4G++: Advanced Performance Boosting Techniques in 4th Generation Wireless Systems

A National Telecommunication Regulatory Authority Funded Project

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Work Package 4

Inter-Cell Interference Coordination

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Abstract

This document provides an overview of the inter-cell interference management in LTE/LTE-A as tackled in the 4G++ project work package 4. The 4G++ project addresses two areas: Inter-cell interference coordination schemes and in particular autonomous schemes for uplink interference management, interference alignment techniques and its application in wireless cellular systems, and interference management and deployment issues heterogeneous wireless networks consisting of macro, pico, and femto-cells.

List of Abbreviations

<table>
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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ABSF</td>
<td>Almost Blank SubFrame</td>
</tr>
<tr>
<td>BC</td>
<td>Broadcast Channel</td>
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<tr>
<td>BF-IA</td>
<td>Optimized Beamforming Interference Alignment</td>
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<tr>
<td>CCH</td>
<td>Control Channel</td>
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<tr>
<td>CCI</td>
<td>Co-Channel Interference</td>
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<td>CCU</td>
<td>Cell-Center</td>
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<td>CEU</td>
<td>Cell-Edge Users</td>
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<td>CQI</td>
<td>Channel Quality Indicators</td>
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<td>CRS</td>
<td>Common Reference Signal</td>
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<td>CSG</td>
<td>Closed Subscriber Group</td>
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<tr>
<td>CSI</td>
<td>Channel State Information</td>
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<tr>
<td>CSIR</td>
<td>Channel State Information at Receiver</td>
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<tr>
<td>CSIT</td>
<td>Channel State Information at Transmitter</td>
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<tr>
<td>DL</td>
<td>Downlink</td>
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<tr>
<td>DoF</td>
<td>Degrees of Freedom</td>
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<tr>
<td>eICIC</td>
<td>Enhanced Inter-Cell Interference Coordination</td>
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<tr>
<td>eNB</td>
<td>Enhanced Node B</td>
</tr>
<tr>
<td>EUTRA</td>
<td>Evolved Universal Terrestrial Radio Access</td>
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<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
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<tr>
<td>FFR</td>
<td>Fractional Frequency Reuse</td>
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<tr>
<td>FFR-FI</td>
<td>Fractional Frequency Reuse – Full Isolation</td>
</tr>
<tr>
<td>FRF</td>
<td>Frequency Reuse Factor</td>
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<tr>
<td>GIA</td>
<td>Group Based Interference Alignment</td>
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<tr>
<td>HeNB</td>
<td>Home eNodeB</td>
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<tr>
<td>HetNet</td>
<td>Heterogeneous Network</td>
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<tr>
<td>HUE</td>
<td>Home User Equipment</td>
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<tr>
<td>IA</td>
<td>Interference Alignment</td>
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<tr>
<td>IC</td>
<td>Interference Channel</td>
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<tr>
<td>ICI</td>
<td>Inter-Cell Interference</td>
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<td>ICIC</td>
<td>Inter-Cell Interference Coordination</td>
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<tr>
<td>IFR</td>
<td>Incremental Frequency Reuse</td>
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<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
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<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>LTE-Adv</td>
<td>Long Term Evolution -Advanced</td>
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<tr>
<td>MBMS</td>
<td>Multimedia Broadcast/Multicast Service</td>
</tr>
<tr>
<td>MBSF</td>
<td>Multicast Broadcast Single Frequency Network SubFrame</td>
</tr>
<tr>
<td>MBSFN</td>
<td>Multicast Broadcast Single Frequency Network</td>
</tr>
<tr>
<td>MeNB</td>
<td>Macro-cell eNodeB</td>
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<tr>
<td>MIB</td>
<td>Master Information Block</td>
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<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
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<tr>
<td>MISO</td>
<td>Multiple Input Single Output</td>
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<tr>
<td>MMSE</td>
<td>Minimum Mean Square Error</td>
</tr>
<tr>
<td>MSE</td>
<td>Mean Square Error</td>
</tr>
<tr>
<td>MUE</td>
<td>Macro-cell User Equipment</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency-Division Multiple Access</td>
</tr>
<tr>
<td>PBCH</td>
<td>Physical Broadcast Channel</td>
</tr>
<tr>
<td>PCFICH</td>
<td>Physical Control Format Indicator Channel</td>
</tr>
<tr>
<td>PDCCH</td>
<td>Physical Downlink Control Channel</td>
</tr>
<tr>
<td>PDSCH</td>
<td>Physical Downlink Shared Channel</td>
</tr>
<tr>
<td>PFR</td>
<td>Partial Frequency Reuse</td>
</tr>
<tr>
<td>P-RNTI</td>
<td>Paging Radio Network Temporary Identifier</td>
</tr>
<tr>
<td>PSS</td>
<td>Primary Synchronization Signal</td>
</tr>
<tr>
<td>PUE</td>
<td>Pico User Equipment</td>
</tr>
<tr>
<td>RB</td>
<td>Resource Block</td>
</tr>
<tr>
<td>RS</td>
<td>Reference Signal/Symbol</td>
</tr>
<tr>
<td>SFFR</td>
<td>Soft Fractional Frequency Reuse</td>
</tr>
<tr>
<td>SFN</td>
<td>System Frame Number</td>
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<tr>
<td>SFR</td>
<td>Soft Frequency Reuse</td>
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<tr>
<td>SIA</td>
<td>Successive Interference Alignment</td>
</tr>
<tr>
<td>SIB</td>
<td>System Information Block</td>
</tr>
<tr>
<td>SIMO</td>
<td>Single Input Multiple Output</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal-to-Interference plus Noise Ratio</td>
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<tr>
<td>SIR</td>
<td>Signal to Interference Ratio</td>
</tr>
<tr>
<td>SI-RNTI</td>
<td>System Information Radio Network Temporary Identifier</td>
</tr>
<tr>
<td>SISO</td>
<td>Single Input Single Output</td>
</tr>
<tr>
<td>SLR</td>
<td>Signal-to-Leakage Ratio</td>
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<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>SSS</td>
<td>Secondary Synchronization Signal</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TP</td>
<td>Throughput</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UL</td>
<td>Upload OR Uplink (depending on context)</td>
</tr>
<tr>
<td>UT</td>
<td>User Terminal</td>
</tr>
<tr>
<td>ZF</td>
<td>Zero Forcing</td>
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1 Introduction

This work package tackles the area of Inter-cell interference coordination. One of the most important performance-limiting factors in 4G future wireless systems, which limits the achievable data rates, is interference whether intra- or inter-cell. While intra-cell interference can be easily mitigated through the use of orthogonal resources (such as frequencies (in OFDM) or codes (in CDMA)), decreasing the inter-cell interference remains a difficult task that needs to be addressed.

LTE allows for the total available spectrum to be in each cell (frequency reuse factor =1). This is possible since LTE provides intra-cell orthogonality between users in both uplink and downlink. Interference is mainly dominated by inter-cell interference due to users in neighbouring cells using the same radio resources. Reducing this interference should result in significant enhancement in the achievable data rates particularly at the cell-edge. It is possible to allocate part of the bandwidth specifically to cell edge regions through a frequency planning scheme with a reuse factor larger than 1. However, the gains due to less interference are typically larger than the loss due to reduced bandwidth.

The 3GPP LTE standard suggests a different approach for inter-cell interference handling termed Inter-Cell Interference Coordination (ICIC). ICIC provides tools for dynamic inter-cell-interference coordination of the scheduling in neighbouring cells such that cell-edge users in different cells are preferably scheduled in complementary parts of the spectrum when required.

The goal of the first task in this work package is to analyse autonomous ICIC based on limiting interference to neighbouring cells. The second task tackles the challenging area of interference alignment (IA) in wireless systems where we handle both theoretical and practical issues related to IA. The third task focuses on challenges related to femtocell and more generally heterogeneous networks. We tackle a variety of techniques in interference management and handover management related to femtocells within a self-organizing network setup.

This report is comprised of the following parts:

- An extended survey of ICIC in LTE/LTE-A Systems
- Formulation of the Autonomous Uplink Interference Coordination
- An extended survey of Interference Alignment in Wireless Systems
- Enhanced Inter-cell Interference Coordination in LTE-based Heterogeneous Wireless Systems
- Femtocells in LTE/LTE-Advanced: Issues and Future Directions
2 Inter-Cell Interference in LTE and LTE-Advanced: A Survey

In 3GPP LTE systems, downlink makes use of Orthogonal Frequency Division Multiple Access (OFDMA). By orthogonal allocation of the OFDMA sub-carriers, intra-cell interference can be avoided. However, inter-cell interference (ICI) presents a great challenge that limits the system performance, especially for users located at the cell edge. Inter-cell interference coordination (ICIC) has been investigated as key technology to alleviate the impact of interference in LTE systems to improve system performance and increase bit rates at the cell edge. Several ICIC techniques have been proposed in the literature. Some of these techniques can be useful under particular network conditions and requirements. Generally speaking, ICIC techniques can be classified into mitigation and avoidance techniques.

In interference mitigation, techniques are employed to reduce the impact of interference during the transmission or after the reception of the signal. Examples of these techniques include: (1) Interference randomization, where some cell-specific scrambling, interleaving, or frequency-hopping (spread spectrum) can be used to reduce interference, (2) interference cancellation: where the interference signals are detected and subtracted from the desired received signal, or if multiple antenna system is employed, the receiver can select the best quality signal among the various received signals, (3) adaptive beamforming: where the antenna can dynamically change its radiation pattern depending on the interference levels.

Interference avoidance techniques, on the other hand, controls the allocation of the various resources (time/frequency and/or power) to users with the objective of increasing the SINR (and thus, the throughput) experienced by the users at the cell edge, and to ensure that the ICI remains within acceptable limits. Various avoidance (allocation) techniques have been studied in the literature under various traffic conditions and/or network structures. Techniques under this category can be classified along several orthogonal dimensions to differentiate mainly between static vs. dynamic and central vs. distributed techniques. Moreover, techniques under this category also differ with respect to the resources that are being allocated/ coordinated between users, and whether various power levels need to be used at different locations in the cell.

This report studies the inter-cell interference avoidance in downlink. The common theme of Inter-cell interference coordination/avoidance is to apply restrictions to the usage of downlink resources e.g. time/frequency resources and/or transmit power resources. Such coordination of restrictions will provide an opportunity to effect on interference generation in the cellular network area. It thus has potential to improve the signal to interference ratio (SIR) experienced at the receivers in the coverage area, this will provide potential for increased (cell-edge) data-rates over the coverage area, or increased coverage for given data-rates. As the coordination of restrictions applies between different cells of the same site and cells of different sites, the impact is expected to be the largest at the cell edges and cell borders, which are the most critical for the 95% coverage target set for the LTE evaluation.

The report is organized as follows. Section 2.1 summarizes various techniques used for interference mitigation. Basic concepts of interference avoidance are reviewed in Section 2.2. In Section 2.3, frequency reuse-based and are discussed. In addition, a new parameterized classification for frequency reuse-based schemes is presented in section 2.4. Section 2.5 discusses cell coordination-based interference avoidance techniques. Summary is given in Section 7.

2.1 Interference Mitigation

In any cellular mobile communication system, two major classes of interference must be considered, namely: intra-cell interference, and inter-cell interference. In the former, interference is caused between frequency channels, within the same cell, due to adjacency of both frequencies and power leaked from one channel to an adjacent channel. In the latter, interference is caused by a frequency channel in one cell, on the same frequency channel used in an adjacent cell.
Generally speaking, based on an (Fractional Reuse Factor) FRF of n (FRF-n) configuration, the corresponding SINR ($\gamma^n$) can be expressed as:

$$\gamma^n = \frac{P_{desired}}{P_{intra-cell} + P_{inter-cell} + \frac{P_{noise}}{n}}$$

(1)

Where:

$\gamma^n$: signal to noise and interference ratio

$P_{desired}$: power of the desired user’s signal

$P_{intra-cell}$: power of intra-cell interference

$P_{inter-cell}$: power of inter-cell interference

$P_{noise}$: white noise power

n: frequency reuse factor (FRF)

As the user equipment (UE) moves away from the serving eNB, the degradation in its SINR can be attributed to two factors. On the one hand, the received signal strength decreases. On the other hand, ICI increases as the UE moves close to a neighbouring eNB, as illustrated in Figure 1.

In LTE, orthogonality between users, within the same cell, is guaranteed in both uplink, and downlink. Therefore, it can be said that the LTE system, is an inter-cell interference limited system. The SINR equation reduces to be:

$$\gamma^{(n)} = \frac{P_{desired}}{P_{inter-cell} + \frac{P_{noise}}{n}}$$

(2)

According to Shannon’s theorem, for a flat fading channel, the channel capacity can be expressed as:

$$C_n = \frac{W}{n} \cdot \log_2 (1 + \gamma^{(n)})$$

(3)

where, W is the carrier bandwidth.

The simple schematic in Figure 1 implies that the most susceptible users to the ICI are those located at the cell edge. Therefore, the cell-edge performance is of great interest for LTE-based system’s designers, as it represents an important aspect of design.
In the literature [1] [2] [3], a wide range of techniques is presented in order to improve the throughput of the cell-edge users, by reducing or suppressing the inter-cell interference (ICI). A combination of these techniques can be formed; moreover, some of them can be applied on specific cases basis, and not the whole network. According to [4] three major inter-cell interference mitigation techniques exist: cancellation, randomization, and avoidance. Interference cancellation is based on receiver processing, for example, cell-specific scrambling/interleaving which aims to whitening the inter-cell interference in case of unicast transmission [2]. Also downlink macro diversity has been proposed as a possible solution for the inter-cell interference in unicast transmissions [2]. In [4] interference randomization (frequency hopping) is discussed briefly. Inter-cell interference randomization is based on randomizing the interfering signal(s) and thus to allow for interference suppression at the UE in line with the processing gain.

Among them, ICI randomization is unlikely to meet the EUTRA requirements regarding cell edge throughput as there is no SINR gain for cell edge UEs. Therefore, their performance cannot improve or approach that of UEs in the cell interior. ICI cancellation is a UE-specific technique that may provide some SINR gains. However, only a few dominant interferers can typically be effectively cancelled limiting the SINR gains. Moreover, certain UEs may only experience a lot of small interferers making ICI cancellation with reasonable UE complexity largely ineffective [5].

### 2.2 Interference Avoidance

It is important to understand the relation between SINR, and FRF-n configuration. In order to do that, let $\Delta_n$ be the spectral efficiency improvement factor [6]:

$$\Delta_n = \frac{C_n}{C_1}$$  \hspace{1cm} (4)

Thus, $\Delta_n$ is a measure of the spectral efficiency improvement that is obtainable with a FRF-n configuration compared to full reuse (i.e., $n=1$). For the FRF-n configuration to have a higher spectral efficiency than the full reuse case, we require that $\Delta_n > 1$. Using Eqn. (3) and Eqn. (4), this requirement is equivalent to:

$$\gamma^{(n)} > n\gamma^{(1)} + \binom{n}{2} (\gamma^{(1)})^2 + \cdots + (\gamma^{(1)})^n$$  \hspace{1cm} (5)

In the case of the UE which is closer to its serving eNB (cell-center UE), the SINR value is usually high, that is $\gamma^{(1)} \gg 1$. Eqn. (5) is approximated to:
\[ y^{(n)} > (y^{(1)})^n \] (6)

On the other hand, for cell-edge UEs, \( y^{(1)} \ll 1 \), and Eqn. (5) can be approximated to be:

\[ y^{(n)} > n \cdot y^{(1)} \] (7)

While it is possible to obtain a large SINR improvement for cell-edge UEs by eliminating ICI, the SINR improvement will be smaller for cell-center UEs, as ICI is not as dominant and important for the UEs as in the cell-edge. Also, since a cell-center UE’s SINR is typically much higher than unity, the spectral efficiency increases only logarithmically with SINR. However, for a cell-edge UE with SINR value much less than unity, the spectral efficiency increases almost linearly with SINR. From Eqn. (6) and Eqn. (7), we can conclude that in general, only cell-edge UE’s spectral efficiency will improve from using a high FRF value.

In [7], an example is introduced which supports the above analysis. In this example, both cell-edge’s SINR, and channel capacity are computed. Important conclusions are made from this study: at low reuse factors (i.e. 1 and 2), larger available bandwidth exists for each cell, however, lower SINR due to the co-channel interference from the surrounding eNBs, resulting in a low channel capacity at the cell-edge. For the reuse factor of 3, a cell-edge capacity improvement is achieved, due to the elimination of co-channel interference from the surrounding eNBs. It is important to point out that the gain in SINR counteracted the loss of bandwidth (as we only use one thirds of the total available spectrum). Beyond the reuse factor of three, co-channel interference decreases and SINR increases. However, the gain of the high SINR cannot counteract the loss in bandwidth. Therefore, the channel capacity decreases as the reuse factor increases with a low rate, and remains above the channel capacity of reuse factors of 1 and 2.

In order to improve the performance of the cell-edge users, the Fractional Frequency Reuse (FFR) scheme was proposed. In this scheme, part of the total available resources is used for cell-edge users’ transmission. This will result in reducing the interference for cell-edge users. However, clearly this improvement comes at the cost of reducing bandwidth utilization. Several research efforts have focused on improving the performance of the FFR by introducing several variations of the basic scheme. The concepts of FFR and its variants are discussed in greater details in the following section.

Frequency reuse-based schemes are relatively easy to implement as they require no frequent interaction among involved eNBs. However, since it is considered to be static frequency reuse, once this allocation scheme is used, it is not easy to perform modifications to the major frequency distributions [1]. Thus, this scheme is not adaptive to dynamic demand changes per sector as it adapts to the cell loads only by changing power used over different sub-carriers.

To avoid the above problem, cell coordination based schemes were proposed. As the name suggests, this scheme involves coordination among neighbouring eNBs, on both sub-carriers and power levels. Accordingly, it can efficiently adapt to the variations in cell loads.

Figure 2 depicts the various types of the frequency reuse schemes.
Figure 2: Inter-Cell Interference Mitigation Techniques.
2.3 Frequency Reuse-based Schemes

This section surveys the various ICIC schemes based on frequency reuse. In particular, the section reviews conventional frequency planning schemes, fractional frequency reuse (FFR), partial frequency reuse (PFR), and software frequency reuse (SFR). Other variants of these techniques are also discussed. In addition, a new classification technique for frequency reuse-based schemes is presented and its use is demonstrated in this section.

2.3.1 Conventional Frequency Planning

The simplest scheme to allocate frequencies in a cellular network is to use a FRF of 1, i.e. available frequency spectrum is reused in each sector without imposing any restriction to frequency resource usage or power allocation (Figure 3-a), leading thus to high peak data rate. However, this case presents the worst inter-cell interference scenario, where high inter-cell interference is observed especially at cell edges.

On the other hand, the whole frequency band can be divided into three equal, orthogonal sub-bands, allocated to sectors so that adjacent sectors always use different frequencies (Figure 3-b).

This setup is called reuse of 3 scheme. This clustering obviously leads to an improved (low) inter-cell interference, with a price to a large capacity loss due to the restrictions imposed on the resources, where only one third of the resources are used in each sector.

In conventional frequency planning two extremes are presented. While reuse 1 does not employ any interference coordination, reuse 3 can be regarded as an extreme case of partition based static interference coordination.
2.3.2 Fractional Frequency Reuse (FFR)

The basic idea on which the FFR schemes rely is to divide the whole available resources into two subsets or groups: major group, and minor group. The former is then used in order to serve the cell-edge users means the cell-edge users are served with a fraction of the available resources, while the latter is used to cover the cell-center users. Different combination of frequencies, and powers used form different schemes. Different FFR schemes aim is to achieve a FRF between 1 and 3.

Generally speaking, the FFR scheme has two main classes:

1. Partial Frequency Reuse (PFR): in this scheme a common frequency band is used in all sectors (i.e., with a frequency reuse of 1) with equal power, while the power allocation of the remaining sub-bands is coordinated among the neighbouring cells in order to create one sub-band with a low inter-cell interference level in each sector.

2. Soft Frequency Reuse (SFR): in this scheme, each sector transmits in the whole frequency band. However, the sector uses full power in some frequency sub-bands while reduced power is used in the rest of the frequency band.

Several variations of the above two schemes have been proposed over the last few years and will be discussed briefly later in this section.

In [8] a study that searches for the optimum FFR is presented in which the problem is formulated as sum-power minimization problem subject to minimum rate constraints in both the regions. In particular, the study considers the optimal FFR factor for the cell-edge region, bandwidth assigned to each region and subcarrier and power allocation to all the users in the cell. The key result is that for the same minimum demanded rate for all users, it is found that the power consumed is minimal when the reuse factor used for the cell-edge region is 3. In the following subsections, a detailed discussion of different frequency reuse schemes is presented.
2.3.2.1 Partial Frequency Reuse (PFR)

The above discussion indicates that it is not bandwidth-efficient to use the same FRF value for the entire cell [6]. One way to improve the cell-edge SINR, while maintaining a good spectral efficiency, is to use an FRF greater than unity for the cell-edge regions and an FRF of unity for the cell-center regions [9]. In a homogeneous network, the cell centre regions have equal areas.

The idea of the partial frequency reuse (PFR) is to restrict portion of the resources so that some frequencies are not used in some sectors at all. The effective reuse factor of this scheme depends on the fraction of unused frequency [10].

The PFR is also known as FFR with full isolation (FFR-FI), as users at cell-edge are fully protected (isolated) from adjacent cells’ interference [6]. An example for sites with 3 sectors is shown in Figure 4. The effective reuse of PFR is greater than one. To see this, consider a system with available bandwidth equal to $\beta$. This bandwidth is divided into inner and outer zones with bandwidth equal to $\beta i$ and $\beta o$, respectively. Band is used with a reuse factor of 1, and for the tri-sector BSs, the reuse factor for is usually 3 in the outer zone. In this case, the effective frequency reuse factor is given by $\beta i (\beta i + (\beta o/3))$. Therefore, the effective reuse of PFR scheme is always greater than 1 [10].

![Figure 4: Partial Frequency Reuse with Full Isolation (PFR-FI)](image)

A numerical method for calculation of interference generated by co-channel cells is proposed and discussed in [11] [12]. The level of co-channel interference in three different scenarios is compared, in particular, cellular system with universal frequency reuse, cellular system with reuse of three and cellular system with implemented ICIC based on fractional frequency reuse. Analysis shows that, interference experienced by users in their own cells is almost two times smaller when using fractional frequency reuse instead of frequency reuse factor 3 and approximately three times smaller than universal frequency reuse case.
2.3.2.2 Soft Frequency Reuse (SFR)

The PFR scheme may result in under-utilization of available frequency resources due to its strict no-sharing policy. Soft Frequency Reuse (SFR) was proposed in [3] [7] to present a balance between the FRF and the PFR schemes. It avoids the high ICI levels associated with the unity FRF configurations, while providing more flexibility to the PFR scheme. The term soft reuse is due to the fact that effective reuse of the scheme can be adjusted by the division of powers between the frequencies used in the centre and edge bands.

SFR makes use of the concept of zone-based reuse factors in the cell-center and cell-edge areas. Unlike the PFR; however, frequency and power used in these zones are restricted. In particular, a frequency reuse factor of 1 is employed in the central region of a cell, while frequency reuse factor greater than 1 at the outer region of the cell close to the cell edge.

For example, consider the 3-sector cell sites shown in Figure 5, the cell-edge band (major band) uses 1/3 of the available spectrum which is orthogonal to those in the neighbouring cells and forms a structure of cluster size of 3. The cell-centre band (minor band) in any sector is composed of the frequencies used in the outer zone of neighbouring sectors. According to the original contribution in which the SFR is proposed [7], the major band can be used in the cell-centre as well if it is not occupied by the cell-edge UTs, resulting in a frequency reuse factor of 1 for the inner part of the cell, but the minor band is available to the centre area only (Figure 5-a). Each group is assigned transmission power depending on the desired effective reuse factor, such that the major band group is higher than the power of the minor group while keeping the total transmission power fixed. Higher transmit power is used on the major band as shown in the right side of Figure 5.

However, Authors in [9] defines the SFR differently. In their work, they refer to the SFR as a scheme in which the available bandwidth is divided into orthogonal segments, and each neighbouring cell is assigned a cell-edge band, where a higher power is allowed on the selected cell-edge band, while the cell-centre UEs can still have access to the cell-edge bands selected by the neighbouring cells, but at a reduced power level. In this way, each cell can utilize the entire bandwidth while reducing the interference to the neighbours (Figure 6-b). A less ICI at the cell-edge is achieved at the expense of spectrum utilization.
In [3], a parameter called “Power Ratio” is defined as the ratio between transmit power limitation of minor sub-carriers and major sub-carriers. Adjusting the power ratio from 0 to 1 effectively moves the reuse factor from 3 to 1. Therefore, SFR is seen as a compromise between reuse 1 and 3 in a network with tri-sector BSs. UTs are categorized into cell-edge and cell-centre based on user geometry determined by the received signal power (averaged over multipath fading) taking into account the large-scale path-loss, shadowing, and antenna gains [10].

Simulation results reported in [3] [7] show that: if the power ratio equals one, the cell-edge bit rate equals the one third of the cell-edge bit rate in case of the universal reuse factor. As the power factor decreases towards 0, the total cell throughput decreases as well. Also, the throughput of the inner zone decreases as well. However, the cell-edge throughput increases due to the increasing transmission power for cell-edge users and the mitigation of co-channel interference.

The above discussion can lead to the general conclusion that the SFR scheme can improve the SINR of the cell-edge UEs using a greater than unity FRF, while degrading the SINR of the cell-centre UEs. This degradation is due to the overlap in frequency resources between the cell-edge band of the neighbouring cells, and the cell-centre band of the serving cell. However, as mentioned earlier, the cell-edge performance improvement is almost linear while the degradation to the cell-centre UEs is logarithmic. In SFR, the power ratio between the cell-edge band and the cell-centre band can be an operator-defined parameter, thereby increasing the flexibility in system tuning.

In [13], the performance of the SFR with partial frequency reuse at the cell centre for large scale networks in realistic radio environments and with irregular cell patterns is investigated. According to simulations, two key conclusions are drawn. SFR’s parameters have to be carefully selected and optimized since any improvement for the cell edge users comes at the expense of performance of the cell centre users. Therefore, it was suggested that the SFR is better used for resolving interference issues at some specific areas rather than being used in the entire network. It is also found that the cell-edge performance is sensitive to the BW allocated; an interesting result is that the two sub-bands have better performance over the conventional three sub-bands. A recommendation for further work is then presented for performing comparison studies between the SFR scheme and other schemes. Also they recommended the use of sub-bands of unequal sizes which can better adapt the reuse pattern to cell layout.
According to the definition of the SFR in this document, it would be interesting to investigate the performance of the original SFR under the same conditions mentioned in [13], and compare results to those obtained before.

### 2.3.2.3 Soft Fractional Frequency Reuse (SFFR)

The PFR and SFR schemes can improve the throughput for the cell-edge users by reducing the ICI experienced by users in that region. However, both schemes may lead to a lower cell throughput as compared to the conventional reuse of one scheme. The PFR scheme does not utilize the whole available frequency bandwidth, and thus, it has a lower cell throughput as compared to reuse of one scheme. Moreover, although SFR can make use of the overall frequency band available in the cell, and thus, increase the overall system capacity compared to that of the PFR; however, the overall system capacity of SFR maybe lower than that of reuse one scheme.

Soft FFR (SFFR) scheme has been proposed as a way to improve the overall cell throughput of FFR [14]. Unlike the PFR that does not make use of the sub-bands allocated to the outer region in the adjacent cells, the Soft FFR scheme utilizes these sub-bands for the inner UEs, but with low power levels (See Figure 6). As a result, the SFFR is similar to the SFR in that both adopt a non-uniform power profile (it uses high power levels for some sub-bands and low power levels for others). Unlike the SFR; however, the Soft FFR uses the common sub-band which can enhance the throughput of the inner users.

![Figure 6: Soft Fractional Frequency Reuse (SFFR)](image)

In [15], several variations of the power profile used in the Soft FFR scheme are investigated. Several interesting observations were presented and can be summarized as follows:

- Transmission power level of the common part does not have a significant influence on the overall cell throughput. Accordingly, the total transmission power used in the cell can be reduced by minimizing the power level of this common part without impacting the required cell throughput level.
Transmission power level in the outer region has a direct impact on the throughput of that region. In particular, it was observed that the throughput of this region is directly proportional to its power, and inversely proportional to the inner region’s throughput. As the power in the outer region decreases, the overall capacity increases since the spectral efficiency in the inner region is higher than the one in the outer region. As a result, according to the throughput requirements in the outer region, the power consumption for the outer region can be reduced, while maintaining high overall system throughput.

Downlinks transmit power allocation in soft FFR under two different coordination cases namely; loosely and tightly coordinated cells are studied [16]. In the loosely coordinated cells case, the sub-band transmit powers are allocated so that the cell edge user meets the required throughput. The loss in average cell throughput can be reduced by configuring appropriate number of sub-bands for inner and outer regions. However, in the tightly coordinated cells, sub-band power allocation can be changed packet by packet in each scheduling period. It is found that in this cell coordination case, the loss of spectral efficiency can be minimized regardless of the number of sub-bands due to its fast coordination.

### 2.3.2.4 Other Proposed FFR Schemes

A novel fractional frequency reuse scheme combined with interference suppression for orthogonal frequency division multiple access (OFDMA) networks is introduced in [17]. The proposed FFR scheme (Figure 7) ensures maximum of one interferer to the cell edge users, and hence, it was possible to suppress this interference by using the interference exploitation. Results indicate a reduction in power at no cost of increased complexity. This proposed novel FFR scheme can be classified as a variation of the PFR scheme, it also worth note that this novel scheme has no unique name that can describe it, or ease the discrimination of it from other PFR schemes.

![PFR with only one interference in the worst case.](image)

A scheme that deals with different user classes is presented in [18] [19] in which the concept of dividing cells into concentric zones, each with a different frequency reuse factors is introduced (Figure 8). Under this scheme, the cell uses the entire band but under different power level restrictions based on the type of UEs. Central UEs are served first with the low power sub-band (if it’s not enough next sub-bands can be used, but
still maintaining the low power level). Next, intermediate and finally cell edge UEs are served with the same criterion.

![FFR with multiple user class](image)

**Figure 8:** FFR with multiple user class

### 2.3.2.5 Incremental Frequency Reuse (IFR)

Under the SFR scheme, cell edge users have a maximum of one third of the entire bandwidth to utilize. However; typically, cellular systems have more cell edge users than cell center users. Thus, SFR may result in low spectrum efficiency. Moreover, as shown in Figure 9, under the SFR scheme, co-channel interferences may increase even under low traffic load situation, while there are still subchannels in idle and underutilized in the system. This is due to the fact that resource allocation of all cells under the SFR scheme starts always from the first subchannel up. Again, this may reduce the spectrum utilization efficiency.

![Low spectrum efficiency problem in SFR](image)

**Figure 9:** Low spectrum efficiency problem in SFR.
In addition, results on the usage of SFR showed that the cell throughput is even lower to the conventional reuse of one scheme when loading factor over 0.5 [20]. This is because under the SFR scheme, at most one third of the subchannels can be used to transmit data with higher power while the remaining two third subchannels work with lower power, which induces an overall throughput loss. Thus, the SFR ameliorates performance of the cell edge users at the expense of degrading the overall cell capacity [21].

In order to overcome some of the shortcomings of the conventional SFR scheme discussed above (low spectrum efficiency, increased co-channel interferences at low loading traffic, and loss of cell capacity system when system is over half-full loaded), in [20], Ki Tae Kim et al. proposed the concept of Incremental Frequency Reuse (IFR) scheme. IFR attempts to reduce the ICI effectively under low offered traffic, while maintaining the overall system capacity.

Figure 10 illustrates the operational concept of the IFR scheme in a tri-sector cell system with 3 various types of neighbouring cells. The only difference between the IFR and the classical reuse-1 is, from which point of the available bandwidth it starts dispensing resources to the users. In an IFR system the directly adjoining cells assign resources from different subchannels. Cells of type-A occupy resources from the first subchannel, whereas cells of type-B from one third of the whole bandwidth, and cells of type-C from two third of the bandwidth. They allocate consecutive subchannels successively along with traffic load increasing until the entire bandwidth is used up. The ICI generated by directly adjoining cells can be avoided completely at low traffic situation, since frequency reuse of the first tier neighbouring cells doesn’t occur when loading factor below 0.3, and the whole system operates as in the classical reuse-3 system. Effectively, under the IFR scheme, the system operates with increasing traffic load like moving from a reuse-3 system to a reuse-1 system.

Despite the fact that the IFR scheme can overcome most of the limitations inherited in the SFR scheme; however, the IFR scheme performs better only under low traffic. When the loading factor in the system is above 0.3, the IFR performance is lower than that of the SFR. Simulation results reported in [20] concluded that both the IFR and the SFR schemes do not perform better than the classical reuse-1 scheme in over-
middle-load or full-load situations. The SFR scheme even performs worse than the reuse-1 system. Accordingly, it is concluded that the system capacity cannot be substantively improved by the IFR and the SFR schemes.

### 2.3.2.6 Enhanced Fractional Frequency Reuse (EFFR)

To further improve the performance of the IFR and the SFR schemes and overcome their limitations, a scheme called Enhanced Fractional Frequency Reuse (EFFR) was proposed in [21]. EFFR attempts to enhance the system capacity especially under overload situations.

Similar to the IFR scheme, the EFFR scheme defines 3 cell-types for directly neighbouring cells in a cellular system, and reserves for each cell-type a part of the whole frequency band named Primary Segment, which is shown in the right part of Figure 11 with thick border.

The Primary Segments among different type cells should be orthogonal. The remaining subchannels excluding the Primary segments constitute the Secondary Segment. The Primary Segment of a cell-type is at the same time a part of the Secondary Segments belonging to the other two cell-types. Each cell can occupy all subchannels of its Primary Segment at will, whereas only a part of subchannels in the Secondary Segment can be used by this cell in interference-aware manner.

The Primary Segment of each cell will be further divided into a reuse-3 part and reuse-1 part. The reuse-1 part can be reused by all types of cells, while reuse-3 part can only exclusively be reused by other same type cells. The reuse-3 subchannels cannot be reused by directly neighboring cells, that attenuates the co-channel interferences among them and therefore it is specified for the vulnerable cell edge users to take priority of using these subchannels over cell center users.

Since a cell acts on the Secondary Segment as a guest, and occupying secondary subchannels actually reuses the primary subchannels belonging to the directly neighboring cells, therefore, the Secondary Segment to be reused should be first monitored, then being reused based on the SINR estimation.

Each cell listens on every secondary subchannel all the time. And before occupation, it makes SINR evaluation according to the gathered channel quality information (CQI) and chooses resources with best estimation value for reuse. If all available secondary resources are either occupied or not good enough to a link, it will give up reusing for this link. This will not lead to resource wasting, which means some resources may not reusable for this link, but can be reused by other links. Another gained merit is that it will not generate excessive interference for the neighbouring cells which would degrade their performance. So, an upgrade of spectrum efficiency is expected by using the interference-aware-reuse mechanism on the Secondary Segment.

Simulation results for comparing the EFFR scheme with conventional reuse-1, reuse-3, and the IFR schemes show a significant improvement in the overall capacity gains at cell edge as compared to other schemes.
2.3.2.7 Combined Partial Reuse and Soft Handover

An interesting ICIC scheme that employs both partial frequency reuse (PFR) and soft handover (SH) is proposed in [22]. This proposed scheme differentiates between the cell interior users (CIUs) from the cell edge users (CEUs) using the soft-handover (SH), where a user is considered as a cell edge user if there is at least two cells in its handover list. Effectively, this scheme capitalizes on the information already available from the handover algorithm, and thus, it eliminates the complexity of geometry determination based on the duplicate calculation of SINR. In addition, it eliminates the need for extra signalling. Simulation results reported in [22] shows that the combined approach can provide a significant cell edge throughput gain over the conventional partial frequency reuse scheme. In addition, this scheme is shown to have a low soft handover overhead.

2.4 A Proposed Parameterized Classification for Frequency Reuse-based Schemes

This section presents a new parameterized classification for the various frequency reuse-based schemes, and shows how the proposed classification can be used to characterize and/or distinguish the various schemes discussed in the previous subsection.

2.4.1 Motivation and Basic Concept

Despite their differences, various frequency reuse-based schemes share similar structures and properties. For instance, if we assume a system with tri-sector cells, where sectors have hexagonal shapes, any frequency reuse-based schemes need to define: the set of sub-bands that will be used in each sector, the power at which each sub-band is operating, and part of the sector in which this set of sub-bands will be used (over the whole cell, cell-centre, or cell-edge). Different schemes define different values and approaches for these various parameters.

In addition to the commonality among the various frequency reuse-base schemes discussed above, we believe that current classification (and hence, understanding) of the various frequency reuse-base scheme have some ambiguity. For instance, it is difficult to name the proposed variant of the FFR shown in Figure 7. Also, our literature review reveals that the concept of soft frequency reuse (SFR) is used differently in various papers. We believe that these problems can be avoided if a rigorous precise definition can be used to
specify a frequency reuse-based scheme. Accordingly, various techniques can be better understood and effectively analysed and compared.

To this end, we propose a new classification scheme based on the common parameters shared among the various frequency reuse-based schemes. The idea behind the proposed new classification is to capitalize on the parameters that are similar among all various frequency reuse-based schemes and use these parameters as a base to present a concise and accurate description of the various schemes.

### 2.4.2 Parameters and Definitions

This section defines the basic parameters used in the proposed classification scheme. In the following, we discuss the parameterized classification technique. Then the proposed parameterized technique will be used to describe different frequency reuse schemes discussed in the previous section.

Let \( S \) be the set of sectors per cell, where:

\[
S = \{s_1, s_2, s_3\}
\]  

(8)

It is assumed that all sectors in the same cell are identical. Hence, for the sector \( S_k \), let:

\[
s_k = \{\mathcal{R}_\alpha, \alpha \in \mathcal{D}\}
\]  

(9)

where \( \mathcal{R} = \{\mathcal{A}, \mathcal{C}, \mathcal{E}, \mathcal{O}, \Phi\} \) is an alphabetical set that describes the part of the sector that is covered by a certain set of sub-bands, and can be expressed as follows:

\[
\mathcal{R} = \{\mathcal{A}, \mathcal{C}, \mathcal{E}, \mathcal{O}, \Phi\}
\]  

(10)

where:

- \( \mathcal{A} \): The whole sector
- \( \mathcal{C} \): sector’s center.
- \( \mathcal{E} \): sector’s edge.
- \( \mathcal{O} \): in between the cell center, and cell edge (this is used only in the case of FFR with different user types, which is the concentric case of the FFR).
- \( \Phi \): a sub-band that is not used by the sector, however, it exists, and used by other sectors.

If more than concentric level in between the cell center and cell edge, \( \mathcal{O} \) can be expanded to be \( \mathcal{O}_1, \mathcal{O}_2, \ldots \) etc.

Also, we define the following parameter:

- \( \mathcal{A} \): which represents the power ratio that expresses the used power level within a certain sub-band with respect to the maximum available power in the system, where:

\[
\partial = \frac{P}{P_{max}} = \{a_0, a_1, \ldots, a_j\}
\]  

(11)
The following properties hold for Equation (11):

\[ \alpha_0 = 0, \alpha_j = 1, \text{ other levels are defined by the system,} \]

\[ \alpha_1 < \alpha_2 < \cdots < \alpha_j \]

\[ \sum_{\text{cell}} \alpha = \text{constant} \]

Finally, we define the following parameter:

\( \beta_x \): which represents the sub-band allocated. Each sub-band is defined with a particular \( \beta_x \) that represents the upper limit of this particular sub-band, whereas the lower limit is the previous limit \( \beta_{x-1} \). For the sub-band with boundary of \( \beta_1 \), the, lower band is 0. Hence, four contiguous sub-bands can be expressed as:

\[ 0 \rightarrow \beta_1, \beta_1 \rightarrow \beta_2, \beta_2 \rightarrow \beta_3, \text{and } \beta_3 \rightarrow \beta_4 \] (12)

### 2.4.3 Instantiation of Various Frequency Reuse-based Schemes

Table 1 shows how to use the classification presented above to instantiate the various frequency reuse-based schemes discussed in the previous section.
### Table 1: Frequency Reuse Schemes using Parameterized Classification

<table>
<thead>
<tr>
<th>Frequency reuse scheme</th>
<th>Expression using parameterized classification Techique</th>
</tr>
</thead>
</table>
| **1- Universal reuse scheme (Reuse of 1)** | The three sectors are identical, hence:  
\[
S_1 = S_2 = S_3 = \{ \mathcal{A}_{\beta_1}^{\alpha_1} \} 
\]
where $\beta_1$ implies that there is only one band which is the whole available spectrum ($0 \rightarrow \beta_1$).
\[\alpha_1\] is the power level that is defined by the system. |
| **2- Reuse of 3 scheme** | \[
S_1 = \{ \Phi_{\beta_1}^0, \Phi_{\beta_2}^0, \mathcal{A}_{\beta_3}^{\alpha_1} \} \\
S_2 = \{ \Phi_{\beta_1}^0, \mathcal{A}_{\beta_2}^{\alpha_1}, \Phi_{\beta_3}^0 \} \\
S_3 = \{ \mathcal{A}_{\beta_1}^{\alpha_1}, \Phi_{\beta_2}^0, \Phi_{\beta_3}^0 \} 
\]
| **3- FFR - Full Isolation** | \[
S_1 = \{ \mathcal{C}_{\beta_1}^{\alpha_1}, \Phi_{\beta_2}^0, \Phi_{\beta_3}^0, \mathcal{E}_{\beta_4}^{\alpha_2} \} \\
S_2 = \{ \mathcal{C}_{\beta_1}^{\alpha_1}, \Phi_{\beta_2}^0, \mathcal{E}_{\beta_3}^{\alpha_2}, \Phi_{\beta_4}^0 \} \\
S_3 = \{ \mathcal{C}_{\beta_1}^{\alpha_1}, \mathcal{E}_{\beta_2}^{\alpha_2}, \Phi_{\beta_3}^0, \Phi_{\beta_4}^0 \} 
\]
where $\alpha_1$ and $\alpha_2$ are power levels chosen between 0 and 1. |
| **4- Original Soft Frequency Reuse (SFR)** | |
\[
\begin{align*}
S_1 &= \{C_{\alpha_1}^{\beta_1}, C_{\alpha_1}^{\beta_2}, C_{\alpha_1}^{\beta_3}, C_{\alpha_2}^{\beta_3}\} \\
S_2 &= \{C_{\alpha_1}^{\beta_1}, C_{\alpha_1}^{\alpha_2}, C_{\alpha_1}^{\beta_3}, C_{\alpha_2}^{\beta_3}\} \\
S_3 &= \{C_{\alpha_1}^{\beta_1}, C_{\alpha_2}^{\alpha_2}, C_{\alpha_1}^{\beta_3}, C_{\alpha_1}^{\beta_3}\}
\end{align*}
\]

where \(\alpha_1\) and \(\alpha_2\) are power levels chosen between 0 and 1.

---

5- SFR - variation

\[
\begin{align*}
S_1 &= \{C_{\alpha_1}^{\beta_1}, C_{\alpha_1}^{\beta_2}, C_{\alpha_2}^{\beta_3}\} \\
S_2 &= \{C_{\alpha_1}^{\beta_1}, C_{\alpha_2}^{\beta_2}, C_{\alpha_1}^{\alpha_1}\} \\
S_3 &= \{C_{\alpha_2}^{\beta_1}, C_{\alpha_1}^{\beta_2}, C_{\alpha_1}^{\beta_3}\}
\end{align*}
\]

where \(\alpha_1\) and \(\alpha_2\) are power levels chosen between 0 and 1.

---

6- Soft FFR (SFFR)

\[
\begin{align*}
S_1 &= \{C_{\alpha_1}^{\beta_1}, C_{\alpha_1}^{\beta_2}, C_{\alpha_1}^{\beta_3}, C_{\alpha_2}^{\beta_4}\} \\
S_2 &= \{C_{\alpha_1}^{\beta_1}, C_{\alpha_1}^{\alpha_2}, C_{\alpha_1}^{\beta_3}, C_{\alpha_2}^{\beta_4}\} \\
S_3 &= \{C_{\alpha_1}^{\alpha_1}, C_{\alpha_2}^{\beta_1}, C_{\alpha_1}^{\beta_2}, C_{\alpha_1}^{\beta_3}\}
\end{align*}
\]

where \(\alpha_1\) and \(\alpha_2\) are power levels chosen between 0 and 1.

---

7- FFR with only one interference in the worst case
### 2.5 Cell Coordination-based Schemes

Although the schemes discussed above are suitable for homogeneous networks (with the same load in all cells), it is not adapted to non-homogeneous networks as the path loss threshold is the same in all cells. A dynamic frequency allocation is thus required in order to cope with the continuous heterogeneous load’s changes in cells.

Cell coordination schemes have emerged as an efficient solution to cope with the natural dynamic nature of cellular systems. In cell coordination, interference reduction is realized by real time coordination among all involved cells to avoid that two cell edge UEs in neighbouring cells use the same subcarriers. Adaptive algorithms are developed in order to efficiently manage the resource utilization among cells without a priori resource partitioning.

Although this solution presents a flexible with no apriori frequency planning; however, it requires an interface between different eNBs in order to achieve the required coordination which be considered as a serious complexity with respect both, overhead and delay. Coordination between cells can be performed in either a centralized, semi- distributed or distributed fashion (See Figure 2). Various techniques present trade-offs between implementation complexity, the overhead of signalling, and coordination level. This section presents a brief overview on the various coordination schemes for interference avoidance.
2.5.1 Centralized

In centralized cell coordination avoidance schemes, all eNBs report corresponding channel quality information to a central unit, namely, the radio network controller (RNC). This centralized entity is responsible of performing the complete coordination process based received information. Example of this centralized scheme can be found in [23] [24] [25].

2.5.2 Semi-Distributed

This scheme is called semi-distributed since it is neither completely centralized, nor distributed. However, the coordination is performed through a process of two different levels: eNBs level and radio network controller (RNC) level [10] [26] [27] [28] [29].

In [26], the authors present a radio resource control (RRC) scheme for OFDMA systems. To perform global optimization, RNC must have knowledge of all users’ channel state information (CSI) and traffic status information at all time, from all cells. In reality, the amount of information needed from BSs to RNC will be prohibitively large. The proposed semi-distributed scheme reduces the overhead and computational load by splitting the decisions between RNC and BSs. Mechanically, RNC updates all users’ CSI from all BSs every super-frame. Decisions made by RNC include the specific set of traffic channels assigned to each BS for that super-frame and the recommended user assignment for the traffic channel set. Locally the BS makes the actual pairing between the traffic bearers and the users. In a specific frame, if the recommended user by RNC has traffic to send, the BS will agree with RNC’s recommendation, otherwise the BS will make its own decision based on users’ traffic conditions (buffer occupancies) and channel fading levels.

The decision algorithm of RNC performs interference avoidance and the decision algorithm by BS performs channel/traffic adaptation. Specifically, RNC will be dedicated to coordinate the mutual interference between cells, reducing the information update rate between RNC and BSs to a super-frame level. BSs will make real time decisions on channel assignment at user packet level (frame level). As a result, both the mutual interference diversity and the fading channel/bursty traffic diversity can be efficiently exploited.

In [27] a heuristic approach is presented to solve the resource allocation problem in a multicell system. In this approach, a sector from what is called a wish-list which includes a set of chunks to be restricted in its dominant interferer sectors which are located in its first-tier. Then the eNB processes this list and then report a restriction request to a physical or a logical central entity through the X2 interface. This central entity can be a radio network controller (RNC), or a mobility management entity (MME). The central entity is then required to process all received restriction requests and inform the eNBs about the resource allocation decision.

In [27], this problem is modeled using integer programming (IP), however, a suboptimal solution for this problem is needed due to the high complexity of the IP. Therefore, authors partitioned the problem into a number of smaller problems and used iterative optimization in order to solve it.

On the other hand, in [10], two algorithms are used; one at the eNB and the other is at the central entity. For the eNB, it uses the iterative Hungarian algorithm in order to process and generate the chunk restriction requests which are forwarded then to the central entity that solves the restriction requests in an optimal manner, and return the decision to eNBs to apply it locally.

2.5.3 Distributed

In order to overcome the degradation in the performance due to fixed frequency reuse schemes, and to also make use of different fractional frequency reuse schemes, distributed coordination schemes are proposed. In distributed coordination schemes, a resource allocation is performed in the BS level, without the need of a central entity to perform the coordination. This means that the time wasted, and signaling overhead between
eNBs and the central entity suffered in the semi-distributed schemes, discussed above, are no more needed. Two major types of distributed coordination schemes exist; coordinated distributed ICIC, and autonomous distributed ICIC.

2.5.3.1 Coordinated

In coordinated ICIC, coordination is needed between eNBs in order to perform global inter-cell interference coordination. Several papers have discussed this scheme [30] [31] [32] [33] [34]. These schemes are common as they aim to partition the complex multicell optimization problem into distributed single-cell optimization problems, which can be solved by each individual eNBs with minimal communication among neighboring eNBs.

Implicitly, some of these schemes and models are based on the concepts of frequency reuse schemes discussed before. For example, in [30] [31] power constraints of the soft frequency reuse (SFR) scheme has been adopted.

The scheme proposed in [34] is similar to the semi-distributed schemes in the manner that the coordination process is done on different time levels; frame level and super-frame level. However, the difference is that instead of having a central entity in order to perform the super-frame level coordination, those two steps are performed in this scheme by the eNB. Similar to all other distributed coordination scheme, a backhaul communication between neighbouring eNBs is needed, which can be done through the X2 interface. This scheme is capable of achieving good load balancing in case of different cell loads exist.

In [35] a distributed coordination scheme is used in order to optimize the fractional frequency reuse (FFR) parameters based on the variations in the cell loading. This is done in a distributed manner, with communication between eNBs through the X2 interface. Results show that the proposed scheme yields a cell-edge throughput gain without affecting the overhaul average throughput.

This idea can be viewed as an implementation approach for the concept of dynamic FFR discussed in [36]. In dynamic FFR cell-centre zone boundaries (across the network) are dynamically adapted depending on user behaviour, cell loading, and interference situation from other neighbouring cells. This can be performed based on interference level reports, and/or signalling via interface between base stations.

Figure 12 depicts an example of a possible structure of this scheme. As shown in the figure, cell centre areas have different sizes. For example, in the shown example, Cell 1 is highly loaded while cell 3 experiences a lower load. Accordingly, the region of frequency reuse 1 is then larger in cell 1 than in cell 3.
2.5.3.2 Autonomous

There is not a lot of work reported in the literature for developing autonomous distributed ICIC schemes. However, in [37] Stolyar et al, presented a self-organizing dynamic FFR scheme (for constant-bit-rate (CBR) traffic), which requires no signalling or communication between eNBs. Also, no apriori frequency planning is needed, however, the proposed scheme could efficiently achieve a frequency reuse adopted to the user loading and distribution. The basic idea of this proposed scheme is that each sector aims to optimize its own resource allocation independently in a selfish optimization manner. The objective function to be optimized by each cell is to minimize the total power usage by this cell based on information fed back by cell’s users. Another autonomous scheme was also proposed by Stolyar in [38] for the case of best-effort traffic.

2.6 Summary

This report presents a brief overview for various ICIC schemes used to alleviate the inter-cell interference problem in the downlink in LTE networks in order to improve cell-edge data rates and enhance the overall network capacity. ICIC can be viewed as a scheduling strategy used to limit the inter-cell interference such that cell-edge users in different cells preferably are scheduled on complementary parts of the spectrum when required.

Two main classes of ICIC schemes can be used to avoid interference in LTE systems, namely, frequency reuse and cell coordination. In the former, semi-static methods are used to allocate subcarriers (frequency bands) among cells and sectors, whereas in the latter, dynamic methods are used to perform real-time cell coordination to allocate resources (frequency bands) to cells and sectors. Pre-allocated frequency reuse schemes are generally simple to implement; however, it is not easy to modify their frequency distributions among adjacent cells in response to the dynamics of the network. Cell coordination schemes, on the other hand, are more flexible as compared to frequency reuse schemes; however, they require complex signalling and coordination among cells.

Frequency reuse interference avoidance schemes include the conventional frequency planning schemes, fractional frequency reuse (FFR), partial frequency reuse (PFR), and software frequency reuse (SFR). In addition, several variations of these schemes such as: Incremental Frequency Reuse (IFR), Enhanced...
Fractional Frequency Reuse (EFFR), and Combined Partial Reuse and Soft Handover have been proposed to improve the performance of the FFR and SFR schemes.

Despite their differences, the above frequency reuse-based schemes are based on common parameters. What differentiate one scheme from another is the selection of the type and range of these parameters. However, the lack of a systematic and rigorous approach to describe these techniques has led to several confusions in the literature in both understanding the schemes as well as in fairly comparing them. This report attempted to alleviate this problem by proposing an initial novel parameterized classification for frequency reuse schemes. The report demonstrated how the proposed classification approach can be used to instantiate most known frequency reuse techniques.

Frequency reuse schemes are suitable for homogeneous networks (with the same load in all cells); however, they are not well-suited for non-homogeneous networks as the path loss threshold is the same in all cells. Therefore, dynamic frequency allocations are needed in order to cope with the continuous heterogeneous load’s changes in cells. Cell coordination schemes have emerged as an efficient solution to cope with the natural dynamic nature of cellular systems. In cell coordination, interference reduction is realized by real time coordination among all involved cells to avoid that two cell edge URs in neighbouring cells use the same subcarriers. Adaptive algorithms are developed in order to efficiently manage the resource utilization among cells without a priori resource partitioning. Coordination between cells can be performed in either a centralized, semi-distributed or distributed fashion. Most research reported in the literature is either semi-distributed or distributed via coordination. However, not much research has been reported in developing autonomous distributed ICIC schemes, which makes it an interesting research problem that is worth further investigation.
3 Autonomous Inter-Cell Interference Coordination for the LTE Uplink

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4 Interference Alignment (IA) in Wireless Networks

In the absence of precise capacity characterizations, researchers have pursued asymptotic and/or approximate capacity characterizations. Capacity characterizations have been found for centralized networks (Gaussian multiple access and broadcast networks with multiple antennas), but capacity characterizations for most distributed communication scenarios remain long standing open problems.

It can be argued that the most preliminary form of capacity characterization for a network is to characterize its degrees of freedom (DoF). The degrees of freedom represent the rate of growth of the network capacity with the log of the signal to noise ratio (SNR). In most cases, the spatial degrees of freedom turn out to be the number of non-interfering paths that can be created in a wireless network through signal processing at the transmitters and receivers. While time, frequency and space all offer degrees of freedom in the form of orthogonal dimensions over which communication can take place, spatial degrees of freedom are especially interesting in a distributed network.

Recent work on degrees of freedom characterization for interference networks led to the emergence of a new concept called interference alignment (IA), which has challenged the conventional throughput limits of both wired and wireless networks. This new concept has pointed out some of the earlier work incorrect inferences such as:

1. The number of degrees of freedom for a wireless network with perfect channel knowledge at all nodes is an integer.
2. The degrees of freedom of a wireless network with a finite number of nodes are not higher than the maximum number of co-located antennas at any node [39].

Interference alignment allows many interfering users to communicate simultaneously over a limited number of signalling dimensions (bandwidth) by confining the interference at each receiver into a space spanned by a small number of dimensions, while keeping the desired signals separable from interference. This enables the desired signals to be projected into the null space of the interference and thereby can be recovered free from interference. Interestingly, interference alignment does for wireless networks what MIMO technology has done for the point to point wireless channel. In both cases, the capacity, originally limited to \( \log(1 + SNR) \), is shown to be capable of linearly increasing with the number of antennas. While MIMO technology requires nodes equipped with multiple antennas, interference alignment works with the distributed antennas naturally available in a network across the interfering transmitters and receivers. For example, in the \( K \)-user wireless interference channel, interference alignment allows each user to simultaneously send at a data rate equal to half of his interference-free channel capacity to his desired receiver, even though the number of users \( K \) can be arbitrarily large. Simply put, interference alignment suggests that interference channels are not fundamentally interference limited.

In this survey, we will go through the main research results in the area of interference alignment. First, we will introduce some of the different approaches used to design an interference alignment scheme in: wireless X networks, the \( K \)-user interference channel (IC), the \( K \)-user IC with cooperation and the IC with a helpful relay. Then, we will summarize some of the challenges faced when designing such schemes and the research done attempting to overcome these challenges.

4.1 Interference alignment in different wireless channels

4.1.1 The Wireless X Network

The X network is a communication network, which consists of \( M \) transmitters and \( N \) receivers. There is a message to be sent from each transmitter to each receiver, thus constituting \( MN \) independent messages that
need to be sent from all transmitters to all receivers. The Multiple access channel (MAC), the broadcast channel (BC), and the interference channel (IC) are all special cases of $X$ networks. Thus, any outer bound on the degrees of freedom region of an $X$ network is also an outer bound on the degrees of freedom of all its sub-networks. A general outer bound on the degrees of freedom region of an $M \times N$ wireless $X$ network when using interference alignment is derived in [40]. Three different scenarios are discussed in [40]; the case when all nodes are equipped with single antennas, the case where either $M = 2$ or $N = 2$, and a scrap on the case where all nodes are equipped with $A$ antennas. In all cases, channel coefficients are assumed to be time varying or frequency selective and drawn from a continuous distribution. A perfect interference alignment scheme is also constructed in this paper when the number of receivers $N = 2$ or the number of transmitters $M = 2$. This scheme achieves exactly the outer bound of degrees of freedom with a capacity characterization within $O(1)$, where the “$O$” notation is defined as follows:

$$f(x) = O(g(x)) \Leftrightarrow \lim_{x \to \infty} \frac{f(x)}{g(x)} = 0.$$ 

Furthermore, other interference alignment schemes are designed in this paper to come close to the outer bound on degrees of freedom.

In Figure 1, an example of a $2 \times 2$ user $X$ network is shown where a $4/3$ degrees of freedom are shown to be achievable using interference alignment over 3 signaling dimensions, i.e., 3 antennas per user. In this example, both users are allowed to transmit two data where $x_j$ represents the transmitted data stream from transmitter $j$ intended to receiver $i$, $V_{ij}$ represent the precoding vectors at transmitter $j$, and $H_{ij}$ represents the channel coefficients between transmitter $j$ and receiver $i$.

![Figure 13: An Example 2 × 2 user X network Channel.](image)

**4.1.1.1 Wireless X Network with Single-Antenna Nodes**

An asymptotic interference alignment scheme is proposed in [40], where the total number of degrees of freedom achieved is shown to be close to \(\frac{MN}{M+N-1}\) with a capacity characterization within $O(\log(SNR))$ for single-antenna nodes and using large channel extensions. Another useful result that is shown in this paper is that when the number of transmitters is much larger than the number of receivers or vice versa, the $M \times N X$ network achieves a number of degrees of freedoms that is close to that achieved by an $M \times N$ MIMO network. This is evident when $M \gg N$ or $N \gg M$, as $\frac{MN}{M+N-1}$ becomes very close to $\min(M, N)$.

**4.1.1.2 Wireless X Network with Multiple-Antenna Nodes**

It is also shown in [40] that for an $M \times N X$ network where each node is equipped with $A$ antennas, the total number of degrees of freedom is outer bounded by $\frac{AMN}{M+N-1}$ per orthogonal time and frequency dimension.
Moreover, a lower bound of \( \frac{AMN}{M+N-1/A} \) is shown to be achievable in [40]. This lower bound is close to the outer bound if either \( M \) or \( N \) is reasonably large.

In [41], a study on the case of the 2-user X network where each node is equipped with three antennas is conducted. Three different precoding schemes based on iterative random search approach are considered in this paper. The three schemes are designed based on zero-forcing (ZF), minimum mean square error (MMSE), and maximum signal-to-leakage ratio (SLR) criteria. The proposed schemes are designed to satisfy the interference alignment conditions and at the same time optimize system performance. Three optimization approaches are considered; for ZF criteria, the optimization objective is to maximize the minimum of SINRs for each data stream, for MMSE criteria, the optimization objective is to minimize the mean square error (MSE) of the detected data, and for SLR criteria, the precoding vectors are optimized based on maximization of SLR, and the receive steering vectors are optimized based on maximization of SINR. Simulation results show that the proposed schemes are very efficient and can provide good performance for the MIMO network.

4.1.2 The \( K \)-User Interference Channel

For a \( K \)-user IC, we have \( K \) pairs of transmitters and receivers, where each receiver has a message from its intended transmitter and receives interference from the other \( K-1 \) transmitters. It is shown in [39] that, with perfect channel knowledge, the frequency-selective IC is not interference limited. In fact, after the first two users, additional users do not compete for degrees of freedom and each additional user is able to achieve 1/2 degree of freedom without hurting the previously existing users. What makes this result even more remarkable is that linear scaling of degrees of freedom with users is achieved without cooperation in the form of message sharing that may allow MIMO behaviour.

In Figure 2, an example of the 3-user IC is shown where interference alignment is applied. In this example, interference alignment is applied over 3 frequency dimensions and user 1 is allowed to transmit two data streams while users 2 and 3 are allowed to transmit one data stream where \( x_i \) represents the transmitted data stream at transmitter \( i \), \( V_i \) represents the precoding vector at transmitter \( i \), and \( H_{ij} \) represents the channel coefficients between transmitter \( j \) and receiver \( i \).

![Figure 14: An Example 3-user Interference Channel.](image)
4.1.2.1  K-User Interference Channel with Single Antenna Nodes

Networks of single-antenna nodes with no cooperation between the transmitters or receivers could be considered uninteresting from the degrees of freedom perspective as intuition would suggest that these networks could only have one degree of freedom. However, it is shown in [39] that by using interference alignment, the total number of spatial degrees of freedom for the K-user IC is almost surely $K/2$ per orthogonal time and frequency dimension. Thus, only half the spatial degrees of freedom are lost due to distributed processing of transmitted and received signals on the interference channel.

In [39], Cadambe and Jafar (CJ) proposed an interference alignment scheme that is able to achieve a total of $K/2$ degrees of freedom as the number of channel extensions reaches infinity, for any arbitrarily chosen $K$. For the special case of 3-user interference channel, it is shown that the CJ scheme can offer a total of $\frac{3n+1}{2n+1}$ degrees of freedom, where $n$ is an integer that is related to the number of channel extensions $N$ by $N = 2n + 1$, $n \in \mathbb{N}$. It is also shown that the design of the precoding vector for the proposed interference alignment scheme becomes more complex as the number of users and channel extensions increase. Thus, we find that much of the following work on IA precoding design focuses on the case of 3-user IC and with limited channel extensions.

In [42], Shen, Host-Madsen, and Vidal (SHV) proposed an enhancement to the achievable rate in terms of high SNR offset and at the same time maintain the optimality of degrees of freedom achieved by the CJ scheme. Two new schemes have thus been proposed for the K-user IC with single antenna per node. While one of the schemes try to find better precoding subspaces than those obtained by the CJ scheme, the other one optimizes the precoding vectors within the subspaces obtained from this scheme. It is shown that by using the second scheme and by choosing ortho-normal precoding matrices at the transmitters, an increase in sum rate with probability one can be observed.

In [43], Douglas and Murat (DM) provided two new algorithms that optimize the precoding subspaces, which maximizes the data rate performance of the CJ scheme while maintaining the achievable degrees of freedom. One design is obtained as a global solution of a constrained convex (concave) optimization problem that maximizes the sum rate. The other design provides a low complexity closed-form solution to a constrained maximization problem with a suboptimal sum rate objective function. The proposed algorithms optimize the precoding subspaces obtained by CJ scheme to maximize the data rate performance of the scheme. It can also be combined with the ortho-normalization procedure proposed by SHV to achieve further gains in sum rate.

Both CJ and SHV schemes are designed to work with receivers employing ZF decoding. On the other hand, the proposed schemes by DM are mainly designed to work with receivers employing MMSE decoding.

4.1.2.2  The K-User Interference Channel with Multiple Antenna Nodes

It is shown in [39] that for the 3-user IC with $M > 1$ antennas at each node, one can achieve $3M/2$ degrees of freedom with constant channel matrices, i.e., multiple frequency slots are not required. It is also shown that exactly $3M/2$ degrees of freedom are achieved by zero forcing and interference alignment, which gives us a lower bound on sum capacity of $3M/2 \log(1 + \text{SNR}) + O(1)$. Since the outer bound on sum capacity is also $3M/2 \log(1 + \text{SNR}) + O(1)$, we have an $O(1)$ approximation to the capacity of the 3-user MIMO IC with $M > 1$ antennas at all nodes.

Two precoding design schemes have been proposed in [39], one is for the case when $M$ is even and the other is for the case when $M$ is odd. Both schemes are shown to provide a total of $3M/2$ degrees of freedom.
Thus, we can conclude that the 3-user interference network where all nodes are equipped with multiple antennas can achieve optimal degrees of freedom without the need for long channel extensions.

4.1.3 The $K$-user Interference Channel with Cooperation

One of the important channel types for which DoF inner and outer bounds are investigated and IA-based schemes are developed and applied is the $K$-user IC with cooperation. It is a $K$-user IC in which users cooperate together in order to get more DoF, hence, more data rates, than they would obtain without cooperation.

If all the users of a $K$-user IC cooperate together, the resulting channel will be similar to the point-to-point MIMO channel with $K$ antennas at both the transmitter and the receiver. Hence, the maximum achievable DoF of this channel can be shown to be $K$ DoF, i.e., each user sends data with similar rate to that if there is no interference. However, in practical scenarios, not all the users of the $K$-user IC are allowed to cooperate together, but rather sub-groups of them. Hence, researchers were motivated to investigate the outer bound and achievable DoF of the $K$-user IC when partial cooperation between users exists. Throughout the following points, the main results in this topic are summarized.

![Figure 15: The K-User IC with Partial Cooperation](image)

**4.1.3.1 The Outer Bound of the $K$-user IC with Partial Cooperation**

In [44], the authors defined the cooperation order to be the number of users that cooperate together. Considering the $K$-user IC with cooperation order of $M$ where $M < K$, they proved that the achievable DoF can not be more than $\frac{KM}{M + 1}$. For instance, for the 5-user IC with cooperating subsets of order 3, the outer bound of the achievable DoF is 15/4. It can be noticed from this outer bound that as $M$ increases, the DoF that each user achieves approaches unity.

**4.1.3.2 Achievable DoF of the $K$-user IC with Partial Cooperation**

In [44], the authors also developed an IA-based scheme that proves the achievability of the outer bound $\frac{KM}{M + 1}$ only for the case of $K = 4$ and $M = 2$ leaving the achievability of the outer bound in the general case to be an open problem. In [45], the achievability of the outer bound $\frac{KM}{M + 1}$ is proved for any $K$, but when $M = K - 2$. Moreover, they developed an algorithm called Successive Interference Alignment (SIA) that enables users to achieve this DoF.
4.1.3.3 Full and Local Connectivity

In [44] and [45], the networks are assumed to be fully connected, i.e., each user is receiving interference from all the non-intended transmitters in addition to the message of its intended one. In [46], the outer bound and achievable DoF of the $K$-user IC with partial cooperation is studied but with the assumption of local connectivity. For the 4-user IC, with cooperation order of 2, and assuming that each receiver receives messages from only 2 out of the three non-intended transmitters in addition to its desired one, the authors proved that the achievable DoF is surprisingly 12/5 which is less than 8/3 that are achievable in case of fully connected network. This means that receiving interference may increase the achievable DoF.

4.1.4 Relays Aided IA

Using relays has mostly been for the purpose of amplifying the signal in order to make it detectable by the receiver as the transmit signal power may not be sufficient. An interesting application of relays is to use them in interference alignment. It was found in [47] that relays do not increase the DoF for the fully connected network but they render the use of IA more feasible.

The most important type of relayed networks are relayed multi-hop networks where the destination cannot hear the source but only the relay hears the source then the destination hears the relay. With a MIMO relay, we can view the network as a MAC channel from the distributed sources to multiple antenna relay followed by a BC channel from the multiple antenna relay to the distributed destinations.

Finding the DoF of relayed network is challenging. DoF of two hop layered interference networks are known when there is a single relay that is equipped with sufficiently many antennas [48] [49] or when there is a large number of distributed relays [50] [51]. In all cases the goal is to completely eliminate interference between communicating transmitter-receiver pairs.

The 2x2x2 interference channel, where two transmitters wish to send independent messages to their corresponding receivers over a concatenation of two interference channels. While several studies of this channel [52] [53] treat the two hops as interference channels, it is evident that any such approach cannot achieve more than 1 DoF (because the 2 user interference channel has only 1 DoF).

On the other hand, by treating it as a concatenation of two X channels, Cadambe and Jafar have shown in [40] that 4/3 DoF can be achieved almost surely. This requires that the sources split their messages into two independent parts, one for each relay. The four independent messages transform the 2x2x2 IC into the X channel setting over each hop and 4/3 DoF become achievable.

4.2 IA Schemes Design Issues

4.2.1 Absence of Channel Knowledge (Blind IA)

IA schemes introduced in [39]-[54] assumes global channel knowledge at both transmitters and receivers in order to be able to align the interference at the desired receivers. Other schemes, such as the one proposed in [55], only needs local channel knowledge in order to align interference at the receivers. Blind IA techniques tend to align interference at the receivers without CSI at neither the transmitters nor the receivers. Among those techniques that managed to align interference without any knowledge of the CSI, are those proposed in [56] and [57], which assume different channel correlations between different transmitters and receivers in order to achieve a total DoF of $\frac{MK}{M+K-1}$ for BC channels, where $M$ is the number of antennas at the transmitter.
and $K$ is the number of receivers. This work was extended in [58] where the receivers are equipped with $N$ antennas in order to achieve a total DoF of $\frac{MNK}{M+KN-N}$. In the following subsections, we will summarize the main points of some of the most recent work in this topic.

4.2.1.1 Exploiting Channel Correlations – Simple Interference Alignment Schemes with no CSIT

The work in [56] explores a few selected multiuser communication problems where the possibility of applying interference alignment, and consequently the total number of DoF, with channel uncertainty at the transmitters have not been determined before. The configurations investigated in [56] are MISO BC with no CSIT for one user, MISO BC with no CSIT for two users, the X Channel and the MIMO IC. The main contribution was to show that, even with no knowledge of channel coefficient values at the transmitters, the knowledge of the channels correlation structure can be exploited to achieve interference alignment.

In [56], the possibility of blind interference alignment through simple examples that illustrate the key concept were highlighted. A staggered block fading model with a coherence interval $T = 2$ is assumed. In this model, each user channel state is constant for 2 channel uses and then switches to a different generic value (i.e., drawn from a continuous distribution but not necessarily independent). This staggered block fading generates a super symbol as shown in Figure 16: Super Symbol Structure due to Staggered Block Fading below.

![Super Symbol Structure due to Staggered Block Fading](image)

The main conclusion in [56] is that the achievable DoF for MISO BC with no CSIT for one user is 3/2, for MISO BC with no CSIT for both users is 4/3, for the X Channel is 4/3 (which is the same as MIMO BC) and for the MIMO IC, user 1 achieved a DoF of while user 2 achieved a DoF of 3/2.

4.2.1.2 Blind Interference Alignment through Staggered Antenna Switching

Staggered antenna switching is a key technique for blind IA. The switching antennas may be a single antenna or multiple antennas at each receiver switching between a number of different preset modes in order to create the block fading effect (super-symbol construction).

In [57], blind IA for the MISO BC is introduced. More specifically, a blind interference alignment scheme for the vector broadcast channel where the transmitter is equipped with multiple antennas and the receivers are each equipped with a reconfigurable antenna capable of switching among preset modes is proposed.
Without any knowledge of the channel coefficient values at the transmitters and with only mild assumptions on the channel coherence structure, it is shown that a total of \( \frac{MK}{M+K-1} \) DoF are achievable. The key to the blind interference alignment scheme is the ability of the receivers to switch between reconfigurable antenna modes to create short term channel fluctuation patterns that are exploited by the transmitter. The proposed scheme does not require cooperation between transmit antennas and is therefore applicable to the \( M \times K \times X \) network as well. Only finite symbol extensions are used, and no channel knowledge at the receivers is required to null the interference.

The goal of manipulating the channel naturally leads us to reconfigurable antennas. A reconfigurable antenna is an antenna that can change its characteristics by dynamically changing its geometry. A schematic diagram of the reconfigurable antenna is shown in Figure 17.

Figure 17: Reconfigurable Antenna Structure

In [57], beam forming and channel matrices are found for a general \( K \)-user \( M \times 1 \) MISO BC configuration. The proposed scheme relies on designing an antenna switching pattern for each user and a beam forming strategy based on the corresponding temporal correlation structure in order to generate the super-symbol structure. Some examples are shown for the 2-user \( 2 \times 1 \) and the 2-user \( 3 \times 1 \) MIMO BC before showing the general case of the \( K \)-user \( M \times 1 \) channel.

All the previous work in [57] is extended in [58] for the case of multiple antennas at the receivers. In particular, [58] explores the DoF of the BC where the transmitter is equipped with \( M \) antennas and there are \( K \) receivers, each equipped with \( N \) reconfigurable antennas capable of switching among \( M \) preset modes. Without any knowledge of the channel coefficient values but only receiver antenna switching modes at the transmitter, an interference alignment scheme for this channel is proposed. It is shown that if \( N < M \), then a total of \( \frac{MNK}{M+KN-N} \) DoF are achievable, almost surely.

First some examples for MIMO BC are introduced as the 2-user \( 3 \times 2 \), \( 5 \times 2 \) and \( 5 \times 3 \) channels and the beam-forming matrix and channel matrices are introduced for each case. After that the general case for \( M \times N \) MIMO BC is introduced with its beam forming and channel matrix. Also mapping from the MISO BC matrices and super-symbols (which are introduced in [57]) to the MIMO BC is shown in the last section.

4.2.2 Retrospective IA

Sometimes accurate knowledge of the current channel coefficients is not that practical especially at the transmitter side since in most cases channel estimation takes place at the receiver and the transmitter receives a copy through feedback. In these cases, a challenging topic related to IA appears, which is Retrospective IA, in which the transmitter does not know the current channel values but has some sort of knowledge of past channel values.

Among the works that investigate the achievable DoF in case of delayed CSI are [59] and [60]. The work in [60] gives some details about the different types of delayed settings that could be encountered such as: delayed CSIT, delayed output feedback and delayed Shannon feedback. These settings are explained as follows:
i- **Delayed CSIT**: This is the setting where the feedback provides the transmitters only with the value of the past channel states $\mathbf{H}$ but not the output signals.

ii- **Delayed Output Feedback**: This is the setting where the feedback provides the transmitters only with the past received signals seen by the receivers, but not the channel states explicitly.

iii- **Delayed Shannon Feedback**: This is the setting where the feedback provides the transmitters with both the past received signals as well as the past channel states $\mathbf{H}$.

The authors in [60] also discuss the achievable DoF in the cases of MIMO BC, the X-network and the K-user IC in the various settings mentioned above and it is found that delayed CSIT has mostly lower achievable DoF than delayed output feedback. The 2-user MISO BC with delayed CSIT easily achieves the outer bound of $4/3$. It is not known if the same DoF can be achieved on the X channel, i.e., without cooperation between transmitters. It is also shown that delayed CSIT is still useful in the X channel from a DoF perspective, as one can achieve $8/7$ DoF. The scheme operates in two phases, and with two layers of variables as the scheme proposed in [60]. The novelty of retrospective alignment appears in the construction of auxiliary variables that aid in the alignment of the previously transmitted information symbols based on only the information symbols available to each transmitter. The same scheme was used to prove the achievability of $9/8$ DoF for the 3-user IC with delayed CSIT. Also, it was found that the X channel and the 3-user IC can achieve $4/3$ and $6/5$ DoF, respectively, when delayed output feedback is available to the transmitters.

### 4.2.3 Imperfect Channel Estimation

All IA techniques assume perfect CSI while practically most of the time imperfect CSI is present. This becomes more significant especially at finite SNRs in which noise affects the accuracy of the channel coefficients estimation. The work in [61] investigates the effect of imperfect CSI for lattice interference alignment for the K-user quasi-static interference channel. The IA scheme proposed is the alternating minimization technique presented in [62].

Also, some work was done on investigating the effect of imperfect CSI for vector IA with correlated antennas [63]. The authors in [63] quantified the impact of imperfect CSI and transmit antenna correlation via the per-stream post-processing SINR distribution. Upon using zero-forcing equalizers in a Rayleigh channel, post-processing SINR is shown to be exponentially distributed with the mean value being a function of the number of antennas at each node, the transmit antenna correlation, the imperfection in CSI, and the transmit power. It is shown that, in the presence of imperfect CSI, the performance of IA degrades with the increase of the total number of streams in the network and if the imperfection does not vanish at asymptotically high transmitting powers, the multiplexing gain is zero. Moreover, it is shown that as long as the channel matrices are full-rank, the impact of transmit correlation is less detrimental; confined to a constant power loss, which does not decrease the multiplexing gain achievable through IA. The performance of the two most commonly used transmit techniques in orthogonal access networks; beamforming and spatial multiplexing, were compared to the performance of IA by utilizing the derived SINR distributions where it is shown that IA is not always the optimum transmission strategy given realistic system parameters.

### 4.2.4 Feasibility of IA with Constant Channels

When the channel coefficients are constant, the feasibility of a certain degrees of freedom is not guaranteed in general and it depends on number of users (K), number of antennas at each node, desired number of degrees of freedom to be achieved, and the channel realization. In the following subsections, we summarize some of the main results in this topic.
4.2.4.1 A Criterion Determining the Feasibility of a Solution in IA based Schemes with Constant Channels

In [64], the authors introduce a criterion that determines the existence of a solution for the IA equations. They found that for a given system, a certain number of degrees of freedom $d_i$ is achievable if the system of equations is proper, i.e., if the number of equations in not less than the number of unknowns.

4.2.4.2 Lattice Interference Alignment

In [65], IA over constant channels is shown to be possible through lattice alignment scheme. Lattice alignment depends on aligning the interference in the signal space instead of the vector space. The main progress in this area is presented by Bresler et al., in [65] for the many-to-one IC, and by Cadambe et al., in [66] for the fully-connected IC. Despite the advantages of the lattice alignment schemes, this scheme loses its attractiveness when dealing with a practical environment with intermediate SNRs.

4.2.4.3 Iterative Algorithms

Many iterative algorithms are developed in order to give insights for the achievable DoF of the different ICs under constant coefficients assumption. In the following section, the main results in this area are illustrated.

4.2.5 Iterative IA Schemes

Closed-form interference alignment schemes are not found for all channel types or for a general number of users. A significant portion of the IA literature is based on iterative algorithms. One of the main issues, which differ between the iterative types, is the number of iterations that is needed in order to converge and also whether convergence occurs to a local or a global minimum. In what follows, we introduce some of the most common work in this topic.

4.2.5.1 Distributed IA

One of the earliest works presenting distributed IA is [55], which introduces some iterative algorithms trying to reach the capacity of wireless networks. It proposes iterative algorithms that take a cognitive approach to interference management and utilize only the local side information available naturally due to the reciprocity of wireless networks. The two key properties considered in this work can be summarized as follows:

- **Cognitive Principle:** Unlike selfish approaches studied in prior work where each transmitter tries to maximize his own rate by transmitting along those signaling dimensions where his desired receiver sees the least interference, an unselfish approach is followed where each transmitter primarily tries to minimize the interference to unintended receivers. The cognitive approach is found to lead to interference alignment, and is thus capable of approaching network capacity at high SNR.

- **Reciprocity:** the signaling dimensions along which a receiving node sees the least interference from other users are also the same signaling dimensions along which this node will cause the least interference to other nodes in the reciprocal network where all transmitters and receivers switch roles.

The paper introduces two main iterative algorithms; in both algorithms they first begin with any arbitrary precoding vectors ($V$) then optimizes the values of the decoding vectors ($U$). After that the transmitters and receivers switch roles (due to networks reciprocity) and then it is assumed that receivers are now the transmitters and vice-versa and the pre-coding vectors are optimized at this time, as shown in Figure 18 which summarizes the process.
The optimization criteria, which were proposed in order to optimize (Vs and Us), are interference alignment (does not maximize desired signal) and SINR maximization.

Later in [67], this algorithm is modified for mainly the 3-user IC in order to converge with less number of iterations, which was proved to perform much better for overhead limited scenarios. First, it investigates the SISO networks then extended it to MIMO networks for 3 users only.

**4.2.5.2 Interference Alignment via Alternative Minimization**

More work was extended in the iterative algorithms in order to minimize the interference as in [62], which proposes an algorithm for MIMO IA that alternatively optimizes the precoders at the transmitters and the interference subspaces at the receivers. The precoders and interference subspaces are constrained to be orthonormal and, with the optimization used, will be shown to lie on the Grassmann manifold. The gradient of the objective function on this manifold has a closed-form solution so an alternating minimization approach can be applied. It establishes convergence of the algorithm, although convergence to a global optimum requires additional work. The proposed algorithm gives insight into when MIMO interference alignment is feasible without any assumptions on the number of users, the method of obtaining CSI, reciprocity of the channel [55], antenna distribution, or stream allocation.

Also, methods based on MMSE–iterative minimization algorithm were also proposed in several works as in [68], for example, subject to individual transmit power constraints. It shows that the transmitter and receiver under such criterion could be realized through a joint iterative algorithm. It also discusses the MMSE-algorithm with imperfect channel state information (CSI). It is shown to be less sensitive to channel estimation errors. Other methods based on convex optimization are also introduced in [69].

**4.2.5.3 Limited Number of Available Dimensions**

In [39], the authors proposed an IA scheme that achieves the maximum $K/2$ DoF that are available for the $K$-user IC. However, to achieve these DoF, symbols are needed to be extended over a huge number of dimensions that are asymptotically infinite. When the number of available dimensions in limited, this scheme is no longer optimal and seeking better schemes becomes a target for many research works. In the following points, the main research results concerning this topic are illustrated.
4.2.5.4 Efficient Interference Alignment Beam-Forming Design

In [70], a new IA scheme is proposed and shown to obtain more DoF than [39] at any given number of dimensions; it is based on optimized design of the beam-forming matrices (BF-IA). Using this scheme for the $K$-user IC, the DoF for $M$ available dimensions can be shown to be:

$$\eta(K, M) = \frac{(K - 1)d_3 + d_1}{M}$$  \hspace{1cm} (13)

where $M = d_1 + d_3$, $d_1$ and $d_3$ are the numbers of transmit directions (independent streams) of users 1 and 3, respectively. It can be noticed from equation (1) that as $d_3$ approaches $d_1$, the DoF approaches $K/2$ in less dimensions. Based on this observation, the beamforming matrices in [70] are designed, resulting in the following values for $d_1$ and $d_3$:

$$d_1 = \left(\frac{n + D + 1}{D}\right), \quad d_3 = \left(\frac{n + D}{D}\right)$$  \hspace{1cm} (14)

where $D = (K - 1)(K - 2) - 1$ and $n$ is a positive integer.

4.2.5.5 Group-based Interference Alignment

The schemes in [39] and [70] assume that resources will be allocated to all users simultaneously; consequently, the design of the beam-forming matrices of the $K$ users should be done together. If the number of dimensions is limited, [71] shows that allocating resources to all users simultaneously is not optimal. A group-based IA (GIA) scheme is proposed to get the optimal DoF achievable. It assumes that the BF-IA scheme will be used only by a group of the $K$ users rather than all of them. In this paper, an optimization problem is formulated and a dynamic-programming-based algorithm is developed in order to determine the optimum groups that should be chosen in order to obtain the maximum possible DoF for a certain number of dimensions.

4.2.5.6 Fair Group based Interference Alignment:

Despite the optimality of the GIA scheme with respect to total achieved DoF, it provides no guarantees on fairness between users. As this algorithm does not guarantee any DoF for any randomly selected user, this may lead to a user with zero DoF. In [72], the authors propose a GIA-based scheme but with fairness constraint, i.e., they attempt to find the groups that maximize the total achieved degrees of freedom within a given number of dimensions, but with a minimum achieved DoF for each user. An optimization problem is formulated, and optimal and greedy-optimal algorithms are developed in order to determine which groups to choose for the aim of maximizing the achieved DoF with certain fairness constraints. Figure.1 (5 please correct) shows a comparison between the DoF achieved by this algorithm and by the algorithms in [70] and [71], for the case of $K$-user IC, $K = 6$. 
Figure 19: A Comparison between the DoF achieved by the proposed greedy algorithm and the algorithms in [27], [26] for the case of 6-user IC
5 Survey of eICIC Techniques in HetNets

A heterogeneous network (HetNet) is a network comprised of different types of wireless access points with different capabilities, constraints and operating functionalities [73]. Macro-cells, pico-cells, relays, remote radio heads (RRHs), and femto-cells are examples of the available types of access points in LTE release 10 (LTE-Advanced). Throughout the write-up, we refer to a Macro eNB as MeNB and to a Home eNB (or femto-cell) as HeNB.

The main challenge is that the interference that occurs between femto-cells and macro-cells can limit the performance increase, which is gained due to the spatial spectrum reuse. This leads to the need for enhanced techniques to avoid or at least mitigate the interference between the macro-cells (MeNB) and the femto-cells (HeNBs). HeNBs are always deployed without operator planning, and operators do not control either the number or the location of these cells. The unplanned deployment of HeNBs generates strong interference to MeNB subscribers.

Enhanced Inter-cell Interference Coordination (eICIC) is a proposed framework by the 3GPP project to handle ICI in HetNet environments. The focus in this article is eICIC issues and techniques in a HetNet environment comprised of macro-cells and femto-cells.

5.1 eICIC Techniques

There are three different categories of eICIC solutions that are proposed to mitigate the interference between macro-cells and femto-cells. These solutions can be categorized as following:

- Time-domain techniques.
- Power control techniques.
- Frequency-domain techniques.

Each category has some proposed techniques as illustrated in Figure 20. In the following subsections each category and its associated techniques will be explained in details.
### 5.1.1 Time-domain Techniques

Time-domain eICIC techniques depend mainly on the utilization of time-domain resources across nodes in a coordinated manner through backhaul signalling [74]. In macro-femto deployment a non-CSG macro UE (MUE) is exposed to dominant interference in the downlink from the femto-cell, and the CSG femto UE (HUE) is exposed to strong uplink interference from the MUE as shown in Figure 21. In time-domain eICIC techniques this interference is avoided or at least mitigated through the coordinated usage of the time-domain resources such as the subframes or the OFDM symbols [75]. In the following subsections these techniques are discussed.
5.1.1.1 Subframe Alignment

In this category the subframe boundary of MeNB and HeNB is aligned through backhaul signalling. This leads to that the control and data channels of both MUE and HeNB are overlapped, and hence to avoid the interference between them, the HeNB has to coordinate its transmission. Two alternatives have been proposed for this coordination.

5.1.1.1.1 Almost Blank Subframe (ABSF)

In this approach the HeNB configures some of its subframes as ABSF. An ABSF is a subframe in which no control (PDCCH) or data (PDSCH) is transmitted. It is almost blank because that some resource elements are mapped to reference symbols (RSs) and all other resource elements are nulled. This approach is sometimes called No PDCCH approach. Almost blank subframes are fully backward compatible and characterized by lack of unicast transmission on any physical channel as stated in [76]:

- PSS/SSS transmission occurs in subframe 0 and 5 (FDD) and 0, 1, 4 and 5 (TDD for 5 ms periodicity), and 0 and 1 (TDD for 10 ms periodicity)
- PBCH transmission occurs in subframe 0
- CRS transmission occurs in all subframes
- CRS transmission in the data region is avoided if a subframe is configured as MBSFN subframe
- PDCCH transmission masked with P-RNTI may occur only in subframes configured for paging (subframes 0, 4, 5 and 9)
- PDCCH transmission masked with SI-RNTI occur only in subframe 5 in even SFNs
- PCFICH transmission occurs only in subframes where PDCCH transmission occurs

The ABSF concept is illustrated in Figure 22, and the MUE scheduling is illustrated in Figure 23. Subframe blanking at femtocells mitigates the interference between MeNB and HeNB. But interference still exists due to the RSs existing in the ABSF at HeNB. Another drawback for this approach is that the throughput of the femtocell is degraded due to the blanked subframes.
A final note to mention is that there is a set of available ABSF patterns for FDD and TDD deployments. The blanking rate \( \leq 2/8 \) (for FDD) and \( \leq 2/10 \) (for TDD), and the patterns shall apply from subframe 0. These patterns are defined in [77] and are illustrated here in Figure 24 and Figure 25 respectively.

- **FDD patterns:**
  - (1/8, 1, ABSF) \[ 10000000, \ldots \]
  - (2/8, 2, ABSF) \[ 11000000, \ldots \]
  - (3/20, 1, MBSF) \[ 1000010000 1000000000 \]

- **TDD patterns:**
  - (1/10, 1) \[ 0000000001, \ldots \]
  - (2/10, 2) \[ 0000011000 0000011000 \]
  - (2/10, 1, MBSF) \[ 0000100001 0000100001 \]
- Other candidate patterns for consideration if the group is Ok with the work load:
  - **FDD patterns:**
    - \((3/8, 1, \text{ABSF})\) \([11100000, \ldots]\)

1/8 pattern

2/8 pattern

3/8 pattern

3/20 pattern

Figure 24: FDD Blanking Patterns

1/10 pattern

2/10 pattern

2/10, MBSF pattern

Figure 25: TDD Blanking Patterns
5.1.1.1.2 Lightly-loaded Subframe

This approach is to a large extent similar to the previous scheme. But with a difference that the load of the PDCCH and the corresponding PDSCH is controlled in the HeNB side, this is to limit the control-to-control interference to the MUE. In this approach the transmission of PDCCH and PDSCH is allowed in every subframe in general at HeNB, but the data-to-data interference is avoided by means of RB-level coordination. The HeNB does not transmit any PDSCH in some RBs of some configured subframes (those used by the MeNB to transmit to MUE’s) as illustrated in Figure 26.

The above two discussed approaches suffer from the RS-to-control and data interference because the HeNB should keep transmitting RSs even in the coordinated subframes. This RS interference can be avoided by configuring the HeNB’s subframe as MBSFN subframe [75]. MBSFN subframes are special subframes that are used in the operation of MBMS services in LTE, and they are structured differently from regular subframes. The key features of MBSFN subframe to support MBMS services are using extended cyclic prefix instead of normal cyclic prefix, and the reference signals pattern is modified compared to regular non-MBSFN subframes. The reference symbols are spaced more closely in the frequency domain to be on every other frequency instead on every sixth subcarrier. This can thus improve the accuracy of the channel estimate [78]. The RSs in MBSFN subframes are independent of the cell ID as a group of cells will transmit the same data to be received at UE as a composite channel; this means that the RSs structure in MBSFN subframes is fixed as illustrated in Figure 27.
5.1.1.2 OFDM Symbol Shift

In this category the HeNB subframe boundary is shifted by one or more OFDM symbols relative to that of MeNB [75]. This symbol level shift lets the control channel symbols of the MUE to be detected without interference with the PDCCH or RSs of the HeNB as illustrated in Figure 28. But on the other hand it overlaps with the PDSCH of the HeNB, and hence the HeNB has to do some coordination on its PDSCH to avoid this interference. There are two different proposed approaches for this purpose explained in the following:

5.1.1.2.1 PDSCH Symbol Muting at HeNB

In this technique HeNB mutes the OFDM symbols or some REs of the OFDM symbol which overlap with the control channels of the MUE in some subframes. By this muting the MUE can receive and decode its control information with no or mitigated interference from HeNB [75]. To avoid data-to-data channel interference, the next subframe is configured as ABSF in the HeNB as illustrated in Figure 29. One drawback of this approach is the impact of PDSCH symbol muting on the HUE’s performance. If the HUE is a Rel-8/9 UE, there is no way to inform the HUE of the location of the muted symbol and this will lead to PDSCH throughput loss especially when the high level MCS is applied. The throughput loss can be mitigated by informing the muted symbol location if the HUE is a Rel-10 UE so that the corresponding PDSCH is rate-matched around the muted symbols [75]. Rate Matching is the process in which bits are selected for transmission from the rate 1/3 turbo encoder via puncturing and/or repetition. Rate matching increases or decreases the coding rate, and hence the data rate. By rate matching around the muted symbols via increasing the code rate, the throughput loss that is caused by symbol muting can be compensated [78].
5.1.1.2.2 Consecutive Subframe Blanking

In this approach the HeNB configures the whole subframe to be blank not only muting some of its symbols. So the MUE still receive interference free control channels. If the MUE in close proximity to the HeNB is scheduled to N-1 subframes, there are N-1 more subframes that also have to be blanked in the HeNB to protect the PDCCH and the PDSCH of the MUE. So a total of N subframes have to be configured as ABSFs in the HeNB if the MUE is scheduled to N-1 subframes as illustrated in Figure 30. In this operation the impact of PDSCH symbol muting approach does not need to be considered [3], the drawback of this approach is the loss of resources at the HeNB.

![Figure 30: Consecutive Subframe Blanking with OFDM Symbol Shift in HeNB](image)

5.1.2 Power Control Techniques

Power control eICIC techniques are heavily discussed in 3GPP for handling of the interference scenarios between MeNB and HeNB in HetNets [73]. This approach depends mainly upon reducing the radiated power of femtocells to improve the performance of victim MUEs. However, this sacrifices the total throughput of the femtocell users which is also reduced. Different proposals are discussed and it will be presented as follows:

5.1.2.1 Backhaul Signalling of Power Reduction

Power reduction based on backhaul signalling is recommended between MeNBs due to the existence of the backhaul x2 interface between MeNBs as shown in Figure 31. Power reduction applies to reference symbols and control transmission of recipient node [76]. This scheme of power control needs backhaul communication with constrained delays, which is supported in MeNB to MeNB interference scenarios via x2 interface. But in MeNB to HeNB interference scenarios the backhaul of HeNB rely on the consumers’ broadband connections [73]. HeNB backhauling through broadband connections (like DSL) face difficulties in maintaining Quality of Service (QoS), and hence it’s not recommended to use this scheme in macro-femto interference environments.

![Figure 31: Backhaul Signalling of Power Reduction between MeNBs](image)
5.1.2.2 Power Setting based on HeNB Measurements

Power setting of the HeNB is another approach to limit the interference between the MeNBs and HeNBs. The main concept of this approach is to control the radiated power of the HeNB to limit its coverage to the premises boundary of the owner of that HeNB as shown in Figure 32 [79]. Different proposals are discussed in 3GPP for this purpose where all of them depend on measurements performed locally by the HeNB. In the following sub-sections a brief description for those proposals is provided.

![Figure 32: Power Setting of HeNB](image)

5.1.2.2.1 Strongest MeNB at HeNB

In this approach the transmit power of the HeNB is adjusted based on the measurement of the received power from the strongest co-channel macrocell. The adjustment of the HeNB radiated power is according to the following formula:

\[
P_{tx} = \max(\min(\alpha \cdot P_m + \beta, P_{max}), P_{min}) \quad [dB_m]
\]

(15)

where parameters \( P_{max} \) and \( P_{min} \) are the minimum and maximum HeNB transmit power settings, while \( P_m \) is the received power from the strongest co-channel macro cell. Parameter \( \alpha \) is a linear scalar that allows altering the slope of power control mapping curve and as such adjustment to different sizes of macro cells. \( \beta \) is a parameter expressed in dB that can be used for altering the exact range of \( P_m \) covered by dynamic range of power control [79].

![Figure 33: Power Setting of HeNB based on Strongest MeNB](image)
A PC scheme based on (15) seems realistic and simple to implement, and hence it is a candidate for standardization within the time-frame for LTE Rel-10. It is important also to notice that this approach in power control only affects the standardization and implementation for the HeNBs and rely on HeNB measurements only. Hence no additional signalling between MeNBs and/or HeNBs is required for this solution and also no new measurements or support from UEs is required [79].

5.1.2.2.2  HeNB to MUE Pathloss Measurement

For the power control approach based on the measurement of pathloss between HeNB and MUE, the transmit power of the HeNB should be set as follows:

\[ P_{tx} = \text{median}(P_m + P_{offset}, P_{max}, P_{min}) \quad [dBm] \] (16)

\[ P_{offset} = \text{median}(P_{pl}, P_{offset-max}, P_{offset-min}) \quad [dBm] \] (17)

where \( P_{max}, P_{min} \) and \( P_m \) hold the same meaning as Eq. (15). \( P_{offset} \) (dB) is the power offset described in details in Eq. (17). Here \( P_{pl} \) is a power offset value corresponding to the indoor path loss and the penetration loss between the nearest MUE and the femtocell. \( P_{offset-max} \) and \( P_{offset-min} \) are the maximum and minimum values of the \( P_{offset} \) to restrict its territory [74].

5.1.2.2.3  Objective SINR of HUE

In this approach the value of the received SINR at HUE is restricted to a target value and the transmit power of the HeNB is reduced to achieve this target SINR leading to lower interference levels with the MUEs in close proximity [73] [74] [80]. The transmission power of the femtocell is set based on:

\[ P_{HeNB} = \max\left(P_{min}, \min\left((P_{Lestimation} + P_{HUE,\text{received}}), P_{max}\right)\right) \quad [dBm] \] (18)

\[ P_{HUE,\text{received}} = 10 \log_{10}\left(10^{I/10} + 10^{N_{background\_noise}/10}\right) + x \quad [dBm] \] (19)

where

- \( I \) represents the interference detected by the served HUE;
- \( N_{background\_noise} \) is the background noise value;
- \( x \) is the objective SINR to be targeted at the HUE for reasonable performance;
- \( P_{Lestimation} \) is the path loss estimation between the femtocell and the served HUE;
- \( P_{min} \) and \( P_{max} \) represent the femtocell minimum and maximum transmission power setting boundary, respectively.

The aim of this method is to depress the interference suffered by the MUE in close proximity of CSG femtocells by restricting received power of HUE to a desired relatively low and acceptable level [74]. The formulation of the proposed power control scheme indicates that the principle is to limit the HeNB transmission power as low as possible with a precondition that almost all HUE could work at a tolerable channel condition. It should be noticed that this power control scheme is R8/9 UE compatible, which means
that no more new UE measurement is needed. The key point of this method is how to obtain suitable input parameters while ensuring the feasibility and robustness of the algorithm [80] [80].

5.1.2.2.4 Objective SINR of MUE

This power control technique restrict the transmit power of the HeNB to a value that guarantees a certain SINR at the victim MUE that is in close proximity to the HeNB. This protects the reception of the CCH of MUE. The power setting of the femtocell is based on the following equation [74]:

\[
P_{tx} = \max(\min(\alpha \cdot P_{SINR} + \beta \cdot P_{\text{max}}), P_{\text{min}}) \quad [dBm]
\] (20)

This method is based on the SINR sensing of the MUE. \( P_{SINR} \) is defined as the SINR of the MUE considering only the nearest femtocell interference. \( \beta \) have the same definition of the algorithm in (15)

5.1.2.2.5 PBCH Measurement

Most HUEs are in good channel condition which implies a HUE can decode the PBCH without receiving the full set of four PBCH. The femtocell could set very low power (e.g. be smaller than the receiving power of MeNB at HeNB) when transmitting PBCH or mute the PBCH transmission in some of its subframe.

5.1.3 Frequency-domain Techniques

In frequency-domain eICIC solutions, control channels and physical signals (i.e., synchronization signals and reference signals) of different cells are scheduled in reduced bandwidths in order to have totally orthogonal transmission of these signals at different cells [74]. While frequency-domain orthogonalization may be achieved in a static manner, it may also be implemented dynamically through victim UE detection. For instance, victim MUEs can be determined by the macro eNBs by utilizing the measurement reports of the MUEs, and their identity may be signalled by the MeNB to the HeNB(s) through the backhaul. Alternatively, victim MUEs may also be sensed by the HeNBs [73]. The aggressor cell refers to the HeNB that is in close proximity to a victim MUE which suffers a strong interference, and the victim cell is the MeNB that serves the victim MUE. Rel-8/9 UE access and operate on the reduced bandwidth without change, and Rel-10 UE access the reduced bandwidth as a Rel-8/9 UE, but may be scheduled over the entire bandwidth. This means that in Rel-10 the orthogonality in frequency domain is for control channels only, but data channels may be scheduled over the entire bandwidth available for the serving cell.

---

1 The broadcast system information in LTE is divided into two categories Master Information Block (MIB) and System Information Blocks (SIBs), MIB is carried on the PBCH and is repeated every 40 ms. MIB is 14 bits encoded in 1920 bits and then segmented into four individually self-decodable units each is transmitted in one frame of four consecutive frames leading to the MIB periodicity of 40 ms [9].
5.2 Summary of the Results of an Initial Assessment of the Schemes

In this section a summary of results for a simulation done by [73] is presented. The DL of an LTE-Advanced HetNet is simulated to test different schemes of eICIC. The simulation scenario as illustrated in Figure 35 is a residential area of size 300m × 300m in Luton (UK), containing 400 dwelling houses of which 63 were selected to host a CSG femtocell. This corresponds to an approximate 50% femto penetration assuming 3 network operators with equal customer share. The scenario is also covered by one macrocell located 200m south and 200m east from the scenario’s center (not presented in Figure 35), and one picocell deployed at the macrocell edge. Both macrocell and picocell operate in open access.

Eight mobile users, utilizing a Voice over IP (VoIP) service, move along predefined paths according to a pedestrian model of mean speed 1.1m/s. Meanwhile, the picocell and the femtocells are fully loaded and
therefore utilize all subcarriers. The cell power is uniformly distributed between subcarriers, and a pedestrian user carrying a VoIP service is considered to fall in outage if it cannot receive control data (i.e., user SINR is smaller than −4 dB for a time interval of 200ms). The provided HetNet simulated scenario based on an LTE-A network of 20 MHz with 1 macrocell transmitting at 46 dBm, 1 picocell transmitting at 30 dBm and 63 femtocells using up to 20 dBm. The dashed lines represent the routes followed by the eight macrocell users.

The simulation results are presented in Table 2, and the SINR of a victim MUE when passing close to two houses hosting a CSG femtocell is illustrated in Figure 36. The careful reading of these results gives a conclusion that the ABSF eICIC time-domain method provides the best MUE protection. There is no interference at all when the MUE is transmitting, as it transmits in subframes overlapping with the ABSFs of the femtocells. On the other hand the behaviour of the eICIC power control techniques depends on their nature and tuning, and they give distinct levels of signal quality protection for the victim MUE.

Furthermore, in Table 2 it can also be observed how the performance of power methods (15) and (17) highly depends on the tuning of their parameters, i.e., α, β, and SINRtar. If they are not fine tuned a large number of outages occurs. On the contrary, power methods (16) and (18) do not depend on this fine tuning, since they are able to adapt to each victim MUE situation considering either its path loss or its SINR. Because of this, power methods (16) and (18) can offer a ‘tailored’ protection for the victim MUE, avoiding outages while recovering the maximum throughput at each femtocell.

The last column of Table 2 indicates the average number of eICIC actions triggered in each femtocell every 10 minutes. When the eICIC power methods are not fine tuned, more than one eICIC action are triggered per femtocell to avoid an MUE call drop. This is because the eICIC actions cannot recover the MUE SINR to an adequate value. Hence, when a new channel quality indicator is fed back from the MUE to its macrocell, new eICIC actions are executed. When this case takes place, the MUE normally incurs outage. Hence, when a new channel quality indicator is fed back from the MUE to its macrocell, new eICIC actions are executed. When this case takes place, the MUE normally incurs outage. In addition, it must be noted that power methods (16) and (18) also cast more eICIC actions. This is because the path losses and SINRs of victim MUEs continuously change when they move closer to the femtocells, and thus femtocells need to update their transmission power in order to prevent MUE outage. Therefore, it can be stated that this tailored protection comes at the expense of larger backhaul signalling between cells.

The eICIC actions are triggered by the macrocells in the femtocells when MUEs report low signal quality using channel quality indicators, i.e., user SINR smaller than -3 dB.
Table 2: eICIC Techniques Performance Comparison (600 secs simulation)

<table>
<thead>
<tr>
<th>eICIC Methods</th>
<th>Number of macro-pico HOs</th>
<th>Number of PUE outages</th>
<th>Number of MUE outages</th>
<th>Average eICIC TP gain at a femto [Mbps]</th>
<th>Average sum TP of pedestrian users [kbps]</th>
<th>Average sum TP of femtocell tier [Mbps]</th>
<th>eICIC actions femto 10 min</th>
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</thead>
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<td>5</td>
<td>267</td>
<td>73.32 (100%)</td>
<td>156.03</td>
<td>3974.25</td>
<td>-</td>
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<td>0</td>
<td>0 (0%)</td>
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<td>2990.50</td>
<td>14.81</td>
</tr>
<tr>
<td>eICIC power 1 α = 1, β = 60dB</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>11.02 (15.03%)</td>
<td>1937.26</td>
<td>3153.88</td>
<td>14.81</td>
</tr>
<tr>
<td>eICIC power 1 α = 1, β = 75dB</td>
<td>5</td>
<td>0</td>
<td>25</td>
<td>46.49 (63.41%)</td>
<td>1139.26</td>
<td>3725.88</td>
<td>56.23</td>
</tr>
<tr>
<td>eICIC power 2</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>34.49 (47.03%)</td>
<td>1499.30</td>
<td>3558.75</td>
<td>20.80</td>
</tr>
<tr>
<td>eICIC power 3 $SINR_{PUE}^{RUE} = 0$dB</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>22.55 (30.75%)</td>
<td>1626.61</td>
<td>3333.75</td>
<td>17.47</td>
</tr>
<tr>
<td>eICIC power 3 $SINR_{PUE}^{RUE} = 5$dB</td>
<td>5</td>
<td>0</td>
<td>19</td>
<td>33.74 (46.02%)</td>
<td>1281.21</td>
<td>3520.75</td>
<td>47.52</td>
</tr>
<tr>
<td>eICIC power 4 $SINR_{PUE}^{RUE} = 5$dB</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>33.74 (66.05%)</td>
<td>1183.35</td>
<td>3751.13</td>
<td>39.78</td>
</tr>
</tbody>
</table>

Figure 36: SINR of a Victim MUE Passing close to CSG Femtocells.

5.3 Conclusive Remarks

The interference avoidance or at least mitigation between femtocells and macrocells in HetNets will affect the performance of both greatly, and this survey is an attempt to investigate the proposed techniques to
achieve this target. Time-domain, frequency-domain, and power control approaches are explained clarifying their strengths and drawbacks.

A mix between two or approaches may be of better effect on the performance of HetNets. Considering realistic simulations for scenarios that apply time-domain and power control techniques may give performance boosting that can be considerable.
Femtocells in LTE/LTE-Advanced: Issues and Future Directions

The mobile data traffic is growing at unprecedented rates. CISCO predicts that mobile data traffic will increase 26 times between 2010 and 2015 with a compound annual growth rate of 92 percent. This unprecedented increase puts significant pressure on network operators to improve the spectral efficiency of their systems. Hence, LTE systems adopt the state of the art technologies such as Orthogonal Frequency Division Multiplexing (OFDM), Multiple Input Multiple Output (MIMO), error recovery techniques, and other evolving techniques to push more bits into the available spectrum. However, these technologies lead to linear gains in the system spectral efficiency. Another alternative to accommodate the exponential growth of mobile data is to employ overlays of base stations to improve the spectrum utilization per unit area. For example, macro base station coverage may overlap with the coverage of other base stations with smaller footprints such as micro-, pico-, and femtocells [81].

Femto-base stations [82], also commonly known as home eNodeB (HeNB), recently evolved as a promising option for creating network overlays. Femtocells radiate very low power (<10mW) and can typically support 4-6 users per cell. Employing femtocells does not impose any special requirements on the client device. This feature is considered a unique advantage over other alternatives such as unlicensed mobile access, e.g. integrating cellular and wireless local area network. Additionally, femto-base stations enjoy other appealing features such as improving indoor coverage and capacity, increasing average revenue per user, longer battery life and enhancing customer loyalty.

All the aforementioned characteristics make femtocell deployment attractive to both network operators and end-user clients. However, femtocell deployment introduces several technical design issues. It is well-known that reducing the cell size is a means to increase the system capacity in any cellular structure. However, this capacity increase is accompanied with increase in the signalling load due to frequent cell border. Additionally, such frequent crossing increases the probability of handover blocking for active mobile terminals. Furthermore, the nature of femtocell as a customer premise equipment mandates designing femto-base stations as a smart self-configuring device capable of adapting its parameters to eliminate any possible conflict and minimize any possible interference between any base stations with coverage overlaps.

In Section 6.1, we highlight possible integrated LTE and femtocell architectures. Different femtocell access modes are presented in Section 6.2 followed by a brief overview for mobility management functions and intrinsic challenges for femtocell deployment in Section 6.3. Finally, we conclude this brief survey with existing research challenges and opportunities for femtocells.

6.1 HeNB Subsystem Architecture

The HeNB Subsystem (HeNS) [83] consists of a HeNB and an optional HeNB Gateway (HeNB-GW). The HeNB Subsystem is connected by means of the S1 interface to the EPC (Evolved Packet Core), more specifically to the MME (Mobility Management Entity) by means of the S1-MME interface and to the Serving Gateway (S-GW) by means of the S1-U interface. These interfaces are implemented over the client broadband internet connection such as a digital subscriber loop connection. More importantly, HeNBs are deployed independently, i.e. there is no direct connection between different femtocells in contrast to Macro-cell base stations that are connected using X2 links. HeNB are expected to be deployed in large numbers inside client premises. This deployment nature imposes direct constraints on the adopted architecture in terms of scalability and security. Several architectural variants are investigated in the literature.

In [84], three different architectural variants are presented. The main differences between the presented architectures are the existence and function of a home evolved nodeB (HeNB) gateway (HeNB-GW) in the network core. In the first architecture, a HeNB-GW is employed as a concentrator for the control plane and also terminates the user plane towards the HeNB and towards the Serving Gateway. In the second variant,
the S1-U interface of HeNB is terminated in S-GW and S1-C interface in MME. Note that in the latter variant HeNB may have connection to multiple MME/S-GW. The third variant, HeNB-GW is deployed and serves as a concentrator for the control plane. The S1-U interface of HeNB is terminated in S-GW, as per eNB. Figure 37 shows the first architecture variant in which the HeNB-GW is terminating both control and data interfaces of the femtocell.

**Figure 37:** A HeNB architecture with gateway terminating both control and data messages

Technically, terminating the control plane at a HeNB-GW reduces the load of MME and therefore scales better. Additionally, it enables paging optimization mechanisms within HeNB-GW. Similarly, employing the HeNB-GW as a termination point towards HeNB and S-GW also scales better as the number of UDP/IP paths and the number of GTP Echo messages that S-GW needs to manage remains minimum. However, it is worth noting that this comes at the expense of an increase of the processing load at the HeNB-GW due to switching the tunnel from HeNB-GW – S-GW tunnel to HeNB-GW – HeNB tunnel and vice versa. From security perspective, the first variant enables hiding IP addresses of MME and S-GW can be hidden. This would result in a more secure architecture as none of the core Network IP addresses / address space is revealed to the home user. Additionally, the HeNB-GW can be employed to perform special security functions such as a Denial of Service (DoS) shield to protect the EPC, specifically S-GW and MME. Last but not least, isolating HeNB by the gateway avoids other operational problems such as avoiding the overflooding of MME in case of massive failure of HeNB, due for example to a power outage. To this end, it is worth noting that the optimal architecture depends on different deployment scenarios such as the number of HeNBs. Additionally, the second and third architecture can still be deployed provided that any scalability issues at control plane and/or data plane is properly accommodated.

### 6.2 Femtocell Access Modes

Generally, three femtocell access modes [85] [86] are defined in the standards

1. **Closed access mode**, in which femtocell access is restricted for a specific set of user equipment terminals. In 3GPP standards, this type of femtocells is referred to as closed subscriber group (CSG) cell. In this case defining a CSG identity that is unique within the public land mobile telephony is a means to allow the UE to determine if it has the right to access such HeNB. The UE should maintain a list of all closed access mode HeNB with which he is a member of its CSG.
2. Open access mode, in which any equipment can access the femtocell. A possible deployment scenario for this type is to provide coverage for an operator coverage hole.

3. Hybrid access mode, in which a pre-specified set of user equipment terminals has a prioritized access and enjoys a preferential charging to the femtocell.

In order to reduce the power usage of mobile devices interested in searching for femtocells, a CSG indicator is proposed in 3GPP standards to identify the type of femtocell. Table 3 summarizes the possible settings used in femtocell identification.

<table>
<thead>
<tr>
<th>Access mode</th>
<th>CSG indicator</th>
<th>CSG ID in system information?</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTE</td>
<td>True</td>
<td>Present</td>
</tr>
<tr>
<td>UMTS</td>
<td>Present</td>
<td>Present</td>
</tr>
<tr>
<td>Closed</td>
<td>False</td>
<td>Absent</td>
</tr>
<tr>
<td>Open</td>
<td>False</td>
<td>Absent</td>
</tr>
<tr>
<td>Hybrid</td>
<td>False</td>
<td>Present</td>
</tr>
</tbody>
</table>

Table 3: Femtocell access mode differentiation

To this end, it is worth noting that obtaining the cell system information is expensive in terms of battery usage especially in dense deployment like that of femtocells. Hence, it would be more beneficial to the user not interested in CSG cells to identify the femtocell access mode earlier. One possible way to realize this is to design physical cell identity (PCI) assignment to reflect the access mode of the HeNB [85]. LTE standards define 504 unique PCIs. One possible approach is to cluster these PCIs to represent different access modes of LTE eNB/HeNB. The assigned cell PCI affects several operations [87] including the construction of synchronization signals that are derived using a unique mapping from the PCI. Additionally, the PCI is used in the scrambling sequence of most of the physical channels.

The misallocation of PCIs may cause several problems. PCI collision is one of these problems and occurs when two overlapping cells are assigned the same PCI. In this case, a UE located in the overlapping area would suffer from conflicts in the synchronization signals and physical channels. PCI confusion is another type of problems that occurs when two cells having the same PCI share a neighbour cell. This problem would impact the operation during handover in which the PCI is used as a cell identity in the measurement reports. While the aforementioned problems may evolve due to bad planning in cellular implementation, they naturally evolve in heterogeneous deployment of mixed femtocells and macrocells.

There are two approaches for PCI allocation in LTE including centralized and distributed mechanisms. In [88], the authors propose a centralized PCI assignment function in a cooperative femtocell setting. Each femtocell exchange a list of sensed neighbours, the configured access mode information (including the CSG ID) with the PCI-AF, and previously assigned PCI if applicable. In return, the PCI-AF as a centralized function assigns the booting femtocell an appropriate PCI based on the information available about pre-assigned PCIs. On any network topology change, the PCI-AF checks for any possible PCI confusion and reconfigure the network accordingly to resolve it in a way that minimizes the number of such reconfiguration process. The key performance indices for the PCI allocation problem may include the response time and the probability of collision or confusion.
6.3 Mobility Management

Mobility management addresses two main problems [89]: location management and handoff management. Location management schemes targets tracking the MT position in the network for successful information delivery. Handoff management schemes targets maintaining the connectivity of active sessions as the mobile UE changes its point of attachment to the network. In LTE, the MME is in charge of mobility management functions.

Typically, location management schemes are based on the definition of tracking area, which contains one or more cells. The MME should receive location registration message from the mobile device whenever it leaves its current tracking area. On receiving a new call for the mobile device, the MME starts a search procedure, technically known as paging, to determine the current point of attachment of the device within the registered tracking area. Considering the expected large number of femtocell deployment, developing efficient paging algorithms evolves as a crucial requirement to minimize the paging message overhead.

In 3GPP standards Release 8, the concept of tracking area list (TAL) is introduced [90]. The user receives its TAL from the base station and only changes it when it moves to a cell not included in its TAL. This approach results in heterogeneous TALs for users within the same cell as the TAL of each user depends on the initial cell registration and the mobility pattern. This heterogeneity complicates the design of location management schemes and it requires new thinking. In [90], the authors propose a heuristic that shows the possibility of reducing the signalling overhead by redefining the TAL of different cells.

Paging optimization is proposed to avoid flooding all femtocells with unnecessary paging messages. The basic idea is to perform paging not only based on the tracking area but also using the CSG identity as well. However this solution is limited to CSG-based femtocells and does not consider open and hybrid access mode femtocells that are introduced later in Release 9. In [91], the authors propose that femtocells and macrocells are allocated different tracking areas. Additionally, they propose that the paging follows multiple stages such that femtocells are paged before macrocells. Hence, the more expensive macrocell paging will be avoided if the mobile device is found in the first step. In [92], the authors propose composing TAL as rings of TAs (each tracking are consists of one cell). The design of the TAL is adapted to the user mobility profile between every two consecutive sessions.

The deployment of large number of femtocells would not only affect location management functions and design but also has a similar impact on handover functions and design. Generally, handover is a process that has three phases: discovery, decision, and execution. In the discovery phase, the mobile device monitors its medium to determine the existence of better point of attachment in the network. It is worth noting that in the existence of overlays, the best base station may not be the one with the strongest signal as there exist other intervening factors such as cost. Hence, new handoff algorithms may be required to reflect the overlay deployment of different access points. Once a decision is taken, a series of signalling messages are exchanged between the entities involved in the handover to allocate resources in the newly visited cell and switch the data path to the new eNB/HeNB. These entities may include the current eNB/HeNB, the MME, S-GW, HeNB-GW and the next eNB/HeNB depending on the type of the handover.

In heterogeneous LTE deployment, there exists three types of handover

1. Inbound handover during which the mobile device moves from an eNB to an HeNB.
2. Outbound handover during which the mobile device moves from an HeNB to an eNB.
3. Inter-HeNB handover during which the mobile device moves between two HeNBs.

To this end, it is worth noting that inter eNB handover does not require the involvement of the EPC due to flattening the architecture and enabling inter-eNB message exchange through X2 interface. On the contrary
eNB-HeNB handovers would introduce additional overhead to the EPC since HeNB are in general employed independently. Similarly, the inter-HeNB handover would require the EPC involvement. Such involvement is considered a significant overhead due to the expected large femtocell deployment.

Several approaches are proposed in the literature to reduce the handover overhead and improve the handover performance. In [93] [94], the authors propose a handover algorithm that adapts the decision to both user velocity and active applications. The velocity adaptation aims to reduce inbound handover for high speed users who are expected to exit the femtocell after a short period. For medium speed users, inbound handover only takes place when the user is using a real-time application. Finally, inbound handover takes place independent of the type of active applications for low speed users. The performance evaluation of this algorithm shows a reduction in ping-pong handovers in which mobile devices perform inbound and outbound handovers in a very short period. In [95], the authors proposed an architectural solution to reduce handover signalling in heterogeneous femto- and macro-cell setup. In this solution, the HeNB-GW appears to the MME as a single eNB and all HeNB associated with the HeNB are assigned a single tracking area code. Note that each HeNB has a unique identifier and hence the HeNB-GW can differentiate all its associated HeNB using this identifier. Based on this architecture, the authors propose employing the HeNB-GW as an anchor point for all inter-HeNB handovers. This approach eliminates the involvement of MME and S-GW for this type of handovers and hence reduces the overall system signalling.

Kim and Lee [96] propose prioritizing the CSG users to non-CSG users in hybrid access mode femtocells. This prioritization is based on introducing a delay for unregistered users before allowing them to join the femtocell assuming persistent good network condition over this waiting period. The scheme shows a natural drop in the number of handovers as the waiting periods increases. It also shows a drop in the unnecessary handover probability defined by rejoining the Macro cell after 50 sec or call termination after 10sec of the handover. In [97] [98], Ulvan et. al extends [96] with a predictive mobility component to reduce the probability of unnecessary inbound handover.

### 6.4 Research Opportunities

The femtocell concept evolves as a very promising approach to increase the available resources that can accommodate the exponential growth of mobile data. However, this success is conditioned on the ability to tackle different technical issues. Designing architectures and mechanisms for femtocells to be self-configurable is crucial for the successful deployment of femtocells as customer premises equipment. Additionally, developing solutions to reduce the expected signalling overhead resulting from reducing the cell size combined with large deployment is another major research avenue. Furthermore, developing interference mitigation techniques is a must to ensure proper operation of different tiers.

All the aforementioned problems can be addressed in two different deployment scenarios including cooperative and non-cooperative deployment. In the former, a group of femtocells can communicate to coordinate different configurations and functions over a local network as could be the case inside a commercial building. In the latter deployment, femtocells are typically installed independently and do not share any local network as is the case in a home deployment.
References


[71] Yan-Jun Ma, Jian-Dong Li, Qin Liu, and Rui Chen, "Group based interference alignment,” *IEEE Communication Letters*, vol. 15, no. 4, pp. 383-385, April 2011.


