University of Piraeus

Department of Digital Systems

M.Sc. " Digital Communications & Networks "

''Uplink and Downlink Decoupling in Future Cellular Networks''

Senior Thesis

Ioannis Mat. Santamouris

''ME14040''

Supervisor

Associate Professor

Ms Aggeliki Alexiou

With the completion of this essay the cycle of my postgraduate education comes to an end, therefore I feel the obligation to thank some people that helped me these great years. First of all I want to thank my supervisor professor Ms Aggeliki Alexiou for all the support she provided me to complete this thesis, for her apprehension and the best collaboration we had, through this year. I also feel beholden to my father for his support all these years and for giving me the opportunity to attend this postgraduate program. Furthermore I want to thank my mother that gave me the courage to continue in a field of studies that I was never associated with. Lastly, I want to thank my good friend and classmate Vassilis Karagiannakis for his technical support and advises on this thesis.

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Ioannis Mat. Santamouris

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Abstract

As Charles Darwin believed ''It is not the stongest of the species that survive, nor the most intelligent, but the one most responsive to change". Based on that theory every aspect and application that help us communicate with each other is being under construction due to the continuously growing needs we have as network technology gives us more possibilities and functions. Evolution is the secret for the next step and this is the essence of impact left behind by every technology. We have all seen the innovations in the field of Communications from Telegraph invented in 18th Century to 5G Communications. Nowadays, the wireless communications had changed radically in order to cover all kind of digital life needs, such as communication with each other or entertainment. To understand how the mobile communications work we have to deeply have a look, in this thesis, at how the cellular networks work and evolved through the years. After that we observe the interference impact on the cellular networks and how technologies like OFDM manage more efficiently the wireless resources. Because of the increasing needs for higher capacity we study the HetNets and future implementations of networks such as Uplink and Downlink Decoupling, which is the main topic of this thesis. From the beginning of cellular network studies these two connections were coupled. We are reasearching the advantages and the benefits of using this decoupled scenario in future network deployments, that could radically change the cellular network status quo.

Lastly, we make simulations in order to prove the advantages of Decoupling associations over the coupled ones.

Chapter 1. Introduction

1.1 Cellular Networks

In 1947 Douglas H. Ring and W. Rae Young first proposed the cellular structure concept. The geographical area was covered with hexagon cellulars in every side which transmitted and received in three directions. The idea of providing wireless communications at the citizens of a huge area rised at Bell laboratories which developed the idea of cellular communications at the 60's. Practically, the age of wireless communications began at 70's, when reliable hardware for radio frequencies were developed. [1]

Cellular networks aim at providing services, on mobile terminals in which there is a big amount of scattering in the streets and on larger areas.

User equipment (UE), such as mobile phones are capable of communicate even if the equipment is moving through cells during transmission. Cellular networks provide users with features such as increased capacity, less battery power consumption, a larger coverage area and reduced interference from others. [1]

It solves the problem of spectral congestion and increases user capacity. The coverage area of cellular networks are divided into cells, each cell has its own set of frequencies used by the system for transmition and generally communication.

Every cell has its own frequency. Data communication is accomplished by its base station transmitter, receiver and its control unit. The shape of cells can be either square or hexagon.

The big advantage of cellular concept is the frequency reuse architecture. This architecture is the concept of using the same radio frequencies within a given area, that are separated by long distance, with minimal interference, to establish communication. [1]

The benefits of frequency reusing are :

- Allows re-use of frequencies in nearby cells
- Limits ovelaping power to adjacent cells
- Allows communications within cell on a given frequency
- Uses same frequency for multiple conversations

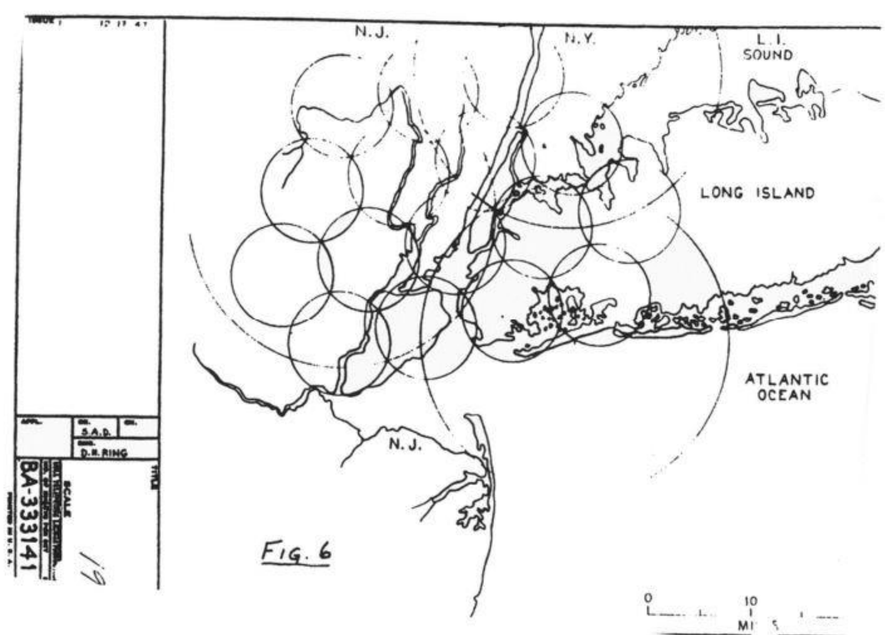


Figure 1. First Cellular Network Concept

1.2 Evolution of Cellular Mobile Networks

Mobile Network models are divided into generations. ''G'', stands for "Generation". This is what each set of telephone network standards is comprised of. It defines the technological implementation details of a particular mobile network system. The first ever mobile device that revolutionized the world of communications used the Advanced Mobile Phone System protocol. This analogue network would later be known as 1G. Phones operated in a voice-only network and worked in a similar way to a regular radio transmission. Being analogue meant calls were susceptible to noise caused by nearby devices and anyone with a radio scanner could eavesdrop in on your call. The second generation (2G) cellular telecom networks were commercially launched on the GSM standard in Finland by Radiolinja in 1991. This technology used digital signals for voice transmission and had a speed up to 64 kbps.

It also provided the facility of Short Message Service (SMS) and used the bandwidth range of 30 - 200 KHz. Third generation (3G) uses Wide Band Wireless Network with which clarity is increased. The data are sent through the technology called Packet Switching. Voice calls are interpreted through Circuit Switching. It supports data services like access to television/video and new services like Global Roaming. It operates at a range of 2100MHz and has a bandwidth of 15-20MHz. Fourth generation (4G) networks are still under progress and provide capabilities defined by ITU (International Telecommunications Union) in IMT Advanced (International Mobile Telecommunications Advanced). Potential and current applications support mobile web access, gaming services, IP telephony, video conferencing and mobile TV. This technology supports speeds from 100 Mbit/s to 1Gbit/s and guarantee great quality and a high level of security.

As the releases of 4G continue to rise (LTE-Advanced) we more approach to what we believe will be the public release of the fifth generation of networks (5G). Fifth Generation promises and expectations are very high such as date rates over 1Gbit/s, improved security features, more coverage range and higher energy consumption savings. [1]

Comparison

Technology	1G	2G/2.5G	3G	4G	5G
Deployment	1970/1984	1980/1999	1990/2002	2000/2010	2014/2015
Bandwidth	2kbps	14-64kbps	2Mbps	200Mbps	>1Gbps
Technology	Analog cellular	Digital cellular	Broad bandwidth /CDMA / IP technology	Unified IP &seamless combo of LAN / WAN / WLAN / PAN	4G+WWWW
Service	Mobile telephony	Digital voice, short messaging	Integrated high quality audio, video & data	Dynamic information access, variable devices	Dynamic information access, variable devices with AI capabilities
Multiplexing	FDMA	TDMA/CDMA	CDMA	CDMA	CDMA
Switching	Circuit	Circuit/circuit for access network air interface	Packet except for air interface	All packet	All packet
Core network	PSTN	PSTN	Packet network	Internet	Internet
Handoff	Horizontal	Horizontal	Horizontal	Horizontal Vertical	Horizontal Vertical

Figure 2. Comparison Between Generations

WIRELESS GENERATION	Download NewYork Times home page (1.4MB)	Download 3-minute MP3 file (4MB)	Download 3-minute web video (10MB)
2G Average speed 125 kbps	90 seconds	2 minutes, 16 seconds	10 minutes, 40 seconds
3G Average speed 800 kbps	14 seconds	40 seconds	1 minute, 40 seconds
4G Average speed 1.5 mbps	7 seconds	21 seconds	53 seconds

Figure 3. Average Generation Speeds

1.3 The Maximum Data Rate of a Channel

Henry Nyquist, in early 1924, who worked at AT&T as an engineer came to a conlsusion that a perfect channel suffer from limited transmission capacity. He developed an equation in order to express the maximum data rate for limited bandwidth noiseless channels. Claude Shannon worked further on that conclusion and took the problem to the case of a channel sudjected to random noice. In a subjectively decided signal has been run through a low pass filter of bandwidth B, the signal that has been filtered can be build again by making 2B samples per second. The signal will be consisted of V individual levels.

Then we have what Nyquist theorem states, which is :

maximum data rate = 2B log2 V bits/sec

Figure 4. Henry Nyquist

Now if we do not consider tha we have a noiseless channel and random noise is there, this situation is getting worse. This is the most realistic case because there is always random (thermal) noise due to the movement of the molecules in our world. [7]

Heres comes the Signal-to-Noise Ration (SNR) that is the measurement for the amount of the thermal noise. We signify the signal power with the letter ***S*** and the noise power with the letter ***N***, so The SNR is ***S/N***. Because the ratio can change dramatically over a huge range, the ratio is expressed in a log scale as the quantity ***10 log10 S/N***. The units of this is called decibels(dB).

By ''deci'' we mean 10 and ''bel'' as a tribute to Graham Bell. For example an ***S/N*** ratio of 10 is 10dB, a ratio of 100 is 20 dB, a ratio of 1000 is 30 dB. So Shannon's breakthrough result is that the maximum data rate of a channel with the noise existence, in which the bandwidth is ***B*** Hz and in which SNR is ***S/N*** is :

maximum number of bits/sec = B log2 (1 + S/N)

This theory expresses the best capacity that real channels with noise can have and it comes from information-theory quarrels. We must say that It is applied to any channel subjected to thermal noise. It is the application of a noise channel coding theory to the archetypal case of a continuous time analog communications channel subjected to Gaussian noise. This law demostrates Shannon's channel capacity ***C*** for a communication link of this kind.[7]

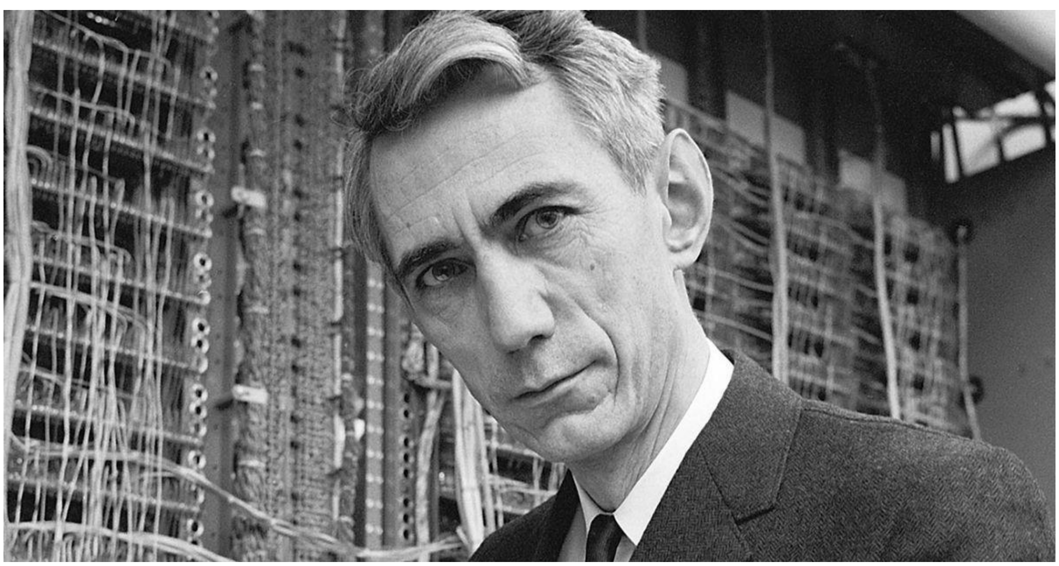


Figure 5. Claude Shannon

1.4 First Generation (1G)

The First Generation of cellular networks were invented in 1980. The main idea was that a base station served a geographical area divided into cells (for instance 10-25km). Many users could be served in a given area because cells were small and the frequence reuse model could make the most of nearby (not in adjoining cells though). The first generation of networks were analog systems and they were functioning in the frequency band of 150MHz. The first public 1G cellular network launched in Japan by NTT (Nippon Telegraph and Telephone) in 1979, in Tokyo. In the next years this network expanded through the whole Japan and became the first natiowide 1G network. This Generation encompassed the following technologies :

- Mobile Telephone Systems (MTS)
- Advance Mobile Telephone Systems (AMTS)
- Push To Talk (PTT)
- Improved Mobile Telephone Service (IMTS)

The security with the first generation networks was an issue. Anyone with possession of an all radio band receiver connected to a computer could record the phone calls of subscribers.[1]

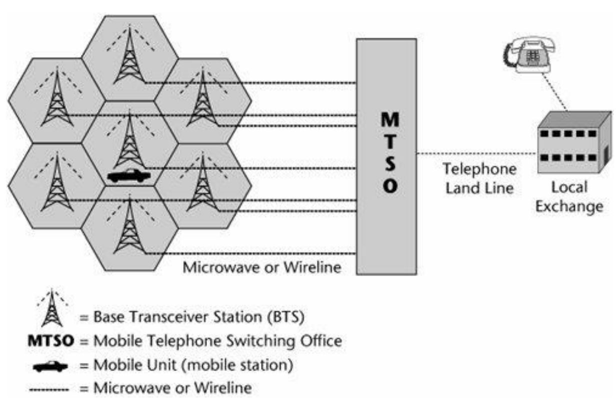


Figure 6. 1G Concept

1.5 Second Generation (2G) and 2,5(G)

The second generation went public in 1991 on the GSM standard in Finland. In opposition with 1G second generation used digital transmission for the traffic and had a speed up to 64 kbps. Second generation gave us the technology of Short Messages Services (SMS) and used a range of 30 – 200Khz. A big benefit over its predecessor was that 2G supported digital encryption which had higher penetration efficiency and for that reason it was more capable for network spectrum. This technologies were included in this generation :

- General Packet Radio Service (GPRS)
- Code Division Multiple Access (CDMA)
- Global System for Mobile Communication (GSM)
- Enhanced Data Rates for GSM Evolution (EDGE)

Some issues was that in less populated areas, the weaker digital signal deployed on higher frequencies and this could be not enough to reach a cell tower.

The next step was the 2,5G network system which conclude an amount of evolutions over 2G networks. The main uprade was the implementation of packet switching. We has an increased data speed ranging from 56 kbps to 115 kbps. So this generation opened a new set of services to the consumers such as WAP which is a simplified version of websites and the ability to send and receive photos and videos via the technology of Multimedia Messages Services (MMS).[1]

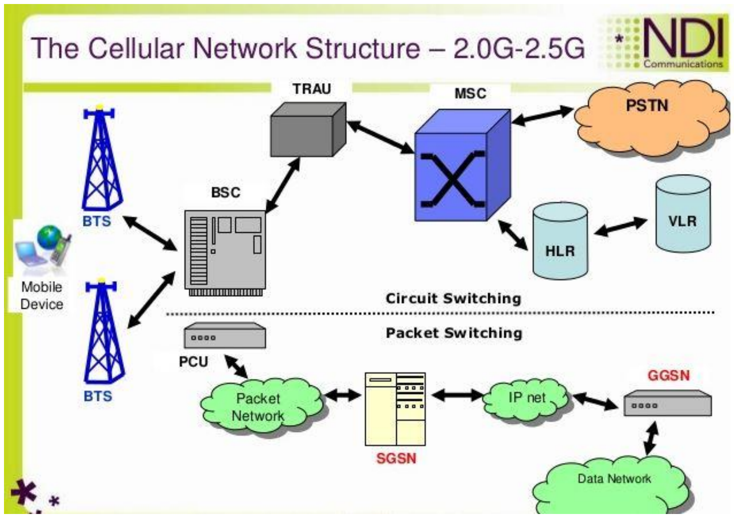


Figure 7. 2G Cellular Network Structure

1.6 Third Generation (3G) and 3.5(G)

Third generation of networks (3G) is a generation of standards for mobile telecommunications services fulfilling the Internation Telecommunication Union (ITU). This generation make use of a Wibe Band Wireless Network in which clarity is better. We can send data through the packet switching technology and voice calls are made through circuit switching. Apart from voice communication it includes data services and access to television and video and a new service called Global Roaming. [1]This generation uses wide band voice channel and from now on a subscriber can reach by voice a person in any part of the world and even send messages too. 3G operates at a range of 2100Mhz and can support bandwidth up to 15-20Mhz which is used for high speed video chatting and video calls. UMTS (Universal Mobile Telecommunications System) is the common exemplar of 3G network and after that comes the US CDMA2000 (Code Division Multiple Access).

In this generation the following technologies are comprehended :

- Wideband CDMA
- WLAN
- Bluetooth
- Universal Mobile telecommunication Systems (UMTS)
- High Speed Downlink Packet Access (HSDPA)
- Global Roaming Clarity

A big issue is that with 3G network technology the power consumption greatly increases which results in reduced device battery life and this is because the high bandwidth transmission that is used. The load on the network sometimes became so heavy due to the high transmission rates and operators used to put data upper limits to subscribers.

The next step was the HSPA commonly known as 3,5G. In this step is included the HSDPA technology ((High Speed Downlink Packet Access) in which the transmission from the base station to the subscriber is five times faster than in the UMTS and fifteen times faster than GPRS. On paper the data rates can reach 14.4Mbps. The functionality of HSDPA is based on the fact that instead of using different DCH (Dedicated Channel) for data transmission it is used a DSCH (Downlink Shared Channel) which subscribers share with each other for the packet transfers. This channel has a much larger bandwidth and for that reason it is called HS-DSCH (highspeed DSCH).

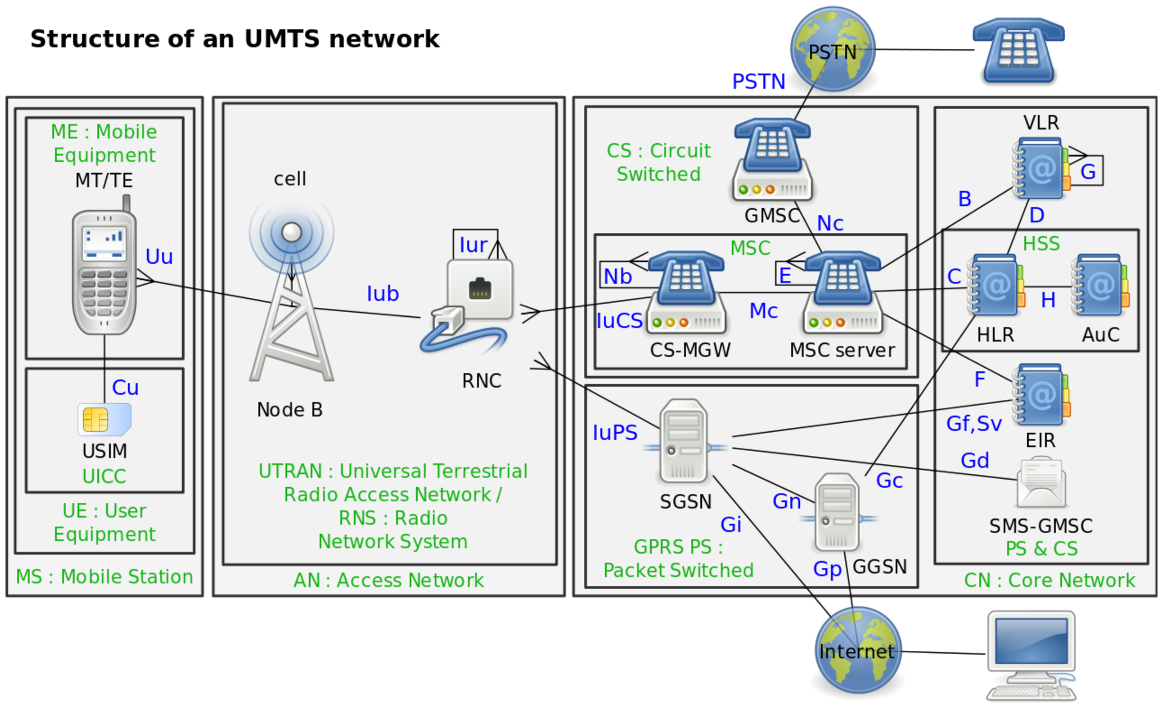


Figure 8. 3G Network Structure

1.7 Fourth Generation (4G) and 4G+

The fourth generation of networks was introduces in 2008 by the International Telecommunications Union-Radio communications sector (ITU-R). They set some standards for 4G requirements such as peak speed requirements for 4G service at 100Mbit/s for situations like being in a train or a car and 1Gbit/s for pedestrians and stationary users. The fourth generation gives has the ability to not only provide 3G services and voice but it also provides ultra broadband network access to mobile devices. In relation with its predecessors it increases tha capacity of the network, the data rate transmission and it reduces delays.

The completion of a 4G system is achieved with the LTE (Long Term Evolution) technology.

Technologies embedded in the fourth generation of networks are :

- Long Term Evolution (LTE) Standard
- Multiple In Multiple Output (MIMO)
- Orthogonal Frequency Digital Multiplexing (OFDM)
- OFDMA (Orthogonal Frequency Division Multiple Access)
- Worldwide Interoperability for Microwave Access (WiMAX)
- Mobile Broadband Wireless Access (MBWA)

The 3rd Generation Partnership Project (3GPP) is a worldwide communications organization which goal is the creation of a worldwide mobile communications system with the same standards. 3GPP set the standards for the LTE technology at the Release 8 and 9 and promises data rates up to 300Mbit/s on the downlink with MIMO antennas 4x4 and 75 Mbit/s on the uplink with a simple antenna for every 20MHz of spectrum.

The advantage of the fourth generation is mainly the efficiency for spectrum of the system, the higher capacity of the network, the high quality of services in order to support new technologies for the subscribers such as HD Mobile Television, video conferencing to gaming services and cloud computing and global roaming. The goal of this generation is the development of systems entirely based on the IP protocol.

The next step is LTE-A(Advanced). The new functionalities introduces are Carrier Aggregation, support for Relay Nodes and enhanced use of multi-antenna techniques.[1]

The biggest step is carrier aggregation which is designed to multiply the bandwidth of LTE connections by letting subscribers to download data from multiple network bands simultaneously.

LTE carriers are split up into data carrying parts with bandwidths of 1.4, 3, 5, 10, 15 or 20Mhz. Carrier aggregation technology allows the bandwidth to increase up to 100Mhz for a single connection and that is because up to five component carriers can be aggregated together for both upload and download connections. When it uses the maximum available bandwidth from all the carriers it can provide up to 1Gbit/s on paper. The commercial version up to the moment combines up to 3 carriers with peak data rates up to 600 Mbps.

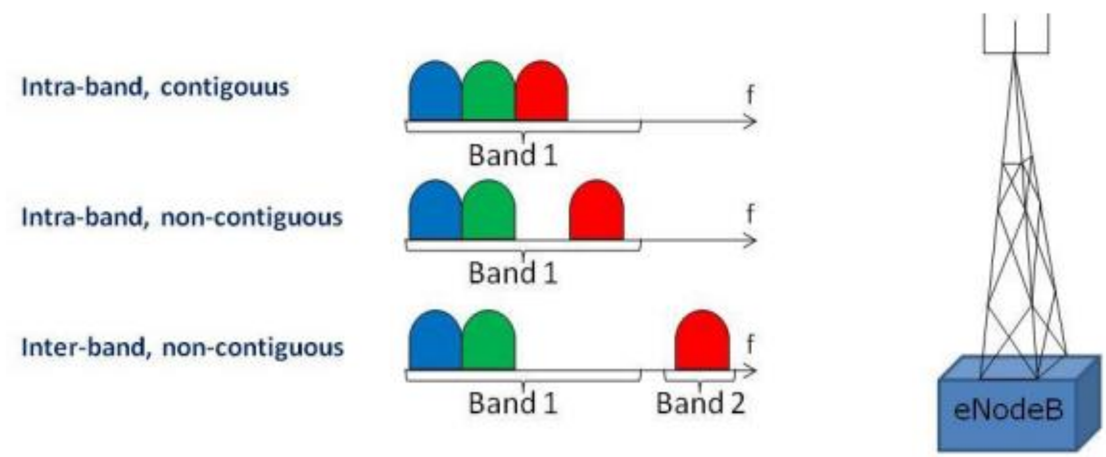


Figure 9. Carrier Aggregation in LTE

1.8 Fifth Generation (5G)

The fifth generation of networks, known as 5G, and its possible functionalities is the main sudject of this thesis so we will have a very close look at this generation. Nowadays, the further releases of LTE-Advance continue to evolve in terms of system performance and adds new capabilities with new application areas. The need of 5G continue to raise as subscribers need:

- better battery consumption
- improved coverage range and higher data rates.

Estimations claim of 1Gbit/s with large broadcast capacity of 65.000 connections at a time. We will also have better security features, worldwide wireless web (WWWW) and higher level of spectral efficiency.[2] Capabilities of the 5th generation have to do with extreme data rates, a lower latency than ever before, energy efficiency, high reliability and will be accomplished with the development of LTE simultaneously with new radio-access technologies. Key technology will conclude :

- extension to higher frequency bands
- access/backhaul integration
- device-to-device communication
- flexible duplex
- flexible spectrum usage
- multi-antenna transmission
- ultra-lean design
- user/control separation.

The fifth generation will also ensure support for wireless connectivity in a wide range of new technologies such as wearables, smart homes, traffic safety and control and very-high-speed media delivery.[4]

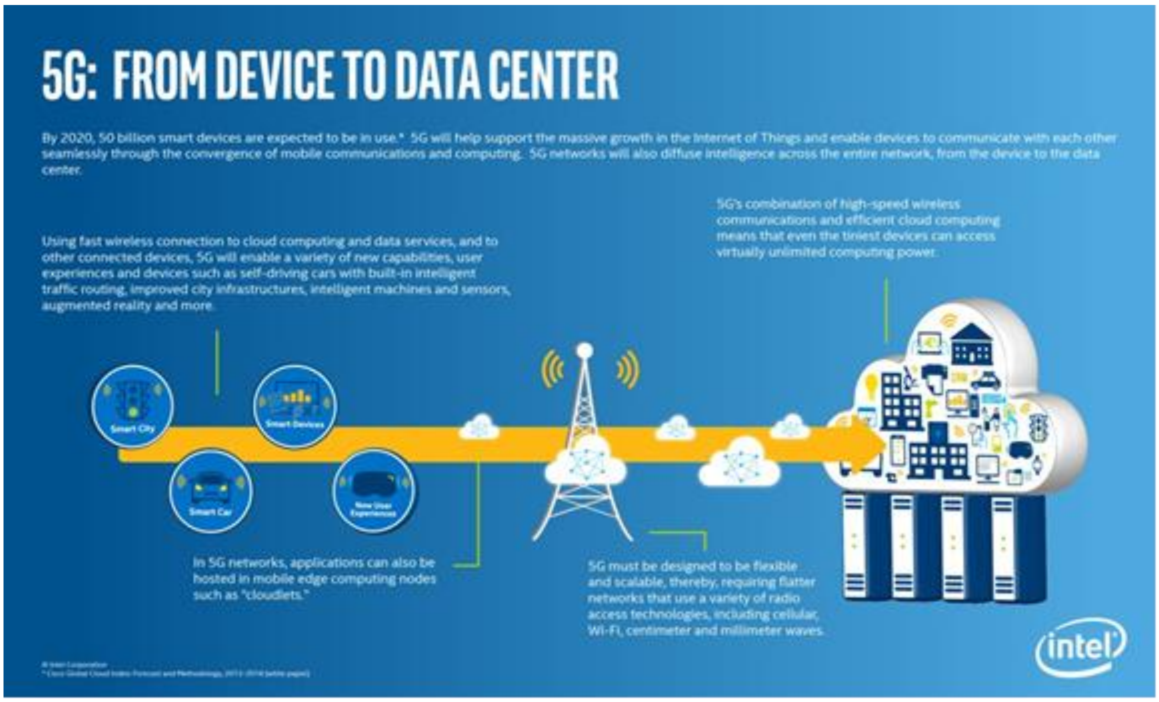


Figure 10. 5G Concept

5G challenge is the spectrum availability. The current spectrum we already use is nearly full. Because of this in high dense implementations of the network it will be essential to go higher in frequency levels. Also the use of a largea area of free strectrum bands will be a necessity. 5G network model is an All-IP based model (AIPN). It is able to satisfy the increasing demands on cellular market. More important is that it includes a general platform for all radio access technologies and standards. 5G architecture consists a user terminal and some autonomous radio access technologies.

It also provides application via Cloud Computing Resources such as Mobile Health-Care or Mobile Banking. In order to satisfy all the increasing needs for mobile traffic it is estimated that 5G technology will achieve a 1.000 fold capacity increase from previous generations. In order to achieve this, heterogeneous networks(HetNet) and convergence of information and communication are some key features for the fifth generation technology. Heterogeneous networks refer to network deployments with different types of network nodes. They support different radio access technologies (RAT) and different backhaul links.[12]The new feature of the fifth generation is the native support of multi connectivity. This is a key feature to satisfy the requirements such as higher data rates, latency, security, reliability and of course availability.

We have to mention as well that operators can make use of the same network to ensure access to fixed and mobile users with a convergence of fixed-mobile networking and that is a feature very handheld for the subscribers.

Every generation of mobile communication has been associated with higher data rates compared with the past ones. The important thing is the real data rate that can be provided under real life situations.

- 5G could support data rates exceeding 10Gbps in cases such as indoor and high dense outdoor situations.
- Data rates of several 100Mbps could be achieved in urban and suburban environments.
- Data rates of at least 10Mbps will be guaranteed almost everywhere.

Very low latency will be needed for the support of new era applications for subscribers.[3] Traffic safety and control for example will require much lower latency compared with the possibilities of the mobile-communication systems of today. To support these latency-critical application for instance, fifth generation networks should allow for an application end-to-end latency of 1ms and maybe less.

The low energy mobile devices was something everyone wanted from the first steps of mobile communications. In order to achieve the vision for wirelessle connected sensors and devices we must take a further step concerning the cot of devices and energy consumption.

5G devices must have very low cost with specifications like a battery lifeof several years with the need of recharging.

The energy efficiency on the network side is a key issue for two main reasons:

- Energy efficiency is an important in order to reduce operational cost.
- Energy efficiency is necessary to fulfill operators ambition for providing wireless access in a viable and more resource-efficient way.

Energy efficiency will be a very important requirement in the design of 5G network. This generation will have to extend the range of frequencies that is used for mobile communications because very high data rates must be supported and in order to do that it is necessary to increase traffic capacity and to enable the transmission bandwidths. New spectrum below 6GHz, as well as spectrum in higher frequency bands is included.

Apart from extending to higher frequencies, there are other key technologies relevant for the evolution of 5G wireless access. One is the backhaul integration. The wireless connectivity already is been used to sovle the backhaul situations. Such solutions operate in under line-of-sight situations by using radio technology in higher frequency bands, including the millimeter wave (mmW) band.[4] In the years to come the link between the base station and the device will also move to higher frequencies. Furthermore in order to support dense low power deployments, wireless backhaul will have to cover non-line-of-sight situations, identical to access links.

In the years of 5G networks the wireless access link and wireless backhaul must integrate as one wireless access solution with tha same technology and a common spectrum pool. This will help a lot in having more efficient overall spectrum utilization.

As mentioned before D2D communication will be a key feature. The technology of direct device-to-device (D2D) communication has already been introduced as an LTE specification. Direct D2D communications can be used to offload traffic, extend capabilities and enhance the overall efficiency of the wireless-access network.

In order to avoid high level of interference to other links, direct D2D communication must be under network control.

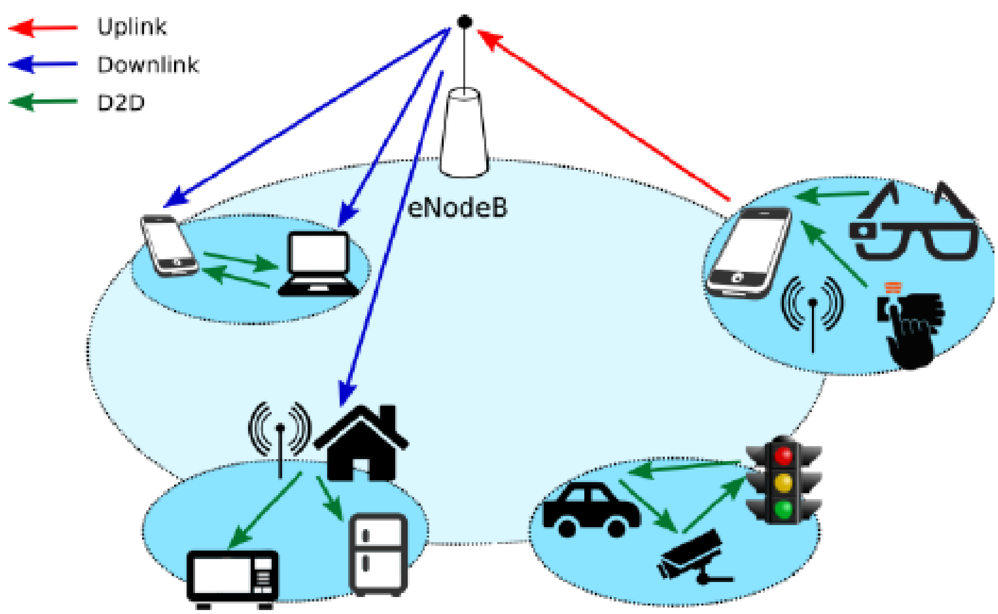


Figure 11. D2D Communication Concept

Flexible Duplex will be a very important feature. Since the beginning of mobile communications Frequency Division Duplex (FDD) was the dominant duplex arrangement. In the 5th generation, FDD will likely remain the main duplex for low frequency bands. Time Division Duplex (TDD) will play a more important role for higher frequency bands especially those of above 10GHz that are targeting dense deployments.

Direct basestation-to-base-station and device-to-device interference will be identical to the common base-station-to-device and device-to-base-station interference that also occurs for FDD, this will happen in situations with lower power nodes. One more thing is the ability to assign time slots to different directions, this will allow more convenient use of the available spectrum. In the 5th generation flexible assignments of TDD transmission resources must be allowed in order to reach full potential specifications. Nowaydays in TDD-LTE there are restrictions on the configurations of the downlink/uplink configurations.

Multi-antenna transmission will play a very important role in the 5G years to come , as it today in the current versions of mobile networks. This is because of the small antennas and the physical limitations they have. As the aperture of the trasmitting and receiving antentas do not change the path loss does not change between the trasmitter and the reciever as a function of frequency. [6] The antenna aperture reduce in proportion to the square of the frequency. This reduction can be countervailed by the use of higher antenna directivity. Hundreds of antenna elements used by 5G networks will play their role in order to increase antenna aperture further from what may be possible with the current cellular networks. Beamforming will be used by the transmitter and the receiver to connect with eatch other In addition, the transmitter and receiver will use beamforming to track one another.

Beamforming will also be used for improving energy transfer over a direct communication link. The radio environment will also be improved by the limitation of interference around a transmitter and a receiver. The beamforming will be useful for lower frequencies too. In sparse deployments the beamforming could extend the coverage and give the subscribers higher data rates.[6]

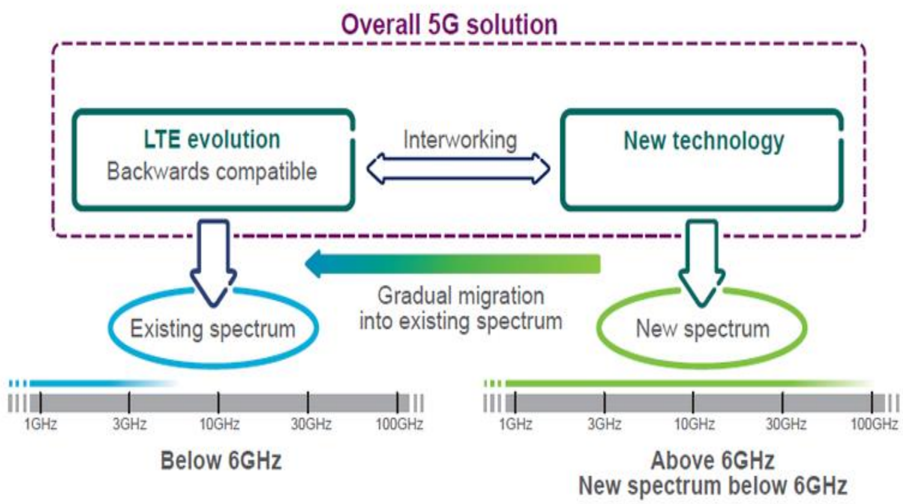


Figure 12. 5G Concept 2 in terms of spectrum and interworking

Lastly, ultra-lean radio access design is important in order to achieve higher efficiency in 5G by minimalizing transmissions that are not directly related to the delivery of data. [5]

This tranmissions could be signals for synchronization, network acquisition and channel estimation. Another transmission could be the broadcast of different types of system and control informations. In dense deployments with many nodes and high traffic conditions situations ultra-lean design is very important as well. By entering low energy in network nodes when there is no transmission ultra-lean design will be able to help in deliverins high energy performance. Interference from non user data transmissions will also be reduced in order to achieve higher data rates numbers, so ultra-lean design will whittle interference of this kind down.

Chapter 2. Techniques for Efficient Use of Spectrum

2.1 Interference in Mobile Networks

The interference problems in mobile networks have been investigated sice the early 1980s in the circumstance of frequency division multiplexing. Interference is one main performance limiting factor in most wireless networks. Interference signals in cellular networks can divided in those that are caused by natural phenomena and we cannot eliminate and those manmade signals that can be controlled. Two basic factors that cause that manmade interference are the network geometry and the path loss law. By saying network geometry we generally mean the spatial distribution of concurrently transmitting nodes and the path loss law is the signal reduction in distance. The fist factor (spatial distribution of concurrently transmitting nodes) is depended on two sides, on the one side is the node distribution and on the other side is the channel access scheme(MAC). The mixture of the two sides is responsible for the distribution of transmitting nodes. For instance, even if we have a model in which the nodes are randomly divided, a good MAC sheme will guarantee a specific space between the transmitters.

Therefore the distribution of the transmitters will be justly regular any given moment. Since the performance of a cellular network is strongly related to the SINRs which is the signal to inerference and noise ratios, or in the free interference model which is SIR (signal to interference ratios), the signal-to-noise ratios are derived in the form of outage probabilities. [10]

$$SINR = \frac{S}{W+I}$$

where S is the desired signal power,

W is the noise power, and I is the interference power

When interference is treated as noise and for a fixed modulation and coding scheme and when we have a simple linear receiver, a common accepted model for packetized transmissions is that they succeed if the SINR exceeds a specific threshold θ. So we can say that transmission success probability is defined as :

$$ps(\theta) = P(SINR > \theta)$$

As for the second factor, when there are not any obstacles between the base station and the terminal, the spreading path characteristics are relative to free space propagation and the path loss is given as :

$$Lpf\ (dB) = 32.44 + 20 \log10\ fc + 20 \log10\ d$$

in which

fc = carrier frequency (megahertz);

d = distance between BS and MS (kilometers);

Lpf = path loss in decibels

On the other hand when there are many obstacles between the transmitter and the receiver the path loss is defined by other models such as lognormal path loss which includes the not regular configuration of the natural space.[7]

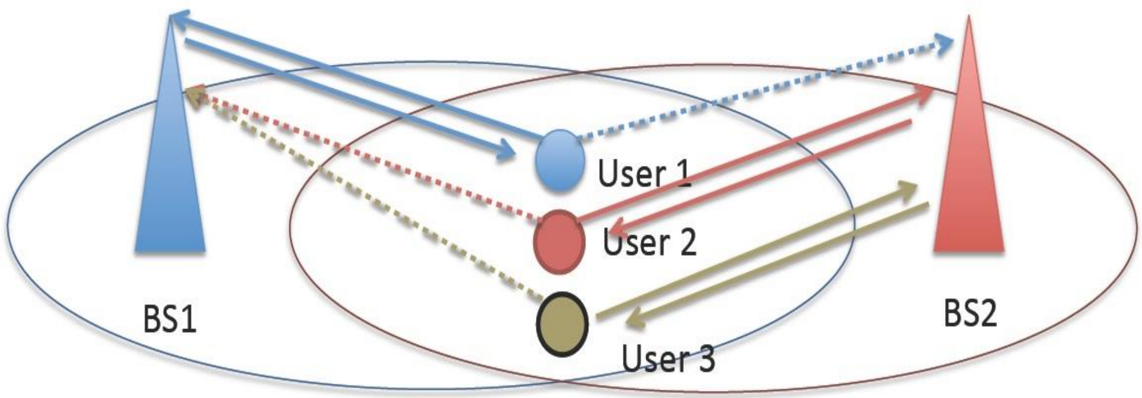


Figure 13. Inter-cell Interference

The lack of wireless spectrum in wireless networks causes the impossibility of separating concurrent transmissions completely in frequency. Some transmissions will happen the same time with others and in the same time. In systems with centralized control in which an access point can organize the channelization and the power of the terminals, the interference can be reduced. Specifically, there can be two types of obligations, the co-channel interference and the adjacent channel interference. In co-channel interference the adjacent cells are using the same channel and in adjacent channel interference we have inadequate frequency distance that is used within the same cell.

In co-channel interference there are signals that have the same carrier frequency.

The interfering signal has the same carrier frequency as the useful information signal. In adjacent channel interference we hace two cases. The case of the inband and the case of out-of-band interference. In the inband case the center of the interfering signal bandwidth falls within the bandwidth of the important signal. In the out-of-band case the center of the interfering signal bandwidth falls outside of the bandwidth of the important to us signal.[9]

In mobile communication systems there is one form of interference that is called near end to far end type ratio interference. [10] That kind of interferences apply only in mobile network communications. It appears when the distance between the terminal and the Bs becomes critical with respect to another signal transmission that is so close that it can override the important Bs's signal.

This occurs when a receiver is far from its desired Bs transmitter at distance d1 and close enough to another transmission at a distance d2 and **d1 > d2**. In this situation the problem that is occurred is that the two transmitters will transmit at once at the same power and frequency and for that reason the signal received by the terminal from the desired source is been masked by the signals that is received from the source that is undesired. This kind of interference can also occur at the Bs because signals are been received at the same time from two terminals that continue to be at unequal distances from the base station. Near end to far ratio interference is called the power difference because of the path loss between the receiving location and the two transmitters (Bs). As said before this can only be happen in mobile radio systems and it may occur both within one or two cells of one system.[8]

2.2 Interference in OFDM systems

In OFDM based LTE networks a fundamental goal is the re-use of all the available frequencies in nearby cells. The basic unit for the scheduling and the resource efficiency is the RB (Resource Block) which represents an amount of subcarriers that a user can use in terms of time and frequency. In LTE networks all the Bs trasmit in all the available time-frequency RBs simultaneously. The intercell interference in OFDM is caused due to the collision of the RBs that are used in-parallel from many cells, usually nearby cells. Moreover, the cells in LTE networks have smaller beam due to the restriction of capacity from the terminals (uplink limited). The efficiency of the system is determined from the collision possibility and from the impact of a collision in the SINR of the collision RBs. The Inter Cell Interference Coordination (ICIC) techniques come to attenuate this problem by the adoption of specific preference of nearby cells for different subset of RBs or by the limitation of power of the collision RBs. In usage it is required the Bs coordination for this technique.

It is important to mention that in real life circumstances the amount of the collision RBs changes dynamically in frequency and in time.

The main drawbacks are three issues that occur.

- The coordination between the BSs could increase the total throughput to the detriment of the backhaul communication.
- By attenuating the use of some RBs the collision of them are attenuated as well, but the resources are underemployed and the ability of multi user diversity in an environment with selective frequency fading, is reduced. Specifically the use of some subcarriers is limited.
- The maximization of throughput could lead in unfair assigning of resources and therefore in infringement of QoS.

In all the 2G and 3G systems there is the concept of PC (Power Control) by which the power transmission for the users is set attached to the distance from the BS. For that reason reason the power transmission is also attached to the transmission losses, for the purpose of the power that is been received by the Bs to be stable. With this solution we do not have optimization of the total throughput but a fair solution for all the cell edge users is guaranteed.

In 4G networks the Fractional Power Control has been proposed. According to this only a part of the spreading loss is balanced. This solution gives an improvement of up to 20% in the sector's throughput for cells occasions with beam from 500m to 1000m and bandwidth of 10MHz.

The fractional frequency reuse (FFR) divides the useful bandwidth into subareas and use these subareas into one cell in a way that the interference is reduced.

FFR in LTE OFDM systems decreases the available RBs that can be used, in scheduling and of course in the maximum throughput, thus the QoS of the applications with large bandwidth is affected. The adaptive FFR (AFFR) adapts the performance of the FFR in relation to the interference levels and adjusts the users in a subarea based on the calculations of the channel quality indicator (CQI). The actualization of the AFFR is based in the idea of Power Bandwidth Profiles (PBPs).[11]

Spatial techniques for reducing interference are:

- Spatial multiplexing
- Cyclic delay diversity (CCD)
- Space Frequency Block Coding (SFBC) in DL
- Multiuser MIMO (MU-MIMO) in UL

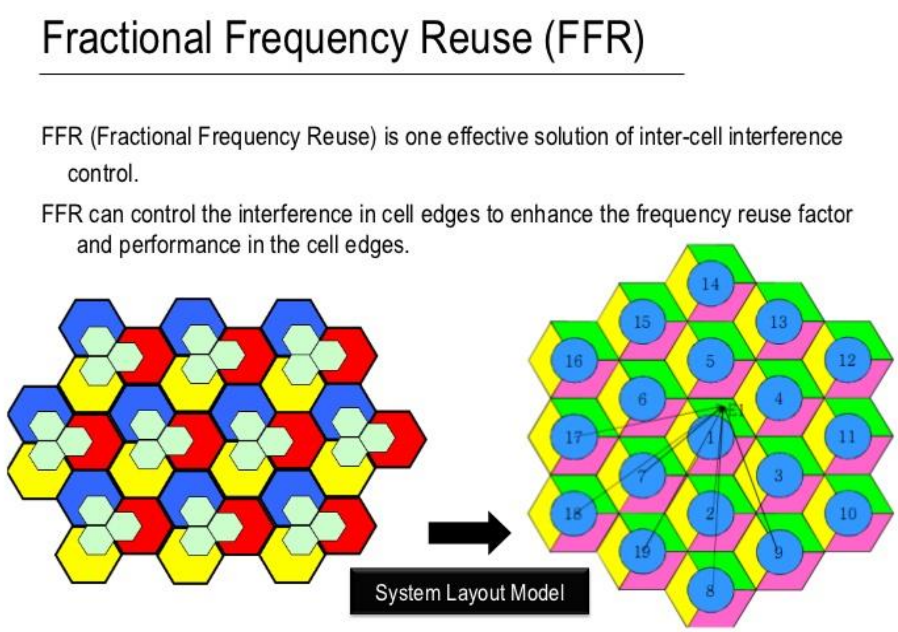


Figure 14. Fractional Frequency Reuse (FFR) Concept

The gains in throughput from the usage of MIMO in real life models are close to the theoretical approach. In downlink, multiple BSs transmit one or more MIMO paths in the UE, and on the UL, the trasmission of one UE could be received from one or more BSs.

Another technique is the interference cancellation (IC). The main idea is the rebirth of the interferences and afterwards the removal from the desired signal. This method requires the saving of the receives signal for furthermore data processing. It is simpler to cancel signals which symbols is familiar to the BS from the beginning, for the avoidance of demodulation and decoding.[11]

The most advanced techniques with the biggest gains in capacity require the cancellation of interferences from unknown symbols. Because of the complexity, the IC techniques are used in the BSs, specifically in UL. The Opportunistic or Organized Inter-BS Access is implemented correlatively with the spectrum, time and space reusage of the scheduled RBs between the BSs (in cases of hierarchical sctructure systems such as femto overlays in macro system. For LTE macro networks the opportunistic access is the dynamic channel allocation (DCA) in the BS which enables the attribution of the same RBs in multiple UEs. The Opportunistic beamforming and scheduling is a recent technique. In DL the gains from the MU diversity, in the field of the frequency, could be capitilized by someone with smart scheduling of the UEs. The big CQI overhead could re reduced with the creation of lobes in a random way based to clustered CQI feedback and the scheduling of a user in a lobe with large Signal to Noise Ratio.

Organized beam hopping (OBH) between nodes in a multi cell layer is another technique. With OBH is implemented a random-fake change of lobe between an organized amount of semi-orthogonal diagrams that are used from the nearby BSs for the purpose of the throughput maximization from the reuse of RBs and reduction of interference between the BSs. The performance of OBH is beyond expectations and it seems to overtake the technique of beamforming and opportunistic beamforming. On the other hand there are problems of complexity in the application of this technique, such as the beam choice and in the collision avoidance. Apart from that, the accommodation of OBH is not convenient in time-shifting telecommunication traffic.

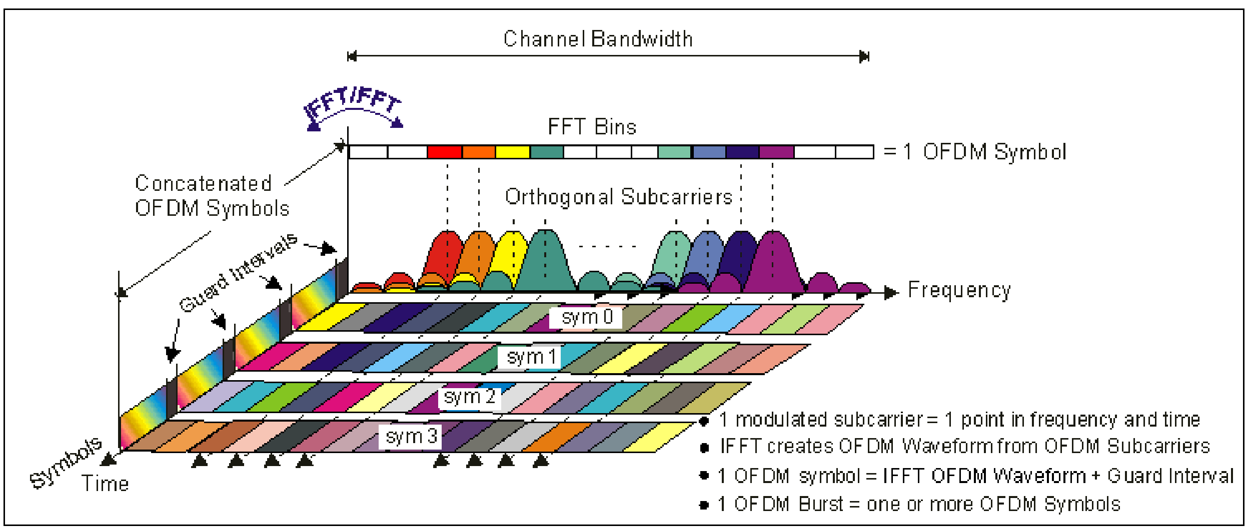
2.3 Orthogonal-Frequency-Division-Multiplexing (OFDM)

History and development

OFDM has a long history behind. It is reported that OFDM-based systems were used in the Second World War. In 1966, Robert W. Chang found that a way in which he could transmit concurrently data through a linear band-limited channel without having inter-carrier interference (ICI) and inter-symbol interference (ISI). In 1970, he acquired the first US patent on OFDM. A radical breakthrough in OFDM history happened in 1971 by Weinstein and Ebert that used discrete Fourier transform (DFT) in order to put on a play baseband modulation and demodulation, concentrated on efficient processing. This reduced the need for subcarriers oscillators and it opened the way for more efficient and convenient implementation of OFDM system. Another historical event that modernized OFDM was in 1980, when Peled and Ruiz introduced the cyclic prefix (CP).

Cyclic Prefix gave a solution in the problem of supporting the maintenance of transmitted signals orthogonal characteristics at very bad transmission conditions. The main idea was using cyclic extension of OFDM symbols instead of guard spaces in frequency. The advantage was that it lead to none ICI but on the other hand Cyclic Prefix caused energy signal loss in proportion to length of CP compared to sumbol length. In 1990s and beyond OFDM took advantage of wideband data communications in FM channels, ADSL up to 6Mbps and VDSL up to 100Mbps.[8]

The first commercial use for OFDM was the Digital Audio Broadcasting (DAB). In the 20th century WLAN (wireless local area network) used OFDM in its system as well.



Frequency-Time Representative of an OFDM signal

Figure 15. Resource Allocation in OFDM

2.3.1 Usage of Multi-carrier Transmission

Delay spread is the distortion of the signal that is obvious by the scattering of the modulation symbols in time, that is revealed by the phenomenon of inter-symbol interference and is represented by time dispersion. This is also revealed in frequency by the reversed connection between coherence bandwidth and delay spread. For example the higher the dalay spread is, the lower the coherence bandwidth is and for that reason the channel frequency is higher.

In paradigms of broadband multimedia connections the coherence bandwidth is lesser than the modulation one. So in a such situation the effect of frequency selectivity has a fortuitous design all the time. This happens because the channel introduces time dispersion and symbol period is smaller than the delay spread. The fading of frequency-selective is difficult to be counterbalanced because the fading is random and can not be predicted. In models where there is not any time dispersionand the symbol period is larger than the delay spread we will have flat fading by that means that all signals will be affected equally.[8]

The systems of single carrier transmissions undergo of inter-symbol interference when the data rate of transmission is high. The idea behind multi carrier transmissions is to rise the symbol duration and for that reason these systems reduce the effect of ISI. The wireless multimedia cases need a large amount of Mbps to have a good QoS. If we use a model of single carrier high speed transmissions the delay spread will be much larger than the symbol duration of the transmission, even in the best outdoor environment.

On the other hand if we use a number of subcarriers because we divided the high data rate channel then it emerges a much larger symbol duration in the subcarriers and of course the symbol duration is larger than the delay spread.[8]

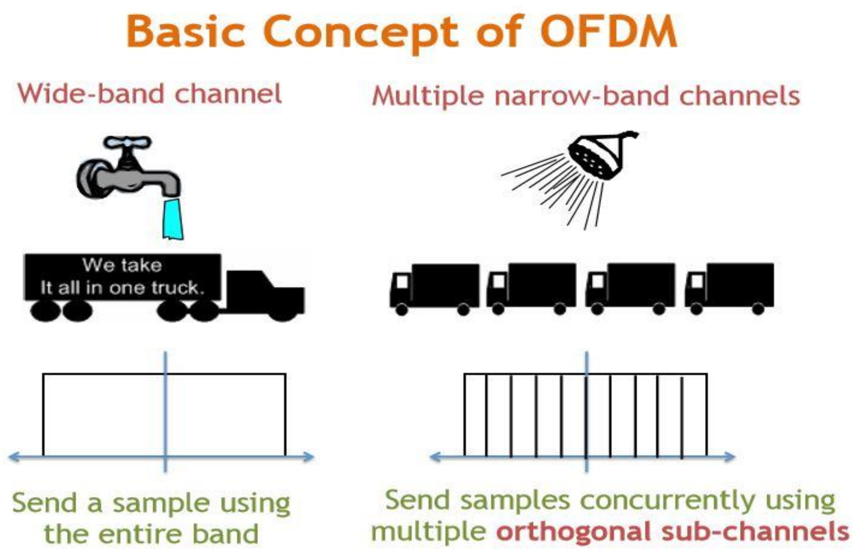


Figure 16. Basic Concept of OFDM

2.2.2 Advantages of OFDM System

Cyclic Prefix is useful is maintaining the orthogonality between the sub-carriers and this is helpful because when signal passes through a time-dispersive channel the orthogonality is in danger. Cyclic Prefix gives two advantages. First by maintaining the orthoganilty of signals it reduces the inter-carrier interference and secondly it removes the inter-symbol interference. Spectral efficiency is one field in which OFDM helps, by maintaining orthogonality between the subcarriers.

When orthogonality is ensured during subchannels in the transmission it is very convenient to divide the signals very easily at the receiver's side. In the classic solution of FDM this is guaranteed by the insert of guard bands between the subchannels but this leads in not efficient use of spectal resources.

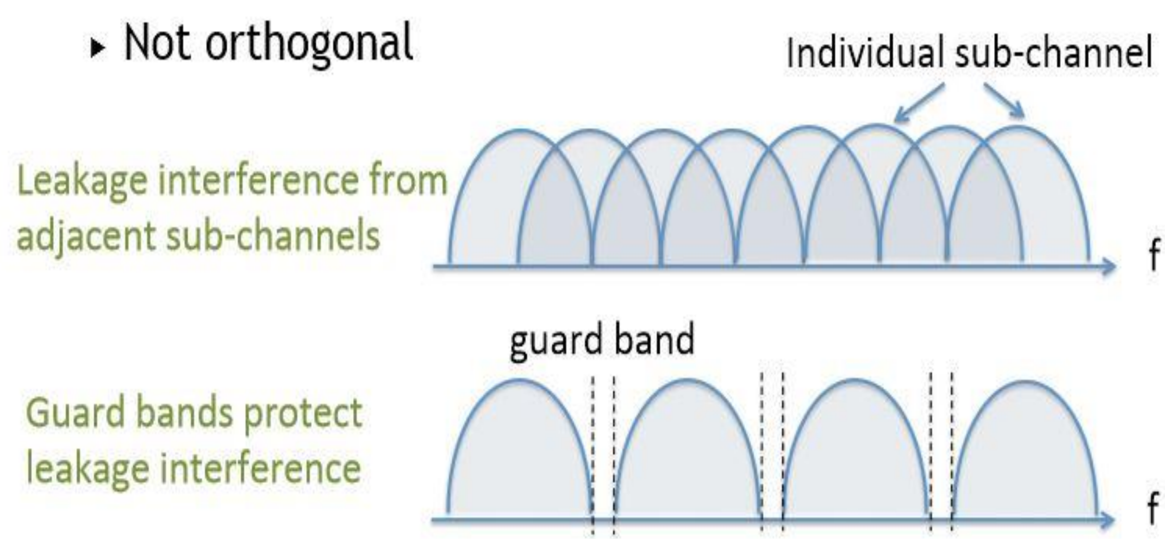


Figure 17. Sub-carriers in OFDM and FDM

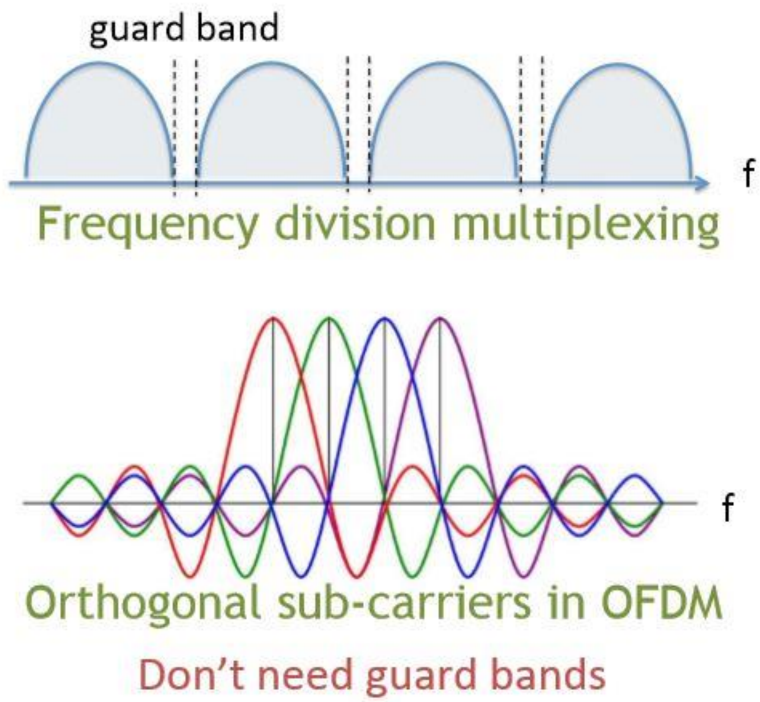


Figure 18. Sub-carriers in OFDM and FDM in terms of guard bands utilization

The orthogonality provided by OFDM gives the possibility of arranging the subcarriers in a way that the sidebands of the different carriers cross each other and the still the signals are not affected by the inter-carrier interference. Other benefits of using OFDM systems are :

- The OFDM transmitters are low cost because they have the ability to put into effect the mapping of bits to unique carriers with the use of IFFT.
- OFDM is more fading proof in frequency selective fading than the single carrier systems.
- OFDM receivers gather signal energy in frequency domain and for that reason they are able to guarantee that there will be no energy loss at the frequency domain.
- In OFDM a more simple receiver structure is more than enough to recover data from transmission because it simplifies the channel effect.

- The protection that comes from orthogonality in OFDM is way to simpler from the CDMA technique.
- OFDM gives us the possibility of using maximum probability detection with a reasonable complexity.
- OFDM can be implemented for high speed multimedia applications at a low service cost.
- It supports dynamic packet access.
- OFDM allows single frequency networks, which are popular for broadcast applications.
- OFDM can use smart antennas. OFDM can make use of all the benefits of MIMO systems.
- Adaptive modulation is possible in OFDM.
- Power allocation is also achivable in OFDM.

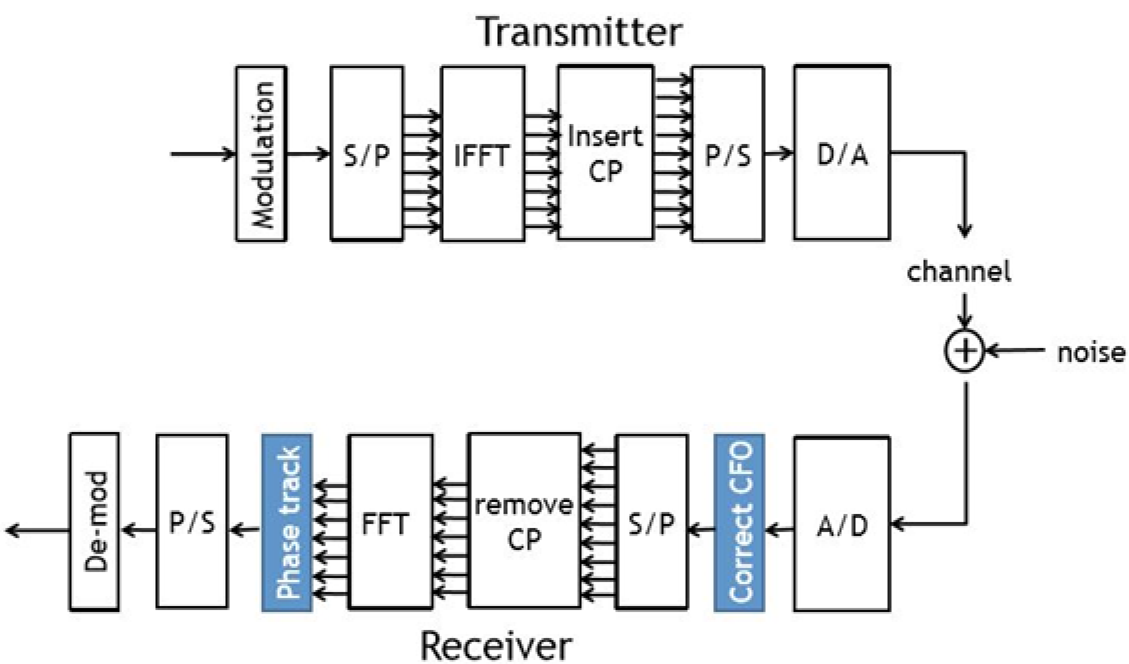


Figure 19. OFDM System Arcitecture

2.4 Orthogonal-Frequency-Division-Multiple Access (OFDMA)

OFDMA is a multi-user version of the OFDM. In OFDMA we can achieve multiple access by giving subsets of subcarriers to different users, therefore we can have concurrent low data rates transmissions for several users. It is a scheme that is used in many high data rates applications and services such as LTE and LTE-A networks. It is highly recommended for broadband wireless networks because of the advantages it has such as scalability and use of MIMO technology. The OFDMA systems are used in many implementation such as the IEEE 802.16 and IEEE 802.20 Wireless Standard, the MoCA 2.0, the downlink of the 3GPP LTE and LTE-A fourth generation networks and others. In OFDMA all the available subcarriers are divided and distributed to all the users at any time. So adaptive user to subacarrier assignment is achievable, moreover if the assignment is fast it improves the OFDM capabilities to the fast fading and co-channel interference.[8]

With these systems we can control the data rate error for a user individually and thus the QoS is better. Apart from that, OFDMA can be used as an alternative in combining OFDM and TDMA (Time Division Multiple Access). Low data rate terminals can have continuous connection using low transmisson power.

These systems have many advantages over OFDM and some of these are :

- As said before it guarantees simultaneous low data rate transmission for several users.
- It provides lower maximum transmission power for data users with low data rate.
- It provides consistent and lesser delay
- Collision avoidance is simplified with OFDMA

Some characteristics of OFDMA systems are:

- The ability to adapt deployment across several frequency bands with almost no change to the air interference.
- It provides low level of interference from nearby cells and this is achieved by using different carrier transformation between individual users in different cells.
- One more thing is that with OFDMA it is enabled the Single Frequency Network coverage where there is coverage issues.
- It allows frequency diversity by scattering the carriers all over the spectrum that is used.
- Different users can get different channel qualities, a deep faded channel for an individual user may still be favorable to others.

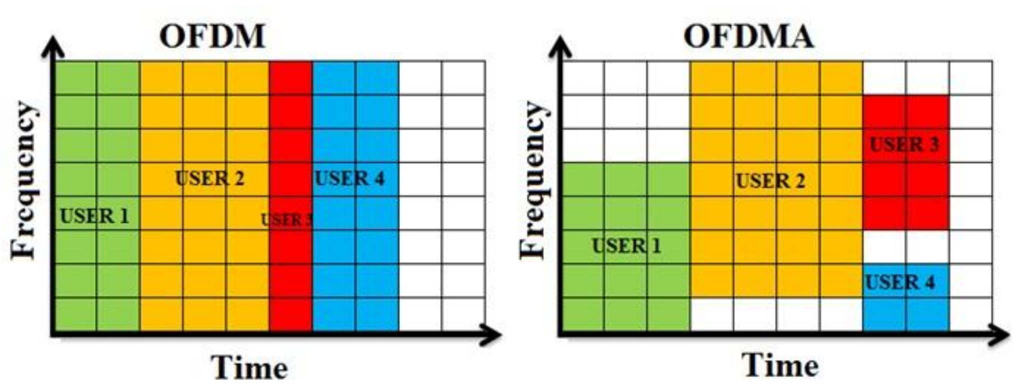


Figure 20. Resource Allocation between OFDM and OFDMA

2.5 Time-Division Duplexing (TDD)

Time-division duplexing is a procedure for imitating full duplex communication over a half duplex communication link. Specifically, it separates uplink and downlink signals by fitting together full duplex over half duplex. This method has many advantages in the cases that there are asymmetry uplink and downlink data rates. The transmitter uses the same frequency as the receiver. The trasmit and the receive traffic is changed in time. The uplink is separated from downlink by the portion of different time slots that use the same band. Time division duplexing classifies a data stream into frames and give separated time slots in order to forward and reverse transmissions. When the data in the uplink are increased, more capacity is shared. This is confiscated when the traffic load decreases.

It works by switching transmission directions over a time pause, which happens instantly and is not perceivable by the user. The Time division duplexing not only supports voice but symmetrical and non symmetrical data services as well. [7]

The downlink and uplink capacities are modified in preference of one direction over another bettet act of allocating for time through time slots to downstream transmission pauses than of these in the upstream.

Some known examples of TDD implementation are :

- IEEE 802.16 WiMAX
- TD-SCDMA 3G Mobile telephony air interface
- Universal Mobile Telecommunications System 3G supporting air interfaces
- PACTOR
- DECT Wireless Telephony

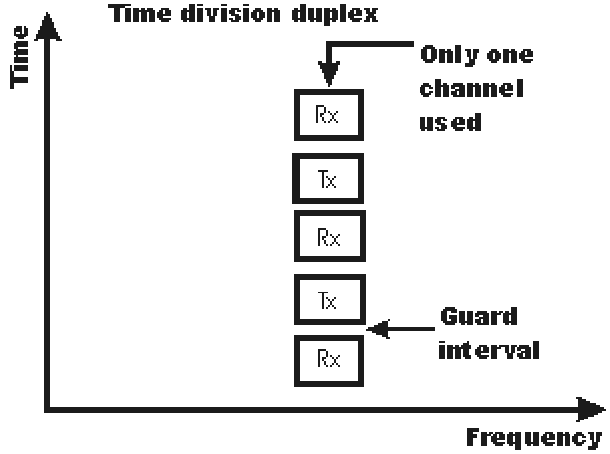


Figure 21. Time Division Duplex

The primary advantages of this technology are :

- TDD allows the use of only a single frequency for operation and drastically increases the spectrum utilization. That especially happens in not wide bandwidth and in license excluded frequency bands.
- It meets the criteria for allocation of throughput between the transmit and the receive directions. This is highly advantageous for applications with asymmetric traffic requirements such as video broadcasting.

Some disadvantages are :

- TDD models submit poor TDM performance bacause of the latency
- Many radios with the same location interfere with each other unless they are synchronized

2.6 Frequency-Division Duplexing (FDD)

In frequency-division duplexing the transmitter and the receiver work at different carrier frequencies. It is a method for creating a full-duplex communications link that uses two frequencies that

differ with each other for the transmitting and the receiving procedures. The transmitting and receiving direction are divided by a defined frequency counterbalance. For example in the mobile wireless networks one block of the spectrum is used for uplink and another block for downlink, these block carries data from the UE to the BSs and reverse.

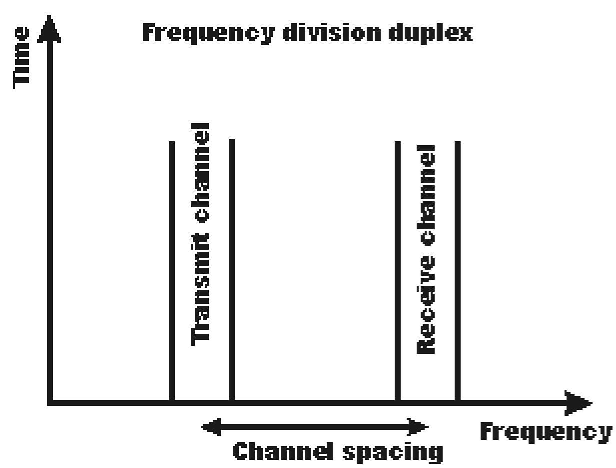


Figure 22. Frequency Division Duplex

The advantages of this technology are :

- It can provide a low latency because the transmit and receive operations are happening constantly and at the same time.
- FDD can be used in both licensed and non licensed bands.
- Full data capacity is available all the time because the transmit and receive functions are separated.
- Because of controlling restrictions the FDD radios that are used in the license bands are well organized and protected from interference

Some disadvantages are :

•It is complicated to install. The paths that are given require the availability of a pair of frequencies. If any of the two frequencies is unavailable then we can not make use in that band

•The traffic allocations, apart from a 50:50 split, between the transmitter and the receiver submit incompetent use of the two paired frequencies that way the efficiency is reduced.

PARAMETER	LTE-TDD	LTE-FDD
Paired spectrum	Does not require paired spectrum as both transmit and receive occur on the same channel	Requires paired spectrum with sufficient frequency separation to allow simultaneous transmission and reception
Hardware cost	Lower cost as no diplexer is needed to isolate the transmitter and receiver. As cost of the UEs is of major importance because of the vast numbers that are produced, this is a key aspect.	Diplexer is needed and cost is higher.
Channel reciprocity	Channel propagation is the same in both directions which enables transmit and receive to use on set of parameters	Channel characteristics different in both directions as a result of the use of different frequencies
UL / DL asymmetry	It is possible to dynamically change the UL and DL capacity ratio to match demand	UL / DL capacity determined by frequency allocation set out by the regulatory authorities. It is therefore not possible to make dynamic changes to match capacity. Regulatory changes would normally be required and capacity is normally allocated so that it is the same in either direction.
Guard period / guard band	Guard period required to ensure uplink and downlink transmissions do not clash. Large guard period will limit capacity. Larger guard period normally required if distances are increased to accommodate larger propagation times.	Guard band required to provide sufficient isolation between uplink and downlink. Large guard band does not impact capacity.
Discontinuous transmission	Discontinuous transmission is required to allow both uplink and downlink transmissions. This can degrade the performance of the RF power amplifier in the transmitter.	Continuous transmission is required.
Cross slot interference	Base stations need to be synchronised with respect to the uplink and downlink transmission times. If neighbouring base stations use different uplink and downlink assignments and share the same channel, then interference may occur between cells.	Not applicable

Figure 23. Comparison Between LTE-TDD and LTE-FDD

Chapter 3. Decoupled Uplink and Downlink

3.1 HetNets

In 10-20 years time we can be sure that the world will be a place with more base stations than cell phones. This is because network operators and cellular communications network business want to satisfy the intense consumer demand for faster data connectivity. To meet this demand the impossibility of adding more spectrum leads in seeking other ways to fulfill these consumer's applications. The chance of adding more and more macrocells (BSs) is getting tougher due to cost and the lack of available places to install the antennas. For example many neighborhood associations are not too cooperative in opening new locations for Bs deployments. The problem that operators are facing right now is not the coverage but the capacity of the network because too many subscribers need huge loads of data transportation. Here comes the solution of heterogeneous networks. [12]

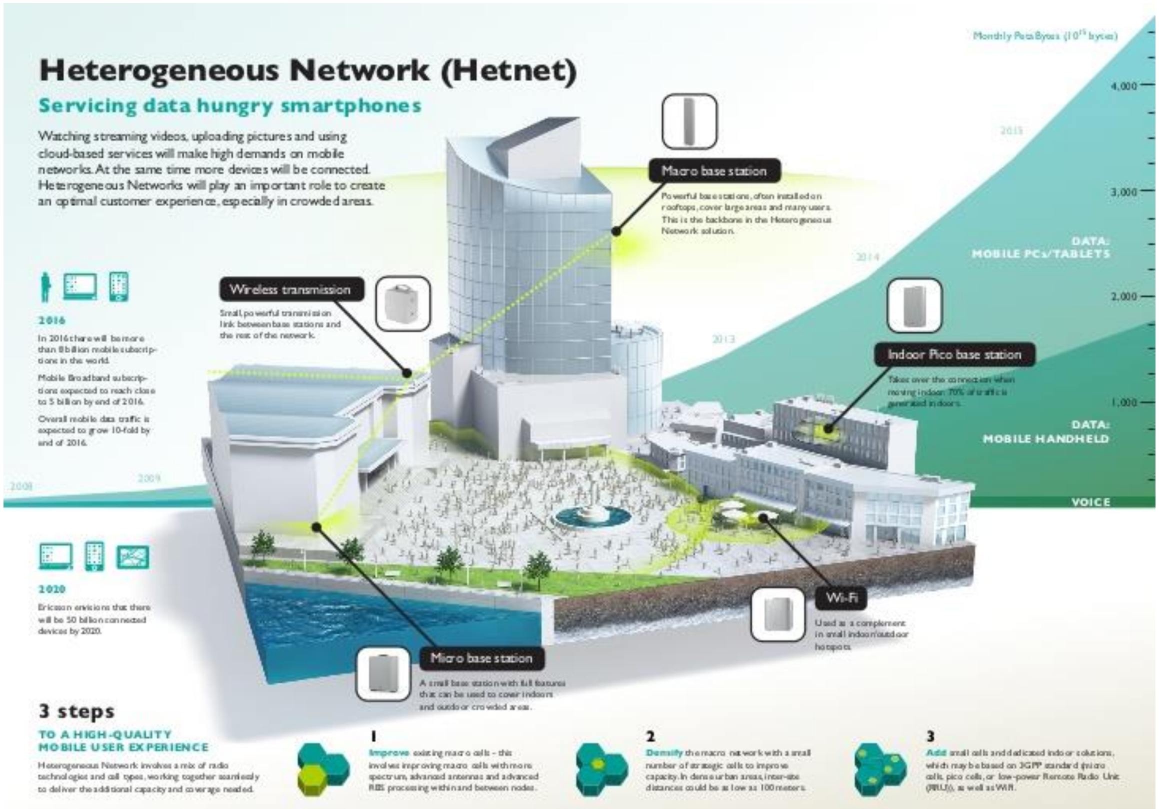


Figure 24. Heterogeneous Network Concept

A HetNet is a modern mobile communications network that can combine different cell types and different access technologies. A typical HetNet combines all the known network models and systems (GSM, UMTS and LTE, WiFi technology). We must say that a WiFi access point meet the standards and the utilization of a Base Station. It is able to accommodate requests for communication from many users in its coverage area. Secondly it provides a reliable backhaul connection to the core network and thirdly has a sustainable power source. A key feature of the HetNet approach is the flexibility in combining the position of small cells deployments such as pico, micro, femto cells.

Apart from that WiFi can play a very important role in HetNets in terms of offloading data and roaming, especially between and outdoor and an in-house environment.[12]

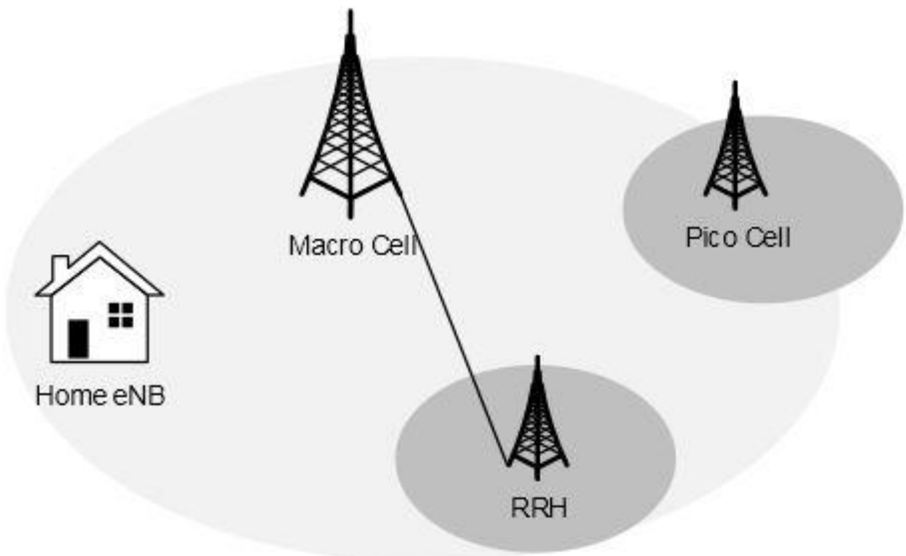


Figure 25. HetNet Concept Setup

We are going to examine ways in which the HetNets will change the way everyone is connected. The first one is the metrics that are used to rate the prformance of a network. One widespread metric is the outage probability and the spectral efficiency. Outage probability is expressed in terms of the SINR. The chance for the SINR to be below a particular value defines the outage probability. The UE most times depends not only on the SINR, load can be so important as well. In HetNets the Law of Large Numbers which is affiliated with the macro-only networks does not apply. In common networks an edge cell user has lower SINR and lower rate and. A user inside the cell has higher SINR and higher rate.

In HetNets pico, macro and femto cells will not be heavy loaded while the macro cells will be. So the data rates will be increased.

Secondly is the uplink and downlink relationship. In HetNets this relationship is different than previous macro-cells networks. [12]

DL and UL should be considered as two different networks. Therefore they will need different models of interference and throughput. For example a user that is on the macrocell edges might need to connect to a nearby pico or femto cell. This is because on the one way (ex. UL) it might have poor SINR and on the other direction not. This leads to a way better QoS.

Lastly when it comes to interference management in HetNets the coordinated multipoint (CoMP) is very important. CoMP is the idea of having neaby BSs encode (DL) and decode(UL) messages for concurrent users. With this technology users will have multiplexing gain instead of been treated as interference. Some results argue that there will be a seven-fold increase in the network throughtput with this technology.

Thirdly is the topology factor. In HetNets the topology has a clear change. The placement of Bs and their related coverage is different. Until now the BSs are spaced. Basically, they are frequently modeled as lying on a lattice, specifically a hexagonal frid. The smaller in size BSs are clustered within the coverage of the existing macrocell and create their own related regions. Small cells are not spaced in a regular way. The association regions are smaller for the downlink because of the lesser trasmit power they have. A typical macro, pico and femto trasmit powers are on the order of Pt = 40 W , 2W and 100mW.

For that reason the trasmit power of each layer of BSs separates the topology by an order of importance. It is clear that the grid-based model of the past is not scalable to a HetNet. Even though someone could create a series of overlapping grids of different densities. An example is the macro-pico model used by 3GPP in which macrocells are designed with a hexagonal grid with six picocell BSs per macrocell. Another model that could be used is a uniform distribution, which in 2D flat surface is a Poisson Model. This model means that the BSs are located in a total randomness. Even though the two models are been examined in which is better to be used in HetNets a basic difference is that of tractability. The grid model is not tractable. For example spread on rate and SINR are calculated through a system-level simulations that model near BSs as an interference. And this leads in ignoring the BSs in longest distances. [12] Small cells are added in the model and that makes the interference larger, this leads in making the simulations more complicated.

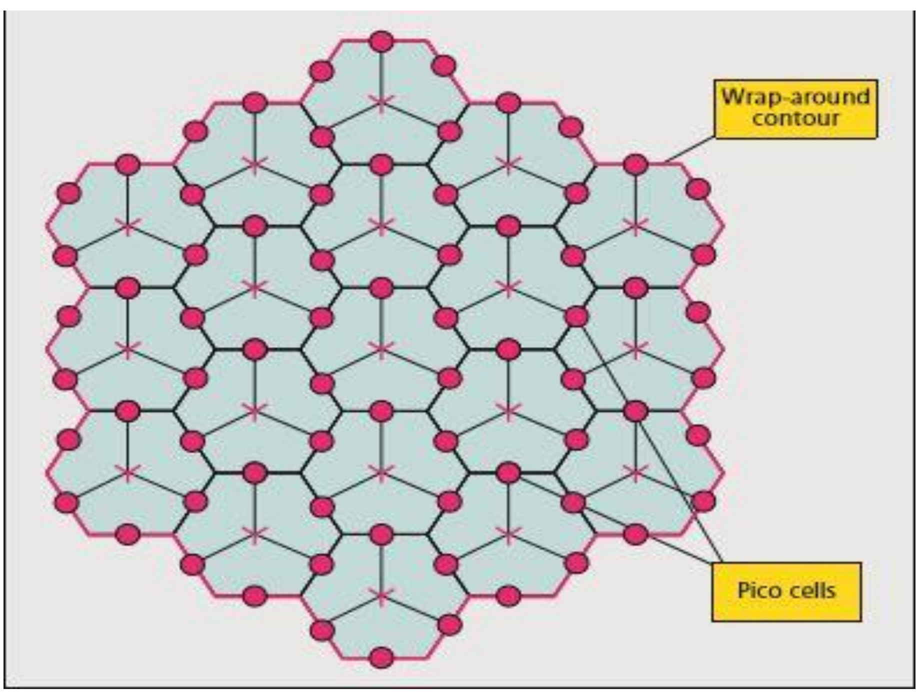


Figure 26. Grid Topology in HetNets

On the other side of the coin the poisson model is vary tractable. Because a big variety of analytical tools are obtainable from the stochastic geometry. The location independence of BSs on the poisson model makes the SINR logistics to be acquired in closed form. This could be happen in models with a large and random number of BSs too, with every BS having different densities or transmit powers. Speaking the truth the Poisson model does not place the BSs in a random way literally. There is little evidence that Poisson model not so accurate as the grid one. [12]

These two models give the same SINR distributions as of the shape. The results that differ the two models are in terms of absolute SINR. The grid model shows the best case for coverage and the Poisson one generally represents the idea that it is difficult to have worse results with so many random located BSs. Lastly we have to say that many facts have to be proven mathematically. For instance, it must be proven that in a model with a network with limited interference, the act of adding more BSs of any size can not change the downlink SINR statistics. Saying that a UE can connect to the strongest Bs, the network is loaded and has limited interference. [12]

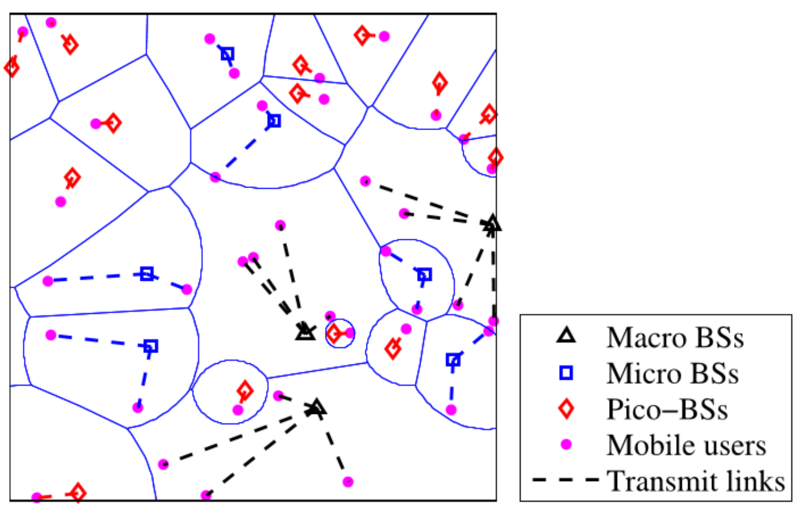


Figure 27. Poisson Topology in HetNets

This means that :

- The interference that comes from smallest BSs is balanced by the decrease of the distance to a near BS, and the increase in the perfect for the case signal strength.
- Placing BSs of any size increases the number of capacity and simultaneously because the congestion is decreased while the SINR remains unvarying.
- The power control on the downlink process is not so consequential beacause the so many power levels can be modeled of different BSs,
  which do not have a bad effect on the SINR.

3.2 Decoupled Uplink and Downlink Access in Heterogeneous Networks

Nowadays, the UEs do not only need more and more capacity but they need Quality of Service (QoS) and equal Quality of Experience (QoE) as well, in both procedures of Uplink (UL) and Downlink (DL). With the technology of today and the implementation of Internet of Things (IoT), the machine to machine services, the social medias and the cloud services, UEs and their devices are more substance oriented than they were in the past years. The not continuous QoE of users in the cell area gives push in expanding the number of eNBs by putting more cells of not so large coverage. This of course brings the network closer to the user. These changes in the deployment of the network makes provision in improving the overall capacity of the network by turn on features of superior load balancing between the cells and get rid of holes in the coverage. This new status quo in the network deployment comes with new challenges in order to guarantee good QoS and QoE simultaneously.

Some of these challenges are the interference management, the backhaul improvement and lastly one area which is the main subject of this thesis. This is the Uplink and Downlink relationship.[13]

Since the beginning of the inception of mobile telephony the two associations of the Downlink and the Uplink was coupled. The UEs had the limit to associate with the same Bs, in both the Uplink and Downlink associations. The status quo of the coupled connection has many benefits such as that the transport and physical channels were more easy to design and operate in a pure network design perspective.

One of the key features when there is a model with many BSs and the network comes closer to the UEs is to allow the user of having the flexibility to connect in the cell that suits better in the needs the user has. DUDe (Downlink & Uplink Decoupling) opens the way in that direction by allowing the users to receive and transmit from different BSs.

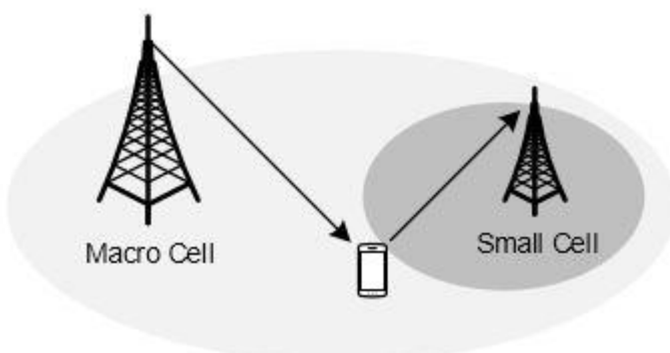


Figure 28, Uplink and Downlink Decoupling Concept

More important is that DUDe changes the constraint of cell selection that is based on the receiver power of the downlink, it gives the network with the pliability of athe association of users to various eNBs in the process of Downlink and Uplink. Therefore the DUDe method is a brand new idea that is recognized as a technique that can successfully make better the HetNet performance.

The technologies that give attention to the main HetNet challenges in the circumstances of radio planning and interference can be divided into tree groups :

- The dual connectivity. Theoritically, it verifies the UL betterments in dedicated deployments. However, it is not yet improved that this is a solution to the lack of equilibrium problem of the UL and DL.
- Cell RE with eICIC. It is verified that there are UL betterments in co channel deployments. This method leads in reducing the lack of equilibrium problem, while there is UL improvement maximization the DL inter cell interference is increased as well.
- The UL and DL decoupling. DUDe provides verified betterments in the UL process in co channel deployments. DUDe laws can meet demands of the different requirements of the two links and can solve the lack of equilibrium problem in the areas of load, interference and coverage.

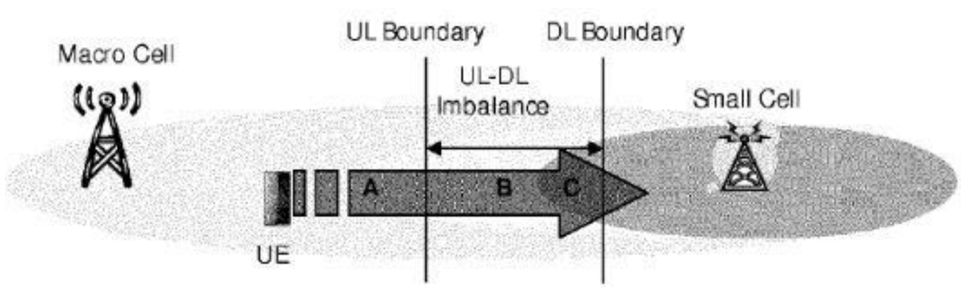


Figure 29, UL and DL Imbalance Depiction

It is clear from the above that Uplink and Downlink decoupling have the advantages of having high RE counterbalance in the Uplink without having the interference effects in the Downlink process. Because of the separation of the two links and the connection in the best serving cell. DUDe can supply important gains in the Uplink in terms of coverage, throughput, load balancing, interference and reliability. Nowadays there is an essential need of improving the Uplink performances due to the rapidly increasing expand of the IoT in which the traffic is Uplink centric and apart of that there is large growth of popularity in symmetric traffic applications such as video calls, real time video gaming and social networking.

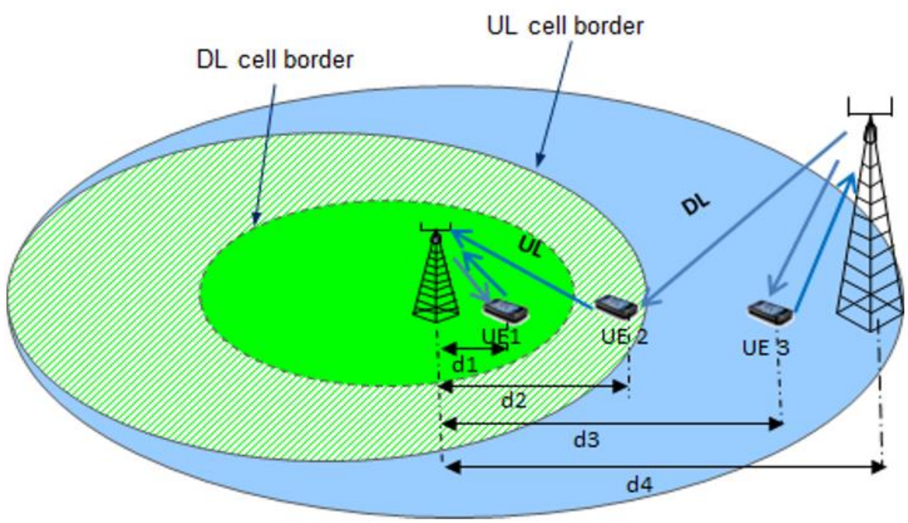


Figure 30. DUDe Cell Borders Concept

3.2.1 DUDe Duplexing

FDD and TDD can both work and cooperate with DUDe association, with different consequences from a spectrum level perspective and from a system level one.

When using TDD duplexing, it allows higher flexibility in the trading of Uplink and Downlink resources when we compare it to a FDD douplexing process. In the decoupling case we need lesser Uplink resources to have the same efficiency of Uplink rates versus a coupled case.[13]

These resources could be associated and related to the Downlink with dynamic TDD. Another advantage of TDD is the potential of calculating the downlink channel by the way of the uplink reference signals. Specifically, this is important significant for channels that have large dimensionality, such as the MIMO. When we have a DUDe implementation the Downlink and the Uplink transmissions come from and come to an end from different locations, breaking the channel mutual relationship. The spectrum that exists is paired FDD spectrum and for these two reasons the massive MIMO has to be supportes without channel reciprocity. So as a conclusion in DUDe the TDD and FDD dichotomy methods may be want a refreshing and rethinking. The hyper densification, the DUDe method, the use of higher frequencies could make use of duplexing approximations over the spatial area of interest.

3.3 Benefits of DUDe

Increased uplink SNR and reduced transmit power

In a HetNet model the macro cell Downlink coverage area is way bigger than that of a smaller Bs. This inequality can be ascribed to the differences in the transmit powers of the Downlink. Also it is attributable to the heights of the BSs and the antenna gains. On the other hand in the Uplink process all of transmitters have approximately the same maximum transmit power. As a consequence a UE that is connected to a certain macro cell for the downlink process it might need to connect to another Bs for the uplink one, in order to take advantage of the reduced path loss. The possifitive effects for this action are twofold. For users that trasmit in the maximum of their power to be connected in a closer BS gives a higher SNR. Furthermore, for a fixed target SNR, there will be trasmit power reduction via power control, because of the lessened path loss.[13]

Improved Uplink Interference Conditions

Downlink and Uplink Decoupling provides the decrease of the Uplink interference. Decoupling gives the freedom of choice for the BS association and that reduces both the interferences at the BS and at the UE. The interference in the Uplink process is a collection of different UEs that trasmit in different cells, it might be possible to trasmit on the same sector of a certain cell, as it is received by a certain BS, for example BSo.

Interference that comes from every of these users is relevant to its location that is relative to its desired BS, its distance to BS0 and the precoding weights of the uplink. On the other hand, the interference of Downlink at a certain user depends on the BSs' downlink beamforming weights, trasmit power and the distance from different BSs.

Apart from that, the scheduling, that is nearly independent, and loading in both the Downlink and Uplink leads to more randomness in the interference. Thus, average interference can differ in Downlink and Uplink associations. As a consequence DUDe which gives the freedom of choice of the desired connection with the lesser interference outperfoms a coupled association.[13]

Different load balancing in the uplink and the downlink

The loads a certain BS has in the Uplink differ from the load it has in the Downlink association. This signifies that it is not the best possible to connect the same sets of UEs with the same BSs in both of the two associations of UL and DL. Furthermore, decoupling gives the opportunity of pressing more UEs to under utilized smaller cells in the Uplink if this is possible because of the interference factor and the same apply in the Downlink as well. This leads in better speading of the UEs in the macro and smaller cells and this opens the way for a more capable resource utilization and better Uplink rates.[13]

Chapter 4. DUDe and Coupled Comparison Simulations

4.1 The Model Setup

In the previous chapter we counted the benefits of DUDe and in this chapter we are going to make simulations to prove the increased Uplink SNR and reduced trasmit power in DUDe associations. The simulations considers that there is a cell with radius of 500m with two BSs, one macrocell and one picocell. The macrocell is located at the edge of the cell and the picocell is at a distance of 380m away from the macroBS. As it is shown on the Table 1. The UEs were putted stochastically across the cell. The simulation considers that there are 80 UEs. We assume that the macro and pico BS divide the maximum transmit power equally to each user. The criterion to decide in which BS the UEs will be associated with, on Downlink and Uplink as well, was the SNR wireless link. The UEs are transmitting in the whole amount of the bandwidth.

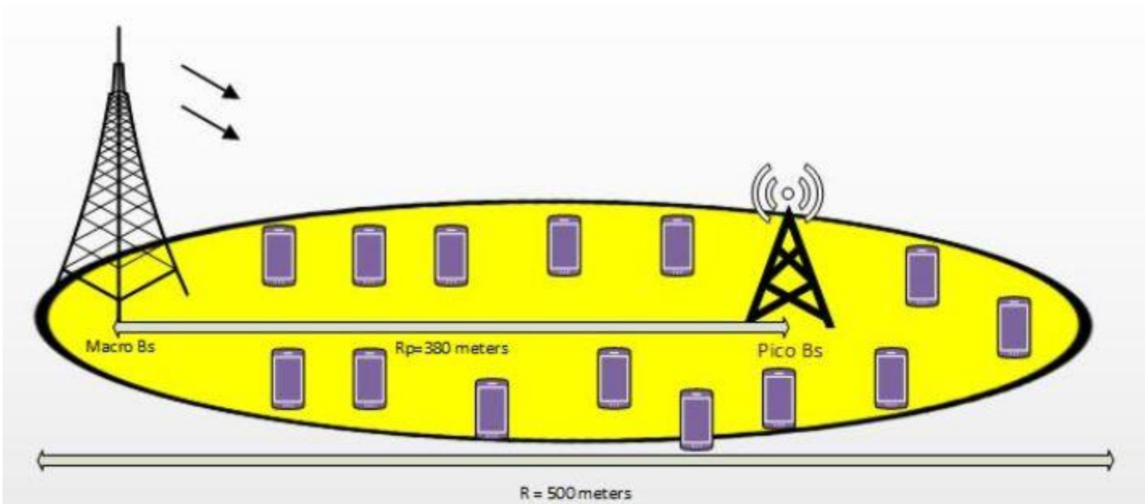


Figure 31. Model Setup

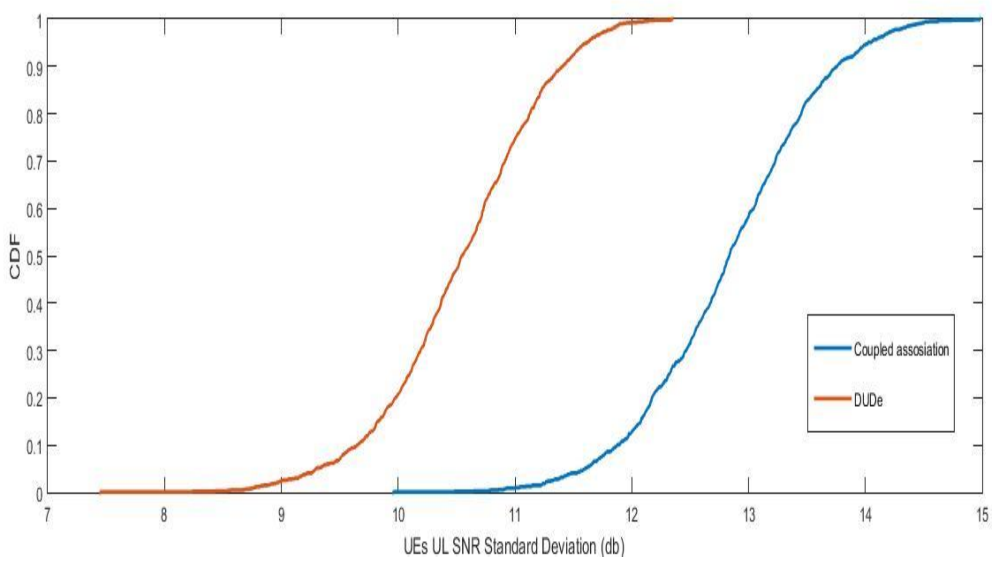
The following parameters are the the specific ones that were used in the simulation[Table1]. When it is considered that a coupled association is used the Downlink SNR assigns in which BS the communication will take place, without considering the Uplink SNR. When there is a decoupled scenario we take into account that the Uplink and Downlink are two different situations. In the simulation there is the acceptance that in Downlink we have antennas with high gains and transmit powers due to the BS heights and real life shape. In constrast, in the Uplink all of the transmitters have lower transmit power. According to that, it is possible for a UE that is associated in the Downlink with a macrocell to connect with the small cell in the Uplink to take advantage of the reduced path loss. Therefore the simulations are associated with the Uplink connection to prove the superiority of this situation (DUDe).

	UEs	Macro cell	Pico cell
Max transmit Power (dbm)	20	46	30
Antenna system gain (dbi)	0	17.8	4
Bandwidth (Mhz)	20		
Environment set up	Users: 80 Position of users: random Cell radius: 500 m Distance between macro and pico Bs: 380 m		
Noise power	$P_{noise} = -174 + 10\log(Bandwidth(hz))$		
Path loss model	Reference distance d0=100 m Path loss exponent n=3.5 Path loss on reference distance PL(d0)=110 db		
	$PL(d) = PL(d_0) + 10n\log(\frac{d}{d_0})$		
Snapshots	1000		

Table 1 Environment Parameters

4.2 Standard Deviation of SNR Simulation

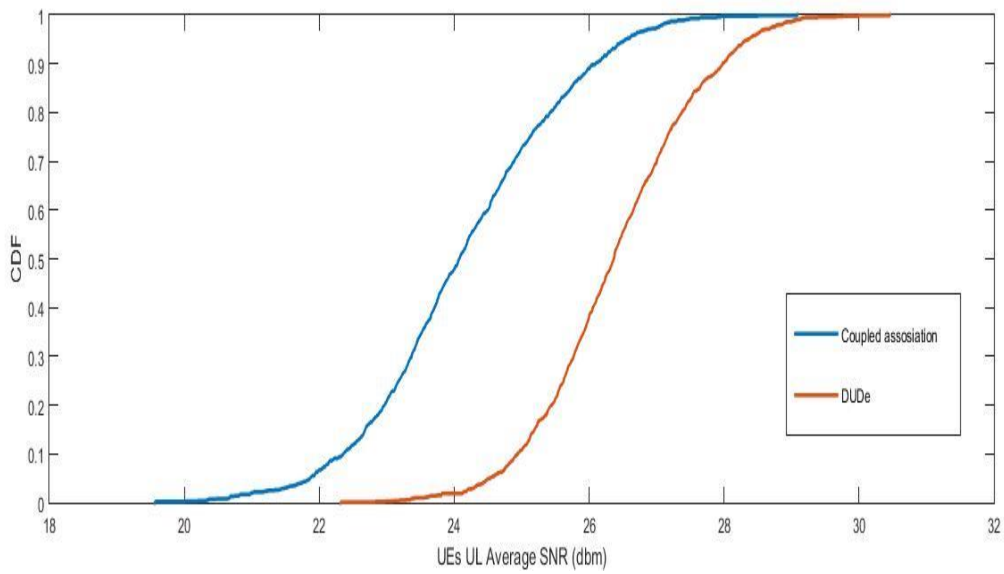
In this simulation it is calculated the SNR of each UE for 1000 snapshots and this fixes the possible SNR in each case (Coupled, DUDe). Afterwards, the Standard Deviation for every snapshot, is calculated. The CDF function for these data is featured in the diagram below.



We observe that in an environment with high deviation it is preferred to have DUDe association than a coupled one. For instance, for a standard deviation of 11db it is almost assured that there will be a DUDe scenario.For a coupled association there is nearly 2% possibility and for a DUDe one 80%.

4.3 Average SNR Simulation

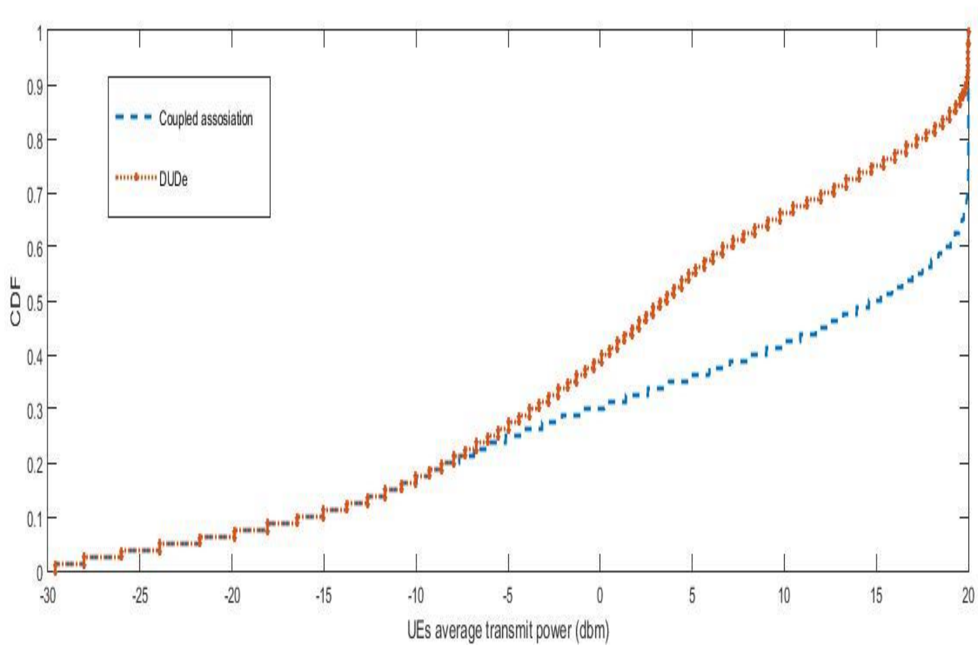
In this simulation scenario by the utilization of the same SNR from the previous case simulation, it is calculated for every of the 1000 snapshots the average SNR in the Uplink. These data will provide us with two CDF curves.



As a result we observe that the lower the SNR value is, the higher the possibility to have a coupled association scenario. Specifically, in the simulation, in values over 28dbm it is more preferred to have a decoupling association scenario. On the other hand in 26dbm the DUDe possibility is almost 40% and the coupled scenario near to 90%. This is because, in the cases with lower SNR the link is managed more efficiently by the macrocell, because of its higher antenna gain.

4.4 Transmit Power Simulation

Firstly it is calculated, for the SNR values that were calcucated before, the average value of every UE for every snapshot. These values were considered as the desired values for the SNR(target in Coupled and Decoupled). Apart from that, the power that the UE must trasmit is calcucated in order to achieve the desired SNR target. In the case that the calculated value is over 20dbm, it is assigned as **Ptransmit = 20dbm**, independently from what it is calculated.



it is orberved that when the trasmit power of the UE is increased it is likely to have DUDe association. Specifically there is a gain of 11.6 db on the DUDe scenario at 50% of CDF value. As a result we can say that DUDe scenarios need lower trasmit power to provide the same result as coupled associations.

Chapter 5. Conclusions and Future Work

5.1 Conspectus

In this thesis it was researched if a Downlink and Uplink decoupled association scenario is preferable in terms of the SNR and the transmit power of UEs. Matlab was used for all the simulations. The set up model that was described in the previous chapter was our scenario for the metrics and calculations. It was proofed in action that there can be increased Uplink SNR and reduced transmit power via DUDe associations.

5.2 Conclusions

Based on the results and on the plots we can clearly extrapolate firstly, in terms of the standard deviation of the SNR, that in an environment with high deviation it is preferred to have DUDe association than a coupled one. Secondly, for the average SNR, extrapolates that the lower the SNR value is, the possibility of having a coupled association scenario is much higher due to the higher antenna gains of the macrocell. So the higher the SNR becomes on the Uplink association the possibility of having DUDe association is higher as well. On DUDe we have higher SNR numbers and as a result higher QoS.

Lastly, we observe the gains in terms of the trasmit power of a UE in a DUDe scenario and as it turns out we can say that DUDe scenarios need lower trasmit power to provide the same result as coupled ones.

5.3 Future Work

In this thesis we proved and established some benefits that arised from the decoupled association scenarios. It will be a big challenge to prove that DUDe can further have more advantages such as improved Uplink interference conditions by calculating the standard deviation of the SINR the UEs could have. Another challenge could be to prove the different load balancing in the Uplink and Downlink as it may result in a better distribution of the UEs among the macro and the pico cells which, could lead in a more efficient resource utilization and higher Uplink rates.

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Matlab

Dude_SNR_TP.m

```
clear all
%environment parameters
BW=20; %bandwidth in MHz
NOISE=-174+10*log10(BW*1000000);
N=80; %number of users
do=100; %reference distance
PL0=110; % path loss on reference distance in db
n=3.5; %path loss exponent

R=500; %radius of macro cell in meters
hbsm=25; % height of macro BS in meters
hbsp=10; % height of pico BS in meters
Rp=380;% horizontal position of pico cell

ptmall=46;% transmit power of macro cell in dBm (for all the BW)
ptpall=30;% transmit power of pico cell in dBm (for all the BW)
ptue=20;% transmit power of user equipment in dBm (for all the BW)

ptp=ptpall-10*log10(N);% transmit power from pico cell per user in dBm
ptm=ptmall-10*log10(N);% transmit power from macro cell per user in dBm

Gm=17.8; %macro base station antenna gain in dBi
Gp=4; %pico base station antenna gain in dBi
Gue=0; %user equipment antenna gain in dBi

% generate random horizontal positions for users
snap=1000; %number of snapshots

x=randi(R,snap,N);

for i=1:snap
    for j=1:N
        %macro cell
        dm(i,j)=sqrt(x(i,j)^2+hbsm^2);% distance of user and macro cell
        PLm(i,j)=PL0+10*n*log10(dm(i,j)/do);%path loss between macro
cell and user
        %pico cell
        dp(i,j)=sqrt((abs(Rp-x(i,j)))^2+hbsp^2);% distance of user and
pico cell
        PLp(i,j)=PL0+10*n*log10(dp(i,j)/do);%path loss between pico
cell and user
    end
end
```

```
%uplink
for i=1:snap
    for j=1:N
        prm(i,j)=ptue+Gm+Gue-PLm(i,j);% received power from macro cell
for fixed transmit power
        SNRmU(i,j)=prm(i,j)-NOISE;
        prp(i,j)=ptue+Gp+Gue-PLp(i,j); %power received from picocell
for fixed transmit power
        SNRpU(i,j)=prp(i,j)-NOISE;
    end
end

%downlink
for i=1:snap
    for j=1:N
        pruem(i,j)=ptm+Gm+Gue-PLm(i,j);% received power from macro cell
        SNRuemD(i,j)=pruem(i,j)-NOISE;
        pruep(i,j)=ptp+Gp+Gue-PLp(i,j); %power received from picocell
        SNRuepD(i,j)=pruep(i,j)-NOISE;
    end
end



%coupled for fixed transmit power
for i=1:snap
    for j=1:N
        if SNRuemD(i,j)>=SNRuepD(i,j)
            SNRcoupledU(i,j)=SNRmU(i,j);
        else
            SNRcoupledU(i,j)=SNRpU(i,j);
        end
    end
end

%decoupled uplink
for i=1:snap
    for j=1:N
        if SNRmU(i,j)>=SNRpU(i,j)
           SNRdecoupledU(i,j)=SNRmU(i,j);
        else
           SNRdecoupledU(i,j)=SNRpU(i,j);
        end
    end
end
%plot of cdf for standar deviation
SNRdevcoupledU=std(SNRcoupledU,0,2);
SNRdevdecoupledU=std(SNRdecoupledU,0,2);
figure(1)
cdfplot(SNRdevcoupledU)
hold
cdfplot(SNRdevdecoupledU)
%plot of cdf for mean snr
for i=1:snap
    SNRcoupledUmean(i)=mean(sort(SNRcoupledU(i,:)),2);
    SNRdecoupledUmean(i)=mean(sort(SNRdecoupledU(i,:)),2);
```

```
end
figure(2)
cdfplot(SNRcoupledUmean)
hold
cdfplot(SNRdecoupledUmean)

% transmit power of UE when a targetsnr is required
SNRtargetmU=(sum(sum(SNRmU),2))/(snap*N);
SNRtargetpU=(sum(sum(SNRpU),2))/(snap*N);
%macro cell
for i=1:snap
    for j=1:N
        %macro cell
        pttargetUm(i,j)=SNRtargetmU+NOISE+PLm(i,j)-Gue-Gm;
        %pico cell
        pttargetUp(i,j)=SNRtargetpU+NOISE+PLp(i,j)-Gue-Gm;
    end
end

%coupled transmit power for specific snr
for i=1:snap
    for j=1:N
        if SNRuemD(i,j)>=SNRuepD(i,j)
            if pttargetUm(i,j)<=20
            pttargetUcoupled(i,j)=pttargetUm(i,j);
            else
               pttargetUcoupled(i,j)=20;
            end
        else
            if pttargetUp(i,j)<=20
            pttargetUcoupled(i,j)=pttargetUp(i,j);
            else
                pttargetUcoupled(i,j)=20;
            end
        end
    end
end
% decoupled transmit power for specific snr
for i=1:snap
    for j=1:N
        if SNRmU(i,j)>=SNRpU(i,j)
            if pttargetUm(i,j)<=20
           pttargetUdecoupled(i,j)=pttargetUm(i,j);
            else
                pttargetUdecoupled(i,j)=20;
            end
        else
            if pttargetUp(i,j)<=20
           pttargetUdecoupled(i,j)=pttargetUp(i,j);
            else
                pttargetUdecoupled(i,j)=20;
            end
        end
    end
end
```

```
  pttargetUcoupledsorted=sort(pttargetUcoupled,2);
  pttargetUdecoupledsorted=sort(pttargetUdecoupled,2);

figure(3)
cdfplot(mean(pttargetUcoupledsorted))
hold
cdfplot(mean(pttargetUdecoupledsorted))
```

Glossary

3 GPP	(3^{RD} Generation Partnership Project)
ADSL	(Asymmetric Digital Subscriber Line)
AMTS	(Advance Mobile Telephone Systems)
BS	(Base Station)
CCD	(Cyclic Delay Diversity)
CDF	(Cumulative Distribution Function)
CDMA	(Code Division Multiple Access)
CoMP	(Coordinated Multipoint)
CP	(Cyclic Prefix)
CQI	(Channel Quality Indicator)
D2D	(Device-to-Device)
DCH	(Dedicated Channel)
DFT	(Discrete Fourier Transform)
DL	(Downlink)
DSCH	(Downlink Shared Channel)
DUDe	(Downlink & Uplink Decoupling)
EDGE	(Enhanced Data Rates for GSM Evolution)
FDD	(Frequency Division Duplexing)
FFR	(Fractional Frequency Reuse)
GPRS	(General Packet Radio Service)
GSM	(Global System for Mobile Communication)
Het Net	(Heterogeneous Network)

HS-DSCH	(High Speed Downlink Shared Channel)
HSDPA	(High Speed Downlink Packet Access)
ICI	(Inter Carrier Interference)
ICIC	(Inter Cell Interference Coordination)
IEEE	(Institute of Electrical and Electronics Engineers)
IMTA	(Inter Mobile Telecommunications Advanced)
IMTS	(Improved Mobile Telephone Service)
ITU	(International Telecommunications Union)
LTE	(Long Term Evolution)
MAC	(Media Access Control)
MBWA	(Mobile Broadband Wireless Access)
MIMO	(Multiple In Multiple Output)
MMS	(Multimedia Messages Service)
MoCA	(Multimedia Over Coax Alliance)
MTS	(Mobile Telephone Systems)
NTT	(Nippon Telegraph and Telephone)
OBH	(Organized Beam Hopping)
OFDM	(Orthogonal Frequency Division Multiplexing)
OFDMA	(Orthogonal Frequency Division Multiple Access)
PTT	(Push to Talk)
QoS	(Quality of Service)
RAT	(Radio Access Technologies)
RB	(Resource Block)
SFBS	(Space Frequency Block Coding)
SINR	(Signal to Interference and Noise Ratio)

SMS	(Short Message Service)
SNR	(Signal to Noise Ratio)
TDD	(Time Division Duplexing)
TDMA	(Time Division Multiple Access)
UE	(User Equipment)
UL	(Uplink)
UMTS	(Universal Mobile Telecommunications System)
VDSL	(Very High-Bit-Rate Digital Subscriber Line)
WAP	(Wireless Application Protocol)
WiMAX	(Worldwide Interoperability for Microwave Access)
WLAN	(Wireless Local Area Network)