Chapter 1

Introduction

Every new generation of cellular network technologies comes with a new set of requirements, dictated by the trends in the use of the mobile connectivity. A common requirement to every single generation is their striving for higher data rates and greater power efficiency. This motivates research and techology innovation in order to achieve the goals set for each generation.

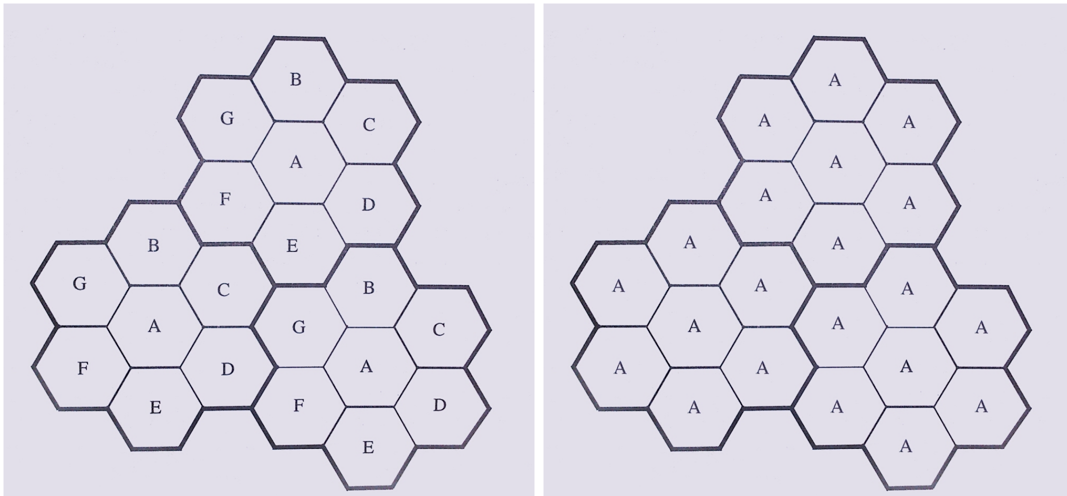
The research associated usually requires revisiting old paradigms used in previous generations, and updating them with novel ideas.

The *release 7* of the 3^{rd} Generation Partnership Project (3GPP) 3^{rd} Generation of Mobile Communications (3G) specifications [1], also known as High-Speed Packet Access Plus (HSPA+), inluded the use of Multiple Input Multiple Output (MIMO) as a means to increase the rates of transmission.

Release 8, more well known by its commercial name Long Term Evolution (LTE) [2], introduced a new physical layer, based on Orthogonal Frequency Division Multiplexing (OFDM) instead of Wide-band Code Division Multiple Access (WCDMA) as in 3G. Although the rates attainable with WCDMA may be comparable to those obtained with OFDM, the latter provides a much easier equalization mechanism that makes dealing with multipath channels a simpler task. Apart from that OFDM provides a higher flexibility in the resource allocation and user and enables the use of Orthogonal Frequency Division Multiple Access (OFDMA).

LTE did not meet the requirements issued by the International Telecommunication Union Radiocommunication Sector (ITU-R) International Mobile Telecommunications-Advanced (IMT-Advanced) radio interface [3] for what is known as 4^{th} Generation of Mobile Communications (4G) though.

The introduction of Long Term Evolution Advanced (LTE-A) in *release 10* of the LTE specification [4] met the requirements to be considered an IMT-Advanced system. The main novelties included in LTE-A are Carrier Aggregation (CA), enhanced use of MIMO techniques and support for Relay Node (RN).



(a) Frequency reuse factor of 1/7. (b) Frequency reuse factor of 1.

Figure 1.1: Different frequency planning options

Release 11 [5] included in the specification the support for Coordinated Multi Point (CoMP) operation. CoMP was included in order to improve the network performance at cell edges, for it uses several transmitters to provide coordinated transmission in the downlink, and a number of receivers to provide coordinated reception in the uplink.

With LTE-A standardized and its deployment already ongoing, further releases of LTE-A still continue but standards bodies and industry are already looking ahead at the future 5^{th} Generation of Mobile Communications (5G), and so is doing the research world. Even though there is no definite idea about what 5G will be, it is clear what it will *not* be, an incremental advance on 4G. It needs to be a paradigm shift [6].

The new 5G systems will be characterized by being heterogeneous, what is known as Heterogeneous Networks (HetNet), formed by multiple small cells, using different radio access technologies [7]. One of the main problems for HetNet is inter-cell interference, because of the possible presence of unplanned deployment of small cells, and the irregular shape of the cells. Hence the importance of interference coordination techniques.

Current MIMO systems used in cellular networks are not achieving the expected performance predicted by the initial theoretical works. The main reason for this is the interference that is present naturally in cellular systems when all cells share the same spectrum for the tranmissions. The effect of this interference is a reduction of the Signal to Interference plus Noise Ratio (SINR) experience by the users, highly reducing the advantages that MIMO could potentially deliver.

The conventional approach for cellular networks was to perform a careful frequency planning in order to avoid the interference among neighboring cells. Clusters of N cells were grouped together, and assigned N frequency bands to be used, and the pattern is repeated for different clusters, yielding what is called a *frequency reuse factor* of $1/N$, as exemplified in Figure 1.1a.

The problem that this poses is that the available spectrum must be split, which is an inherent inefficiency in the use of the resources.

A different option consists on a system where all the cells share a common spectrum, so that all of them can use the full amount of resources available. This is called Universal Frequency Reuse (UFR), and a graphical description can be seen in Figure 1.1b.

It is in this kind of networks that the need for coordination among cells arises, as every cell will interfere with the rest of the cells in the system reducing the SINR operating point of the users.

In the search for higher spectral data rates and a more efficient use of the resources, UFR is a must to make the most out of the scarce resource that the radio frequency spectrum is. Therefore, “A new look at the interference” [8] is needed. The conventional concept of the interference as being an impairment needs to shift to a new point of view where the interference can be used to improve the overall performance of the network. A joint optimization of the resources among all the cells is required in order to globally improve the perfomance of the system [9].

The CoMP operation considered in [5] is just a part of a much broader field of multicell cooperation or coordinated communications where several cells are assumed to cooperate, in the sense that they take measures in order to alleviate to a certain degree the level of interference introduced into other parts of the network, or the use of that interference to their advantage.

Intuitively, the best strategy should be to allow all the Base Station (BS) in the network to cooperate, what is known as *global Coordination*. Even though it may seem that global coordination may solve all the problems of frequency planning and resource allocation, it cannot be ignored that it comes at a non-negligible cost. The BS in the network may need to interchange information in order to cooperatively transmit the information to all the users in the system. The amount of information that needs to be exchanged grows out of control with the size of the network, i.e., the number of BS that form the system. The result of this is that the capacity required to transmit this information renders the alleged solution useless. Not only are the backhaul transmission capabilities required prohibitive, but also tight synchronization among the BS becomes a challenge, and channel information gathering becomes a cumbersome task. Apart from this, theoretical works [10] have unveiled intrinsic limitations of cooperation, whose benefits do not unboundedly grow with the size of the coordination group.

For all these reasons, clustering appears as a means to cope with the limitations of global coordination. In clustering, the coordination is not performed among all the BS in the network but, instead, small groups, or clusters, are formed and the cooperation takes place locally within the cluster. This greatly reduces the amount of control information that should be handled by the backhaul. Also, the reduced size of the group makes the system work at an operating point where the natural limitations mentioned in [10] do not affect the performance of the network.

A schematic representation of a clustered network can be seen in Figure 1.2 where three

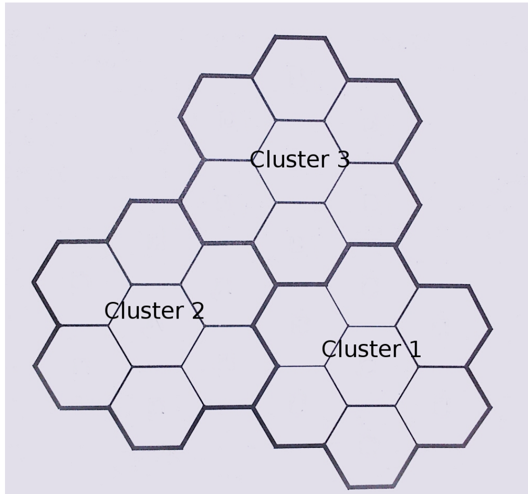


Figure 1.2: Clustered network scenario.

clusters of seven cells are shown.

Grouping the cells in reduced size clusters has an important drawback: If the cooperation is done within a cluster and neighboring clusters are not coordinated in any way, there would be, again, unhandled interference, albeit not the same as in the uncoordinated scenario.

This thesis focuses on a clustered cellular network where Block Diagonalization (BD) is used for coordination within each cluster. The performance of the network, in terms of achievable rate and fairness considerations, is analyzed and its dependence on several parameters of the network is studied. Also, mechanisms to deal with the interference, resulting from clustering, are presented.

The organization of the document is as follows:

- In `\refc{ch:state_art}` a compilation of different alternatives for coordination, as well as for clustering, found in the literature are presented and described.
- `\refc{ch:system_model}` presents the system model used throughout the dissertation, and describes in detail BD and the power allocation strategies used in the rest of the work.
- `\refc{ch:achiev_rates}` analyzes the performance of a cellular network, in terms of the mean achievable rate as a function of the cluster size, when using BD for coordination within each cluster, and taking into account the interference due to external clusters. An analytical expression for the mean achievable rate is developed and the optimum cluster size is obtained.
- `\refc{ch:rate_statistics}` considers the fairness of the system, and studies the variability of the rate, as a complement to the mean obtained in `\refc{ch:achiev_rates}`. The behavior of the rates is shown to follow almost exactly a Gamma distribution.

- The pernicious effect of the Other Cluster Interference (OCI) in the rates is introduced in \refc{ch:adaptive_schedule}, and a mechanism to deal with it, based on a mixed tranmission strategy and on a scheduling algorithm, is presented.

- Finally, some conclusions are discussed in \refc{ch:conclusions}, and future research topis are discussed.

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