c = SF/R_c
? symbols are sent during 1 slot duration = 0.666 ms.

The number of symbols is 3/2x SF/R_c

3/ Without any code, each QPSK symbol holds 2 info bits and is transmitted during SF/R_c.
2 information bits → SF/R_c.
Data rate → 1 s

- ⇨ Data Rate = 2*R_c/SF with R_c = 3.84 Mb/s is the chirp data rate.

The data rate decreases when SF increases.

4/ With an error correcting code with rate 1/2, each QPSK symbol holds 2 bits with only half of the bits holding information and is transmitted during SF/R_c.
2 x ½ information bits → SF/R_c.
Data rate → 1 s

- ⇨ Data Rate = R_c/SF with R_c = 3.84 Mb/s is the chirp data rate.

The data rate decreases when SF increases.

5/

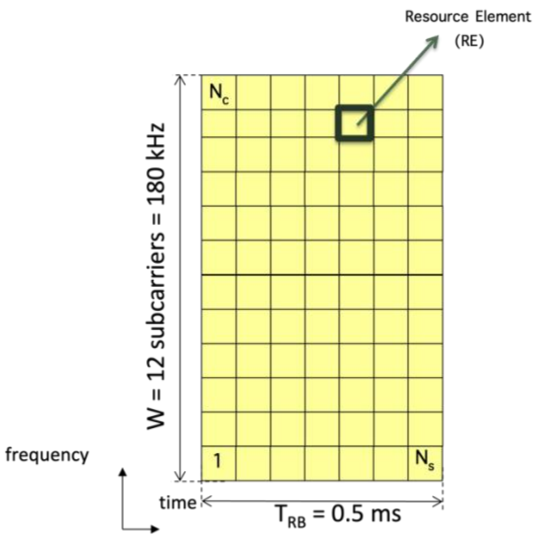
Channel bit rates	Number of allocated spreading codes	Spreading factors SF
3.84/SF Mbps	1	SF = 256 – 4
2x 3.84/SF Mbps	**2**	SF = 4

2x 3.84/SF Mbps	**2** **Note here that all Hadamard codes are used here by the same user. There is no more places for others.**	SF = 2
Line 3 + Line 4	4	$2 \times \{SF = 4\} + 2 \times \{SF = 2\}$ The codes span two different bandwidth of 5 MHz each

6/

Channel bit rates QPSK	**Channel bit rates 16 QAM**	**Spreading codes**	**Number of allocated spreading codes**
2x3.84/SF Mbps	**4x3.84/SF Mbps**	16	1
2x(2x3.84/SF)	**2x(4x3.84/SF)**	16	2
…	**…**	…	…
15x(2x3.84/SF)	**15x(4x3.84/SF)**	16	15

11/ The structure of 4G radio resource is illustrated in the Figure below. In LTE, the carrier spacing is fixed to Δf = 15 kHz.



1. Complete the table with the sampling frequency and the OFDM symbol duration:

Bandwidth	Nb of available RBs	Sampling Frequency $N\Delta f$	OFDM symbol duration $1/\Delta f$	FFT size N
1,4 MHz	6	$N\Delta f$ = 1.92 MHz	$1/\Delta f$ = 1/15 ms	128
3 MHz	15	$N\Delta f$ = 3.84 MHz	$1/\Delta f$ = 1/15 ms	256
5 MHz	25		$1/\Delta f$ = 1/15 ms	512
10 MHz	50		$1/\Delta f$ = 1/15 ms	1024
15 MHz	75		$1/\Delta f$ = 1/15 ms	1536
20 MHz	100		$1/\Delta f$ = 1/15 ms	2048

In the downlink, the modulation and coding scheme (MCS) that can be transmitted on each radio resource depends on the value of the SINR as indicated in the table below.

2. Considering a SISO network and a bandwidth of **20MHz**, complete the table:

SINR (dB)	MCS	Useful Bit per symbol	Maximal cell data rate	1 RB per UE Data rate
-0.75	QPSK-1/3	2*1/3	1.12 Mb/s	112 kb/s
1.5	QPSK-1/2	2*1/2		
3.5	QPSK-2/3	2*2/3		
7	16QAM-1/2	4*1/2		
9.5	16QAM-2/3			
11.5	16QAM-4/5			
12	64QAM-1/2			
14.7	64QAM-2/3	6*2/3 = 4		

In LTE-Advanced, it is possible to use 8X8 MIMO configuration and to aggregate up to 5 carriers of 20 MHz each.

3. Compute the maximal and minimal aggregate data rate in the cell.

The 8x8 MIMO configuration can be used either to multiplex multiple streams towards a single user or to multiplex multiple users on the same radio resource. This is known as multi-user system.

4. Assuming the scheduling policy limits the number of RR to one per user and we are completely using multi-user systems, compute the maximal number of users that can be scheduled in LTE-A networks.

1. **The OFDM symbol should be seen as a super-symbol containing N QAM symbols. The information symbols are transmitted on the N sub-carriers. The spacing between two sub-carriers is equal to 15 kHz.**
   In the time domain, the carrier spacing corresponds to the duration of the whole OFDM symbol T = $1/\Delta f$.

   The symbol duration is then: T_s = T/N = 1/(NΔf)

2. **The resource block (RB) or Radio Resource (RR) is the smallest unit that can be allocated to a user in 4G. It contains 7X12 resources elements = 84 resources elements. On each resource element, a QAM symbol can be transmitted. The duration of one resource block is 0.5 ms and it occupies a bandwidth of 180 kHz.**

   To find the data rate in one RB:

   Data Rate = Useful Number of Bit per Symbol * 84/0.5 (kb/s)

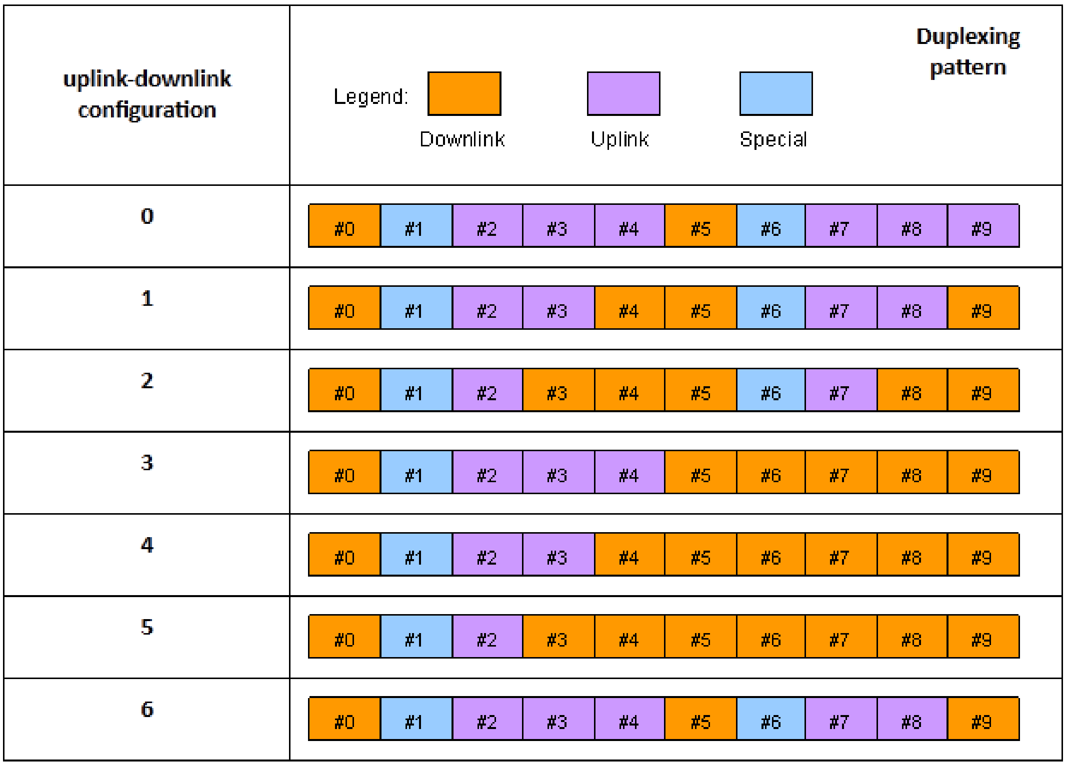
   In 20 MHz, we have 100 RBs. The total data rate = 100 * Data Rate in one RB

3. **When we aggregate 5 carriers of 20 MHz, we multiply the data rate by 5.**
   When using nt x nr MIMO, we can multiplex min(nt,nr) streams on the same RB.

   This means that the data rate = min(nt,nr)x5xUseful Number of Bit per Symbol * 84 symbols /0.5 (kb/s) = 8x5xUseful Number of Bit per Symbol * 84 symbols /0.5

4. **If we use the 8x8 MIMO to multiplex users, we will be able to schedule 8 different users on the same radio resource. With carrier aggregation, we have 5x100 radio resources. The number of UEs is 8*5*100 = 400 Users**
   Note that the scheduling duration is 1 ms in LTE. It is known as time transmission interval = 2x Time duration of one RB = 1 ms.
   This means each 1 ms, we can serve 400 Users.

12/ What is the advantage of the TDD compared to FDD when considering the pattern 0, 4, 5 and 6 of LTE



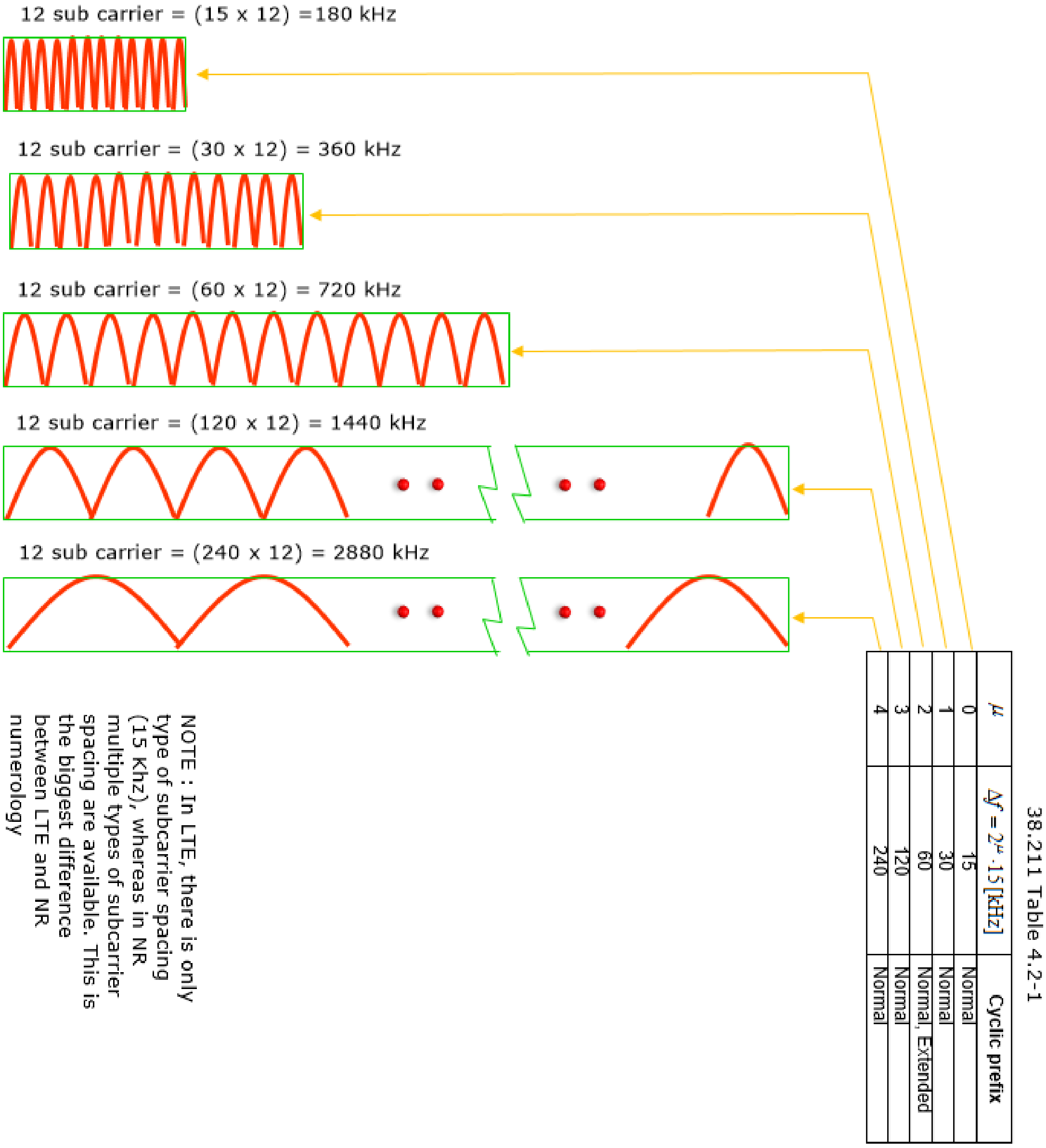
FDD is suitable for balanced traffic between uplink and downlink (attending a visio-conference meeting).
TDD is suitable for unbalanced traffic: most dominant uplink traffic (pattern 0 & 6): upload photos to the Cloud
Most dominant downlink traffic (pattern 4 & 5): streaming application (youtube or others)

13/ Numerology in 5G:

1. Explain how the numerology reduces the delay in 5G.

The OFDM symbol duration T = 1/Δf with Δf being the spacing between subcarriers. In 4G, the spacing is fixed to 15 kHz. In 5G, the spacing is flexible and depends on the application. The spacing can be 15, 30, 60, 120, 240 kHz. This reduces the OFDM symbol duration.
The radio resource block remains = 7 OFDM symbols. The time duration is reduced from 0.5 ms to 0,25 ms with a spacing of 30 kHz; 0.125 ms with $\Delta f = 60$ kHz and so on.

The time transmission interval is equal to the time of two resource blocks and is equal to 1, 0.5 ms, 0.25 ms, etc



2. Compute the data rate that can be achieved with a MCS 256QAM-2/3 for the NR of 5G using numerology 2.

The data rate = 8*2/3*84/0.125 = 3.584 Mb/s in one RR

14/ In an urban area, a new provider of shared biking rental would like to equip all the bikes by smart locks that are activated through a NB-IoT with **only** guard-band mode of LTE 2.6 GHz deployed within a 5 MHz band and a cell radius of 300 m.

We assume that all the coverage areas around stations are circular. The provider estimates within one hour, there is an average number of 120 simultaneous communications of 30 s each and per km^2. All the communications are assumed to be uniformly distributed in the city.

To estimate the number of required radio-resources in licensed bands, the operators use an Erlang B calculator that estimates the radio resources required by a given application, and considering a given blocking probability of 0.01.

1. Find within one NB-IoT cell, the generated traffic in Erlang (indication: https://www.erlang.com/what-is-an-erlang/)
2. Based on the above traffic in Erlang, and the Erlang B calculator available on https://www.erlang.com/calculator/erlb/, find how many radio resources are required in NB-IoT
3. *Estimate how many radio resources are available in the guard band of 5 MHz.*
4. Indicate if these guard band radio-resources are sufficient to handle the traffic.

1. **We have 120*30 communications in 1 km^2. In a circular cell with radius 300m , we have 120*30*pi*(0.300)^2 = 1017.8s**
   The traffic in Erlang = 1017.8s/3600 s = 0.28 Erlang
2. **Using the Erlang table, we need 3 RRs.**
3. **In the band of 5 MHz, only 25 RBs are used. Each RB occupies a bandwidth of 180 kHz. The bandwidth occupied is 25x180 = 4.5 MHz. The unused bandwidth = 5 – 4.5 = 0.5 MHz = 2RBs.**
4. **The guard bands are insufficient. We need to allocate in-band one more RB in addition to the two out-bands.**

15/ One of the scenarios considered by the 5G is the autonomous vehicles. This use case requires a very low latency and a reactive network. For this, different numerologies have been defined in 5G. We assume that a highway is equipped with 5G massive 64 x 64 MIMO antennas operating in the mmwave band (these antennas are positioned at the two-ways separation zones). The density of vehicles on the highway is 0.05 vehicle per m^2 and we assume that 5% of the vehicles are autonomous and are uniformly distributed on the highway. All the vehicles are equipped with a single antenna.

The interspacing between two antennas is a half wavelength.

We assume that the distance between two antennas is equal to 1 km. The coverage area is circular.

1. Explain how the numerology reduces the delay in 5G.
2. Explain why it is better to use TDD rather than FDD in 5G
3. Assuming that the highest numerology is used, indicate what is the lowest latency that can be obtained and the size of the bandwidth that should be allocated to a given vehicle.

The massive MIMO combined with the mmwave can be used either to only focus the beam in the direction of a single-user and/or to spatially multiplex several users on the same radio-resources. The spatial multiplexing is only possible if the positions and the attenuation faced by the devices are completely decorrelated.

1. If no spatial multiplexing is considered, what is the total bandwidth that can be allocated to this 5G network to be able to support the overall traffic?
2. If an intelligent multiplexing of uncorrelated users is made, the base station is able to multiplex up to 10 users on the same radio resource. Indicate the size of the bandwidth that can be allocated in this case.
3. Comment on the advantage of the spatial multiplexing compared to the single user communication.

12/ Resource allocation:

Indicate what are the suitable resources that should be allocated by the network to offer the following services (when the SINR = 5 dB)

Activity	**Required Download Speed**	**3G**	**4G**
Skype/WhatsApp phone call	0.1 Mbit/s		
Skype video call	0.5 Mbit/s		
Skype video call (HD)	1.5 Mbit/s		
Listening to online radio	0.2 Mbit/s		
Watching YouTube videos (basic quality)	0.5 Mbit/s		
Watching YouTube videos (720p HD quality)	2.5 Mbit/s		
Watching YouTube videos (1080p HD quality)	4 Mbit/s		
Watching Netflix (standard definition)	1.5 Mbit/s		
Watching Netflix (high definition)	5 Mbit/s		
Watching iPlayer/Netflix (4K UHD)	25 Mbit/s		