Interference Aware Cognitive Femtocell Networks

Thesis

Abstract

Femtocells Access Points (FAP) are low power, plug and play home base stations which are designed to extend the cellular radio range in indoor environments where macrocell coverage is generally poor. They offer significant increases in data rates over a short range, enabling high speed wireless and mobile broadband services, with the femtocell network overlaid onto the macrocell in a dual-tier arrangement. In contrast to conventional cellular systems which are well planned, FAP are arbitrarily installed by the end users and this can create harmful interference to both collocated femtocell and macrocell users. The interference becomes particularly serious in high FAP density scenarios and compromises the ensuing data rate. Consequently, effective management of both cross and co-tier interference is a major design challenge in dual-tier networks.

Since traditional radio resource management techniques and architectures for single-tier systems are either not applicable or operate inefficiently, innovative dual-tier approaches to intelligently manage interference are required. This thesis presents a number of original contributions to fulfil this objective including, a new hybrid cross-tier spectrum sharing model which builds upon an existing fractional frequency reuse technique to ensure minimal impact on the macro-tier resource allocation. A new flexible and adaptive virtual clustering framework is then formulated to alleviate co-tier interference in high FAP densities situations and finally, an intelligent coverage extension algorithm is developed to mitigate excessive femto-macrocell handovers, while upholding the required quality of service provision.

This thesis contends that to exploit the undoubted potential of dual-tier, macro-femtocell architectures an interference awareness solution is necessary. Rigorous evidence confirms that noteworthy performance improvements can be achieved in the quality of the received signal and throughput by applying cognitive methods to manage interference.

PhD Thesis

Interference Aware Cognitive Femtocell Networks

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Dedicated to

My father; the best man I have ever known.

My mother, the living encouragement for me

My wife Ayesha, my source of inspiration and love

And

Our little angel, Afrah, our source of all happiness

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List of Abbreviation

1G	1^{st} Generation
2G	2^{nd} Generation
3G	3^{rd} Generation
3GPP	Third Generation Partnership Project
4G	4^{th} Generation
ADSL	Asynchronous Digital Subscribers Line
BS	Base Stations
CDMA	Code Division Multiple Access
CFN	Cognitive Femtocell Network
CR	Cognitive Radio
DL	Down Link
DTV	Digital Tele Vision
FAP	Femtocell Access Points
FFR	Fractional Frequency Reuse
FGW	Femtocell Gate Way
GVCF	Generalised Virtual Cluster Formation
HRMA	Hybrid Resource Management Architecture
ICI	Inter Cell Interference
LOS	Line Of Sight
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
MS	Mobile Stations
NCS	Non Clustered System

NLOS	Non Line Of Sight
OFDMA	Orthogonal Frequency Division Multiple Access
PON	Passive Optical Network
PU	Primary User
QoS	Quality of Service
RL	Reinforcement Learning
RNC	Radio Network Controller
RRM	Radio Resource Management
SE	Spectral Efficiency
SIM	Subscriber Identity Module
SINR	Signal to Interference plus Noise Ratio
SLA	Service Level Agreement
SOFN	Self Organizing Femtocell Networks
SON	Self Organizing Networks
SOS	Self Organizing System
SU	Secondary User
TDMA	Time Division Multiple Access
TVWS	Tele Vision White Space
UL	Up Link
VCC	Virtual Cluster Controller
VCF	Virtual Cluster Formation

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1 Introduction to Wireless Communications and Networks

1.1 Emergence of Wireless Communication and Networks

Since the invention of wireless radio transmissions in the early 20th century by Marconi, it has gradually become an indispensable part of our every day life. In the first half of the last century, wireless communication systems were mainly used by ships at sea, industry and various government agencies such as the police force. The first public mobile telephone service was introduced in 1946 across 25 cities of the United States of America (USA). Initially, one high powered transmitter was used to cover an entire city, though the analogue circuitry and poor signal detection technology meant the system was very inefficient and as a result, only 543 subscribers could be supported in New York City even three decades after the introduction of the service [1]. For these early generation phones, a person had to remain within the coverage of the transmitter where the call was initiated, for the entire duration of a call.

The ground breaking innovation of the hexagonal cellular system in 1947 by Bell Lab scientists introduced the idea of reusing the same channel in geographically distant places [2]. However, with the concept of channel reuse, came the insidious effect of co-channel interference, which has been keeping design engineers busy in attempting to manage and minimise its impact. Before 1973, the phone was generally mounted on a vehicle top and heavy in weight. In early 1978, the USA started the *Advanced Mobile Phone Systems*

(AMPS), widely known as 1st Generation (1G) analogue system. The performance of 1G system was limited by the poor performance of the analogue signal processing circuitry that struggled to combat the thermal noise generated by the system hardware.

In the early 1990s, the 2nd Generation (2G) system was introduced mainly in the USA, Europe and Japan, and was based on digital technology. Subsequently, wireless communications have gained momentum and during the past two decades, experienced unforeseen growth worldwide mainly due to the invention of digital circuitry and devices, with much higher capacity than 1G systems. They have also gradually become cheaper and more affordable for the wider population.

Initially, the focus of wireless systems was to enable voice communication and therefore the data rate requirement was relatively low. With the advent of digital technologies, the mobile communication system has gradually shifted from being circuit-switched to packet-switched. This allowed the same wireless channels to be shared by multiple users and thereby increased the channel efficiency significantly. This increased capacity also paved the way for introducing mixed voice and data services together with a variety of mobile applications.

In early 2000, 3rd Generation (3G) systems were introduced across Europe predominantly as a mixed voice and data intensive service. With sophisticated digital signal processing, detection and estimation technology, 3G systems were capable of supporting several mega bits per second data over a 10 MHz channel. This capacity enhancement triggered the introduction of multimedia services, digital audio and video streaming for mobile networks and devices.

Despite providing significantly high data rates, the wireless technologies have been struggling to meet the ever increasing data rate demands of the new and emerging mobile applications. One of the main reasons for this is the limited availability of usable spectrum. The power of the wireless signal decays approximately according to power law with distance and the rate of decay increases with frequency, so only a limited amount of spectrum is suitable for wireless transmissions and due to the massive demand, this is extremely expensive. Thus spectrum needs to be used as efficiently as possible in order to provide the best value for the investment.

To ensure the best possible use, the cellular system goes through a rigorous planning phase before deployment. It also endeavours to ensure the maximum coverage for the minimum number of *base stations* (BS). However, as the signal power decays according to power law, users in the cell edge areas usually receive a lower *quality of service* (QoS). Spectrum distribution typically follows a regular pattern over a geographical area so spectrum is distributed with the frequency at one cell being reused in another cell a certain distance away. This fixed assignment of spectrum is a limitation which has restricted the performance of cellular systems since the demand is not uniform over a geographic area. Therefore in some places, channels remain unused while at other locations, congestion occurs due to an insufficient number of channels leading to an overall inefficient utilisation of the valuable spectrum. Although some techniques like channel borrowing [3] and allocation on demand [4], try to solve this problem, the overall channel distribution system remains broadly rigid.

With the emergence of new high-end, hand-held devices and smart phones, users are tending evermore towards data intensive applications like network gaming, video conversation, online music, and video streaming, so the demand for high data rate services is increasing dramatically. This places tremendous pressure on network capacity and QoS requirement for mobile networks. ITU recommendations for 4^{th} Generation (4G) systems envisages achieving a 1Gbps data rate support for the downlink (DL) and 500Mbps for the uplink (UL) of stationary mobile stations (MS) [5].There is also a vision of achieving a DL data rate of 25 Gbps/km^2 [6]. To achieve these ambitious goals the spectrum needs to be reused much more frequently than currently as the existing wireless system performance is approaching the capacity limit. Also, as mentioned above, cell edge users receive a relatively lower data rate compared to the users in the cell centre. This problem becomes severe if the cell edge users are located indoors as the signal needs to penetrate buildings and walls which lead to a significant loss of energy. Thus the research focus has been gradually shifting from transceiver circuitry to the network architecture itself and resource distribution techniques. Interference generated by neighbouring transmitters limits the possibility of reusing the same spectrum and while reducing the transmit power allows more frequent deployment of transmitters and greater spectrum reuse, the costs involved are prohibitively high.

From the above discussion, it is clear that to achieve the very high data rate requirement as set out in the 4G vision, two key factors need to be considered. Firstly, the massive deployment of low cost, low power devices alongside the planned cellular deployment and secondly, that a more localised and dynamic approach to spectrum use is required. To keep the cost of the transmitter low, it must be simple and easy to install, so instead of a planned deployment, arbitrarily deployed low power wireless nodes are becoming more prominent as they are capable of supporting very high data rate services over short distances. However, in terms of localised and dynamic spectrum usage, this requires instant and up-to-date knowledge of the spectrum and its surrounding radio environment. This means both devices and networks must have an awareness of their surroundings either individually or collectively and also be sufficiently intelligent to make decisions locally. Clearly how best to accommodate randomly deployed short-range cells within the existing pre-planned cellular networks as well as manage resources intelligently and efficiently is a major research challenge to be resolved to achieve the desired goal of enhanced data rates in *next generation* wireless networks.

1.2 Cognitive Radio Networks and Dynamic Spectrum Access

The emergence of cognitive radio (CR) has shifted the paradigm from a fixed and well-planned centralised spectrum distribution regime to an intelligent, dynamic, autonomous and locally managed distribution model. It also facilitates frequent reuse of the spectrum and thereby achieves higher spectral efficiency. The term CR was first coined by Mitola [7], [8] and its primary objective has been to enable robust communication to anything, anytime and anywhere. It can loosely be defined as an intelligent radio that is aware of the surrounding environment, learns from it and adapts itself to the statistical variations of the surrounding environment accordingly [9].This key characteristic means CR technology can enable dynamic allocation of spectrum thereby addressing the fundamental bottleneck in current wireless systems.

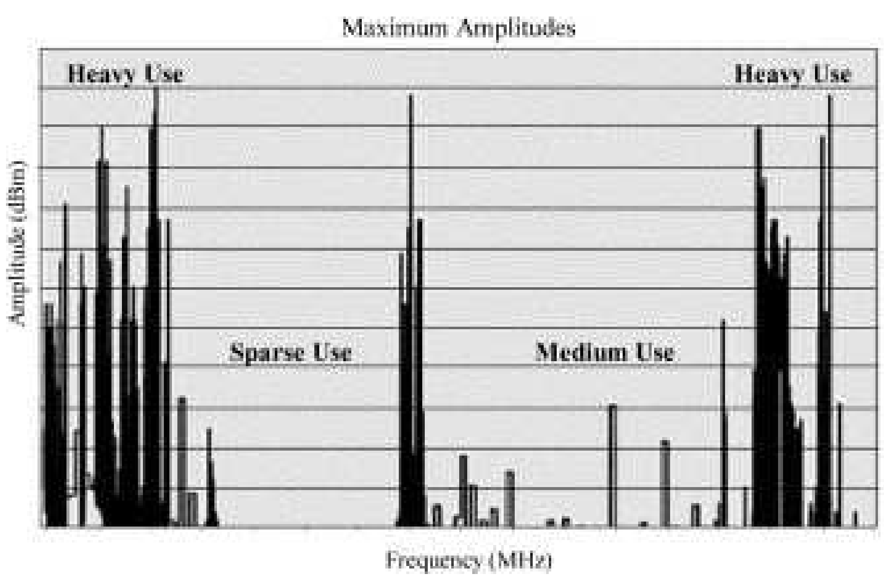


Figure 1.1: Illustration of usable spectrum utilization scenarios [10].

A Study [11] suggests that despite its scarcity, a significant amount of spectrum actually remains unused in certain space and time, as illustrated in the Figure 1.1 example [10]. The CR can sense the radio environment and detect unused spectrum in the vicinity. By sharing these local measurements with the neighbouring nodes or some central entity, a more localized spectrum usage map can be generated which in turn, will enable better use of the available spectrum based on predefined policy agreement between the competing networks [12] [13]. Thus CR can facilitate sharing spectrum opportunistically among multiple competing devices and techniques at the same place as opposed to single operator allocation of the conventional system.

This leads to the emergence of multiple coexisting and overlapping heterogeneous wireless networks. The inherent ability of CR to sense and take intelligent decisions has made it an attractive enabler for *next generation* wireless systems. As will be set out in subsequent chapters, this is the context for the research presented in this thesis, namely to investigate the development of an original cognitive-based framework where interference awareness management is critical, and where no network planning assumptions can be made.

1.3 Cognitive Femtocell Networks

Studies suggest that most high data rate demand is generating from indoor environments where radio coverage is typically poor due to wall penetration losses inside buildings [14]. As has already been highlighted, the problem becomes severe in the cell edge area which is far from the serving macrocell BS. So there exists a clear data rate demand and support mismatch in the indoor and outdoor environment as shown in Figure 1.2.

Femtocells are low cost plug and play home network systems aimed at extending radio coverage in the indoor environment and thereby support the rapidly increasing data rate demand in indoor environments. A femtocell consists of a home base station, called *home node B* (HNB) or *femtocell access points* (FAP), and MS. Femtocells are deployed either underlay or overlay on a macro cellular system. When located indoors, MSs connect to the FAP instead of the macrocell BS, with the traffic backhauled via either a wired *asynchronous digital subscriber line* (ADSL) or *passive optical network* (PON).

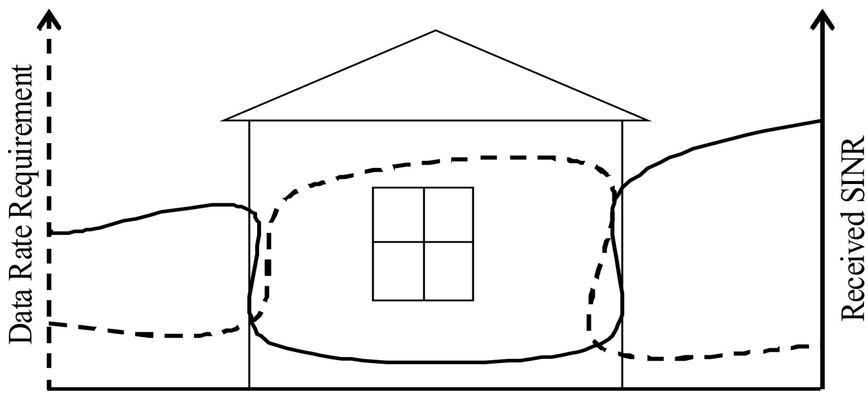


Figure 1.2: Illustrative example showing the data rate requirement (dotted line) and available throughput due to received signal to interference & noise ratio (SINR) (solid line), between indoor and outdoor scenarios for a cellular base station.

A Femtocell offers a number of potential advantages:

1. Due to the short communication distances, the link between the transmitter and receiver is robust and high data rates are achievable by employing higher order modulation.
2. They liberate a number of channels by handing over indoor MSs from the macrocell BS to the FAP.
3. Since the MS connects to a nearby FAP instead of a relatively distant macro BS, it saves battery power.
4. Since the MS is connected to a FAP located in close proximity, the transmission power required for communication is low compared to the macrocell system. This allows the spectrum to be reused more frequently which in turn, significantly increases achievable throughput per unit area.

These benefits collectively mean femtocells offer an attractive design solution for high data rate wireless services in indoor environments which are overlaid on the macrocell systems.

1.4 Research Challenges and Problem Statement

While FAP technology clearly offers users a number of benefits, there are significant technical, regulatory and economic challenges that need to be met. Due to short communication distances, frequent handovers may occur and so it is necessary to devise mechanisms for seamless handover as well as for avoiding the so-called *ping pong* effect [15]. Timing and synchronization, QoS in the backhaul network, portability of FAP are among the other challenges that need to be addressed. Recent research suggests that a femtocell network will most likely operate on spectrum that is either shared with other networks or on lease from other network under some constraints [16].Therefore, it is important to devise an efficient spectrum sharing strategy between the macrocell and femtocell networks.

Since femtocells are deployed arbitrarily, the biggest challenge in their deployment is to manage interference. Figure 1.3 shows the interference scenarios in a joint macro-femto deployment. Two types of interference can occur: i) between the macrocell and femtocell users, which is known as *cross tier interference* and ii) amongst the femtocells which is referred to as *co-tier (inter-femto) interference*.

Although the device architectures are similar for both the FAP and macrocell BS, the former is limited in power and functionality and there is a fundamental difference in network topology and architecture. The macrocell network is generally deployed by highly technical personnel after rigorous network planning, testing and evaluation. In contrast, the femtocell network is unplanned and user deployed, although the deployment area and density can be either estimated or predicted from the population distribution together with the building structure and/or city layout. Thus, existing resource management architectures which were originally designed for pre-planned cellular networks, and which are mainly centralised entities, cannot be applied directly in this new scenario.

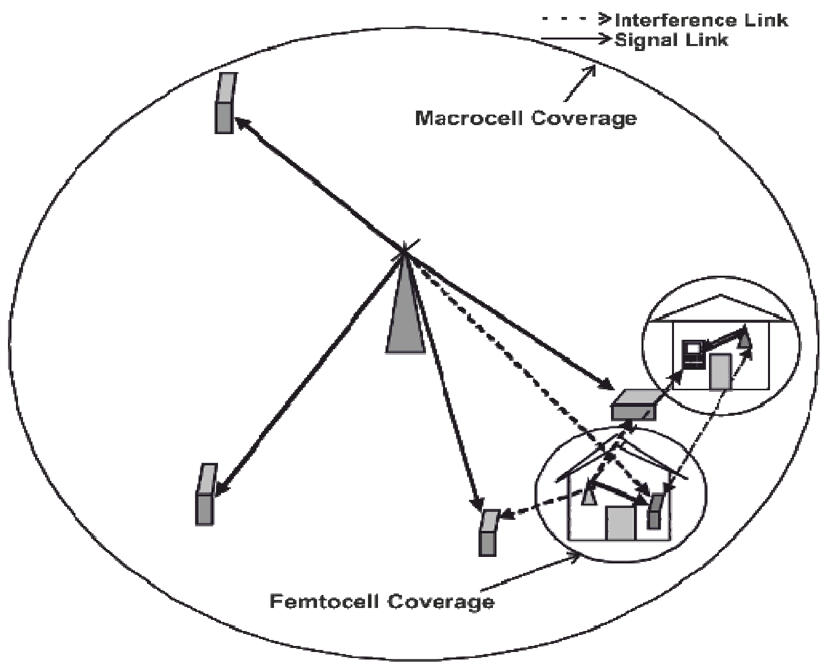


Figure 1.3: Interference Scenarios in joint macro femto deployment

Femtocells are expected to be deployed in both rural and urban areas, with the latter having very high density. Femtocells are also expected to replace the existing *Wireless Fidelity* (Wi-Fi) services as it will provide the same service in addition to conventional cellular services. Wi-Fi operates on an unlicensed band and its resources are managed in a distributed manner which is suitable for any large scale deployment such as in ad hoc and sensor networks. Despite the similarity in deployment, this kind of completely distributed resource management technique is unsuitable because femtocell networks are heavily dependent on the macro network for its resource allocation, which is centrally controlled. This is because the macro and femto networks must share the same resources. The resource management architecture therefore needs to be designed taking all these key facts into consideration.

As it is assumed FAP will be deployed by the end users in an uncoordinated way, inter-femtocell interference can become very high especially in dense scenarios. Existing mechanisms for interference and resource management, which are primarily designed for pre-planned networks, are simply not applicable for femtocell networks. This means the development of new and effective interference aware resource management strategies is a key objective for successful femtocell network deployment and provided the main motivation behind the research presented in this thesis.

The thesis will embark on developing efficient spectrum sharing strategies between the macro and femto tiers to mitigate cross-tier interference before studying the influence of FAP deployment density on the interference scenario and examining ways to effectively mitigate co-tier interference to achieve the desired QoS performance levels.

The DL of both the macro and femtocells will be investigated, particularly for the home environment where femtocells typically operate on a closed access basis. This means a MS moving out of the coverage of a femtocell will be handed over to the macrocell even if it falls within the coverage of the neighbouring femtocells. CR principles will be partially applied in the sense that it only scans the predefined spectrum, not the whole spectrum. This information coupled with cross-tier information will then be exploited to intelligently allocate resources in the whole system.

Since the resource allocation techniques for macro cellular systems are well established and mature, it will be wise to keep the macro-tier allocation model as intact as possible while exploiting opportunities available in the system for the femto-tier. Initially, both cross and co-tier interference will be analysed in moderately dense deployments of femtocells on the macrocell. For cross-tier interference mitigation, a *fractional frequency reuse* (FFR) technique for macro-tier is applied as it inherently creates spaces where a partition of the spectrum is not utilised by the macro-tier. FFR divides a macrocell into an inner and outer area and then allocates each divided area with an orthogonal set of channels exclusive to those areas. The standard FFR technique has been modified to dynamically adapt to the changes in the radio environment and resource demand in both tiers. While cross-tier interference will be mitigated via the centralised management of the dynamic FFR, the femto-tier interference will be mitigated with certain decisions made centrally and others taken locally leading to the creation of a new hybrid resource management architecture.

Subsequently, high density femtocell deployments will be investigated. An original network management architecture based on the novel concept of *virtual clustering* will be presented for femtocell networks, while keeping the dynamic FFR as the overarching model for macro-femto spectrum sharing and cross-tier interference mitigation. The term virtual cluster is used in the sense that the femtocells will be grouped not based on physical location but based on minimum interference generation criterion. Unlike ad hoc clusters, femtocells located far apart can essentially be members of the same virtual cluster.

While the preliminary investigations into virtual clustering assume a fixed set-up and rigid resource availability, these assumptions are subsequently relaxed and a generalised virtual clustering framework (GVCF) paradigm will be presented which uniquely incorporates intelligent algorithms to enable the system to flexibly adapt to changes in both the resource availability and radio environment.

Finally after rigorously analysing the performance of the new hybrid resource management GVCF architecture, the thesis will examine a slightly different, but nevertheless very important challenge which highlights the robustness of the new GVCF model. Since femtocell coverage is very small, MSs connected to a FAP may frequently move out of the coverage and will be required to be handed over to the macrocell. In a highly dense deployment scenario, if a large number of femtocell users are moving out of the coverage of femtocell simultaneously, a macrocell may need to handle a high number of users together and this may lead to significant delays in scheduling. A common alternative is to keep the MS forcefully connected to the femtocell by applying handover bias or some other technique, so expanding the coverage of the femtocell. In the final thesis chapter, the impact of the coverage expansion on closed access cognitive femtocell networks will be thoroughly investigated for various network deployment scenarios.

In summary, this thesis will present original scientific contributions in the area of interference aware resource management including resource partitioning, channel assignment, interference mitigation and coverage optimisation in a joint macro-femtocell deployment framework.

1.5 Organization of the Thesis

The rest of the thesis will be organized as follows:

Chapter 2

The chapter introduces the basic concepts of cognitive femtocell networks, their design and operational challenges and a review of the technical challenges such as spectrum sharing and access methods, co-existence of joint macro-femto systems, cross and co-tier interference management issues and existing approaches to addressing these challenges. Part of this chapter has been published in [17].

Chapter 3

This chapter focuses on a new hybrid resource allocation model for both cross and co-tier interference management in low to moderately dense femtocell deployments. It explains the concept of *Fractional Frequency Reuse* (FFR) and its application to cross-tier interference management in joint macro-femto deployment. A dynamic FFR technique is introduced which forms the basis of *hybrid resource management algorithm* (HRMA). Its performance is rigorously tested and evaluated and then compared with a distributed random allocation system. The hybrid architecture remains as the overarching framework for resource management in all subsequent chapters. Work from this chapter has been published in [18].

Chapter 4

This chapter focuses on moderate-to-high density deployment scenarios for femtocell networks. Building upon Chapter 3, which shows dynamic FFR effectively mitigates cross-tier interference, this chapter addresses the issue of intra-femtocell network interference management where FFR remains the underlying spectrum sharing model between the macrocell and femtocell. The original idea of *virtual cluster formation* (VCF) is presented in this chapter and its performance investigated for a fixed cluster size setting at various femtocell deployment densities. The novel contribution detailed in this chapter has been published in [19].

Chapter 5

The idea of virtual clustering has been generalised to make it more flexible and adaptive to the resource availability and requirements. The *generalised virtual cluster formation* (GVCF) framework has been established and extensively tested for various radio environment and interference setting and compared with the distributed random allocation model. The superior performance of the GVCF has been proven in different FAP deployment densities. A part of this chapter contributes to [20].

Chapter 6

This chapter extends the ideas in Chapters 4 and 5 to incorporate additional flexibility and robustness against frequent handover between the macrocell and femtocell. Since the coverage of femtocells are very low, users with very low mobility can briefly move out of the coverage, so handover may occur very frequently and this can trigger a lot of control data generation for handover management. An alternative strategy is investigated; to expand the coverage by keeping the MS connected to the femtocell. In this chapter the impact of coverage shrinking and expansion on the overall system performance is investigated for closed access femtocell networks. The results can also be used to develop a *look up table* (LUT) that defines the performance and resource requirement nexus.

Chapter 7

This chapter discusses various ways that the current work can be extended and also provides some other future research directions including interference alignment, self organisation and green network operation and management.

Chapter 8

Finally, this chapter concludes the thesis by summarising the contribution. It also discusses the possible ways of validating the results presented in the thesis.

2 Cognitive Femtocell Technologies: A Review

2.1 Introduction

To meet the demand of rapidly increasing wireless data over the last decade, strategies like the spatial reuse of spectrum and cell-size reduction have been employed, though both approaches increase co-channel and adjacent channel interference. In addition, reducing the cell size leads to more BSs being required which is not practical due to their high deployment cost. The majority of the traffic is now generated from indoor environments where poor received signal strength due to penetration losses increase the demands upon QoS provision, with the problem being particularly acute when users are located at cell boundaries. Increasing the transmit power of the base station will not solve the problem as this only increases the *Inter Cell Interference* (ICI). As discussed in Chapter 1, the concept of femtocells was originally introduced to extend macrocell coverage for indoor scenarios where the FAP covers a small area of several metres [21].

In this chapter, a thorough review of femtocell technologies will be presented including femtocell network architecture, deployment and operations. A review will be provided of the technical challenges and research opportunities. Finally the chapter will be concluded with a discussion on the research issues and approaches addressed in this thesis.

2.2 Femtocell Network Architecture

As femtocells are principally designed to extend macro cellular services into indoor environments, the key design requirement for the network is to ensure the same services are provided as the macrocell, without user intervention. As mentioned earlier, to secure high data rate services, traffic is backhauled via a wired network such as xDSL or xPON. To guarantee coexistence with the macrocell system, as well as maintaining call continuity by appropriately managed handover, there must be a communication path between the macro and femto systems via this wired connection.

A typical femtocell network architecture is shown in Figure 2.1, where each femtocell is connected to a local *femtocell gateway* (FGW) which provides authentication, initial configuration and security related support for each FAP [22]. The FGW is the interface between the FAP and the core macrocell network, and depending upon the radio resource management paradigm being used, certain resource allocation and control functions are undertaken by the FGW. For example, the *radio network controller* (RNC) can share information concerning the allocation of spectrum to macrocell users in a particular location with the local FGW, so it can inform a nearby FAP to avoid operating in those spectra.

The FGW allows the RNC to offload various management and control functions, including authentication and IP security issues. It acts as an aggregator for physically co-located FAP groupings, and is able to execute joint resource allocation and traffic scheduling by considering both the capacity of the FAP and backhaul network. The location of a FGW is also important, since if it is too far away from the FAPs connected to it, route optimisation will be required to avoid redundant communications [23].

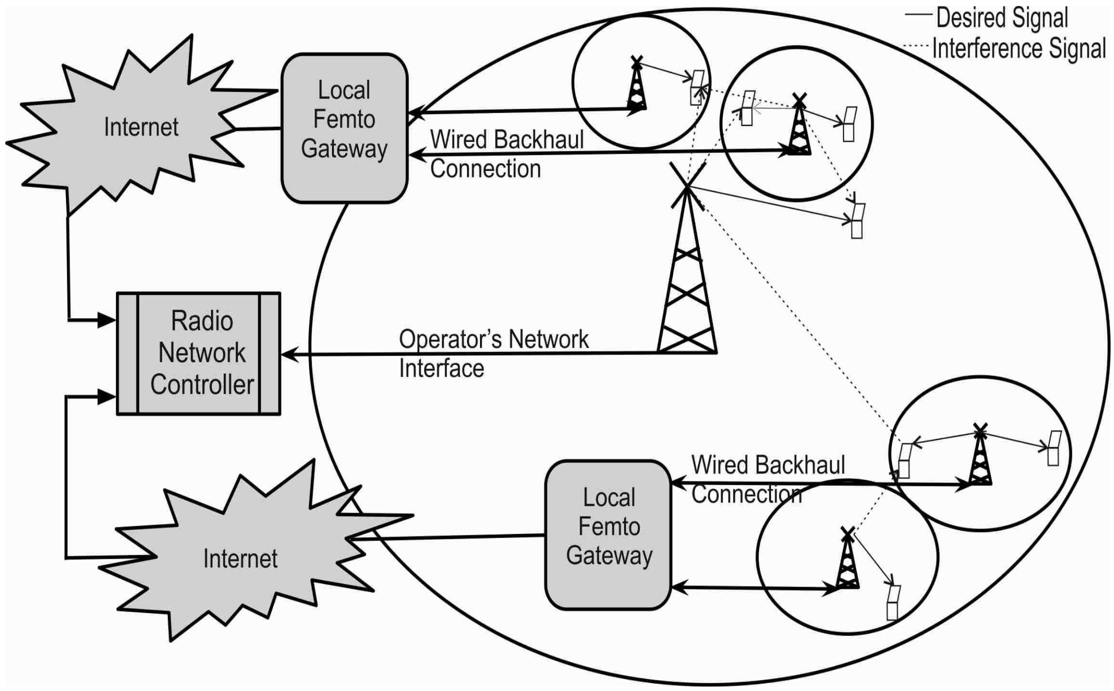


Figure 2.1: A joint macro-femto cell deployment architecture

In the remainder of this section, different network related issues for joint macro-femto cell deployment such as underlay and overlay architectures, classification based on coverage and capacity and possible operating spectrum will be briefly discussed.

2.2.1 Underlay and Overlay Architectures

In joint macro-femto cell deployments, the macrocell users normally have priority in accessing the spectrum. To ensure harmonious coexistence between the two systems, femtocells can access the spectrum by operating either in an underlay or overlay mode [24].

In underlay architectures, the femtocell is able to use the same spectrum as the macrocell at any collocation, provided the femtocell does not exceed a defined interference power threshold. This threshold is usually set by the spectrum owner or lender, under the strict proviso that it does not generate harmful interference to the *primary user* (PU) devices

[25]. In this scenario, the femtocell network is solely responsible for maintaining the threshold set by the macrocell system, though depending upon the policy and regulations, the macrocell network may assist in the spectrum allocation decision making process. The macro-tier can maintain a geo-location spectrum occupancy database and share this information with the femto tier via the FGW, which updates all its connected FAPs either on a regular or needs basis [26].

To facilitate local decision-making, FAPs must have an intelligent or cognitive capability. To make localised decisions, cognitive femtocells need to regularly sense the environment to detect the arrival of new macrocell users and any changes to the radio environment. The main disadvantage with the sensing-based system however, is the extra energy expended by the FAPs and its users, together with the resources required for sharing information [27].

In overlay architectures, the femtocell network shares the same spectrum with the macrocell, though at any location, the spectrum used by the macrocell and femtocell must be mutually exclusive. Where macrocell users have the priority, femtocell users must avoid using the spectrum of all macrocell users in their vicinity. In other aspects, notably in geo-location database information sharing and sensing-based spectrum allocation, the overlay and underlay systems are very similar.

In both deployment scenarios, it is imperative to resolve whether a channel is to be considered either occupied or not. Inaccurate decisions can lead to inefficiencies with false alarms, i.e., detecting as an unoccupied channel when it is actually occupied can create harmful interference to others users. Conversely, falsely detecting an unoccupied channel as occupied will leave channels needlessly vacant. In order to effectively make a decision, the level of interference generated at any location needs to be either accurately predicted or measured. This discussion highlights the major design objective for effective femtocell deployment, namely the minimisation of cross- and co-tier interference, while retaining high spectrum efficiency (throughput).

In an underlay system, the primary system always gets preference and it is the responsibility of the secondary system to ensure that it operates within the resource restrictions. In contrast, an overlay system operates more flexibly in allowing both systems to transmit in a cooperative manner. In joint macro femto systems, the same MS will be connected to both the femtocell and macrocell depending on the location. Thus, overlay systems will be suitable for femtocell networks and therefore adopted for the thesis.

2.2.2 Home and Enterprise Femtocell

Home Femtocell

The most common FAP scenario is in home environments with between 1 and 4 subscribers. The normal coverage is around 10 m radius with a maximum transmit power of 10 dBm. As it can be reasonably assumed that most home femtocell owners are non-technical people, the installation, operation and management must be kept straightforward. Once switched on, the FAP should be self-configuring and able to register itself and since each household will be responsible for paying the bills, the envisaged deployment mode of access is via a closed subscriber group, where only authorised users can gain access. Interference can be particularly high if a user in the vicinity of the FAP attempts to connect to the macrocell BS.

As femtocells can be freely deployed by the end user without any network planning, in dense deployment scenarios such as apartment blocks, the coverage of either two or more neighbouring femtocells may overlap. If a MS falls between the coverage of two femtocells operating on the same channels as illustrated in Figure 2.2 (a), then severe interference can occur. Mechanisms for avoiding co-channel transmission for overlapping femtocells are therefore an essential design requirement.

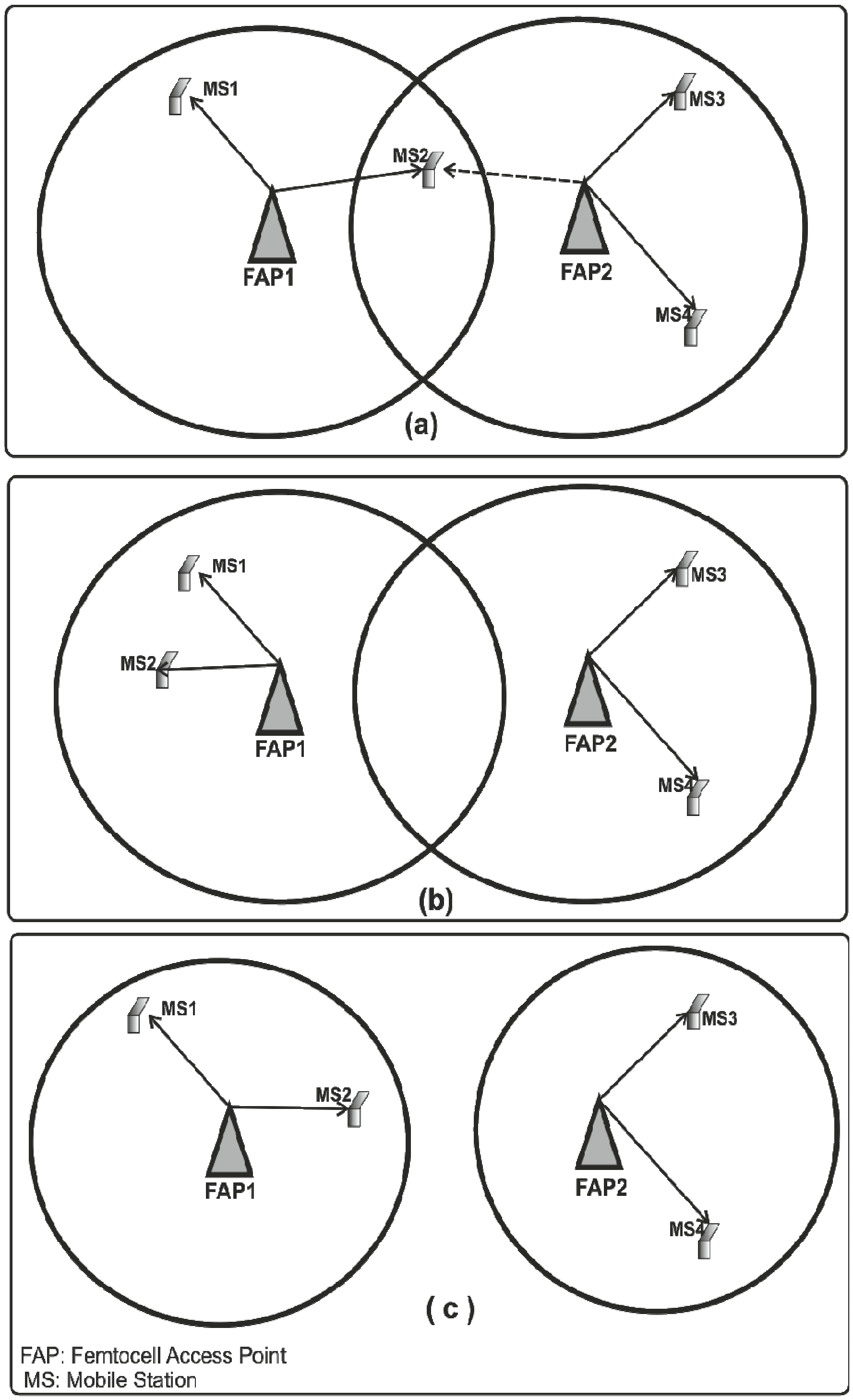


Figure 2.2: Example showing various femtocell deployments: a) Overlapped, b) Overlapped but not interfering, and c) Non-overlapped

The simplest approach is for one of the femtocells to hop channels, though if there is not another channel available, it can request the interferer to change channel. The latent danger in randomly hopping to another channel however, is the possibility it will generate interference with another neighbour. Consequently, FAPs should have some radio environment knowledge of their vicinity before making a decision to switch channel. An alternative strategy is the implementation of hybrid control where during authentication and registration, location information and pilot channel measurements are reported to the FGW, which can then avoid allocating the same channels to any overlapping femtocells which are generating severe interference to their neighbours [28].

It needs to be borne in mind that not all overlapping femtocells will necessarily be interfering as illustrated in Figure 2.2 (b). In this scenario, the femtocell coverage areas overlap but they do not create interference with each other's users as there are none in the overlapping zone. Correctly identifying these instances can help in saving both superfluous channel hopping and communications with the FGW. Finally, femto-to-femto interference is much less sensitive when the cells are not overlapping as shown in Figure 2.2 (c). The net outcome, particularly for those non-interfering femtocells is that they can be granted greater flexibility and autonomy in selecting their transmission channel.

Enterprise Femtocell

Although femtocells were originally designed for home use, with smart adaptation in regard to capacity and functionality, the technology has emerged as an equally effective and low-cost solution for business enterprises. Enterprise femtocells are suitable for small offices, shopping malls, railway stations, airports and other public areas, and can be configured to act as an outdoor relay [29]. Typically, they have a range of up to 100 m, with a higher capacity than that of home femtocells [30]. They also are more likely to employ either an open or hybrid access system to accommodate the larger numbers of visiting users in the anticipated operating environments.

Despite clear similarities, the design requirements for an enterprise femtocell are distinct from those of their home counterparts [31]. Intelligent handover management is necessary as guest users may frequently move from the coverage of one femtocell to another in office environments, as well as to the coverage of a macrocell. During busy periods, there may be many users in the coverage area of one femtocell while an adjacent cell may have only a few or even no users. Proposed solutions include, artificially triggering handover by adjusting the threshold to offload certain users to a neighbouring cell to reduce congestion [32], and coverage optimisation whereby power consumption is adjusted to balance the load between cells [33].

As mentioned earlier, home femtocells will be the most common scenario for femtocell deployment and the density of them will be much higher than their enterprise counterpart. Therefore, managing cross and co-tier interference for home femtocell will be more challenging. For this thesis, cross and co tier interference will be addressed in the home femtocell scenario. However, most of the interference management solutions in principle will be applicable for enterprise with some modifications.

2.2.3 Possible Operating Spectrum

As femtocells are considered an extension of macro cellular systems, affording coverage in areas where macrocell coverage is difficult, it is reasonable to assume they will operate in the same frequency band as the cellular system. To safeguard the successful coexistence of devices, appropriate strategies need to be developed to address a myriad of regulatory and economic hurdles. By embedding some cognitive capability, femtocells have the potential to operate on other bands which may opportunistically become available for secondary operations. It is in this context, the operating spectrum and related challenges are now discussed.

The operating spectrum for femtocell operation can be broadly classified as either licensed or license exempt. If the femtocell is using the operator's cellular spectrum in the 2G and 3G bands, then it is deemed to be licensed. In these circumstances, the operator must ensure femtocell operation is fully compliant with the prevailing regulatory statutes, with the management of cross tier and co-tier interference being the principal concern to be resolved.

Whenever the femtocell operates as a secondary user in a spectrum, it is defined as *license exempt*. Such operations are divided into two different spectral categories. The first covers operating in license exempt bands such as 2.4 GHz, 5.8 GHz, 24 GHz and 900 MHz (in USA only). Despite the WiFi band (2.4 GHz) being already very crowded, studies advocate that successful femtocell operation is still feasible in this band provided coexistence policies are *in situ* [16]. A recent study [34] has shown femtocells can opportunistically operate in both licensed and unlicensed bands, with an interesting proposal being that simultaneous scheduling in both licensed and unlicensed bands is a promising option for femtocells to avoid congestion or blocking when licensed band is heavily crowded.

The second category of license exempt operation is where a femtocell operates in *white space,* i.e., unused licensed spectrum in space and time. This involves various regulatory restrictions being imposed by the spectrum owner, i.e., the *primary user* (PU), such as upholding an interference threshold. As a result of the digital television (DTV) switchover across Europe, America and in other developed countries, a sizeable number of frequency bands from analogue TV channels have been released [35]. These bands are popularly referred to as *TV white space* (TVWS), and offer an exciting and potentially lucrative option for femtocells.

Radar and military bands represent another alternative as usage of these bands is both infrequent and location specific. However, for security reasons it must be guaranteed these bands will not be used when the PU is transmitting, so mechanisms must exist to switch to alternative bands in order to avoid any disruption in communications.

One disadvantage with this out-of-macro cellular band operation, (when the macrocell remains in the licensed band of the 2G/3G spectra), is that any MS must be able to support a multi-band radio system, which may lead to more expensive MS devices. This thesis will thus consider the case where femtocells and macrocells will operate on the same 3G spectrum.

2.2.4 Femtocell Standardization

Since femtocells need to interact and integrate seamlessly with traditional cellular network, it is important to make the system compatible with the cellular system. Therefore different functionalities such as authentication, handover, billing, interference management, transmission power need to be standardised. *Femto forum* (currently renamed as *small cell forum*) was established in 2007 for promoting femtocell worldwide and coordinating and liaising the standardization effort in cooperation with different standardization authority such as ITU, 3GPP, broad band forum (BBF) and ETSI [36].

Although there are some instances of second generation (2G) femtocells, industries are more focused on third and subsequent generation femtocells. Both in 3GPP and 3GPP2, a lot of effort has been made to standardise the channel and propagation model in the indoor environment, QoS requirement at different layers and other functionalities for CDMA2000, UMTS and LTE based systems. In 3GPP, from release 8, femtocell (termed as HNB) has been given special provision. In release 11, self organization has been emphasised for multi-tier networks. A summary of the standardisation effort is discussed in [37] and [38].

In the following sections, different technical challenges related to femtocell deployment and operation will be discussed. A comparative review of pros and cons of the existing solutions will be provided along with opportunities to improve them or of new solutions.

2.3 Femtocell Technical Challenges

Since femtocell networks will effectively work as an extension of the existing cellular network in indoor environments and will be deployed overlaying the existing cellular coverage area, a number of technical issues need to be resolved for their successful operation. These technical issues include, but are not limited to, access control policy, spectrum sharing techniques, handover management, spectrum/channel allocation, resource control policy and interference management. In this section, some of these technical issues and approaches for addressing those will be briefly discussed.

2.3.1 Femtocell Access Mechanisms

Femtocells generally operate in three different access modes: closed, open and hybrid, with each having their respective advantages and drawbacks. Crucially, the choice of the access mechanism influences not only the operation of the femto-tier, but also the macro-tier, and in particular cross-tier interference mitigation and handover management [39].

Closed Access

In this mode, a fixed predefined number of users are allowed for network access. An unregistered user cannot access the femtocell even if it has the strongest link with a particular FAP. The consequence for any unregistered user entering the coverage of a closed femtocell is that it will receive severe cross-tier and co-tier interference when it respectively connects to a macrocell and another femtocell. A closed access system must therefore have strategies in place to either cancel or avoid these two types of interference. *Multiple-input and multiple-output* (MIMO) antenna-based beamforming for directional transmission is one approach to attenuate this type of interference [40]. However, to keep the cost low, a single antenna can be used. In this case, a negotiation mechanism between interfering transmitters needs to be implemented so that they can switch operating frequencies in the case of strong interference. The main attraction of this system is that because of the limited number of users, both management and billing is relatively easy.

Open Access

This mode, in contrast to closed access, permits any user located within the range of FAP to gain access to the network. The benefit is the downlink (DL) can offload large amounts of traffic from the macrocell to the femtocell, so liberating channels for reuse. This is especially useful at cell edges where macrocell coverage is generally poor. Despite freeing up valuable macrocell resources, open access systems do have a number of limitations. Since coverage is small, the system will experience an increased number of handovers if users are mobile, so innovative design methodologies are required to minimise handovers. In addition, if the number of unregistered or guest users becomes too high, then registered users in a femtocell may experience call blocking. There are also security implications, as an open access system is inherently vulnerable, for example, to hacking, illegal monitoring of activity, location detection, and malicious node attacks [41]. Appropriate measures thus need to be employed to stop malicious manipulation of on-board software which can alter location information to hinder network management [42].

Hybrid Access

This mode combines the advantages of the above two systems. By considering its capacity and gain, the hybrid mode allows a limited number of unsubscribed users to gain network access alongside the existing registered and subscribed users. This constraining of the number of guest users, achieves significant performance improvements without compromising the subscribed users [43]. A mechanism to prioritise the needs of registered over unsubscribed guest users must be implemented to ensure the satisfaction of the subscribed users. Preferential billing represents an alternative option, where subscribed and unsubscribed users are charged different tariffs [44]. A comparative summary of the key characteristics of all three access mechanisms is provided in Table 2.1.

Table 2.1: Comparison of the three different access mechanisms

Attribute	Closed	Open	Hybrid
Handoff	No/Limited	Very high	High
Interference to Macro	High	Low	Low
Congestion Management	Not Possible	Possible	Possible
Security Risk	Low	High	Low
Outage	High	Low	Low
Billing	Easy	Complex	Moderate
System Throughput	Medium	High	High

The performance of each access mode will inevitably be scenario dependant. It is also governed by whether an orthogonal or non-orthogonal channel allocation is adopted. For high user densities, systems employing either *time division multiple access* (TDMA) or *orthogonal frequency division multiple access* (OFDMA) as their physical layer technique will perform better in closed access mode. Conversely for open access systems, significant improvements are derived when *code division multiple access* (CDMA) is employed [45]. Furthermore an estimate of the number of handovers is a key parameter in selecting the most appropriate access mechanism, which renders the intelligently designed hybrid system a particularly attractive solution as it combines the best features of the two access modes.

In home femtocells, as with existing wi-fi systems, owners will not allow unauthorised users to access unless there is some incentive. As mentioned above, it also makes the network management and billing easier for both the operator and the subscribers. Therefore, in this thesis closed access femtocells will be considered.

2.3.2 Security

Security of femtocell networks mainly involves two functionalities. First, authentication of the femtocell access points and the MS connecting to them and second, encryption/decryption of the control information across the unreliable internet connection between the femtocell and the gateway or RNC. In an effort to reduce different types of threat such as subscribers list theft and *denial of service* (DoS) attack, UMTS and LTE femtocells include functionalities such as IPSec and unique identity for each FAP. Encryption over the IP transport network between the FAP and FGW is performed using IETF IPsec protocols [46] following the IKEv2 femtocell device and hosting party authentication procedures. [47]. IPSec allows creating a secured tunnel between FAP and the FGW. Security in an open access scenario is much more critical compared to the closed and hybrid access mode femtocells and hence special care needs to taken in this case. However, security issues are beyond scope of this thesis.

2.3.3 Awareness of Backhaul Characteristics

One major difference between existing cellular and femtocell networks is the backhaul system. The macro-cellular system use dedicated backhaul interfaces known as S1 and X2 [48], which are dedicated for cellular system traffic. On the other hand, for femtocells, it is anticipated the traffic will be backhauled via existing xDSL or xPON infrastructure which needs to be shared with other internet services and applications. So the nature of backhaul issues is different for the macrocell and femtocell networks. This implies the femtocell network management system must be designed to be compatible with this shared service other wise excessive delay may occur due to congestion.

Current broadband networks have asymmetric uplink (UL) and downlink (DL) architectures, with the former using less bandwidth than the latter. This implies cognisance needs to be taken to ensure sufficient bandwidth is always available for femtocell-to-macrocell backhaul communications [49]. *Service level agreements* (SLA) are one viable option to ensure bandwidth is reserved for femtocell operations [50].

Considering that the femtocell network will generally share the backhaul infrastructure with other networks and applications, congestion can occur at peak periods leading to potential scheduling delays. The femtocell network must therefore have appropriate mechanisms for prioritising traffic in delay-sensitive, low latency applications such as video conferencing and voice calls. Furthermore, the femtocell network must have an alternative route for backhauling traffic to maintain communications when there is either disruption or failure of the backhaul network. In most scenarios, the backhaul network is not owned by the femtocell service provider, so its capacity can vary between locations.

The onus is thus on the service provider to make sure the network and resource management system incorporates these variations when scheduling any user for a particular service. From a design perspective, a joint scheduling strategy between the backhaul network and FAPs is therefore desirable to enable optimal performance in terms of the application specific QoS requirement, the throughput and overall system capacity [51]. However, these require taking consideration of other systems sharing the wired backhaul network such as internet service and voice communications. The thesis focuses on wireless network and considers macrocell and femtocells only and hence backhaul constraint is not considered.

2.3.4 Spectrum Sharing Strategies

To enable short range FAP operation in an indoor environment, various spectrum-sharing methods have been proposed [52] which can be graphically summarised as shown in Figure 2.3. These spectral allocation options can be categorised as being dedicated, shared or hybrid. Each of these will now be individually considered.

Dedicated Spectrum Allocation:

In this arrangement, both the macro and femtocells are allocated separate bands as shown in Figure 2.3 (a). This ensures the interference only occurs between co-channel femto cells, and inter-channel interference between macro and femtocells is avoided. The drawback is that some bands in either system can remain unused if the number of users is low as bands allocated to macrocells cannot be reallocated or released to femtocells. Greater efficiency could be achieved if the respective channel widths allocated to macro and femtocells can be dynamically varied depending on user density and system requirements [53].

Shared Spectrum Allocation:

In the scheme shown in Figure 2.3 (b), no particular band is given to either system, but rather there is a common frequency pool from which both macro and femto cells are allocated channels which are governed by either a resource allocation policy or some criteria such as pricing, application priority and so on. This scheme is the most efficient in terms of resource utilisation, but also inherently leads to interference with other users. Coordination between femto and macro cells and/or a strong sensing system along with power control mechanism is essential to manage interference to within acceptable levels suggested by the regulatory authority or the original spectrum owner.

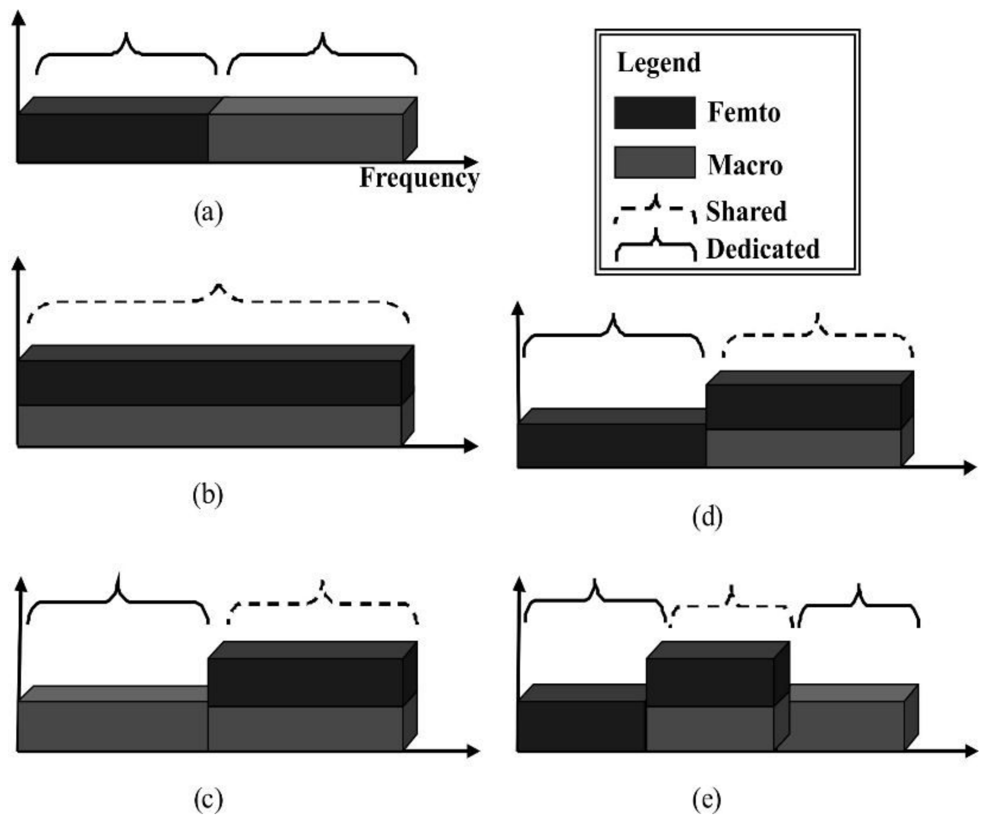


Figure 2.3: Spectrum Sharing Techniques (a) dedicated (b) shared (c) (d) and (e) hybrid

Hybrid Spectrum Allocation:

Figure 2.3 (c), (d) and (e) illustrate various different options for this scheme. In each case, a dedicated band is allocated to either a macro or femto cell or both and a portion of remaining bandwidth retained in the pool to be shared between macro and femto cells according to demand. The ratio of dedicated to shared band depends on system parameters such as the underlying allocation strategy, priority, user-density and cost.

Aside from the aforementioned spectrum access methods, flexible spectral utilisation technology enables the radio to operate on multiple bands [54]. Since the unlicensed band is already overcrowded, most of the studies recommend operating in the licensed band such as cellular bands which can suffer from potential co-channel interference.

2.3.5 Mobility and Handover Management

Since femtocells have limited coverage, even users with low mobility may frequently move out of the range of connected FAPs for a short interval. This can mean a disproportionate number of handovers being incurred compared to a conventional cellular system. Vigilance must thus be exercised in managing both the mobility and handover procedures to guarantee seamless operation.

In a closed access femtocell network, if a user moves out of FAP coverage, it must be handed over to the macrocell BS. In contrast, for an open access network, the user firstly attempts to hand over to a different femtocell if one is available, otherwise it is handed over to the macrocell BS. The decision making process for the femtocell-to-femtocell scenario is more complex as it not only needs to consider the strongest signal strength, but also the admission control policy of possible femtocells, the capacity and load of neighbouring FAPs, resources, potential interference creation and the signalling and processing overheads [55].

The handover process is triggered whenever the received MS signal strength falls below a threshold. The MS then searches for available FAPs or for a macrocell BS signal and reports back to the serving FAP, which if required, cooperates with the RNC or FGW to decide which FAP is to be handed over to the MS. This technique is known as reactive handover. Handovers can also be proactive where the MS initiates the process before its signal strength falls below the threshold. Mobility can be predicted and the radio environment of the position analysed in choosing the most appropriate FAP to be handed over the MS [56]. This can be useful for reducing both packet loss and latency during the handover procedure.

The femtocell must safeguard against unnecessary handovers and apply an adaptive threshold to minimise their number [57]. There should also be a mechanism to automatically detect frequent handovers or the so-called *ping-pong* effect and directly terminate such incidences. One proposed solution [58] uses a call admission process to force MS to remain connected to either the femtocell or macrocell for a certain time interval before permitting handover. Though minimizing the number of handovers is crucial, the impact of keeping the MS connected to the femtocell on the network needs to be carefully investigated before adopting any handover minimization policy.

2.3.6 Radio Resource Management Architecture

Radio resource management architecture for a cellular network is a system level entity for addressing issues such as spectrum reuse, coverage optimization, inter and intra system handover, resource partitioning and channel assignment with the primary aim of enhancing the spectral efficiency, user experience, system capacity and performance [59].

The conventional cellular network is extensively analysed and planned before deployment, so a centralised resource management is more appropriate for these systems. The advantage of centralised management is that it has access to global information and so the best possible solution can be made. It also ensures efficient control of the resources. However, with increasing entities, the amount of redundant communication required increases geometrically. So the centralised solution is not scalable.

In contrast, unplanned and massively deployed systems, such as adhoc networks, do not have any rigid structure and the topology also varies dynamically, so a distributed resource management is better suited with this kind of scenario.

Although the femtocells are deployed by the end users without any network planning, their resource usage significantly relies on macrocell resource allocation. The combination of predicted large-scale femtocell deployment allied with a dynamically varying radio environment means that, it is extremely difficult to centrally control femtocells. This means hybrid system control is more propitious for femtocell network management with some functionalities controlled centrally and some devolved to either the FAP or local FGW.

In radio resource management techniques, resources are exploited intelligently to reduce and mitigate interference. Due to the importance of interference mitigation in successful deployment of femtocell networks overlaid on macrocell systems, an in depth discussion is necessary and therefore in the following section, different interference mitigation techniques are discussed in detail.

2.4 Cross and Co-tier Interference Management

Mitigation of interference between macrocells and femtocells, and among femtocells is crucial for efficient operation. Depending upon the operating spectrum for the macro and femtocells, the interference scenario may change. For example, if the macrocell and femtocell operate on different dedicated spectrum, then there will be no cross-tier interference. Conversely, if both operate in the same band, there will potentially be both cross and co-tier interference. Table 2.2 summarises the types of interference assuming a shared spectrum arrangement for the macrocell and femtocells.

There are many recognized techniques for handling interference including for instance, those dedicated towards interference randomization [60], cancellation [61] and coordination or avoidance [62]. Interference cancellation requires an advanced signal processing capability at the receiver which is expensive due to the extra hardware complexity. This has meant interference coordination and avoidance methods are more preferable since they do not increase the complexity of the transceiver system. The following subsections will explore different cross-tier and co-tier interference management schemes. For clarity in the ensuing discussion, the two interference types are separated according to the system in which they are more prevalent.

Table 2.2: Summary of the various interference scenarios in a joint macro-femto cell deployment.

Link	Transmission Mode	Interference Scenario
Macro BS to Femto MS	DL	Macro to Femto
Macro MS to FAP	UL	Macro to Femto
FAP to Macro MS	DL	Femto to Macro
Femto MS to Macro BS	UL	Femto to Macro
FAP to Femto MS	DL	Femto to Femto
Femto MS to FAP	UL	Femto to Femto

To fully mitigate cross tier interference, separate spectra need to be allocated to the macrocell and femtocell, though the pyrrhic cost of this solution is spectrum inefficiency.

Femtocells can be arbitrarily positioned by the end users, which prevents any form of pre-deployment network planning. This means different types of interference have to be either coordinated or mitigated in order to guarantee successful operation. Femto-to-femto interference can be particularly severe in dense deployments. A centralised solution is precluded simply because it is not scalable in high density scenarios. Therefore, either a fully distributed or a hybrid interference management system is more suitable for these scenarios. Graph-based allocation and cross tier cooperative power control technique are two prominent technologies for distributed and hybrid interference management approach.

Interference management is the biggest challenge for successful operation of femtocell networks [63]. So a careful investigation of existing methods and possible alternative solutions for managing interference is necessary. In the following section, a detailed review of the interference management techniques will be provided.

2.5 Interference Management Strategies

The methods of interference management mentioned for cross and co-tier interference is valid for both cases of interference. However, due to scalability and some other issues some methods are preferred for cross tier interference mitigation, while some others are preferred for intra femto tier interference mitigation. Some of the methods are discussed below:

Macro/Femto Aware Collaborative Resource Allocation

Cross-tier interference can be efficiently reduced if the femto-tier avoids channels used by macro users in their vicinity [64]. Initially, the macro-tier shares allocation information with the femto-tier, which can then exploit sensing feedback from its users to attain better accuracy in cross-tier interference avoidance. Similarly, a femtocell can report on its channel usage via the backhaul network, so the macrocell can avoid allocating those resources to neighbouring macrocell users. Efficiency can be further improved by applying joint scheduling in a collaborative macro-femtocell arrangement, with a portion of the channels dedicated to both tiers and the remainder used in a sharing mode.

Directional Beamforming

Beamforming is another emerging technique for cross-tier interference minimization which requires multiple element antennas. Since an omnidirectional antenna generates interference in all directions, when a macrocell is transmitting to a user at a certain distance, that channel cannot be used by any FAP within the *safety distance* regardless of the position of the femtocell compared to that macrocell user within the cell. Directional transmissions only generate interference to users located in the LOS direction, so FAPs located outside this direction will be free to use that channel. For each macrocell user, the beamforming vector can be selected based on the highest received SINR [65]. The macro user then senses the signal from the FAP and provides feedback via the backhaul about the beam subset which generates the minimum interference power. Femtocells can then use this beam subset to avoid interfering with the macrocell users. A reciprocal scheme can be embraced by macrocell users to avoid interference with femtocell users.

Power Control

Power control has been effectively used as a mitigation strategy for both cross-tier and co-tier interference. Its main advantage when applied to the macrocell is that it creates more space for a femtocell to reuse the channel. A FAP can also adjust its power in order to have shared access to the channel with macrocell system. To facilitate this, macrocell users need to accurately measure the interference and relay this information via the macrocell BS and backhaul network. After receiving this feedback, the FAP can then fine-tune its transmission power accordingly.

In large-scale deployments, centrally managing the transmission power is extremely problematic. Game theoretic approaches afford a distributed solution to this problem with both cooperative and non-cooperative strategies existing to find the optimal Nash equilibrium power value for a given set of objectives and constraints [66]. An alternative distributed solution to cross-tier interference minimization is *reinforcement learning (RL)* [67], [68], where femtocell users sense the system and combine the current transmission experience with previous experiences to decide the most appropriate power level. While RL is an attractive solution for distributed environments and works well for lower numbers of users, learning can be a slow process in the case of highly dense deployment and hence the solution risks inefficiency in interference management.

Graph Colouring Approach

This technique is often applied for channel assignment in wireless networks to avoid interference [69] and has been examined as a means of interference minimisation in femtocell networks [70], [71].

If it is assumed each colour represents either a single channel or set of channels to be allocated, and the connections (links) are the interference, then the underlying premise is that no connected nodes can be assigned the same colour. The resource allocation problem can essentially then be considered as a graph colouring solution.

The interference graph is generated as:

$$\overline{G} = \left(V, \overline{E}\right) \tag{2. 1}$$

where V is the vertex that represents each transmitting femtocell and is defined as:

$$V = \{v_1, v_2, v_3, \dots v_n\} \tag{2. 2}$$

with edge $\overline{E}$ being the interference link for each V defined as:

$$\overline{E} = \{e_1, e_2, e_3, \dots e_n\} \tag{2. 3}$$

After constructing the set of edges *en*, each vertex is assigned a colour such that no connected vertexes have the same colour.

The example in Figure 2.4 illustrates the basic graph colouring idea. Firstly, interference link edges are constructed for all 5 FAP. As FAP1 has the highest number of links, it is assigned the first colour, while since FAP2 and FAP3 have the next highest number of links, they are accordingly given two separate colours as they are connected to each other as well as FAP1. FAP4 only has a single link to FAP1 so is given a different colour to FAP1, while FAP5 is assigned the same colour as FAP2. This provides the minimal intra-tier interference result for this particular example.

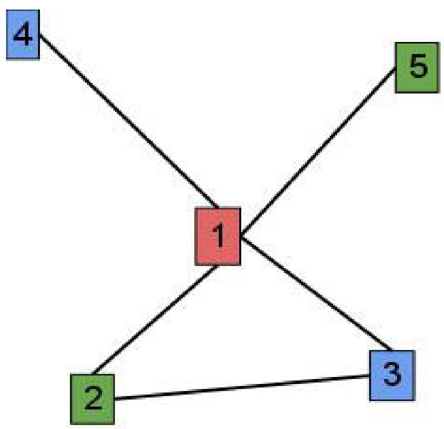


Figure 2.4: An example of the graph colouring problem for 5 FAP

Several other issues can be addressed by modifying the graph colouring problem. Fairness in channel usage can be assured if the number of times a particular colour is allocated is taken into consideration while assigning the next colour. For example, in Figure 2.4, both FAP4 and FAP5 are free to choose the same colour as either FAP2 or FAP3. If it is assumed FAP4 selects the FAP3's colour, then despite FAP5 having the choice of either colours, to ensure fairness it must choose the FAP2 colour.

Although graph colouring is suitable for ad-hoc like structures, it may not be suitable for hybrid systems like joint macro femto deployment, which is a blend of planned and unplanned deployment. Moreover, the graph needs to be reconstructed for all connected nodes if a MS moves out of the system. If the graph is managed centrally, then this will generate a huge number of control data exchanges which will make it inefficient.

FFR based resource Allocation:

FFR was originally proposed to be used for macro cellular systems to avoid ICI particularly at the cell edge, to reduce the impact of co-channel interference and co-channel reuse distance for a certain portion of the spectrum and thereby improving the overall system capacity up to around 30% compared the conventional methods [72], [73], [74]. To both alleviate and coordinate ICI, FFR divides a macrocell into an inner and outer area and then allocates each divided area with orthogonal set of channels exclusive for those areas. This ensures that there is no conflict between inner and outer cell areas. Intelligent and coordinated allocation of mutually exclusive channels in the outer cell area of neighbouring cells will also ensure the mitigation of ICI. Thus the macrocell will have a set of channels exclusive for each area. This means certain frequencies are not used by the macrocell in some areas, creating the opportunity for the femtocell to exploit this vacant spectrum.

A key design precondition for the femtocell to exploit this unused resource is that localised spectral information is available at the femto-tier, which as mentioned above, mandates cross-tier information sharing within the system. A number of variations are proposed on how the spectrum will be split in the outer cell areas of neighbouring macrocell, each with their distinct features and advantages [75] [76], [77].

The main advantage of this method is that the information sharing between tiers is very low as only occasional updates are necessary for both the tier. This will save a lot of redundant control data and make the cross tier interference management much simpler and efficient. This feature particularly made it attractive for the resource partitioning in joint macro-femto deployment scenario.

2.6 Conclusion

In this chapter, the state of the art in CFN research has been presented. CFN is an emerging technology for enhancing the indoor coverage where traditional network performance is typically poor. It consists of low power access points overlaid on the existing macrocell networks. It typically operates on the same band as the macrocell forming a dual-tier network. This network architecture is presented followed by a detailed investigation of the challenges involving joint deployment, possible operating spectra and the different access technologies. Standardisation activities, backhauling and security issues are also briefly discussed for completeness. A thorough review of the technical challenges including access control mechanism, interference mitigation, cross and intra-tier spectrum sharing problems has also been provided. Finally, some of the challenges and opportunities for new radio resource management techniques to minimise interference in dual-tier networks have been discussed to define the research scope of the thesis.

3 Hybrid Resource Management for Cross and Co-Tier Interference Reduction

3.1 Introduction

Femtocell networks are overlaid on existing macrocell networks and operate on the same licensed band as conventional macrocell networks. The MSs will be connected to the femtocell or macrocell depending on whether they are located indoors or outdoors and the access policies set by the operators. Since they share the same set of wireless resources, there are similarities in resource requirements and operating procedures between macrocells and femtocells. For any wireless network, intelligent design of *radio resource management* (RRM) techniques is crucial for effective interference reduction and successful network operation and management.

Despite many similarities, there is a fundamental difference between macrocell and femtocell deployment that prohibits the straightforward use of RRM techniques designed for macrocells in the femtocell networks. From the downlink transmission point of view, macro BS is deployed after careful planning considering available resources and possible traffic patterns in the whole coverage area. On the other hand FAPs are deployed by the end users who are normally non technical persons. In addition, it must be assumed the FAP is likely to be located at a convenient place in a house regardless of the implications upon either other FAPs or the macrocell interference scenario and resource management policies.

This inherent uncoordinated and overlaid deployment of femtocells makes the existing RRM techniques, which are designed to manage well organized and pre-planned network, often ineffectual. Therefore, RRM techniques designed for macrocells need to be modified to suit the requirement of the femto tier. As any major changes to either the resource management architecture or network control topology may be expensive to realize, so a careful investigation into the existing systems and possible opportunities for exploiting them are necessary for successful femtocell network deployment.

Another major contrast between macro cellular and femtocell systems is the area covered by a cell. The macrocell has a typical coverage radius up to 500m in urban areas and a few kilometres in rural areas. Since they are deployed in a planned manner, a dedicated backhaul communication (known as an X2 interface) among macro BSs are also established for faster and reliable communication and data transfer. Thus managing the resources from the RNC, offers the best and most efficient performance as it affords global traffic information and a dedicated communication medium.

In contrast, the coverage radius of a femtocell is generally only between 10m and 30m. So, for example, in 1 km^2 area there might be only one macro BS, but in the same coverage area, hundreds of femtocells may be required. Centralised solutions - although best for macro cellular systems - are not scalable and therefore not suitable for femtocell networks due to the anticipated massive deployment. Furthermore, since they are deployed arbitrarily in buildings, the only viable option is to use existing fibre optic or ADSL-based wired networks for backhaul communication and data transfer, which needs to be shared with other internet service providers and systems.

So controlling the system from a central location through this shared medium will not be very effective and poses a potential risk of failure. The number of FAP deployed will vary widely depending on the location and one particular solution may not fit all cases. This implies a RRM solution for joint macro femto deployment will inevitably be hybrid in nature to combine the advantages of both architectures. It must also have the capability to adapt to changes in the radio environment caused by frequent users joining and leaving the network.

This chapter investigates seamlessly embedding a femtocell tier within a resource distribution framework to create a two-tier system, which crucially incorporates a cross-tier spectrum sharing strategy. *Hybrid Resource Management Architecture* (HRMA) is proposed where cross tier channel allocation is managed centrally and channel allocation for individual MSs is performed by the respective FAP in a distributed fashion.

In the following sections, HRMA will be discussed with both cross and co-tier interference management problems being addressed. For cross-tier interference management, a modified FFR method will firstly be introduced and this will subsequently be integrated into the new HRMA framework. As conventional FFR techniques have been designed solely for macrocell systems, an alternative solution needs to be developed for dual-tier, joint macro-femto networks. The HRMA algorithm for intra femtocell interference mitigation will then be explained in detail. A system model will be developed in order to evaluate the performance of the proposed architecture and algorithm with rigorous simulation results presented and analysed.

3.2 Hybrid Resource Management Architecture

As stated in the previous chapters, despite many benefits, femtocells can cause potential interference with co-located femtocell and macrocell users operating in the same frequency band. The intrinsic uncoordinated nature of femtocell deployment compounds the challenge of managing interference in such two-tier models. Traditional RRM policies have been static in nature, with the spectrum assigned to a user being fixed regardless of instantaneous changes to the radio environment. This leads to inefficient spectrum and energy usage. To ensure better utilisation of locally available spectrum in rapidly changing environments, an assortment of dynamic RRM techniques have been proposed [78], [79], [80], where both spectrum and energy can be either dynamically switched or modified according to the radio environment variables at particular geographic spatial and temporal values.

Recent advances in dynamic RRM have emphasised the need for more efficient resource management strategies. While centralised resource management offers improved coordination and operator control giving better interference management, it is not scalable for increasing node densities. Distributed management techniques in contrast, do afford scaled deployment, but at higher node densities incur performance degradation in both system throughput and link-quality because of poor coordination.

Radio resource allocation and distribution can be done most effectively if the decision is taken centrally with global information. However, this requires considerable control data transfer to a central entity. As the control data overhead increases geometrically with the numbers of FAP deployed, centralised resource management becomes unaffordable for higher number of nodes as it requires cross-tier information sharing. Thus a hybrid resource management is proposed whereby spectrum sharing between the macro and femto tiers is decided in a centralised fashion, with periodic updates to the femto-tier being carried out by the RNC and FGW. Depending upon the spectrum sharing decision, in the femto-tier, each FAP decides the resource allocation for its own associated users in a distributed fashion. These together form the hybrid resource management architecture which will be presented in this thesis.

The HRMA avoids both unnecessary communications via the backhaul networks and innate delays in the decision making. The RNC undertakes the range of management and control functions usually assigned in a traditional cellular system, including: registering and authenticating FAPs, assigning spectrum chunks to each FAP by considering the macro-tier load and MS allocations to ensure mutual exclusiveness between the two tiers; dispute handling between FAPs and the management of the database containing the FAP location information. The FAPs in contrast, manage MS information and make local spectrum allocation decisions based upon feedback received from the MSs.

As mentioned earlier, the easiest way of sharing spectrum between the macro and femto tiers is to allocate dedicated resources to each tier so that there will be no cross-tier interference. However, this method is inefficient in terms of spectrum usage. The best policy would be to share the whole available spectrum between the macro and femto tiers, though there is the potential danger of creating huge cross-tier interference if the same channel is used by the FAP and macro BS to serve co-located femto and macro users respectively. So, if the macrocells and femtocells can intelligently avoid using the same channels for co-located macro and femto users, then both systems can use the whole spectrum. One mandatory requirement for enabling this is to share cross-tier spectrum usage information in real time. The cognitive capability of emerging network technologies can be utilised to do this, though the amount of data sharing requirement remains a major design challenge [63].

3.2.1 Fractional Frequency Reuse technique

A recently proposed frequency reuse technique in macro-cellular spectrum is *fractional frequency reuse* (FFR) [76] [77], where the reuse factor $n_r > 1$, is the number of distinct sets of channels used in the system. FFR is applied at cell-edges to avoid ICI. The basic idea is to divide the macrocell area into two regions, namely the *inner cell region* (ICR) and the *cell edge region* (CER). The same set of channels in the ICR is used by all cells and a different set of channels for CER of the neighbouring cells. Each colour represents the portion of spectrum assigned to the macrocell users in that region correspondi0ng to the right bar shown in Figure 3.1 (a).

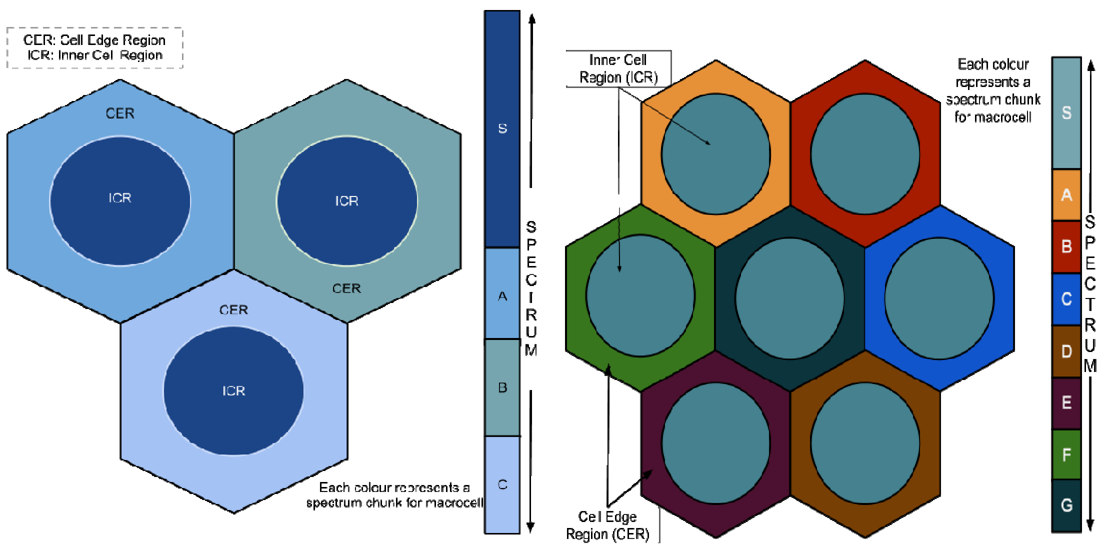


Figure 3.1: Spectrum distribution in ICR and CER for FFR scheme with (a) 3 cells and (b) 7 cells.

The ICR will use spectrum S in all the cells while the CER for the three cells will use spectra A, B and C respectively which are all mutually exclusive. This ensures that the users in the CER of neighbouring cell will have a different channel set for access and there will be no ICI. Depending on the reuse pattern and antenna sectorisation, 3 cells and 7 cells reuse can be applied either with or without sectorisation. Figure 3.1(b) shows the 7 cell case.

The minimum SINR that can be achieved at the boundary is given by [81]:

$$SINR_{\min} \leq \frac{0.5}{\left(\frac{1}{\sqrt{3N}-1}\right)^n + \left(\frac{1}{\sqrt{3N}}\right)^n + \left(\frac{1}{\sqrt{3N}+1}\right)^n} \qquad \textbf{(3.1)}$$

where, N is the number of hexagonal cells per cluster and n is the path loss exponent. The value of N is related to radius of the cell, R and channel reuse distance, D according to:

$$\frac{D}{R} = \sqrt{3N} \qquad \textbf{(3.2)}$$

Assuming the radius ratio of ICR and the cell, α is related to the ICR radius R_1 by $R_1 = \alpha R$, then the SINR required at the ICR boundary can be calculated by using the value of α in (3.1) yielding:

$$SINR(\alpha) \leq \frac{0.5}{\left(\frac{\alpha}{\sqrt{3N}-\alpha}\right)^n + \left(\frac{\alpha}{\sqrt{3N}}\right)^n + \left(\frac{\alpha}{\sqrt{3N}+\alpha}\right)^n} \qquad \textbf{(3.3)}$$

Using the above relations, the transmit power of the BS for users located in the ICR and CER can be calculated. In both single and multi-tier systems, the ratio of CER and ICR has a significant impact on the overall system performance, so the ratio of spectrum between CER and ICR needs to be carefully designed to balance the load per channel in those areas. While finding the optimum radius of the ICR is relatively straightforward in single-tier systems, the optimum radius for multi-tier systems is more complex. Further details on the ICR and CER ratio and its impact on system performance can be found in [82].

By introducing a suitable modification, this FFR technique can be readily exploited for cross tier spectrum sharing. A design prerequisite for the femtocell to be able to exploit this unused resource is that localised spectral information is available at the femto-tier, which mandates some level of cross-tier information sharing within the system. This technique is particularly rewarding as only regular updates at certain intervals between tiers is necessary and this keeps the control data transmission to the RNC or central entity very low compared to all other methods. The key idea is to share the ICR and CER spectrum allocation information with the femto-tier so it can use the whole band, apart from that which has already been assigned to the macrocell in that location. The principal advantage of this FFR-based scheme is that it eliminates cross-tier interference because mutually exclusive spectrum is used for each tier at any particular location, which allows the design focus to be on managing interference in the femto-tier only.

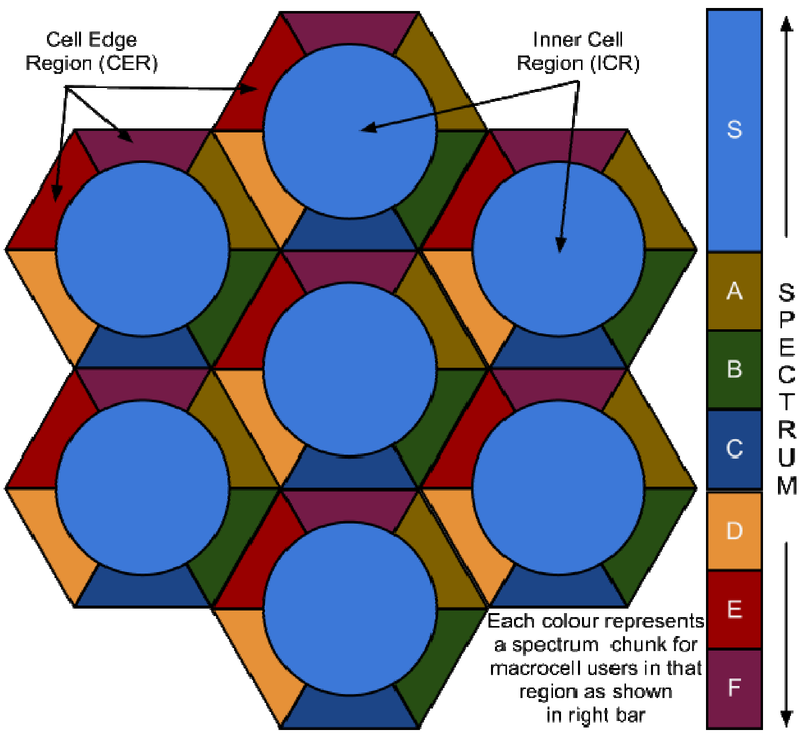


Figure 3.2: A Sectoring FFR reuse scheme for macrocells, with femtocells are allowed to use the whole spectrum except the chunk used by macrocell users in that sector.

Dividing macro users into more sectors means fewer channels required per sector as fewer users will be located in each sector. This means a higher number of channels will be available for the femto tier. For example, in Figure 3.2, the CER is divided into six sectors (each colour represents one sector with the corresponding spectrum is shown on the right hand bar). In each CER sector, FAPs can use the whole spectrum except the part that is allocated to the macro tier on that area. Since the sectoring area is now halved in comparison with the three sector system (see Figure 3.3), the spectrum available for the femto-tier has increased on average, by between 6% and 7%, under the assumption of a uniform user distribution.

With increasing numbers of sectors however, the sector area becomes correspondingly smaller which increases the possibility of more handovers and macro-tier load imbalance in some sectors. Also, due to the dynamic nature of the resource allocation, a higher number of updates between tiers will be necessary which will incur additional control data exchanges, so a balance between the performance and associated risk factors needs to be considered for successful network operation and management.

3.2.2 Dynamic FFR

One such dynamic FFR algorithm partitions the macrocell channels in proportion to the traffic load in that area. Additionally, a reserve channel set is proposed for the femto-tier which is regularly updated based on changes in usage in the macro-tier. This reserve channel set is available to femtocell users which are overlapping and in a severe interference scenario.

The amount of spectrum available in a certain sector for the macro-tier can be calculated by the following relation:

$$K = BW \times \left(\frac{N_K}{N_U} \right) \tag{3.4}$$

where, K is the sector number, for which spectrum availability is calculated. BW is the total bandwidth of the system. N_K is the average number of macro users in that sector, while N_U is the average number of users in the whole macrocell.

Figure 3.3 illustrates the dynamic FFR scheme used in this thesis. Each colour represents an available spectrum band for the macrocell users in that area and femtocells are not permitted to use these bands at all. For example, in the outer cell area of sector 1, macro users are allowed to use channel C, so femtocells are only permitted to use the other three channels in this area, namely S, A and B. However, vigilance is required for femtocells located at the border of a cell as they may interfere with the macro users in an adjacent macrocell.

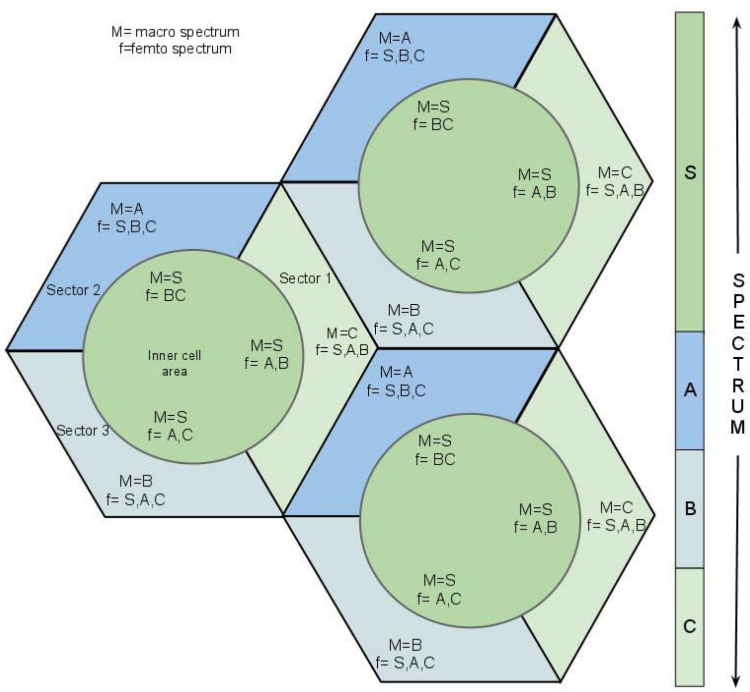


Figure 3.3: Dynamic FFR scheme for joint macro femto deployment.

Likewise in the outer cell area of sector 3, femtocells can use the entire spectrum except the B channels. In the inner cell areas, macrocell users are allowed to use S channels, though unlike the outer cell area, femtocells are not allowed to use any other channels except S. In addition to avoiding the S channels, femtocells need to avoid those channels used by the macrocell users in the outer cell in that sector. For example, if a femtocell is located in the inner cell area of sector 1, then along with channels S, it also needs to avoid channel set C.

It is assumed the average user demand remains constant, so the amount of spectrum allocated to a particular area varies with time in accordance with the user density and this is updated after some predefined time interval. After making this cross-tier spectrum sharing decision, HRMA then allocates resources for the FAPs from the spectrum chunk delegated by the RNC for the femto-tier, with each FAP being independently responsible for assigning channels to the users connected to it. The main functional blocks of HRMA will now be described in detail in the following subsection.

3.2.3 Functional Blocks of HRMA

HRMA comprises three constituent blocks as shown in Figure 3.4, with the functions of each block now being individually explained.

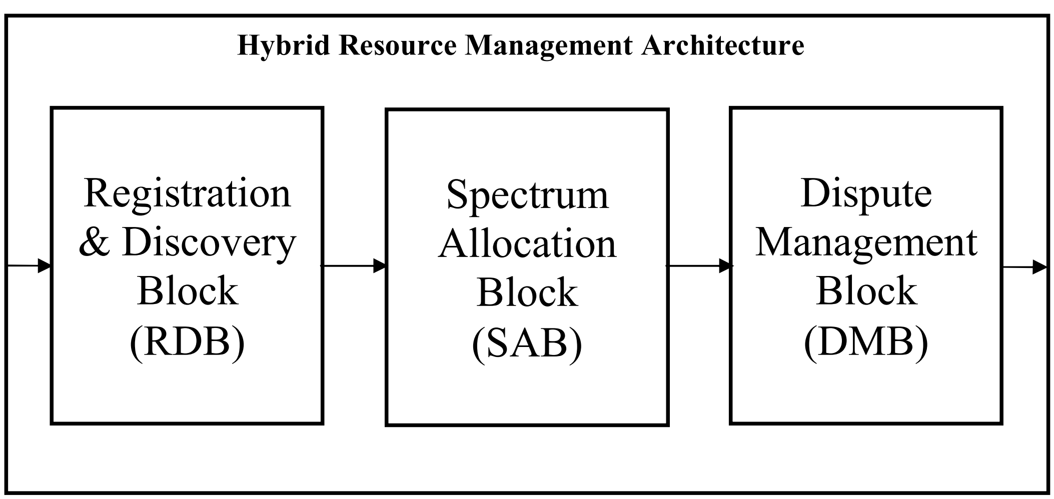


Figure 3.4: Functional Blocks of HRMA.

a) Registration and Discovery Block: When a FAP switches on, it registers with the RNC via the FGW and is assigned a unique ID. As each FAP is connected to the RNC and FGW via a back-haul network, the approximate position of both the FAP in the sector and neighbouring BS is known to the central controller. Utilising this information, the FGW updates the database for each femtocell located within its mandated area as $FAP_i(N_{fi};S_i;R_{fi})$, where FAP_i is the i^{th} femtocell at time t and S_i is the area in which the femtocell is located. N_{fi} is the set of neighbours which may potentially overlap coverage. The list of overlapping FAP is generated by monitoring whether a registered FAP falls within a distance of d_{nb} of the FAP in the given sector. The concept of overlapping and non overlapping FAP is shown in Figure 3.7. R_{fi} is the set of channels accessible to a femtocell, with the following relation needing to be upheld, $R_{fi} \cap R_m = \Phi$ where R_m is the set of channels allocated to the macro-tier in the same area and Φ is the null set. This condition means a femto-tier channel and a macro-tier channel at any location, must be mutually exclusive.

b) Spectrum Allocation Block: One of the principal RNC roles is to notify the FGW about the spectrum partition for the FAPs under its control. The FGW then notifies each FAP concerning its allocated spectrum partition. This ensures members receive mutually exclusive channel sets to avoid severe interference, before each FAP allocates the channel from the assigned set to each user independently. This allocation is based on the channel state information (CSI) measurement as defined in the Section 3.3.

c) Dispute Management Block (DMB): When a MS performance degrades below a prescribed threshold, the corresponding FAP firstly attempts to hop to the second best available channel for the next transmission of the relevant MS. If the problem persists, it flags the RNC via FGW with the ID of the interference creator FAP. The RNC then examines the allocated frequencies of the disputing MSs and reassigns new channels to each. If all partitions are fully used, it will then allocate channels from the reserve set.

The database containing the spectrum partitioning details is regularly updated as is the corresponding femto-tier information. After a certain time interval, all the FAP are updated with the latest macro-tier spectrum partition information and then execute the localised component of the HRMA until a dispute occurs, whereupon control is relinquished to the RNC to centrally manage the resolution via this *dispute management block* (DMB).

3.3 System Model and Simulation Set-up

A Wireless network is inherently complex and dynamic in nature as they involve a high number of time-varying interactive components which often impact on the entire system architecture. Thus analytically modelling a multi-user wireless network remains an intractable problem [83]. A further problem is very few theoretical results on Shannon's capacity for cellular network are available. While some progress has been made recently in this domain applying stochastic geometry [84], the fundamental assumptions underpinning the model remain problematic. The net result is that a simulations-based approach is still widely employed in cellular network modelling and performance evaluations. In this section, the simulator platform, its core building blocks, various system parameters and key performance indicators will be discussed.

3.3.1 Choice of simulator platform

There have been a number of programming languages and coding platforms available for system simulation development including C/C++, Java and Matlab. While the first two offer much faster execution of the program, they require developing libraries or components for each and every element, which is very time consuming. Sometimes, open source libraries for different functions are available, but their reliability is not guaranteed. On the other hand, Matlab is relatively slow in terms of execution speeds but has numerous built-in functions and specially developed tool boxes for communications and signal processing which makes the coding both simple and straightforward. Since the focus of this thesis is not developing new basic tools, but rather using those tools for evaluations purposes, these built-in functions save significant time and energy. Also, the powerful computers can run the system at a reasonably fast pace, so for this reason, Matlab has been chosen as the underlying platform for all simulator development work.

3.3.2 Basic Simulation Scenario Assumptions

A dual-tier (macro-femto) system model is considered in this thesis, where the femtocell is overlaid upon the macrocell system. A closed access mechanism is adopted for all femtocells so only authorised MSs can connect to a particular FAP. FAP transmission power is fixed, though different power levels are used for the inner and outer macro cell MSs. Flat fading over one transmission time is assumed, though this can between one transmission interval and another and it is also assumed that the *channel state information* (CSI) for all the MS is known by the transmitter.

The interconnection network for joint macro-femto deployment was shown in Figure 2.1. The FAPs are connected to a local FGW which retains some FAP control functionality relating to the registering of FAP and its user, assisting in the initial configuration, allocating available femto-tier resources, managing local disputes, routing traffic in both directions and most importantly as a link between the RNC and individual FAPs. The FGW maintains communications with the macro-tier via the RNC, the Internet and the operator’s interface (also known as the S1 and X2 interface), routing traffic in accordance with the RNC. The FGW plays a crucial role in cross-tier information sharing and is an intermediary between the macro and femto networks.

3.3.3 Simulator Building Blocks

The major constituent building blocks of the simulator that has been developed are shown in Figure 3.5. The *macro tier deployment module* creates the hexagonally-shaped macrocells with up to 7 macrocells of various radii being able to be implemented. The macro BS is always located at the centre of the cell and comprises three sectors. It also randomly deploys the generated MSs in each sector following a uniform distribution.

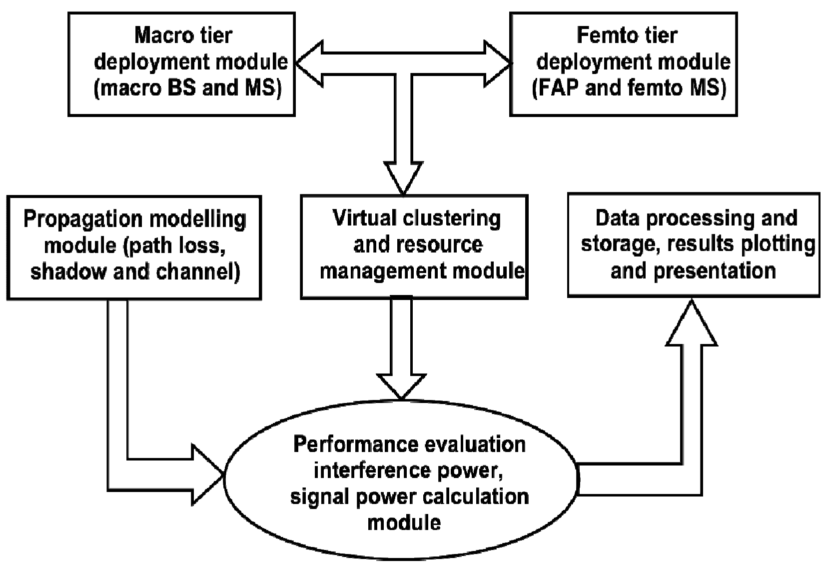


Figure 3.5: Main building blocks of the simulator

The *femto tier deployment module* deploys FAP and the MSs which are connected to it. Femtocells are circular in shape and uniformly distributed inside every macrocell. The FAP is assumed to be located at the centre of a femtocell and the MSs connected to it are uniformly distributed across the femtocell. Figure 3.6 shows an example snapshot of 50 femtocells and 30 macrocell MS located within a macrocell of radius 400m.

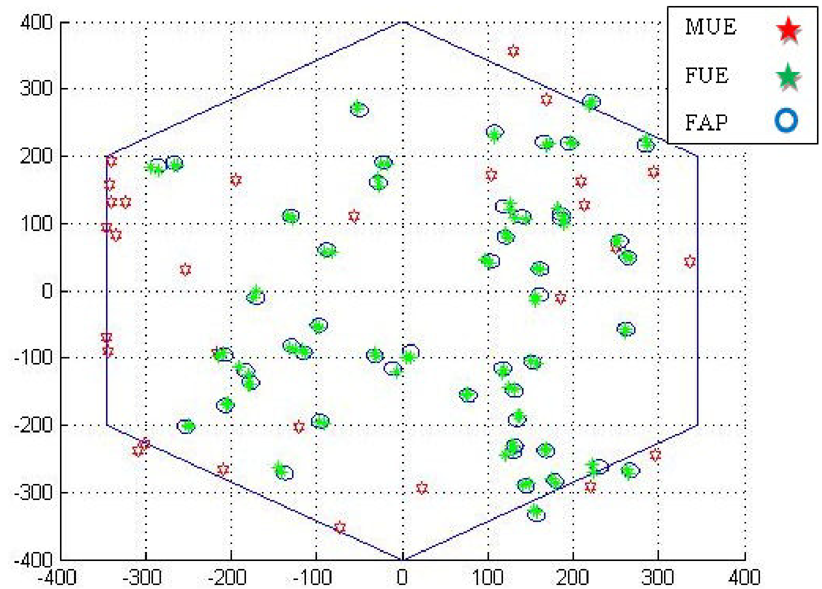


Figure 3.6: A snapshot of simulation test environment with 30 macrocell MS and 50 FAP in one macrocell area with radius of 400m (the x and y axes are distance (m) from centre of the cell).

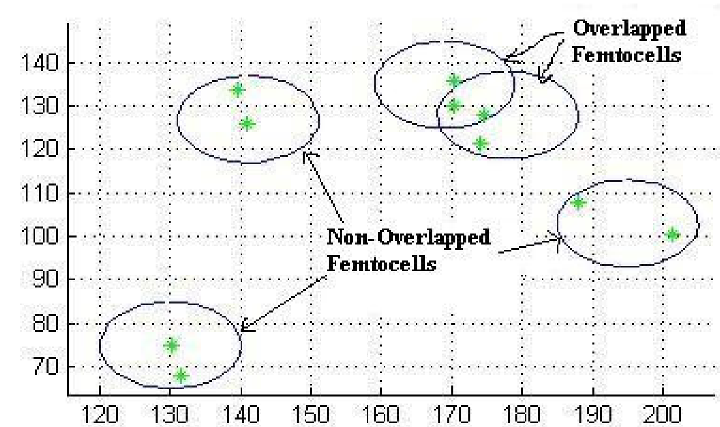


Figure 3.7: Example of overlapping and non-overlapping FAP, where the x and y axes are distance (m)

Another important building block is the *virtual clustering and resource management module.* This receives information from both the macro and femto tiers, and based on this information, resource distribution and cluster formation decisions are taken. One of the notable features of this module is the automatic detection of overlapping femtocells which is crucial for avoiding severe co-tier interference. This detection mechanism is based either upon the geometric distance between the FAPs or alternatively on a predefined signal power threshold received by the MS in the neighbouring femtocells. Figure 3.7 provides an example of the former. The task of this layer also includes channel allocation and depending on the policy employed, the channels are either allocated by the FAP or the FGW. The basic principle for allocating channels is now described.

Channel Allocation

It is assumed that every FAP is responsible for allocating channels to its member MSs, based upon feedback from the MSs on the respective received SINR. To assign the best available channel, each FAP calculates the SINR for all MSs attached to it, which is formally defined as:

$$SINR = \frac{P_{t0} h_0}{\sum_j P_{nj} + N_0} \qquad \ldots \qquad \ldots \qquad \textbf{(3.5)}$$

where $SINR$ is the signal to interference-plus-noise power, P_{t0} is the transmit signal power, h_0 the channel power gain, P_{rj} the received interference power on n^{th} channel from user j and N_0 is the noise power.

The achieved user throughput b can then be calculated from Shannon's capacity relationship [85]:

$$b = BW \cdot \log_2(1 + SINR) \qquad \textbf{(3.6)}$$

Where, BW represents the bandwidth over which the SINR has been measured.

Finally, the *Propagation modelling module* is another integral building block that generates path loss, shadow fading and channel models. A detailed treatment of this module is provided below.

Path Loss Model

As joint femto-macrocell deployment is the focus of this thesis, the respective path loss models for both indoor and outdoor environments need to be considered. For the outdoor scenario, the path loss model is chosen according to the widely used 3GPP LTE standard specification described in [86]. The path loss from the macrocell BS to MS is given by:

$$PL_{NLOS}^{m} = 128.1 + 37.6 \cdot \log\left(\frac{d}{1000}\right) + 21 \cdot \log\left(\frac{f_c}{2.0}\right) + L_{WP} \tag{3.7}$$

where PL_{NLOS}^{m} is the path loss from the macrocell BS, d is the distance of the user from the FAP in metres, and f_c is the carrier frequency.

For indoor scenarios, the WINNER II [87] path loss model is utilised. This model has a number of path loss scenarios, with different coefficients values being determined for the path loss equation in a combination of analytical and experimental cases. These values are valid for the spectrum range between 2GHz and 5GHz. Among the various scenarios, A1 represents the indoor and small office environment and because the indoor set-up is considered for femtocell networks, both the LOS and NLOS path loss values for the A1 scenario of the WINNER II model were selected for this analysis. For the LOS, where there is no obstacle between a FAP and the MS, the path loss is given by.

$$PL_{LOS}^{f} = 18.7\log(d) + 46.8 + 20\log\left(\frac{f_c}{5}\right) \tag{3.8}$$

where PL_{LOS}^{f} is the path loss component. In the NLOS situation, it is assumed there is at least one wall between the FAP and the MS. When there are walls between the transmitter and receiver, an additional *wall penetration loss* (L_{WP}) component is included in (3.8):

$$PL_{NLOS}^{f} = 20\log(d) + 46.4 + 20\log\left(\frac{f_c}{5}\right) + L_{WP} \tag{3.9}$$

where PL_{NLOS}^{f} are the femtocell path losses for the NLOS signals.

Shadow Fading

Also known as large scale fading is modelled according to the well established zero mean lognormal fading model [88] for a given standard deviation as specified in the LTE standard.

Small Scale Fading

It has been assumed small scale fading follows a Rayleigh distribution, which in the absence of a dominant LOS component, is the most appropriate distribution. The signal becomes scattered as it is transmitted to the receiver, and if the amount of scattering is sufficiently high, it follows a Gaussian distribution with the phase evenly distributed between 0 to 2π radians.

Once the resource allocation or virtual cluster formation has been undertaken, data transmission takes place and the performance is measured by the *performance evaluation, interference power and signal power calculation module*. This measures both the interference and signal power using information provided by the *propagation module.*

The received power at a femto MS is calculated according to the following relation:

$$P_r^{fms}(dBm) = P_t^{fap}(dBm) - (PL(dB) + P_{shadow}(dB) + P_{ff}(dB)) \quad \textbf{(3.10)}$$

where P_t^{fap} is the transmit power of the FAP, PL is the path loss component, P_{shadow} is the shadow fading and P_{ff} is the small scale fading. Similar relations can be used to also compute the interference power, from which then the overall SINR can be calculated.

These parameters are calculated for each system run and stored in the *storage and presentation module* for subsequent processing and/or plotting as and when required. Figure 3.8 shows the complete high-level flow diagram of the developed simulator used throughout this thesis.

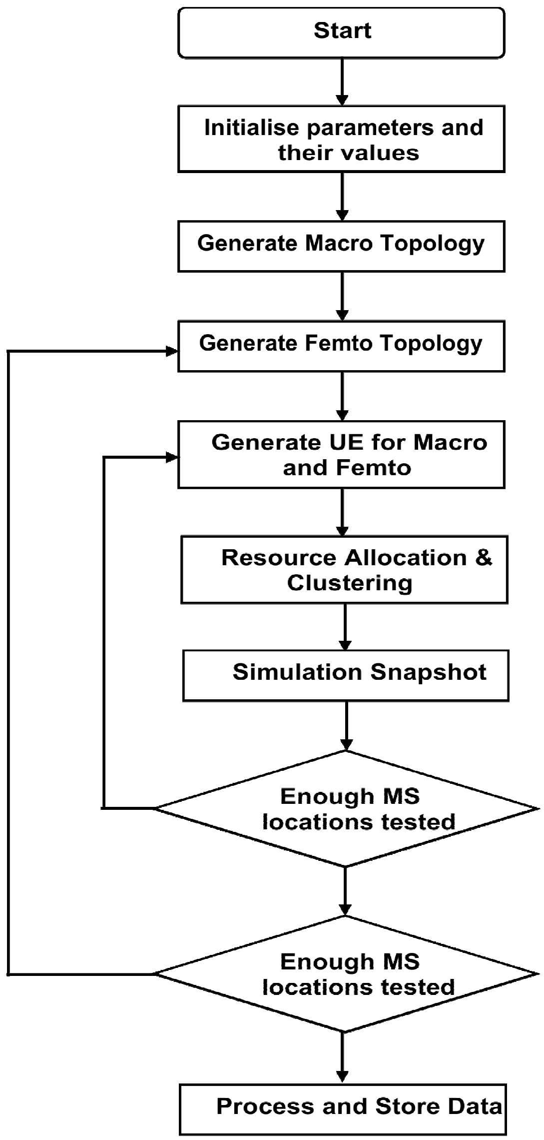


Figure 3.8: High level simulation flow diagram

3.3.4 Key Performance Indicators

Since a simulation-based approach is adopted, a large amount of data has been generated during the course of the research. Summarising and representing data in an informative way is very important for drawing conclusions of the findings. Since the work has focused on developing an interference aware system, it is important to measure system performance in relation to its capacity to combat interference. For this, one of the widely used measures of the signal strength, *signal to interference plus noise ratio* (SINR) has been adopted. The ultimate goal of a communication system is to transfer information from the transmitter to receiver using the spectrum. So, performance in terms of achieved throughput for a given spectrum is also an important measure. As mentioned earlier, from the achieved SINR, the *spectral efficiency* (SE) in *bits per Second per Hertz* (bps/Hz) is estimated by exploiting Shannon's capacity formula.

Different statistical description tools are utilised to represent the results. The main parameter used is the *cumulative distribution function* (CDF). The main advantage of using the CDF is that it represents the whole spectrum of performance and different statistical information can be readily identified as necessary. For example, the median of the performance can be computed from the CDF representation. Another important indicator often used in wireless communication research, is known as the *outage probabilit*y can also be obtained from the CDF curves. Outage probability is defined as the probability of the receiver SINR being less than a predefined threshold, so *p*% outage value means *(100-p)*% users are performing at or above the threshold. In this thesis both the 50th percentile (median) and 90th percentile values have been used to evaluate system performance, with both being widely applied in the literature as wireless communication system performance indicators [16].

Finally, the average minimum distance provides further insight into the performance comparison of the developed algorithms. It represents the average of the minimum distance between the members of a cluster. This minimum distance measure indicates how frequently the set of channels is reused in the spatial domain and since the interference power reduces with distance, the algorithm with a highest average minimum distance indicates the best performance.

3.3.5 System Parameters Choices

A dedicated software simulation environment was developed, to simulate various network scenarios and as a flexible test-bed to quantitatively evaluate the corresponding performance mentioned earlier. The various network parameters and their corresponding values used in the MATLAB simulations are defined in Table 3.1.

The values presented in the table are common for all the simulations, with some being varied in different experimental set ups and these will be highlighted in the respective discussions. All system parameters in Table 3.1 have been taken from 3GPP LTE standard definitions and are also proposed by the industry consortium called the femto forum (currently known as the small cell forum) [89].

The SINR threshold varies widely depending on the service and other issues. For a voice call, a very low SINR is acceptable while conversely for video transmission a relatively high SINR [90] is required. So, when an investigation does not consider a particular application, the SINR threshold varies widely from work to work [91]. 3GPP LTE release 8 [92] applies adaptive modulation and coding scheme with minimum value of SINR is less than –6.5dB where QPSK with 1/8 coding rate is applied. Although links can be maintained, the effective bit rate is very poor at this level. The same QPSK is applied with different coding scheme for SINR values <1.5dB, though some research considers 0dB as the threshold to maintain QoS in LTE systems [93] [94]. For this reason, a 0dB SINR threshold has been adopted in this thesis.

Table 3.1: Network parameters and their corresponding values used in all the simulations

System Parameter	Value or Range
Femtocell radius	10m in general, except Chapter 6
Macrocell radius	500m
Number of femtocells (FAP)	Variable (up to 200)
Maximum number of MS per FAP	4
MS noise figure	8 dB
Internal wall penetration loss	5 dB except Chapter 3
External wall penetration loss	10 dB except Chapter 3
Shadowing	6 dB
Macrocell transmission power	46 dBm (max)
Femtocell transmission power	0 dBm, 10 dBm
MS minimum QoS requirement	>0 dB
Total bandwidth	10 MHz
Carrier frequency	2 GHz
Channel width	180 kHz
Total number of channels	50
Number of channels available in experimental area for femto-tier	<21

One key advantage of using standard values for the system parameters is that the results can be validated with the performance boundary of the LTE systems. Despite this, it is very difficult to compare results of any other system as interference greatly varies with different parameters, i.e., deployment density, user numbers, channel availability, the number of interferers and transmission power. However, received power for a single transmitter and single receiver considering the path loss value only can be used as the upper performance bound. Another way of verifying simulator performance is to use fixed values for different fading components at a known distance in the absence of any interference and compare the calculated value with the results from the simulator.

Although this method will validate the simulator accuracy for single-user cases, validating results in multi-user cases in the presence of interference remains a complex issue. Since heterogeneous network research widely vary in scenario description, comparison with other research work or algorithms is very difficult. Therefore, in most work a baseline performance for a given scenario is usually used to compare the performance of the developed system. However, a combination of analytical evaluation (where a tractable solution is available) and simulated system for a preset values can be developed to validate the system.

Call Admission Control

The overarching objective was to make the system interference aware and thus focus on physical layer performance evaluation and discussion on the basis of SINR and corresponding SE measures. The goal was to understand how well it will it perform in a dual-tier arrangement with unplanned deployment scenarios. *Call admission control* (CAC) is a vast field of research [95] [96], so a detailed discussion about its impact on the system performance is beyond the scope of the thesis. When the SINR performance of a receiver falls below the required SINR threshold, a simple CAC has been employed whereby both the designed algorithms (HRMA and GVCF in Chapters 4, 5 and 6) and their respective performance comparators (BLA and NCS) hop to a different channel for the next transmission, subject to availability. However, it does not drop the call if no alternate channel is available and may continue to make a small contribution to the interference of the co-channel MSs. An intelligent and application specific CAC would improve the performance of the system.

3.4 Simulation Results and Analysis

To analyse the performance of HRMA, a number of different FAP deployment densities and scenarios were considered. One of the major differences between macro BS and FAP is that the former is located outdoor while the latter is usually indoors. The main motivation behind the development of femtocells is the poor quality of the radio signal received inside a building or house transmitted from the outdoor macro BS. This happens mainly due to losses which occur when a signal penetrates the wall.

The wall penetration losses vary depending upon the thickness and material of the wall, angle of arrival of the signal and number of walls inside the house. This means for example that, performance of the macro MS will be poorer in places like Japan where most of the walls are wooden and very thin and hence unable to prevent signals from interfering FAP or macro BS. Because of this significance, the impact of wall penetration losses needs to be analysed in detail.

To analyse the impact of wall penetration loss, firstly, a simulation was undertaken for various number of FAPs with a fixed and varying wall penetration loss and the corresponding performance evaluated. For simplicity it is assumed that there is no cooperation either between the femtocells and macrocells or among the femtocells as well. Each FAP decides its channel independently and in a distributed fashion. In order to capture the impact on interference, it is further assumed that all the MS have LOS connections to their FAP, i.e. there is no internal wall penetration loss.

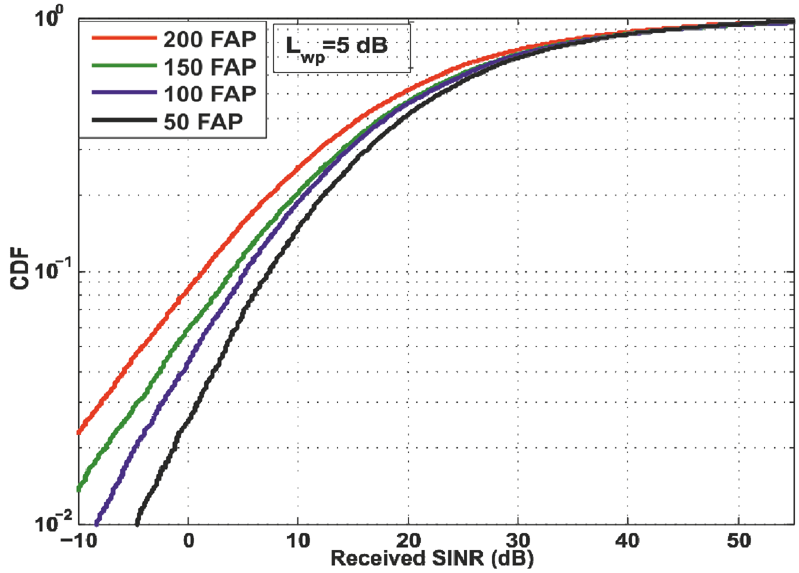


Figure 3.9: Impact of wall penetration loss on SINR performance at different femtocell deployment density (L_{WP}=5 dB)

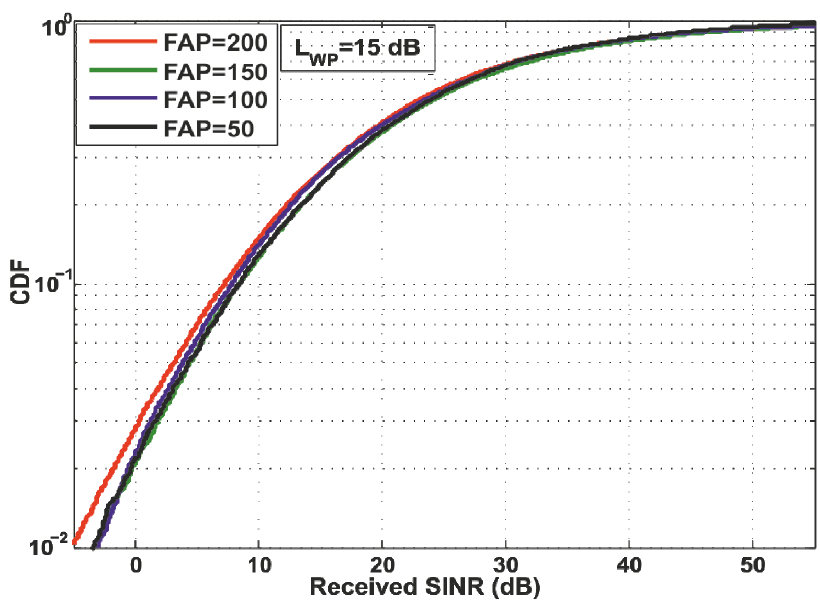


Figure 3.10: Impact of wall penetration loss on SINR performance at different femtocell deployment density (L_{WP}=15 dB)

Figure 3.9 and Figure 3.10 show the impact on various FAP deployment densities (50, 100, 150 and 200) when the wall penetration loss, L_{WP} is 5 and 15 dB respectively. It is clear from the figures that when wall penetration loss is low, the users experience higher interference. With increasing FAP density, interference also increases and the performance of the system may become unsatisfactory at higher FAP densities. However, when the L_{WP}

is higher, i.e. 15 dB, there is little impact of increasing FAP density. This is due to better isolation from the interfering signals. Thus wall penetration loss needs to be considered carefully in deploying any two-tier networks, which is the focus of this thesis.

Now for a fixed FAP deployment, the impact of varying wall penetration losses (5, 10 and 15 dB) is shown in Figure 3.11. It is readily apparent for L_{WP} = 15 dB, that the corresponding interference is lower, leading to a higher SINR, because of the higher absorption by the wall compared to both 10 dB and 5 dB losses.

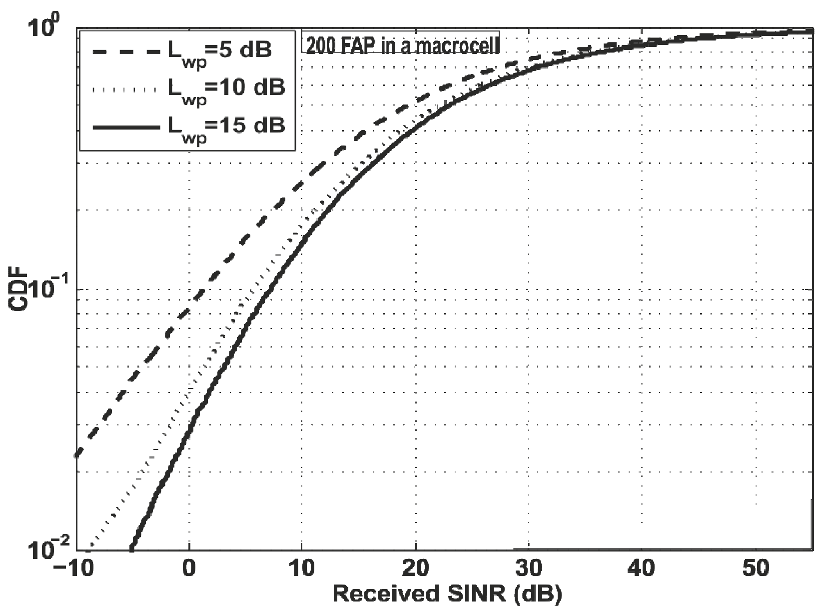


Figure 3.11: Impact of various wall penetration losses on SINR performance of femtocells.

After evaluating the impact of wall penetration loss on the system throughput, a modified wall penetration loss model was designed and implemented in the simulations to better reflect real-world situations. In most simulations, fixed wall penetration losses L_{WP} of 5 dB, 10 dB or 15 dB are assumed for evaluation purposes. However, it has been shown in [97], that wall penetration losses can vary anywhere between 3 dB and 16 dB, so in the simulations, a randomly generated L_{WP} value between 3 dB and 16dB has been used for each house or FAP to compute the interference power, which was fixed for each simulation run. To calculate the received signal power, a thin indoor wall was assumed and values for each MS generated in the 0 to 6 dB range.

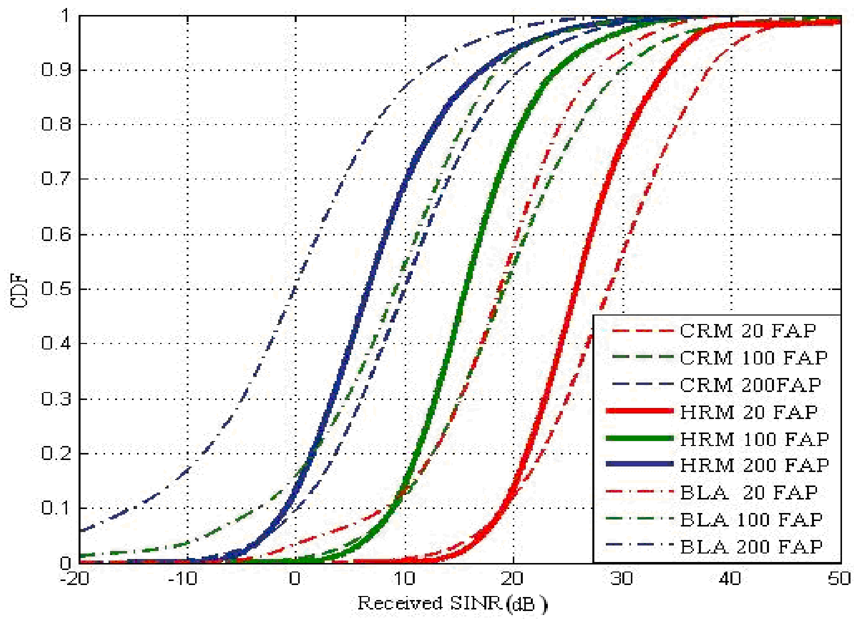


Figure 3.12: SINR performance of different algorithms at various FAP deployment densities.

To quantitatively analyse the HRMA performance, it was compared with: i) a base-line algorithm (BLA), representing the condition where the femto-tier operates independently of the macro-tier and there is no inter-tier information sharing and ii) a centralized resource management (CRM) scheme, which makes all decisions at the RNC, and where full cross-tier information is available so all spectrum decisions can be made by considering interference from all co-channel operators, regardless of their location in the macrocell. Each layer has access to the full spectrum. The number of femtocells was varied between 20 and 200, and HRMA, CRM and BLA applied to each test deployment scenario. The network environment parameters used in all simulations are detailed in Table 3.1.

Figure 3.12 plots the respective SINR performance of each algorithm for three different deployment densities of 20, 100 and 200 FAP in one macrocell. The results reveal that for each deployment density, HRMA outperformed BLA and had a very similar SINR performance to the CRM scheme, which consistently performed best due to all the inter-tier information being continually available. Since there is no cross-tier information sharing in BLA, interference is comparatively high because of the simultaneous allocation of the same channel to both macro and femto tiers. In addition, there is interference from neighbouring femtocells operating in the same channel at the same time instant. In contrast, as HRMA centrally exploits dynamic FFR to assign mutually exclusive spectrum for inter-tier users, no such macro-tier interference affects transmissions in the femto-tier.

Table 3.2: Number of overlapping instances and averaged normalised allocation disputes as a ratio of the total number of allocations, for different FAP deployment densities.

FAP deployed	Number of overlapping cases	Average normalized disputes
20	2	0.01
100	13	0.04
200	38	0.11

The main disadvantage of CRM is that it communicates with the central entity (RNC) during every decision leading to significant redundant data transmissions which consume valuable bandwidth. This problem is compounded at higher deployment densities, with the corresponding computational cost increasing geometrically. HRMA in contrast, achieves an analogous SINR performance to CRM while incurring a much lower computational overhead.

Table 3.2 displays the occurrences of FAP overlapping together with the average normalised dispute ratio (the number of disputes divided by the total number of spectrum allocations and number of iterations) for various FAP deployment densities. This reflects those instances where RNC communication is necessary. For 20, 100 and 200 FAPs, HRMA required only 1%, 4% and 11% respectively of the time in RNC spectrum decision communications, compared with 100% for CRM. As anticipated for larger FAP numbers, intra-tier interference increased and the corresponding SINR dropped in all three algorithms, though HRMA still maintains a superior performance compared to BLA. This improvement is directly related to the DMB mechanism described in Section 3.2.3, which avoided severe femto-tier interference in overlapping FAPs by referring any dispute to the RNC.

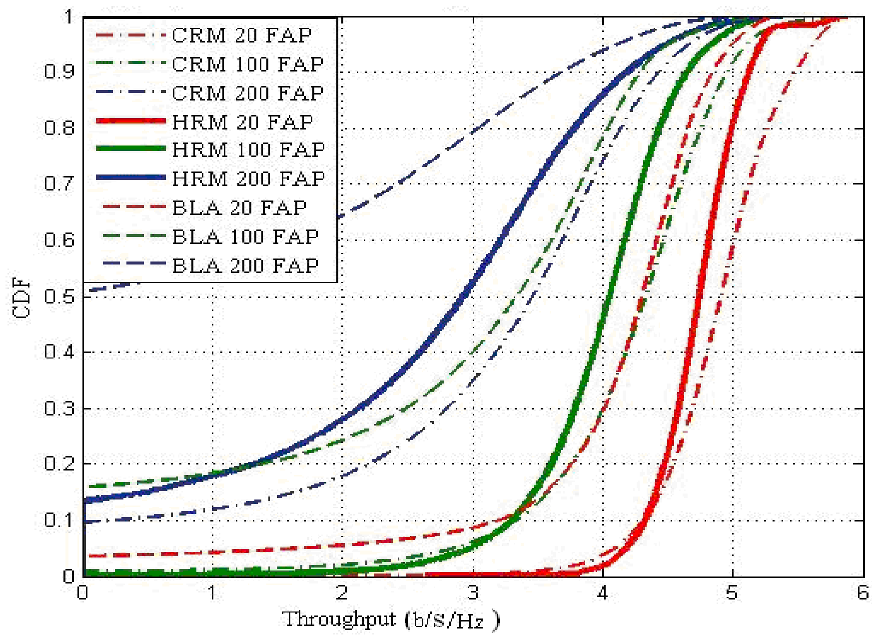


Figure 3.13: Throughput curves (bits/s/Hz) for various FAP deployment densities for different algorithms.

The results in Table 3.2 also confirm that the dispute level increases with deployment density, and since BLA does not have a DMB mechanism to manage such situations, its performance deteriorates markedly as shown in Figure 3.12. Conversely for CRM, all the FAP allocation information is available to the RNC, so it can apportion spectrum in such a way that the total interference is always a minimum, giving it better performance than the other algorithms. Interestingly an analogous trend is observed in the corresponding throughput curves for HRMA, BLA and CRM in Figure 3.13.

As evident from Figure 3.12, for the 200 FAP deployments the severe interference in BLA means almost 50% users fail to achieve minimum SINR requirement of 0 dB, which worsens further to 70% when the minimum SINR of 5 dB is specified. In contrast, since the HRMA paradigm has been designed to attenuate femto-tier interference, it respectively exhibits significantly lower outage probabilities of 12% and 38% respectively for the 0 dB and 5 dB SINR requirements, which is again very similar to the CRM performance.

From Figure 3.13, it can be seen that HRMA clearly provides an enhanced performance in terms of achieved throughput compared to BLA. Even for 200 FAP deployments, where the interference level is at its highest, 50% of the time users achieved a bit-rate of at least 3 bits/Hz per transmission frame or greater for HRMA compared with only 20% for BLA. Commensurate improvements in HRMA throughout are also evident in the other FAP deployment density curves.

As evidenced earlier, HRMA outperforms BLA at all the FAP deployment scenarios analysed. Despite this superior performance, it can be observed from both Figure 3.12 and Figure 3.13 that with increasing femtocell density, the performance of all systems gradually reduces. The average received SINR falls from 25 dB when 20 FAP are deployed to only 7 dB when 200 FAP are deployed. Since the macrocell MS deployment density remains the constant in all these various scenarios, the corresponding cross-tier interference for each scenario will approximately be the same. Furthermore, since the signal power is constant, the increasing trend of aggregated interference can be directly related to the contribution of the co-tier interference component. This interference increases with the number of co-channel FAP deployed, while the available resources remain fixed.

In urban environments, where much higher FAP deployments are predicted than have been considered in this analysis, there is clearly the very serious risk of performance degradation falling below a satisfactory level unless appropriate measures are taken to combat the co-tier interference in high density deployments. This means further investigation into co-tier interference minimisation is a paramount design objective for successful FAP network deployment and resource management.

The analysis and simulation in this chapter has focused upon a low-to-moderate density femtocell network. While HRMA in combination with dynamic FFR removes cross-tier interference, at increasing FAP densities, co-tier interference starts to dominate and the performance of the system begins to degrade despite being at a satisfactory level. In densely populated urban areas, much higher deployment is anticipated and special attention must therefore be given to managing co-tier interference. The next chapter will investigate co-tier interference minimisation techniques for high density FAP deployments, where HRMA-based dynamic FFR has been retained as the overarching policy for cross-tier resource sharing.

3.5 Conclusion

This chapter has presented a new hybrid resource management algorithm (HRMA) for femtocell networks. Various alternatives of FFR techniques have been discussed in detail along with the opportunities of exploiting them for cross-tier spectrum sharing. A dynamic FFR scheme for joint macro-femtocell deployment has then been investigated. HRMA exploits cross-tier information to concomitantly eliminate macro-femto interference and significantly reduce femto-tier interference, which can be particularly severe at high FAP deployment densities. Superior performance in regard to outage probability and system throughput has also been corroborated.

4 Virtual Clustering of Femtocells for Co-Tier Interference Mitigation

4.1 Introduction

Femtocell Networks promise multi-fold increments in system throughput by making the best possible reuse of the available spectrum. They also improve the QoS in indoor environments where radio coverage is typically poor. Since the femtocell network is overlaid on a macrocell network, interference from both macrocell BS to femtocell users, and FAP to nearby macrocell users causes significant performance degradation unless it is managed properly. From the results analysis in the previous chapter, it was clear that FFR and its variants, including dynamic FFR, can be successfully applied to mitigate cross-tier interference.

Despite this improvement however, at increasing femtocell densities, both the SINR and throughput performance of the femtocell networks progressively decreases. While the HRMA performance may be deemed satisfactory, the results indicate that at higher FAP densities, the femto-to-femtocell interference, i.e. the co-tier interference component becomes dominant, so that special attention is required for high density deployment scenarios such as in urban areas [98], [99]. In this chapter, the challenge of higher density femtocell deployments will be addressed, with the underlying cross-tier interference management architecture remaining the same as presented in Chapter 3. The focus will thus shift from cross to co-tier interference management strategies.

The case of dense femtocell deployments and their associated challenges have previously been addressed in different work [100] [101]. One interesting strategy, known as graph colouring, also addressed the issue of interference mitigation and resource allocation in dense femtocell deployments [102]. Although the performance of these algorithms is promising, the graph needs to be constructed at every change in the area. This is computationally intensive, given the dynamic and rapidly changing nature of the radio environment.

In [103], a cognitive radio resource management algorithm is presented for cross-tier interference mitigation. It requires regular sensing of the macrocell spectrum usage in order to find a spectrum hole to use it opportunistically. Also, the efficiency of the scheme largely depends on the load of the macro tier. Moreover, the co-tier interference problem is mostly ignored. The energy and computation required for sensing cross tier interference can easily be saved by cross-tier spectrum usage information sharing techniques such as FFR.

In this chapter, the novel concept of a new resource distribution architecture based on virtual clustering is introduced, with a dedicated virtual cluster controller (VCC) operating between the RNC and the FAPs, being used to manage particular resource functionalities for a specific grouping of FAPs which are logically assigned to it. A new VCF algorithm exploits FAP location information to create virtual (logical) clusters of FAPs. VCF maximizes the minimum distance between the FAPs of a cluster, thereby minimising the overall interference.

The rationale behind the femtocell clustering is that since interference decreases according to power law with distance, by maximising the inter-FAP distance operating on the same channel, will therefore guarantee minimum interference. The concept of *virtual clustering* [19], extends this idea by embedding a dedicated *virtual cluster controller* (VCC) to operate between the RNC and the FAPs, to manage particular resource functionalities for a specific FAP grouping which have been logically assigned to it. In the following sections, the virtual cluster architecture and algorithm will be discussed in detail before presenting a rigorous analysis of the simulation results. Finally, the chapter concludes by discussing the benefits and limitations of VCF and explores strategies for improving the virtual clustering concept.

4.2 Virtual Clustering Architecture and Algorithm

Clustering has been widely investigated in both the wireless sensor networks [104] [105] and ad hoc network [106] [107] [108] domains, with the normal approach being to select a *clusterhead* from a group of nodes according to some criterion, so neighbouring nodes are assigned membership of a cluster based upon for instance, being physically co-located. In contrast to physical clustering, the creation of virtual (logical) clusters using an interference-based Euclidean distance measure is proposed in this thesis.

The terminology virtual cluster has been adopted to reflect that cluster members are virtually linked together rather than as in the traditional ad hoc cluster sense, where members are located within some defined distance of the clusterhead. Members of a virtual cluster may not necessarily be physically co-located, but instead are grouped together to exploit the same set of channels according to a minimum interference generation criterion.

Virtual clusters are formed according to a minimax criterion by combining FAPs operating on the same set of channels, while concomitantly maximising the closest FAP distance. The rationale for the VCF algorithm is that as power decays according to power law with the distance, the FAP furthest away from a particular FAP will correspondingly generate the lowest interference. Hence, by maximising the distance of the closest FAP operating on the same channels the interference can be minimised. Figure 4.1 shows the block diagram of the logical architecture of the virtual clustering femtocell network. Each VCC has specific resource allocation functionality. It assigns the channel set to cluster member FAPs and manages disputes between the MSs connected to different FAP on behalf of its FAP membership. If a dispute occurs with either a macrocell user or a MS connected to a FAP belonging to another VCC, which is very unlikely, then it is forwarded to the RNC for arbitration. The RNC cooperates with the MBS to create a list of channels available for allocation in a certain area under the dynamic FFR framework described in [18].

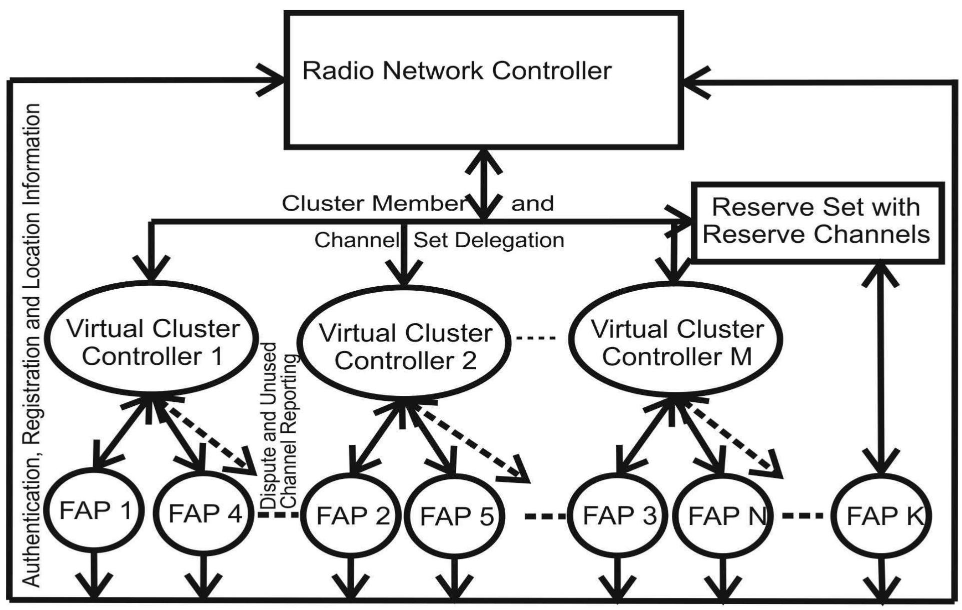


Figure 4.1: Logical diagram showing a virtual clustered femtocell network system

Unlike distributed resource allocation techniques where each FAP independently chooses a channel, the virtual clustering architecture devolves this task to the VCC which maintains an updated list of available channels. Furthermore, distinct from centralised resource management where every decision, including channel assignment, is performed by the RNC, each VCC takes responsibility for channel set allocation and dispute management on behalf its cluster members. This means the virtual clustering system inherently provides hybrid resource management, combining the best features of the aforementioned resource allocation models. It also saves a significant number of redundant data transfers between each FAP and the RNC.

Depending upon the maximum number of MS permitted to connect to a FAP, the RNC creates M_V number of individual VCC which are each assigned a corresponding set of channels, in accordance with the following relationship:

$$M_V = \left\lfloor \frac{C_f}{\max(N_f)} \right\rfloor \quad \textbf{(4.1)}$$

where C_f is the number of available channels in the considered area under the dynamic FFR-based distribution framework between femtocells, while N_f is the number of MS connected to the *fth* FAP where *f=1,2, 3.....n*. with n being the total number of FAP under consideration.

When a FAP is switched on it goes through an initialisation phase. It firstly connects to the RNC via the backhaul network and since the FAP is connected by a wired network, its location is approximately known by the RNC. In addition, femtocell network topology can be designed to a certain level of accuracy by employing RF measurements [109], so position information coupled with RF measurements from the MSs connected to the macro BS and FAPs can be exploited to obtain an accurate FAP location. The VCF algorithm then assigns each FAP to a designated VCC, which provides access to a set of channels.

The VCF also creates and maintains a reserve channels list C_R derived from the reporting of unused channels by the FAPs. This list is periodically updated via the RNC and also includes unused macrocell BS channels. These reserve channels are allocated to FAPs either in the case of disputes or to members of the reserve set S_R, which include those FAPs that failed to uphold the safety distance D_{th}. This is the distance all FAPs must sustain from their co-channel FAP to ensure effective femtocell operation, and is determined by setting the maximum level of admissible interference and then calculating the corresponding minimum distance requirement to preserve the SINR level. An estimate of D_{th}, can be obtained from the PL model defined by the relations (3.2) and (3.3) in Chapter 3. The value of D_{th} depends on the transmission power and amount of interference that can be tolerated by a FAP as shown in Figure 4.2.

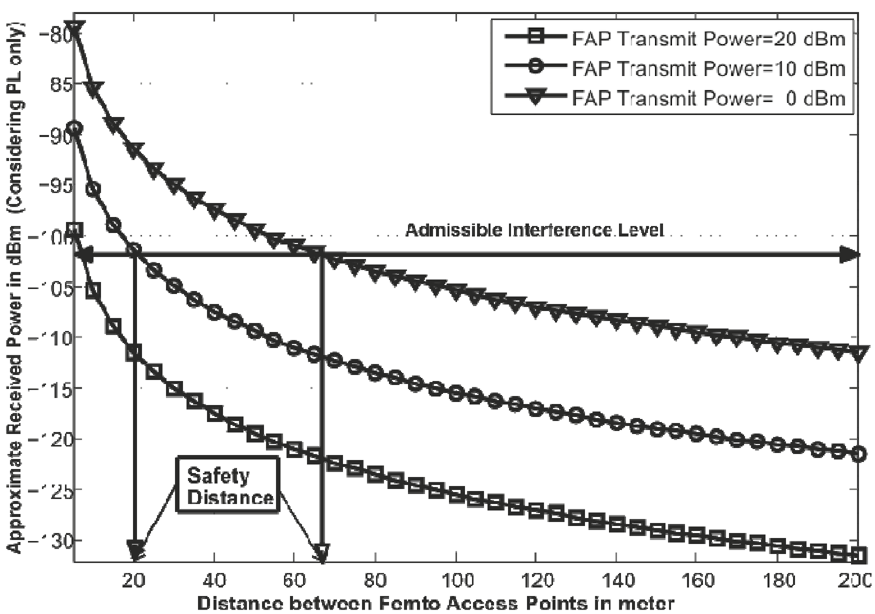


Figure 4.2: Safety distance D_{th} measurements for FAP deployments at different transmission powers

Algorithm 1 provides the pseudo code representation of the VCF algorithm, which comprises three steps. STEP I initialises all key parameters including; the number of FAPs and MSs connected to it; the safety distance D_{th} and the number of available channels for the area under consideration. It also creates the reserve set S_R and determines both the

VCC number M_V from **(4.1)** and the inter-FAP distance matrix for N FAPs which is given by:

$$D = \begin{bmatrix} d_{11} & d_{12} & \dots & d_{1N} \\ d_{21} & d_{22} & \cdots & d_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ d_{N1} & d_{N2} & \cdots & d_{NN} \end{bmatrix} \qquad \textbf{(4.2)}$$

where d_{ij} is the Euclidian distance between FAP_i and FAP_j and $d_{ij} = d_{ji}$. Note, all diagonal elements of D are zero, i.e., $d_{ii} = 0 \;\; for \; i = 1, 2, \cdots, N$ and are excluded from the minimum distance calculations. d_{ij} is calculated according to the following relationship

$$d_{ij} = \sqrt{\left(x_{FAP\,i} - x_{FAP\,j}\right)^2 + \left(y_{FAP\,i} - y_{FAP\,j}\right)^2} \qquad \textbf{(4.3)}$$

where x and y are the Cartesian co-ordinates for each of the N FAPs.

Following initialisation, STEP II is firstly preceded by an allocation loop, which identifies the FAP pair from D in (4.2) with the minimum Euclidean distance. STEP II checks whether this FAP pair have already been allocated. For an unallocated FAP, it ascertains whether there are any empty VCC and if so, the FAP is duly allocated to an empty VCC. Otherwise, it moves to STEP III. If both FAPs have already been assigned, then the distance pair is excluded from D and both FAPs are expunged from the list of unallocated FAP. The next closest pair of FAPs from D is then sought and STEP II repeated.

In STEP III, the VCF algorithm selects the distances from D of the candidate FAP to all FAPs already assigned to the VCCs, and the minimum distance to each VCC is found. The FAP is assigned to the VCC with $d^h_{\min} = \max(d_{\min}(n))$ subject to $d^h_{\min} \geq D_{th}$, where *n=1, 2,…MV*, and $d_{\min}(n)$ is the minimum distance of the candidate FAP to the members of the *nth* VCC. If the FAP cannot uphold D_{th}, it is assigned to the reserve set S_R instead, whose members are allocated reserved channels. D is then updated, with the FAP pair assigned during this iteration being excluded. This procedure is repeated until all FAPs have been allocated.

Algorithm 1 The Virtual Clustering Formation (VCF) Algorithm

```
STEP I
Initialize variables: n, N_f, D_th, C_R, S_R;
COMPUTE M_V, the number of VCC by (4.1);
COMPUTE D by (4.2);
Set D_temp = D
while Number of unallocated FAP ≥ 0 do
  Find closest FAP pair FAP_i and FAP_j from D_temp
  for FAP_i and FAP_j do
    STEP II;
    if the FAP is already assigned to a VCC then
      Go to the End of STEP III ;
    else
      if Any VCC is empty then
        Assign FAP to empty VCC;
      else
        GOTO STEP III
      end if
    end if
    End of STEP II

    STEP III
    for All the VCCs do
      COMPUTE distances between the FAP and VCC
      members
    end for
    FIND minimum distance, d_min for each VCC
    FIND maximum minimum distance d^h_min
    if d^h_min ≤ D_th then
      Assign FAP to S_R;
    else
      Assign FAP to VCC with d^h_min
    end if
    End of STEP III
  end for

  UPDATE D_temp excluding d_min;
  REMOVE FAP_i and FAP_j from unallocated FAP List;
end while
END
```

If a new FAP is now switched on within the area, only STEP III needs to be executed and the FAP is assigned to the VCC with the highest minimum distance to ensure it both receives and generates the minimum interference compared to the other clusters. It also means the VCF algorithm is very computationally efficient once the initialisation and FAP allocation STEPS I and II have been completed, because the only extra overhead involves FAP co-ordinate calculations.

In exceptional circumstances where an MS fails to meet the minimum SINR requirement due to severe interference, the affected FAP attempts to switch to a new channel with a higher SINR. If it is still unable to uphold the minimum SINR threshold, the FAP then forwards the MS to the VCC with a severe interferer ID tag, which then allots a reserve channel, provided one is available.

4.3 System Model and Simulation Environment

The system model and its associated parameters described in Chapter 3, is also applied to the new virtual clustering architecture, with some minor modifications. The varying wall penetration loss model is replaced by fixed wall penetration loss of 10 dB for external wall and 5 dB for internal walls. Although it was advantageous to have a realistic measure of the total loss when cross and co-tier interference was evaluated, it made it difficult to compare the impact of the interference of one scenario to another. Also the transmit power of the FAP is increased to 10 dBm, the maximum allowed limit in the various standards. The advantage of doing this is that by increasing all the FAP power simultaneously, better protection against macrocell interference is ensured, while keeping the co-tier interference the same, since increased FAP interference is cancelled out by higher transmission powers.

In Chapter 3, the whole area under a macrocell was evaluated. This was necessary as both cross-tier and co-tier interference components were being considered. However, in this chapter since the focus has now shifted to only co-tier interference, instead only the area belonging to a femtocell gateway is chosen. To evaluate the performance of the VCF algorithm, a 200 m X 200 m area of one sector in a hexagonal macrocell was considered, for three specific FAP node deployments of 50, 100 and 200. It was assumed 12 channels were available for femtocell downlink operation, so from **(4.1)** the requisite number of VCC was 3. As a performance comparator for VCF, a distributed resource allocation framework was implemented here each FAP independently chose its operating spectrum. This scheme will be referred to as the *Non-Clustering System* (NCS) in the ensuing discussion.

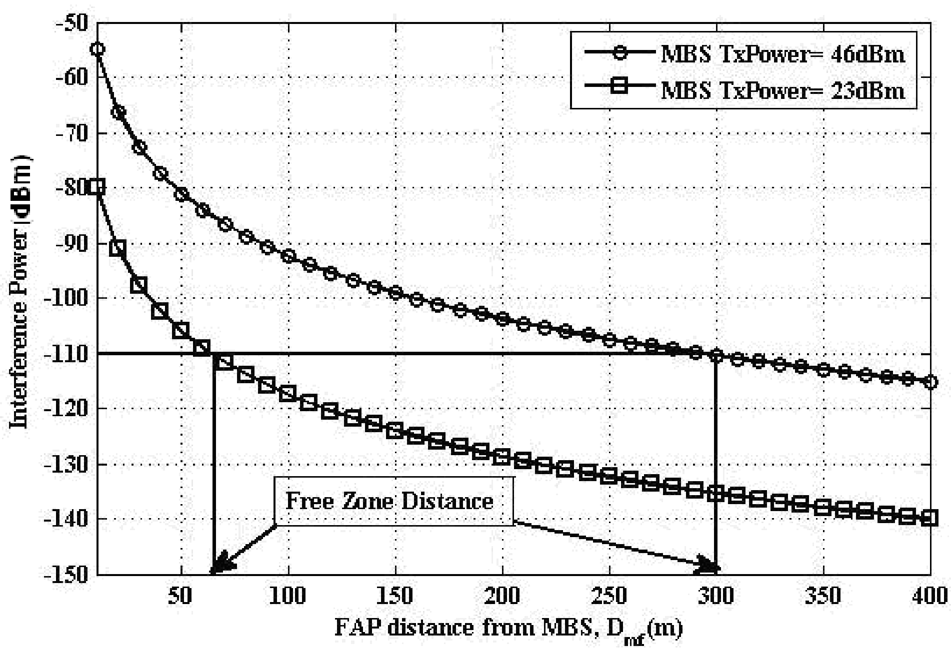


Figure 4.3: Approximated received interference power from the macro BS at various distances.

Before analysing the performance of the VCF algorithm in detail, some preliminary measurements were taken. Figure 4.3 shows the femtocell interference generated by the downlink transmission of a macrocell BS at two different power levels. Depending on the admissible macro-to-femto interference, a free-zone distance threshold D_m^{th} can be obtained from the curves. For values greater than this threshold, FAP interference will be negligible so a FAP can freely operate on any channel used by the macrocell system. The higher the permitted interference, the smaller the D_m and vice versa, so if for example the interference limit is -110 dBm, then D_m^{th} will be approximately 300 m for a transmission power of 46 dBm. Note that this value varies with the macrocell BS transmission power, with a lower power giving a commensurately smaller D_m^{th}.

4.4 Results Discussion

Analogously, to minimise the interference between a FAP and the MS connected to other FAPs, the safety distance, D_{th} is applied. This is highlighted on Figure 4.2, which shows the MS interference at various distances from an interfering FAP at three different transmission power levels. The results reveal the safety distance threshold varies with tolerable interference level, so if the tolerable interference requirements are for example: -110 dBm and -120 dBm respectively, then the corresponding D_{th} values are 16 m and 36 m for a transmission power of 10 dBm. This means that lowering D_{th} enables more FAP to be successfully deployed within the same area.

The three plots in Figure 4.4 represent simulation snapshots which illustrates the cluster formations for 40 FAPs both before (Figure 4(a)) and after application of the new VCF algorithm (Figure 4(b)), together with the NCS in Figure 4(c) within a 100 m-square area. It can be seen that in the case of NCS, many neighbouring FAPs operate on the same portion of spectrum which will cause severe interference while for VCF, neighbouring FAPs will always on a different spectrum chunk. This highlights why it is essential to employ appropriate post deployment network planning techniques in order to avoid severe interference.

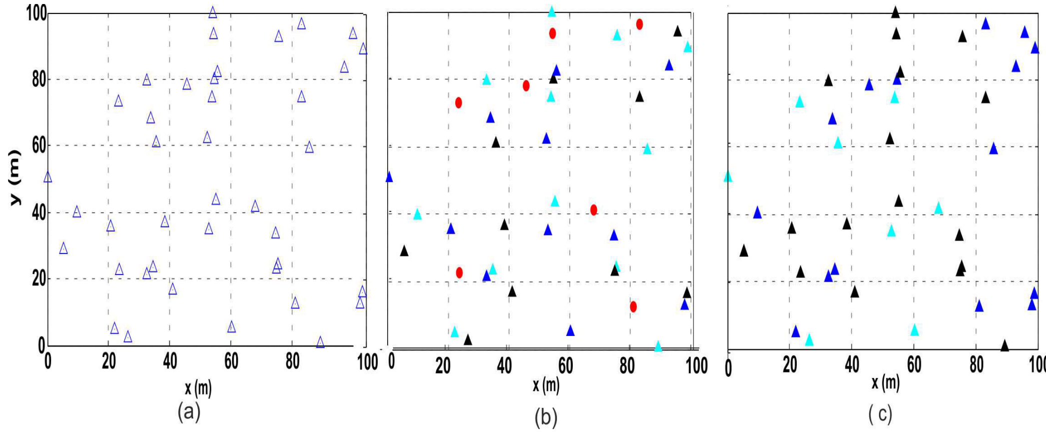


Figure 4.4: FAP deployment scenarios: (a) before cluster formation, (b) after clustering (applying VCF), and (c) the non-clustered system (NCS) where each colour represents channels of a VCC. (Red circles represent FAPs operating on reserve channel sets.)

The performance of both VCF and NCS were evaluated in terms of three key system metrics; the safety distance D_{th}, the received SINR and the spectral efficiency. These will now be individually analysed.

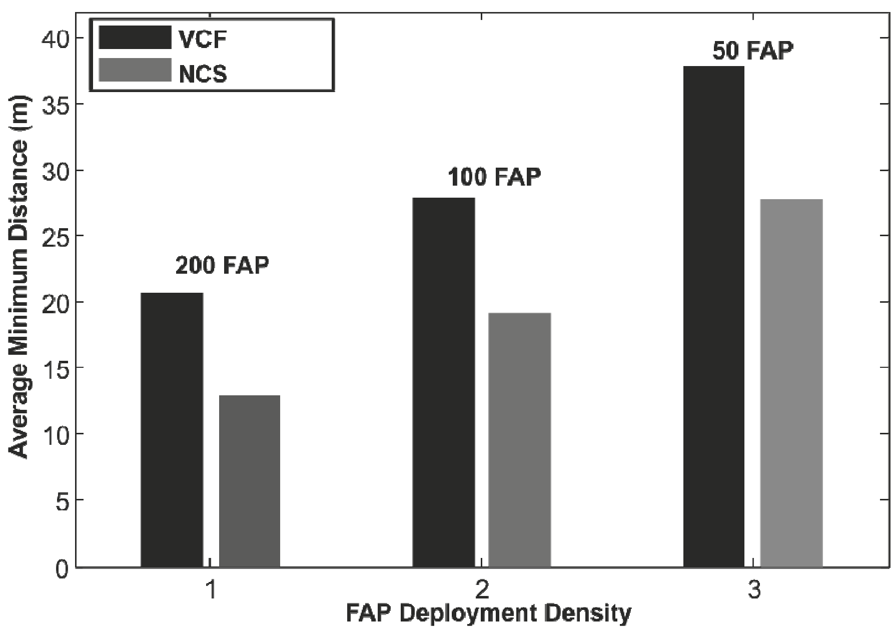


Figure 4.5: Performance comparison between clustered and non-clustered network for various FAP deployments

Figure 4.5 displays the average distance between a FAP and its nearest interfering FAP for both VCF and NCS at D_{th}=20 m. The clustering system consistently maintained the minimum safety distance to give significantly improved performance over NCS at different FAP deployment densities. Table 4.1 contrasts the corresponding number of FAP failures in upholding D_{th}, with the VCF model clearly affording lower failure rates. For example, when clustering is employed for 50 FAPs, no spectrum reuse was required for any femtocell within the safety distance threshold, whereas 18% of FAPs failed to maintain this threshold for the traditional NCS. This trend is even more palpable at higher femtocell densities, where for 200 FAPs around 46% of FAP failed to preserve the threshold compared with just 16 % for VCF.

Table 4.1: Comparison of the average number of FAP failing to maintain the safety distance

FAP Deployed	Clustered System	Non Clustered System
50	0%	18%
100	04%	31%
200	16%	46%

Figure 4.6 plots the SINR performance for both the VCF and NCS models at various FAP deployments. While predictably the received SINR is attenuated at higher FAP densities, the VCF model still outperformed its non-clustering counterpart in providing superior SINR. For instance, with 50 FAPs, only 40% of FAP transmissions achieved a received SINR greater than 15 dB for NCS compared with over 70% for VCF, with similar judgements applicable at the other FAP densities.

It is also evident from the Figure 4.6 that when 200 FAP is deployed, average received SINR is approximately 13 dB and 18 dB for NCS and VCF models respectively. And for a 100 FAP deployment, the average received SINR is approximately 16 and 21dB for NCS and VCF respectively. So, in both cases, VCF outperforms the NCS by an approximate 5 dB margin. Similar judgements can be observed for the 90th percentile values, with in this case VCF outperforming NCS by a 6 to 7dB margin as evidenced in Figure 4.6.

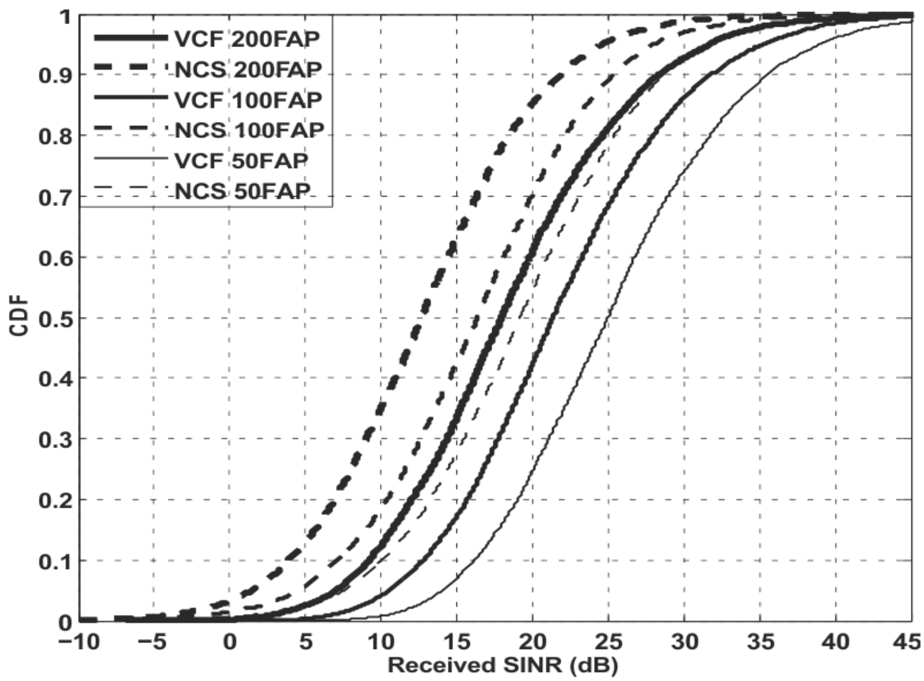


Figure 4.6: SINR performance comparison for clustered and non-clustered system at different deployment densities.

Finally, the spectral efficiency of the new VCF algorithm was evaluated in terms of the throughput achieved with the corresponding comparison shown in Figure 4.7. For 200 FAP, the 50th percentile throughput value, i.e. the average bit rates were 4.25 and 3.7 bps/Hz respectively for VCF and NCS, with similar performance improvements readily apparent for the other deployment scenarios. For 90th percentile performance, in case of the 200 FAP, NCS and VCF achieved 2.5 bps/Hz and 3.5 bps/Hz respectively which corresponds to an approximate 1bps/Hz improvement. Interestingly, Figure 4.6 and Figure 4.7 reveal that for a FAP density of 200, the new VCF algorithm afforded a superior performance to the corresponding NCS solution for 100 FAP from both a spectral efficiency and SINR perspective.

Wireless channels are inherently dynamic and the traffic patterns of the system exhibit considerable variability over time. So in order to maximise the performance efficiency, dynamic adaptation to instantaneous changes in the environment is necessary. Though the new VCF architecture in the current design has exhibited consistent and significant performance gains over the NCS implementation, the architecture is inflexible in that the number of clusters is fixed. This means it is not able to readily adapt to any changes in the radio environment which cannot be predicted.

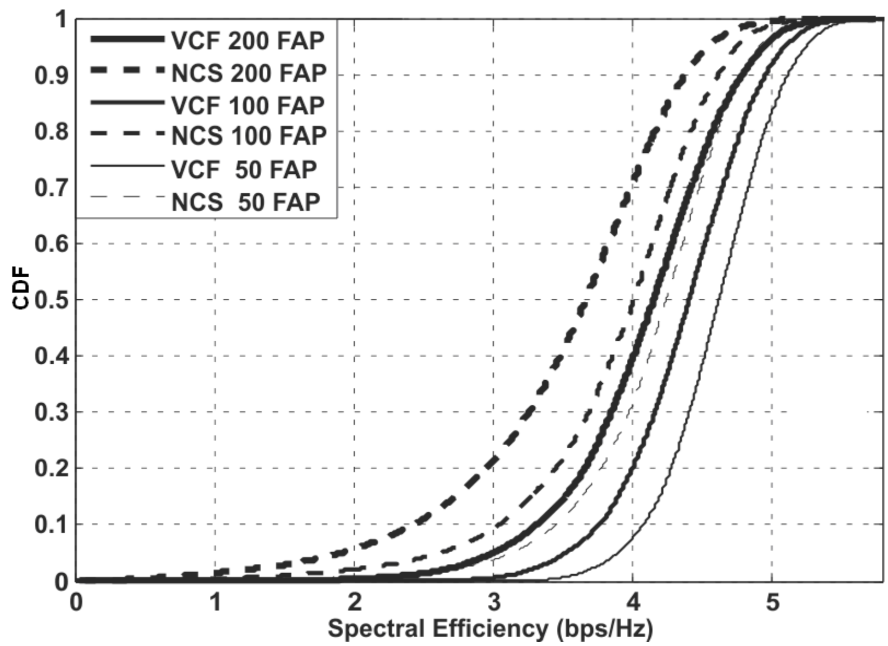


Figure 4.7: Spectral Efficiency performance comparison for clustered and non-clustered system at different FAP deployment densities.

Although, the macro-tier updates the femto-tier with changes in channel usage, any free channel reported is added to the reserve set which is used to manage disputes. In the current design the system is unable to respond to radio environment changes and certain QoS requirements. VCF is also unable to predict the requisite radio resources to maintain a defined performance target and this may lead to either lower performance or wastage of channels in the case of higher availability of resources. A more generalised framework is therefore necessary which can adapt to the changes in the network and resources. It is also necessary to design a system capable of intelligently deciding the most appropriate number of clusters and to demand either more resources from the RNC or to liberate channels in order to maintain a prescribed QoS.

The analysis and simulations in this chapter have concentrated on logical cluster formation based upon the available channels and FAP distribution. Despite notable performance gains, the VCF algorithm is unable to adapt to changes in the traffic and channel availability. In the next chapter, dynamic adaption to changes in the radio network environment and resource availability will be analysed in detail together with their corresponding impact. A rigorous analysis will be undertaken to develop a framework for selecting the best possible cluster number and the resource requirement for maintaining particular SINR and throughput settings.

4.5 Conclusion

This chapter has presented a new virtual clustering framework for femtocell networks based upon a minimax interference solution which maximises the minimum distance of the FAPs operating on the same channel. The *virtual cluster formation* (VCF) algorithm shares certain resource management functionalities with both the RNC and individual FAPs to not only reduce redundant data transfers but maintain a flexible and simple implementation with minimal computational overheads. Simulations have corroborated the VCF algorithm provides significant performance improvements over distributed non-clustered systems in terms of interference reduction, increased spectral efficiency and higher received SINR.

5 A Generalized Virtual Cluster Formation: An Adaptive Flexible Architecture for Co-tier Interference Mitigation

5.1 Introduction

The key to efficient system performance in jointly deployed co-located macro femto networks is to dynamically adapt to the changes in the radio environment and to the changes in either traffic pattern or resource availability. The initial idea of logical clustering was introduced in the previous chapter, with a *virtual cluster formation* (VCF) algorithm being applied to a rigid clustering framework, and FAP location information used to create the respective virtual (logical) FAP clusters. Due to this inflexibility and inability to adapt to the changes, network management decisions taken by the VCF may not necessarily be optimal if there are changes in the radio environment, traffic patterns or resources.

The traffic load and interference scenario of any space can vary greatly over time. For example, during the daytime, the number of active users in a residential area will tend to be much lower compared to the load during evening as people are usually out of their homes. In contrast, traffic loads at offices, shopping malls and in other public places will generally be much higher during the day time and very low during other times. Some specific places such as airports may have high demand with some variations all the time. To accommodate all these diverse profiles, the network architecture and management algorithms must be both flexible and intelligent. Also it is important to properly understand the estimated resource requirement of these various scenarios.

In this chapter, a new *generalized virtual cluster formation* (GVCF) paradigm is introduced which offers much greater flexibility as it can automatically adapt to changes in both the available resources and radio environment, seamlessly handling situations such as when users either leave or join the network. To achieve this efficiency, several scenarios have been firstly investigated which helps to constitute a performance map or *look-up table* (LUT). This information is later exploited for decision making and adapting to the changes in radio environment and resource availability. Furthermore, based on this information, negotiation is carried out with the central controller when more resources are required to ensure the requisite QoS is upheld.

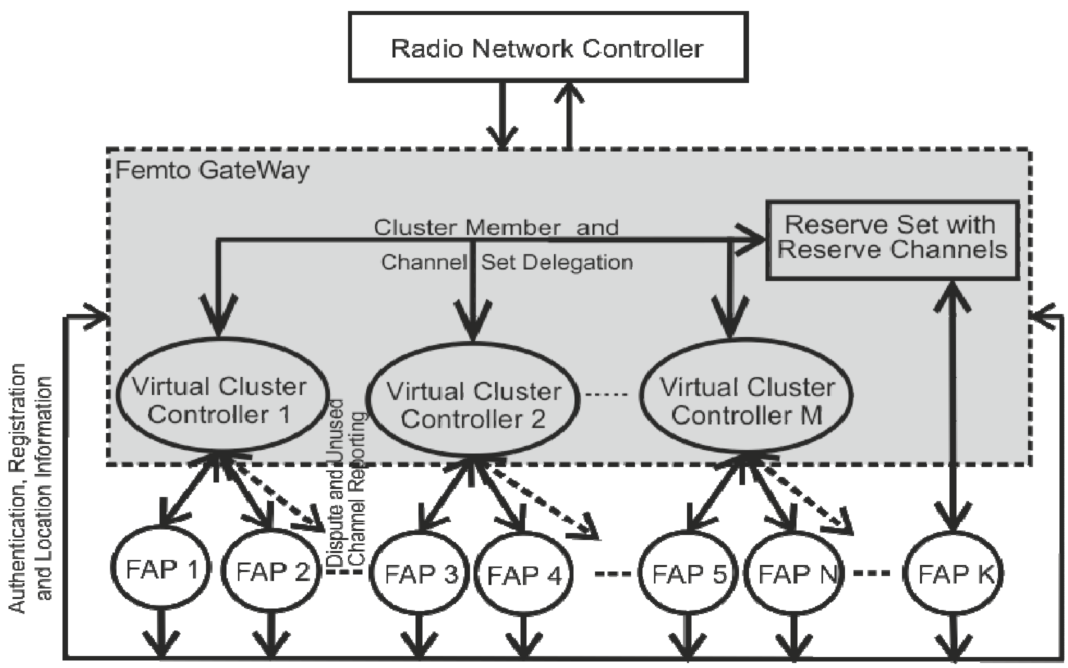


Figure 5.1: Logical diagram of the generalized virtual clustering femtocell (GVCF) network system

The fixed cluster structure described in the Chapter 4 is relaxed in the GVCF model by regular monitoring and performance evaluation. The model has the ability to adapt the cluster numbers and their respective FAP members in accordance with fluctuations in both the available resources and a prescribed set of network design constraints, including the minimum throughput requirement and maximum transmit power. The corresponding results analysis corroborates the enhanced interference management performance and adaptive capability of the new GVCF model in various network scenarios, particularly in high density deployments.

In the following sections, the GVCF paradigm and the flowchart of the algorithm is discussed briefly, as many of the model's components have already been presented in Chapter 4. An extensive simulation is performed, with a comprehensive results analysis. Finally, the chapter concludes by summarising the contribution.

5.2 GVCF Paradigm

As mentioned in Chapter 4, the original VCF algorithm maximised the minimum distance between the FAPs of any cluster, thereby minimising the overall interference. The logical diagram of the GVCF architecture is shown in Figure 5.1. While there is no fundamental difference with the architecture presented for the VCF model in Figure 4.1, some of the key functionality such as cluster formation and membership delegation has been repositioned by moving them from the RNC to the FGW. FAP registration is also now performed by the RNC, via the FGW which is also supported by the emerging multi-tier cellular standards such as LTE Advanced [110].

The cluster member distribution technique remains the same as described in Section 4.2 in Chapter 4. This means that after initialization of the number of VCC and calculation of inter-FAP distance matrix D, a temporary matrix, D_{temp} is created by copying D. The reason for using D_{temp} is to retain D as a reference and then execute the various processing steps of the clustering algorithm on D_{temp} .

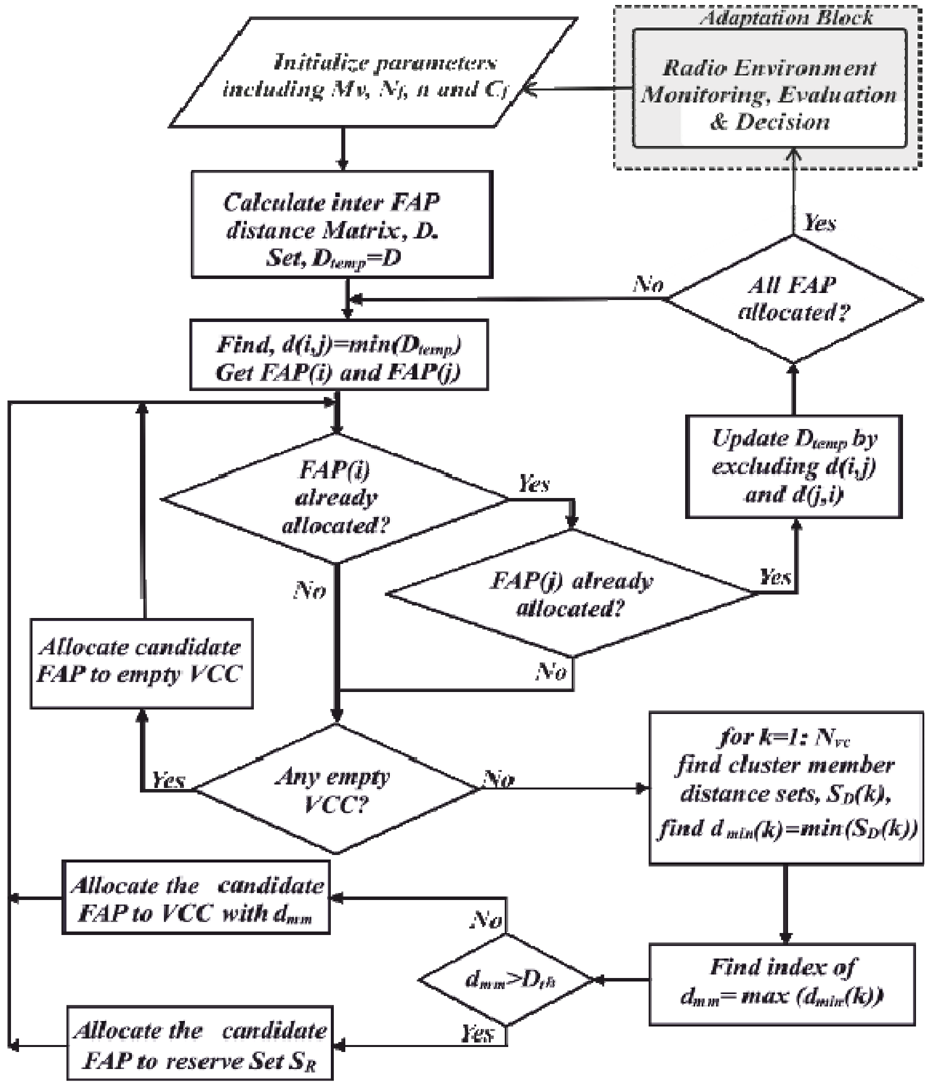


Figure 5.2: Flowchart for the generalised virtual clustering femtocell (GVCF) algorithm

Then the closest FAP pair is taken from D_{temp} and allocated to an empty VCC in step I. The process continues until every VCC has at least one member. Then the algorithm enters step II and for any further FAP allocation, the VCF algorithm needs to consider the distance of the candidate FAP to the members of each clusters which is taken from the distance matrix D (4.2). From these inter-FAP distances, the nearest distance of the candidate FAP to the member of each VCC is selected and the FAP is assigned to the VCC which has the highest minimum distance d_{mm} in the nearest distance set calculated earlier, subject to the safety distance D_{th} being maintained. If the FAP cannot uphold D_{th}, it is assigned to the reserve set S_R instead, whose members are allocated reserved channels. D_{temp} is then updated, with the FAP pair assigned during this iteration being excluded, and the procedure repeated until all FAPs have been allocated. The adaptation phase then starts which is the key enhancement of the algorithm developed from Chapter 4.

5.2.1 Adaptation Phase

In this phase, the GVCF model continually monitors and evaluates the performance of the current FAP clustering arrangement as highlighted in the box in Figure 5.2. For a given constraint such as, an application specific data-rate requirement, if the existing cluster arrangement cannot uphold the requisite performance, then the RNC is requested to allocate more channels in order to increase the number of clusters. Upon receiving these, the iterative virtual clustering process is repeated. Also, if the performance of the system is better than the requisite level, it can reduce the cluster number at which the performance remains above the required QoS and thereby either liberate or report back unnecessary channels to either the RNC or macrocell BS.

This adaptation mechanism importantly identifies radio environment changes such as a MS or FAP either joining or leaving the femtocell network, with the clustering algorithm adjusting accordingly the cluster number and reassigns FAPs to other VCCs to either improve or sustain performance. It also adjusts its clustering arrangement according the changes in resource sharing reported or updated by the macro-tier.

A look up table (LUT) can be formed (exact details of the processes will be discussed in the simulation results in Section 5.4) based on the simulated performance of different cluster number and FAP deployment density. This can be exploited or interpolated to find the amount of resource required or required clustering arrangement in order to meet certain QoS constraint. This uniquely affords the GVCF paradigm flexibility in its ability to automatically respond to changing radio environment conditions and unforeseen network situations such as a surge or drop in the number of FAPs in certain space and time.

The monitoring of the algorithm is done continually and the adaption process is triggered only when the system fails to maintain either a given QoS or when it is found that the required performance can be achieved with lower resources or a smaller cluster size. It also triggers the adaption process if a departing MS from the femto-tier changes the maximum number of MS connected to a FAP in the FGW under consideration. This may in turn permit the number of clusters to be increased. The GVCF performance cannot however, improve the performance in case of the unavailability of the required resources from either the RNC or macro-tier. In these circumstances, the GVCF model will provide the best possible arrangement based upon the existing resource availability.

5.2.2 Computational Complexity

From a computational complexity perspective, the new virtual clustering framework is very efficient as it principally involves processing FAP coordinates, so the time complexity increases linearly with the number of femtocells deployed. This means compared with alternative FAP deployment techniques such as graph colouring, GVCF has significantly lower overheads since in graph colouring any changes in the network or in assignment causes the graph for each FAP to be reconstructed. In contrast, the main virtual clustering task is maintaining the inter-FAP distance matrix D in (5) so when a FAP either joins or leaves the system, a corresponding matrix entry change occurs, i.e., a row and column is either added or removed from D. Thus, for N FAP, GVCF incurs $O(N)$ complexity.

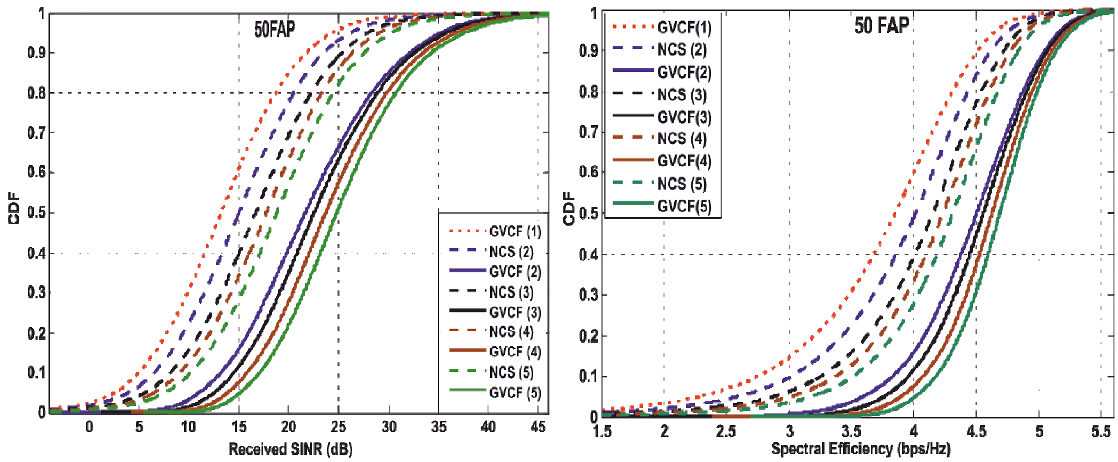
5.3 System Model

To evaluate the performance of the GVCF paradigm, a 200m x 200m area of one sector in a hexagonal macrocell was considered, for four specific FAP node deployments of 50, 100, 150 and 200. The number of available channels in the area was up to 20. As a performance comparator for VCF, a distributed resource allocation framework was implemented where each FAP independently chose its operating spectrum. This scheme will be referred to as the Non-Clustering System (NCS) in the ensuing discussion. For simplicity of comparison, number of channels allocated by VCF and NCS to each FAP is kept equal. The simulation test platform was designed and implemented in MATLAB™, with all the various network environment parameter being given in Table 3.1.

5.4 Simulation Results Analysis

Once the parameter values have been set, the new GVCF algorithm is run under different deployment densities and various cluster numbers. Firstly, the system is simulated for worst case scenario where all the FAPs operate on the same channel set. At this point, all the FAPs are members of a single virtual cluster which means there is no difference between the clustering and NCS solution. The impact of increasing resource availablity for up to 20 channels will then be investigated for different FAP deployment densities.

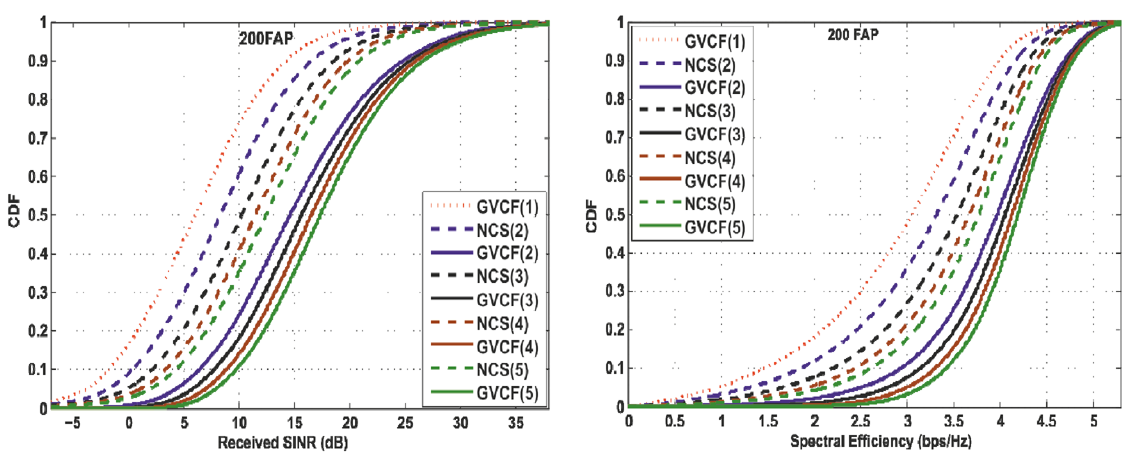
Figure 5.3 (a) and (b) presents the CDF of the received SINR and the corresponding SE respectively for a FAP deployment density of 50. Significant received SINR gains and corresponding throughput improvements have been made by the clustered system compared to NCS.



(a) (b)

Figure 5.3: Performance comparison of GVCF and NCS system when 50 FAP deployed: (a) Received SINR (b) Spectral Efficiency.

Equation (4.1) reveals that the number of virtual clusters increases with the number of channels, so the availability of more channels will increase particular channels' reuse distance and correspondingly reduce the average interference experienced by its femtocells. In all cases of channel availability, the clustered system outperformed the NCS by a margin of at least 6 to 7dB at 50^{th} percentile value (median received SINR). This translates to an average spectral efficiency gain of approximately 0.5 bps/Hz on average and up to 0.8 bps/Hz when 90^{th} percentile value is considered.



(a) (b)

Figure 5.4: Performance comparison of GVCF and NCS system when 200 FAP deployed: (a) Received SINR (b) Spectral Efficiency

In very high density deployment of 200 FAPs, a similar performance pattern is observed but with reduced average received SINR and corresponding SE performance as seen in Figure 5.4. When 200 FAP deployed, the average received SINR for 2 and 3 clusters are 14.5 dB and 16 dB. With similar resources, the averaged received SINR drops to 8 dB and 10.5 dB respectively. Thus in both cases GVCF outperforms NCS by around 6 dB margin. Similar performance results can be obtained for other FAP deployment densities, where SINR and SE increases with decreasing number of FAP but the clustered system provides markedly superior performance to the NCS system. To avoid repetition, the equivalent results for the other analyzed FAP densities are included in **Appendix A.**

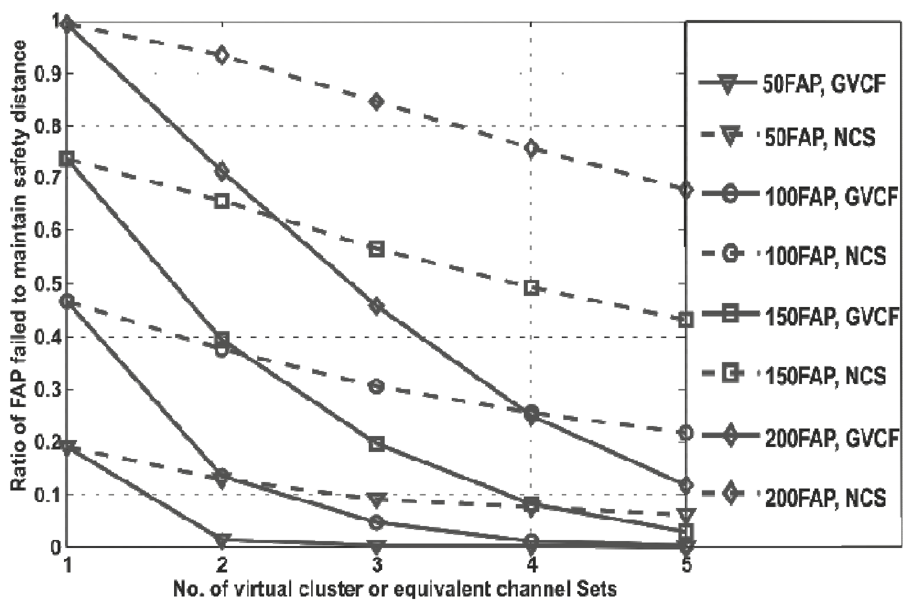


Figure 5.5: Comparison of the ratio of FAPs failed to maintain minimum distance requirement for different number of clusters and non clustered system with equivalent channel set.

Figure 5.5 compares the ratio of FAPs which failed to maintain the safety distance threshold (D_{th}) or both the logically clustered and non-clustered systems at various FAP deployment densities. The single cluster option represents the worst case scenario, where all FAPs operate on the same channels. In this case, when the deployment density is very high, i.e., 200, almost all FAPs fail to maintain the safety distance threshold D_{th}.

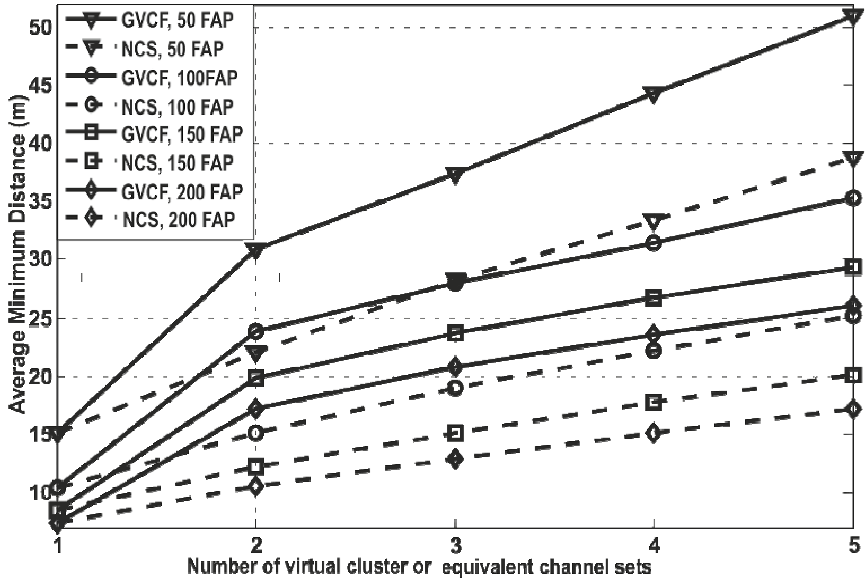


Figure 5.6: Comparison of the average minimum distance at various FAP densities for different number of clusters and non clustered system with equivalent channel set.

With increasing numbers of either virtual cluster controllers or equivalent numbers of channels, many more FAPs are able to maintain the D_{th} threshold. However the rate of improvement is substantially higher for the clustering architecture compared to the NCS. For example, when 200 FAP is considered, if 5 virtual clusters are available, only 10% of the FAPs failed to maintain safety distance compared with nearly 70% for NCS. This confirms a significant improvement in terms of upholding the safety distance. Conversely, when FAP deployment density is low, i.e., 50 FAP in the given area, very little if any improvement is achieved with more than two virtual clusters.

Analyzing the performance from a different point of view, a distance related plot is shown in Figure 5.6. This plot is obtained by averaging the distance of the nearest interferer for each femtocell for the same scenarios given above. Again, by having more clusters, the average minimum distance increases at a higher rate when the FAP density is greater. In all cases, the virtual clustered approach consistently out-performed the NCS, though while these results are a good indicator of system performance, this distance measure alone is not enough to decide on resource distribution. Ultimately, SINR and achieved throughput are the key QoS parameters which need to be evaluated in equitably assessing the GVCF model performance.

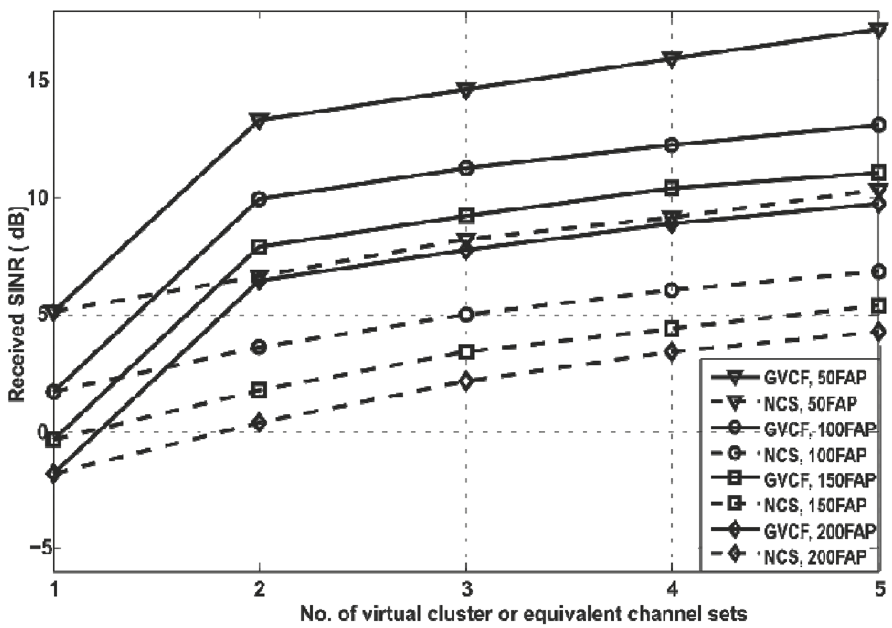


Figure 5.7: Comparison of the received SINR at 90th percentile for various FAP densities with different number of clusters and non clustered system with equivalent channel set.

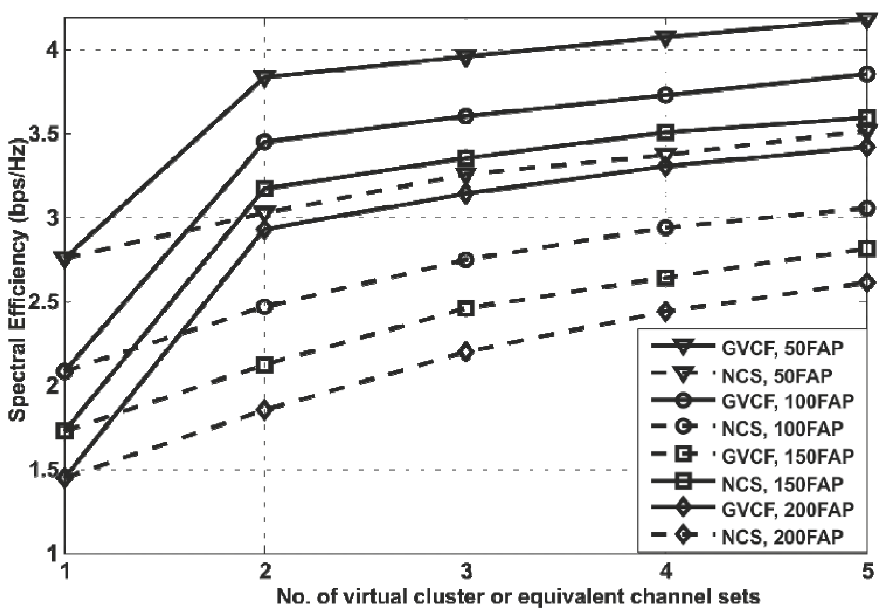


Figure 5.8: Comparison of the 90th percentile *spectral efficiency* (SE) for various FAP densities with different number of clusters and non clustered system with equivalent channel sets.

Figure 5.7 and Figure 5.8 respectively show the 90th percentile SINR and the corresponding SE performance at various FAP densities and cluster numbers or equivalent channel sets. It can be seen that, by clustering with FAP numbers as high as 200 can exhibit similar performance to that achieved by NCS with only 50 FAPs. In summary, the GVCF model provided a performance margin over the NCS of between 6 and 7dB.

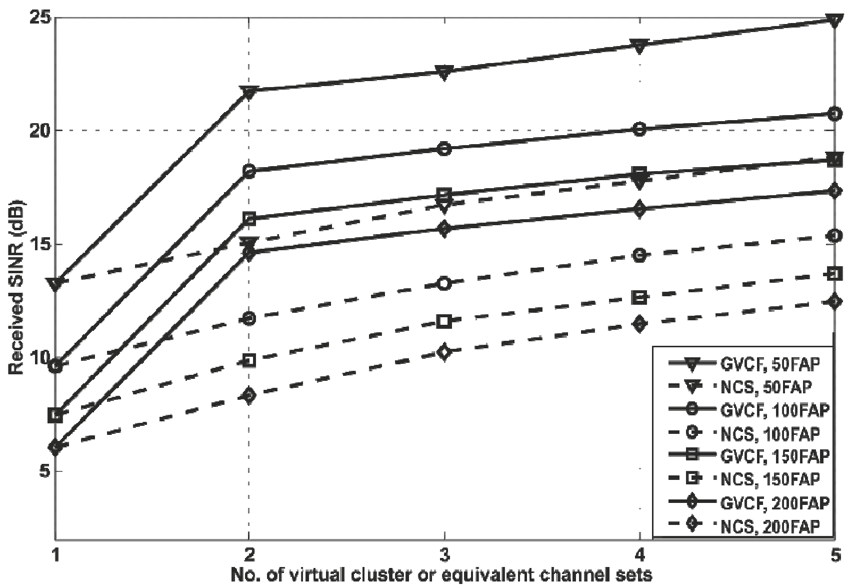


Figure 5.9: Comparison of the average received SINR for various FAP densities with different number of clusters and non clustered system with equivalent channel set.

While at higher FAP densities, the performance of both GVCF and NCS models begins to degrade and interference increase, the clustering system is still able to maintain a 6 to 7dB improvement margin at all deployment densities analysed. Figure 5.9 and Figure 5.10 reveal similar results this time for the 50th percentile or average performance. The same conclusions can be drawn for these figures in terms of supporting the enhanced performance of the GVCF paradigm in minimizing femto tier interference.

These figures also provide another insight which is important from the network management viewpoint. A LUT can be constructed for various SINR and SE values and the corresponding amount of resources required then estimated accordingly, for different sets of constraints. The GVCF paradigm can thus facilitate specific FAP clustering designs for different QoS requirements. For example, if the number of FAPs in an area is more than 150 and the average bit rate requirement is 3.5 bps/Hz, then the RNC must allocate 8 channels to the femtocell tier to form 2 virtual cluster controllers in order to achieve the required performance. However, if the same QoS requirement is to be upheld at the more demanding 90th percentile, then the RNC must allocate at least 20 channels to the femtocell tier.

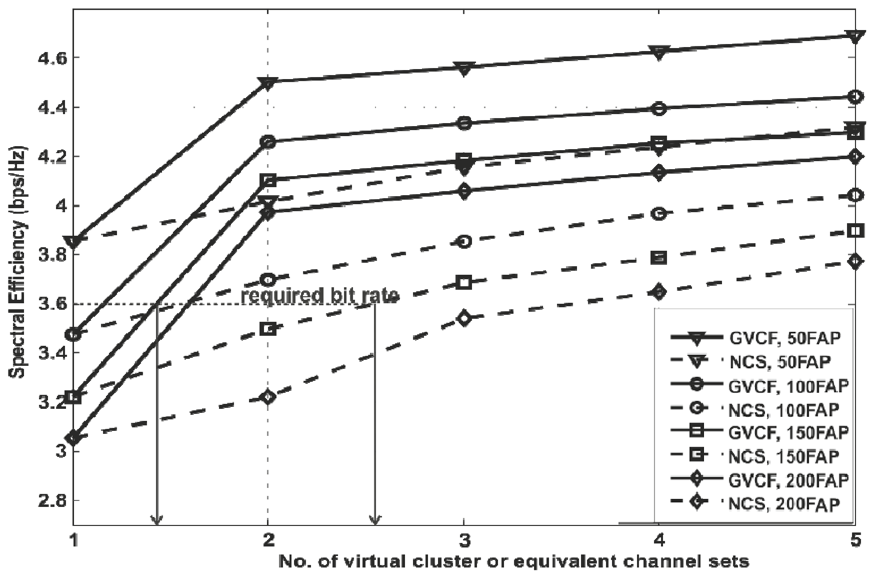


Figure 5.10: Comparison of the average SE for various FAP densities with different number of VCC and NCS with equivalent channel set

With increasing FAP density, the probability of using the same channel by neighbouring FAPs increases and the performance degrades as a result. In order to reduce this, a much higher number of channels is required in the case of higher deployment density (200 FAP) compared to the lower deployment density (50 FAP). This also confirms the need for intelligent and coordinated resource management at high density FAP deployments.

Conversely, if the maximum number of channels available in the femtocell tier is 12 and the required average SINR=14 dB, then GVCF can serve at least 200 femtocells. However, at the 90^{th} percentile, for identical QoS requirements, the system cannot serve more than 50 FAP, while if 16 channels are available and there are 150 FAPs, then the maximum achievable SINR=10 dB at the 90^{th} percentile. This means the RNC has to supply more channels if better performance is to be achieved.

This means for a given set of constraints and QoS requirements, a LUT can be formed from these performance figures which can be used by the FGW to communicate with the RNC in order to demand the necessary resources for the femto tier to achieve certain QoS requirement. Subsequently based upon the received resources, the FGW can then adapt to the best possible number of clusters. Conversely, if the number of available channels required to achieve the desired performance is higher than the requirement then extra channels are either liberated or reported back to the RNC.

From these results, it is clear that GVCF performance is significantly superior compared with the NCS, with the average bit rate achieved in all cases being around 4 bps/Hz, and even using the more conservative 90th percentile, a 3 bps/Hz improvement is achieved. This achieved throughput will be sufficient to satisfy the data rate requirement of most applications. This actually gives flexibility and opportunity to look at a drawback of the femtocell system. Since the coverage of the femtocell is very low, even the users with very low mobility can easily move out of the FAP coverage.

Although GVCF performs very well in mitigating interference to a sufficient level to meet certain QoS requirement mentioned above in all the evaluated scenarios, one drawback is that it does not consider the issue of small coverage range. Due to this small coverage, users may move out of range and trigger a handover. The problem is particularly severe in the case of users with some mobility. In these scenarios, users are handed over to the MBS when a closed access policy is adopted. In high density deployment, there is a potential danger of generating too many handovers and the so-called *ping pong* effect [111].

To avoid handovers, users may be kept connected to the FAP for longer time which needs the coverage to be expanded if necessary. This can solve the problem provided the overall network performance remains above the required level. Therefore, a detailed investigation on the impact of range expansion needs to be performed to make the GVCF model more robust and prevent these adverse effects. The next chapter will address the issue of avoiding excessive handovers by making FAP coverage range more flexible. The corresponding impact of this range flexibility on both the SINR and throughput performance of the femtocell network will be analysed.

5.5 Conclusion

In this chapter the issue of interference aware resource management for femtocells has been discussed in detail. Both cross tier and co-tier interference issues have been addressed with more particular emphasis on femto-to-femto interference management in the downlink. A new adaptive and flexible virtual clustering architecture (GVCF) has been presented and extensive simulations undertaken to rigorously evaluate the performance. Simulation results show that the GVCF successfully mitigate cross and co-tier interference to achieve desired performance. It also outperforms the distributed random channel allocation system in all the scenarios, achieving significant performance improvements in terms of both SINR and throughput. The creation of LUT from a network management point of view has also been discussed to provide the FGW with the necessary information so that it can better fulfil its resource requirement to either the RNC or macro-tier.

6 Femtocell Range Coverage Analysis in the Generalised Virtual Clustering Framework

6.1 Introduction

The key driver for this research into femtocell networks is that they represent a promising solution for extending high data rate wireless services in indoor environments, where the comparative radio signal quality is poor in conventional cellular systems. In the previous chapters, it has been proven that high data rates can be achieved even in dense femtocell deployments (200 FAP) by applying novel hybrid resource management techniques. Despite the many benefits of short coverage distances such as, low power consumption, robust links and high data rates, there are a number of drawbacks. Amongst these, severe cross and co-tier interference is the most prominent, with innovative solutions to these issues already having been proposed in Chapters 4 and 5. However, there is another problem that arises due to short coverage range. Frequent handoffs may occur between the macrocell and femtocells even for users having low mobility. This may potentially generate a large amount of redundant control data for handover management. Furthermore, frequent handovers between the femto and macrocell (also known as the *ping pong* effect) can occur.

In densely deployed areas, if high numbers of users are continually being handed over to the macrocell, then due to the limited resources available, users may incur a long delay to be scheduled for transmission. The paradox is that this will cause a significant drop in the average throughput despite achieving superior SINR performance. An added potential danger is this may trigger a sudden load imbalance between the cells.

To address these problems, the MS can be kept connected to the FAP by expanding the coverage range of the femtocell. Integrating a coverage range expansion policy into the GVCF architecture has a number of advantages. It will not only make the system more robust, but will enable it to better adapt to radio environment changes and crucially provide a flexible mechanism for maintaining the required QoS provision, while minimising excessive user handoffs to the macro-tier, by keeping the MS connected for longer periods of time. As a result, the total number of handovers can be substantially reduced. The inherent limitation of extending the coverage range however is that it also increases interference in the femto-tier. In dense deployments, MS moving away from one FAP may become closer to another FAP and experience severe interference. Thus, before incorporating a range expansion policy to tackle handover related problems, it is important to investigate and analyse their impact on the overall system performance.

In the following sections, an overview of existing range expansion approaches is firstly examined before a detailed analysis of the corresponding simulation results is presented. Finally, the chapter makes some concluding comments.

6.2 Review of Range Expansion Techniques and Policies

Dynamic coverage shrinking and expansion techniques for cellular networks have previously been studied [112] to ensure various performance metrics, such as load balancing, system throughput maximization and fairness, coverage hole elimination and energy saving are considered. Some recent studies [113] have approached coverage expansion from a different perspective, namely how best to support users in neighbouring cells in the case of either an outage or fault in the BS of the neighbouring cell.

Cell zooming is one technique that adaptively adjusts the cell coverage range depending on the traffic load, channel condition and user requirements [112]. There are many ways of implementing cell zooming. The most conventional one is increasing the power of the transmitter for zooming out and then decreasing the power for zooming in. An alternative way of achieving this is by changing the antenna tilt, where tilting down shrinks the coverage while tilting up conversely expands it [114]. However, received SINR will be lower in the expanded region if the transmission power level is kept unchanged.

Cell zooming, particularly expansion, cannot be readily performed to cover areas far away from the cell that lie deep inside the neighbouring cells as this may either require higher transmission powers and also increases the risk of higher traffic loads. In these cases, more cell site deployment may be required. The work in [115] introduces a new parameter for traffic estimation, called the *low traffic time ratio*, which is used for deciding when to switch off a particular cell BS and zooming the neighbours to cover the area. If a cell is overburdened with traffic during busy hours, cell breathing [116] provides an excellent load balancing mechanism to handle client congestion in a wireless LAN. The solution also includes various power management algorithms for adjusting the coverage of access points to handle dynamic changes. The cost of hand-off also needs to be considered in this kind of scenario. In CR-based systems, sensing information can be exploited to extend the coverage while maintaining the required QoS [117]. In dynamically varying networks, automatic methods are essential if the coverage is to be maximised while the overall system interference [118] is minimised.

All of this implies the formulation of an objective function which can then be subsequently optimised. However, optimising wireless networks is a very complex task as it directly affects many system parameters and issues like quality, cost, coverage and capacity, so a detailed investigation of the mutual influences among key parameters is necessary [119]. The optimization of these parameters is usually undertaken by applying established techniques such as: linear and integer programming, heuristics [120], genetic algorithms [121], and RL or fuzzy logic [122].

Existing coverage range modification research which relates to cellular networks has so far mainly focused upon pre-planned network architectures and coverage, which is typically much higher than FAP coverage. Also as mentioned earlier, unplanned femtocell deployments and their short coverage distance make the handover related problem distinct from the conventional cellular network. This provided the motivation to undertake a detailed study of the coverage range issue in a femtocell network context.

Recent work relating to range expansion for dual-tier cellular networks predominantly addresses open access multi-tier heterogeneous networks with the focus being upon the mobility and handover issue between the tiers. Mobility management between network tiers has been addressed in [123], while the handover and *ping-pong* effect involved in range expansion has been analysed in detail in [124]. In a randomly deployed open access femtocell scenario, dynamic coverage adjustment is very important for balancing the load among the collocated FAPs, while minimising the overall coverage [125]. Also, along with load balancing, the level of transmission power can be adjusted to provide energy savings. From a design perspective therefore, to achieve individual throughput fairness among the users, both the power and resources need to be carefully allocated.

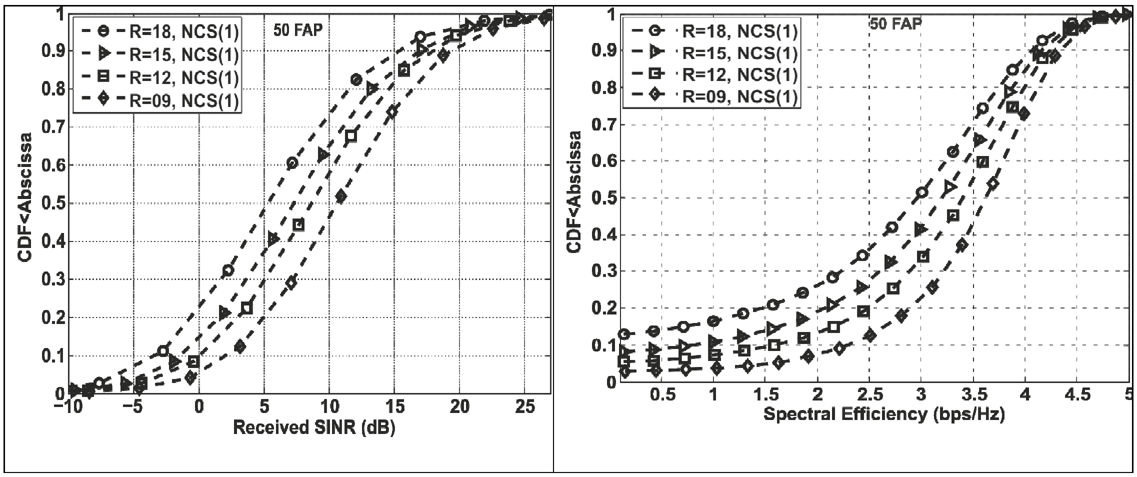
While some literature [126] [127] has sought to address range expansion within dual-tier heterogeneous networks, the impact on closed access femtocell networks has been largely ignored. In this chapter, a pragmatic approach has been adopted where range expansion in closed access femtocell network has been studied. The investigation focuses on analysing the impact of coverage expansion in closed access femtocell networks at various FAP deployments. The aim is to firstly understand how both the throughput (SE) and SINR performance varies as FAP coverage range is expanded, before analysing how the deployment density influences the overall system performance alongside range expansion. This provided the basis for the development of a cross-tier handover minimisation framework for closed-access femtocell networks.

To evaluate the impact of range expansion, the comparative performance of two different resource management techniques has been studied, namely *i)* the GVCF clustering paradigm developed in Chapters 4 and 5 and *ii)* the benchmark randomly allocated NCS algorithm. To maintain consistency in the thesis, the performance analysis was again undertaken in terms of both SINR and throughput. In the following section, the system model will firstly be discussed before a rigorous analysis is presented on the corresponding coverage range expansion performance.

6.3 System Model, Simulation Results and Analysis

As in the earlier thesis chapters, a 200m x 200m area of one sector in a hexagonal macrocell was considered. Four FAP node deployments of 50, 100, 150 and 200 were used, with the number of channels available varying between 4 and 20 for the femtocell DL operation. From (4.1), this meant the requisite number of VCC (clusters) varied from between 1 (the NCS model) to 5. All other systems parameters and their corresponding values remained the same as in Table 3.1, except for the FAP coverage range, which in the simulations was varied between 9m and 18m. It was assumed that despite the coverage extension, all users remained within the indoor radio environment.

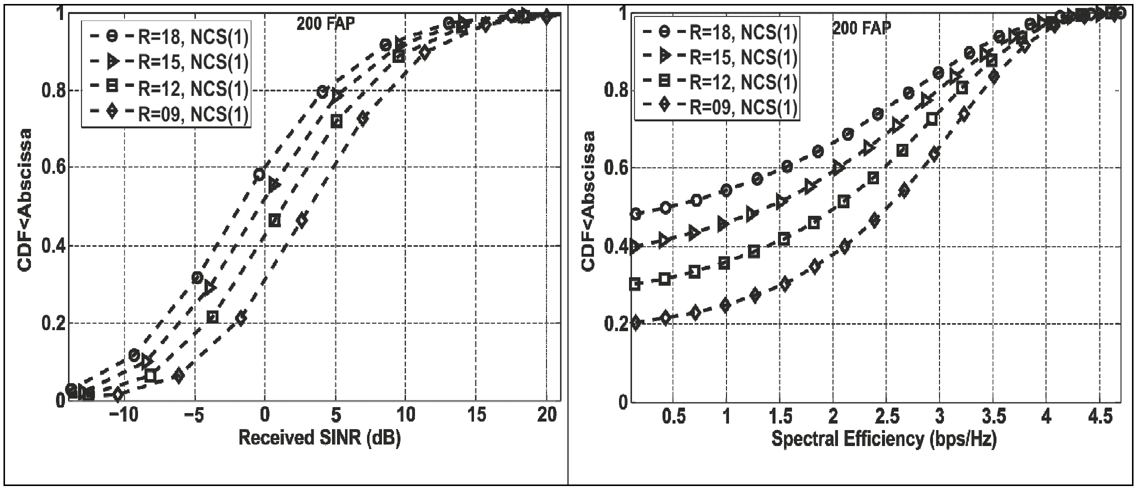
Up to 4 MS could connect to a FAP at any particular time, and they were allowed to remain connected until they reached the coverage range, assuming that the necessary amount of handover bias has been applied for each respective FAP, instead of handing them over to the macrocell BS. Since MS were never handed over to the macrocell, the handover cost was not measured, so instead the penalty incurred in terms of the reduction in the received SINR and average throughput performance was evaluated.



(a) (b)

Figure 6.1: Performance of NCS with 50 FAP deployed and using the same channels set: (a) the received SINR and (b) SE (Spectral Efficiency)

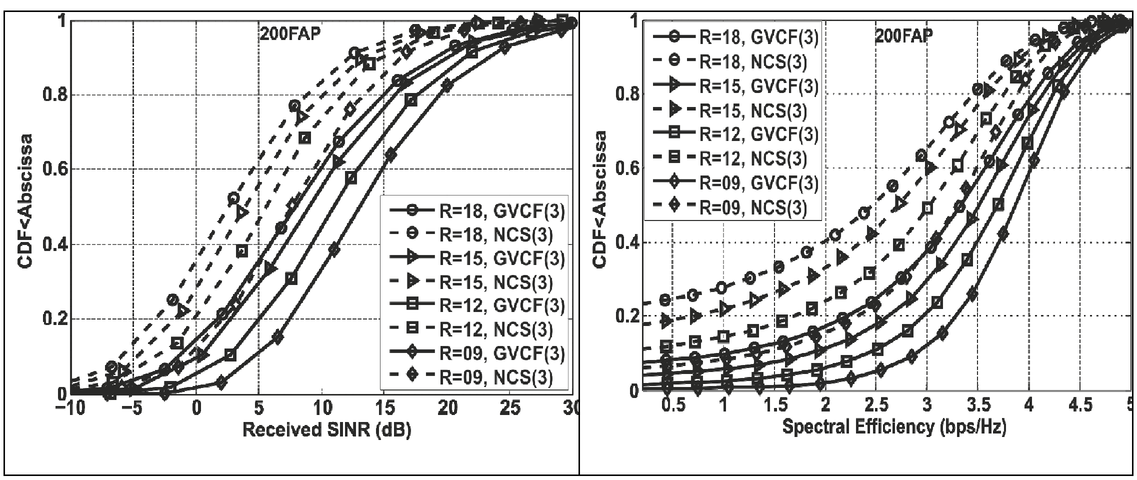
The performance of the worst case scenario was firstly analysed, where each FAP uses the same channel set. This means no clustering is possible or in other words, all the FAPs are members of a single cluster. Figure 6.1(a) shows the NCS received SINR results when 50 FAP are deployed and use the same channels set, while the corresponding throughput performance is displayed in Figure 6.1(b). With a coverage range of 9m, the average achievable SINR is 11dB and intuitively, this will decrease to 5.5dB when the coverage range doubles to 18m. However, the received SINR falls by more than 6dB when the coverage is increased from 9m to 18m, while the achieved SE remains approximately constant at ≈3 bps/Hz. Similar to the findings identified in Chapters 4 and 5, when FAP deployment density is low, interference is also low, so in this particular scenario the system is able to be flexible in expanding the FAP coverage range while still maintaining the defined QoS requirements.



(a) (b)

Figure 6.2: Performance of NCS with 200 FAP deployed and using the same channels set: (a) the received SINR and (b) Spectral Efficiency

If FAP deployment density is now increased to 200, it can be seen from Figure 6.2 (a) that even at 9 m coverage, the average SINR is less than 5 dB which reduces to -3 dB when the range coverage is extended to 18 m. Thus for high FAP deployment densities, increasing the coverage severely degrades the system performance compared to lower numbers of FAPs.

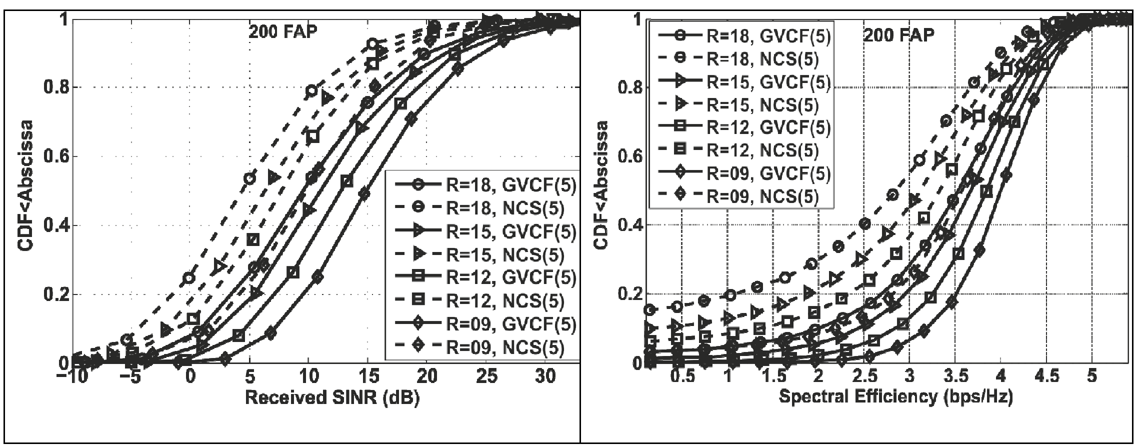


(a) (b)

Figure 6.3: Performance comparison between GVCF and of NCS with 200 FAP deployed when VCC=3: (a) the received SINR and (b) Spectral Efficiency

When the number of available channels for the femto tier was increased to 12, the corresponding number of clusters in the GVCF model becomes 3 i.e., VCC=3. The SINR and throughput performance of the GVCF and NCS models for 200 FAP in this new scenario are respectively shown in Figure 6.3 (a) and Figure 6.3 (b). The results clearly reveal that GVCF outperforms NCS across all coverage ranges by a margin of at least 6 dB in all cases.

As explained in Section 4.2, the central idea behind the GVCF (and VCF) paradigm is to maximise the average spectrum reuse distance amongst those FAPs operating on the same spectrum, thereby reducing interference and increasing the network performance in terms of both SINR and SE. As the MS moving away from the FAP to which they are connected, they will be less close to the FAP operating on the same spectrum, compared with the NCS model, so these FAP are better able to handle the inherent losses which occur during coverage range expansion.



(a) (b)

Figure 6.4: Performance comparison between GVCF and of NCS with 200 FAP deployed when VCC=5: (a) the received SINR and (b) Spectral Efficiency

If the channel availability is increased further to 20, from (4.1) the corresponding number of VCC=5. As mentioned previously, since GVCF always seeks to maximise the minimum reuse distance, and because more channels are available, the received SINR improves significantly compared with the NCS system. The respective SINR and throughput performances of GVCF and NCS for 200 FAP with 5 clusters are shown in Figure 6.4(a) and Figure 6.4(b). Comparing Figure 6.3 and Figure 6.4, it can be seen that the average throughput has increased from 3.3 bps/Hz to nearly 3.6 bps/Hz when the number of clusters has been increased from 3 to 5. Thus for larger cluster sizes, the system performance improves, and this is especially noteworthy at high density FAP deployments because at these densities, the achieved SINR is generally low as evidenced from the results above. While the results discussion in this chapter has focused particularly on the low (50) and high (200) FAP density deployment scenarios, for completeness the corresponding received SINR and SE results for the intermediate FAP densities (100 and 150) for different numbers of clusters, are presented in Appendix B.

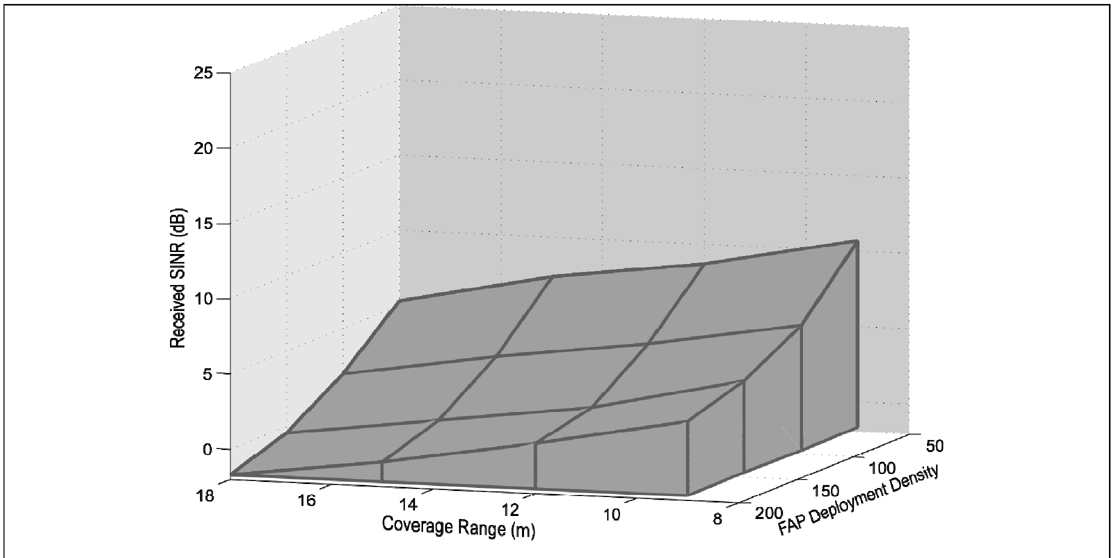
Table 6.1: LUT for QoS requirement of 0 dB SINR

Cluster Size	No. of FAP deployed	Coverage Range (m)			
		9m	**12m**	**15m**	**18m**
		% of MS failing to meet the QoS for various coverage ranges			
1	50	5	9	14	22
	100	15	22	29	38
	150	25	36	44	51
	200	31	42	52	58
3	50	0	0	0	1
	100	0	0	2	3
	150	1	3	6	11
	200	1	5	9	14
5	50	0	0	0	0
	100	0	0	1	1
	150	0	0	1	2
	200	0	1	3	4

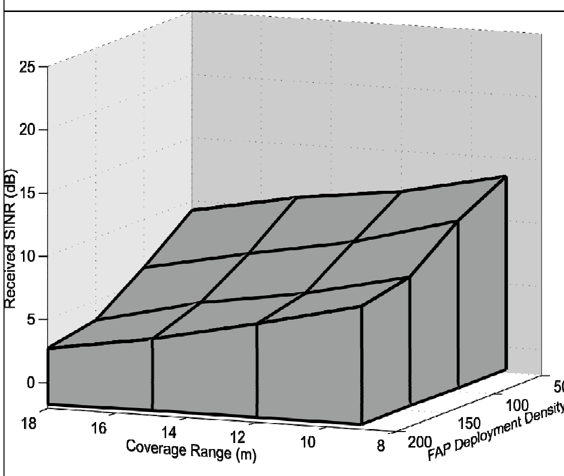
An alternative way of interpreting these findings is to consider whether the minimum QoS requirement has been upheld. Table 6.1 shows the LUT that represents the percentage of MS failing to achieve the QoS criterion for a minimum SINR=0 dB. Similar LUTs can be developed for different QoS constraints. It is evident from the Table that at higher FAP densities, the capability of the GVCF model to adaptively increase the number of clusters in very beneficial in significantly improving system performance. For example, for 3 clusters and a 50 FAP deployment, all the MS were able to achieve the required QoS even when the coverage was extended to 15m. Similar observations can be made for the performance at 100 FAP leading to the conclusion that for low-to-medium FAP deployments of 50 and 100, there is no need to have more than 3 clusters. However, the situation worsens at higher FAP deployment densities, i.e., 150 and 200.

In case of a 200 FAP deployment, the percentage of MS failing to reach the minimum SINR requirement drops from 14% to only 4% by increasing the cluster number from 3 to 5 at the maximum coverage range of 18m. However, for a coverage range of 9m, there is no improvement in terms of achieving the minimum SINR of 0dB as 3 clusters were sufficient to meet SINR requirement for all the FAPs.

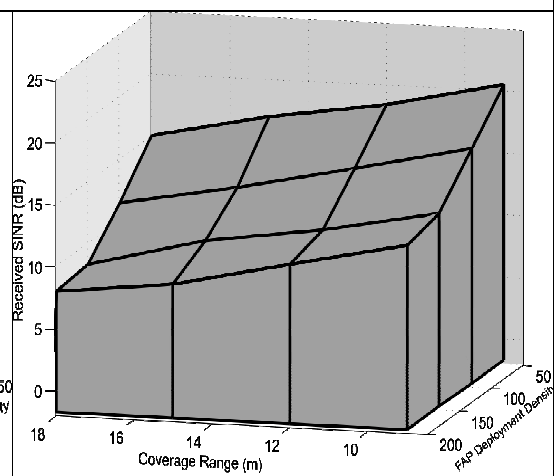
Since the available spectrum is always very precious, careful utilization is vital for ensuring the best possible use of the available resources. Figure 6.5 displays a series of 3-dimensional graphs of the average received SINR performance for various coverage ranges at different FAP deployment densities. Figure 6.5 (a) shows the baseline performance or the worst case scenario when all the FAP operate on the same channels set and there is no clustering (NCS). At every FAP deployment and coverage range, the system performance remains very low. However, the performance significantly improves with higher numbers of clusters as confirmed in both Figure 6.5 (b) and Figure 6.5 (d). Figure 6.5 (c) and Figure 6.5 (e) provide the corresponding NCS performance.



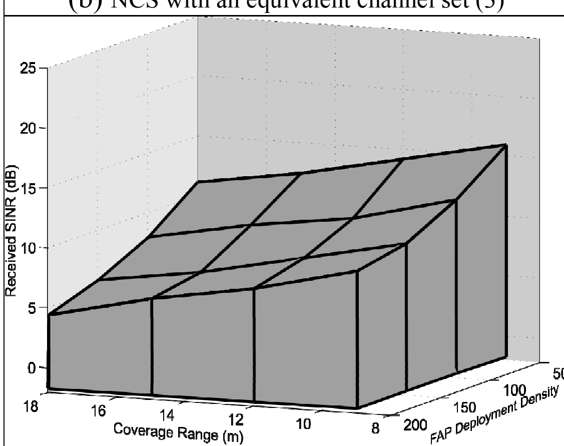
(a) No Clustering System (NCS) when all FAPs use the same set of channels



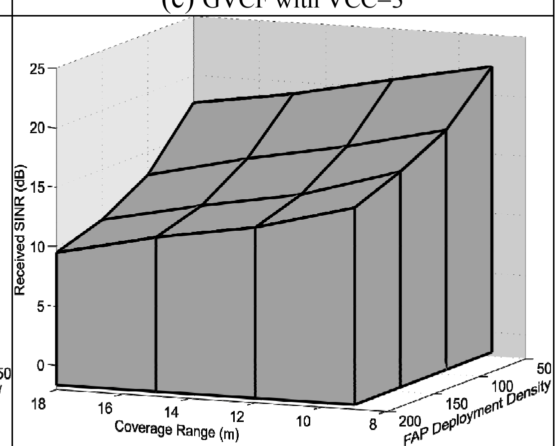
(b) NCS with an equivalent channel set (3)



(c) GVCF with VCC=3



(d) NCS with an equivalent channel set (5)



GVCF with VCC=5

Figure 6.5: Mesh grid representation of the average received SINR performance comparison between GVCF and NCS for different FAP coverage ranges and numbers of clusters at various FAP densities.

The results in Figure 6.5 and LUT presented in Table 6.1 can be exploited to develop a mechanism for incorporating an adaptive range expansion policy into the GVCF paradigm. For a given minimum QoS constraint and average SINR requirement, the best cluster size (and hence the minimum number of channels) can be recommended for different coverage ranges. For example, when the FAP density is 50, and the QoS and average SINR requirements are 0 dB and 10 dB respectively, then the number of clusters needed will be 3 and the maximum allowable coverage 18 m.

Now applying the same criteria to a 150 FAP deployment, the corresponding maximum allowable coverage range becomes only 15 m. To extend the coverage to 18 m, the GVCF model must have at least 5 clusters as otherwise the system fails to meet the average received SINR requirement. Using the same criteria for the 200 FAP case is even more demanding as in order to maintain the average SINR requirement, the cluster size must be 5, though the range has to remain at the minimum (9 m), as increasing the coverage causes the SINR to fall below the defined threshold of 0 dB.

From the above discussion it is clear that incorporating a range expansion policy into the GVCF paradigm affords much greater flexibility and robustness by making it more adaptive to changes in both the radio environment and resources availability. Based upon the framework developed in this chapter, different LUTs (similar to Table 6.1) can be formed for different QoS constraints. The cluster size and FAP coverage range can be dynamically adjusted according to the LUT to meet certain QoS requirement. Importantly these results form the basis for the development of either a FAP handover minimisation or optimization strategy jointly with the macro-tier, though this objective is beyond the scope of this thesis.

6.4 Conclusion

In this chapter the influence of range expansion on the performance of the femtocell network has been studied. The investigation has focused on analysing the impact on received SINR and corresponding SE performance regardless of any handover implications. Since it can be reasonably argued that the number of handovers will reduce if the MS remain connected to the FAP while it moves away from the FAP, the emphasis has been to examine if the received SINR and corresponding SE can be maintained to a satisfactory level. From the detailed analysis presented in this chapter it has been clear that the GVCF paradigm performance is more robust and flexible by incorporating a coverage range expansion policy.

7 Future Directions

In the thesis, a novel multi tier cellular system management architecture is presented. The presented resource management model is flexible and adaptive to network environment changes and has been rigorously analysed to ensure successful robust management of joint macro-femtocell deployments when sharing the same spectrum. Some suggestions for possible new avenues of future research which extend the findings presented in this thesis will now be briefly outlined.

7.1 Theoretical Modelling of the Proposed Framework

The work presented in the thesis was focused on analysing the performance of the emerging multi-tier networks. The model developed here is tested in a simulated platform. The theoretical modelling of the presented architecture can be done to analytically derive the fundamental limits of performance under certain resource constraints and deployment densities. This will also validate the model developed. As mentioned earlier, the fundamental difference between single tier to multi tier system is that the later includes unplanned deployment of FAPs. Hence the analytical modelling techniques used for the planned macrocell system may not be suitable for the multi tier system. Thus, a detailed statistical and mathematical modelling of FAP deployment and their performance evaluation would be a valuable extension of the work. Stochastic geometry and point processes can be exploited for theoretical modelling of this complex networks architecture.

7.2 Macrocell MS Protection at Cell Boundaries

The dynamic FFR has been implemented in the work for resource partitioning between femto tier and macro tier. Although, mutually exclusive channels are assigned to macrocell MS and femtocell MS in any area, macrocell MS particularly situated at the collocated neighbouring CER may be particularly vulnerable to cross tier interference. To avoid this particular type of cross tier interference, special measures need to be taken. One alternative can be create a buffer zone where exclusive set of channels will be used by the macro MS. A careful investigation is required to find the appropriate area of the buffer zone depending on various parameters including deployment density and transmit power.

Another alternative can be employing cooperative resource allocation and localised and distributed negotiation between the interferer and the interfered MS. Also cognitive radio techniques can be examined for suitability in these scenarios.

7.3 Network Assisted Power Control

While femtocells inherently save significant power compared with their macrocell counterparts, further energy efficiencies are going to be mandated to reduce the environmental impact of *next generation* networks. This is particularly important as this topic moves up the political, economic and social agenda for operators and customers alike. In this thesis, the transmit power of the femtocells has been assumed to remain the same regardless of the QoS requirement. However, the new presented virtual clustering architecture can be exploited to save more energy by allowing the VCC to negotiate amongst its FAP members for jointly reducing transmission power, while maintaining the minimum QoS for each FAP. Despite lower transmission power, the effective SINR will remain above the required threshold as the level of interference between FAPs is reduced. Minimum supervision from the various cluster controllers enables the FAP to independently take the majority of the decisions in a distributed fashion, thereby making the framework scalable for higher density FAP deployments.

In the case of open access femtocell networks, as the MS move away from the coverage of the FAP to which it is connected, it can be seamlessly handed over to another adjacent open access FAP, if one is available. For multiple FAP availability, one possibility to investigate is a cell selection algorithm to enable multiple objective functions to be constructed and optimised involving such design issues as: handover minimization, load balancing, system capacity maximisation and energy efficiency.

7.4 Heterogeneous Networks

Apart from femtocells, there are other technologies such pico-cells, *distributed antenna system* (DAS) [128] [129] and cooperative relay nodes [130] which are also widely investigated technologies for enhancing the cellular network coverage and performance. However, most of the solutions consider these technologies individually alongside the macrocell system. All these together can form a truly heterogeneous network and there are number of research challenges to be addressed. When multiple access points are available for an MS to connect, an efficient access point selection algorithm is needed which will optimize certain performance metrics such as the number of handovers, the required bandwidth to achieve a certain QoS, energy consumption and scheduling delays. A modified or enhanced version of *Cooperative Multi-Point Transmission* (CoMP) [131] may also represent a suitable alternative for these particular scenarios.

7.5 Self-organising Femtocell Networks (SOFN)

The main idea behind *self-organizing femtocell networks* (SOFN) is that they are capable of managing their operation autonomously without human intervention. SOFN typically exhibit particular characteristics such as, being adaptive and reconfigurable to dynamic network conditions and self maintaining so faults can be repaired and alleviated. They also optimise coverage to coexist with their neighbours, undertake load balancing to guarantee certain performance criterion and fairness, ensure robustness against FAP failures and self-management of disputes with neighbouring femto and macrocells.

At increasing FAP deployments, network management becomes more complex and expensive. A viable solution for reducing both the capital and operating expenditure is to integrate self-organizing functionalities into the network management. Research to date has been preoccupied with strategies and solutions to specific SOFN design issues, with the corollary being that for instance, new load balancing implementations are concomitantly developed without reflecting on for instance, the self-healing functionality of the solution. There is a clear synergy between these seemingly different SOFN features as they either implicitly or explicitly impact upon each other. In order to truly exploit the self-organizing capability of these networks, a more holistic approach to SOFN design is necessary which takes cognisance of the panoply of features rather than focusing on particular network metrics in isolation.

7.6 Interference Alignment and Cancellation

Interference alignment is a promising technique for interference free communicating over multiuser interference channels. In this technique, cooperating transmitters jointly design the transmission signal in a way so that it is aligned in one dimension at all the non intended receivers and in the other dimension at the intended receiver. Aligning interference for multiple non-intended receivers is the major design challenge for this practical application. In femtocell networks, backhaul networks can be used for information sharing among the interfering femtocells. A detailed investigation is necessary however, to achieve significant interference reduction and throughput enhancements by applying an interference alignment technique in the femtocell networks.

7.7 Communication Hub for Smart Home and Smart Grid

A smart home has been somewhat prosaically defined as *"a dwelling incorporating a communications network that connects the key electrical appliances and services, and allows them to be remotely controlled, monitored or accessed"* [132]. FAP technology may afford an effective communications hub for a smart home where it can form an *ad hoc* network for the home appliances and act as a *de facto* clusterhead. To facilitate remote control of the network, the FAP can integrate the system with any external networks.

For smart grid communications, FAP technology represents a promising solution for developing *home area network* (HAN) and *neighbouring area network* (NAN) which collects data from household devices that consumes energy. If the data volume of this application is very high, then it may require significant bandwidth or communication time which may hinder the voice and internet activity of the FAP and its user. This means careful investigation is necessary for proper management of multiple functionalities in this emerging application domain.

8 Conclusion

The emerging technology of cognitive femtocell networks is changing the accepted paradigm in both vision and concept of cellular networks from the well-planned single-tier arrangement, to a multi-tier system comprising a mixture of both planned and arbitrarily deployed nodes. This offers a multi-fold data rate increase for indoor radio environments and fulfils the dream of high speed wireless and mobile broadband services which is able to fully support multimedia steaming, online gaming and other data intensive applications. This potential for significant data rate growth however, can be severely diminished by the dual challenges of cross and co-tier interference, which need to be very carefully managed. This means new dynamic resource management techniques are of prime importance if cognitive femtocell networks are to successfully achieve their goals.

This thesis has focused upon a dual-tier cellular system, where the femtocell network has been overlaid onto the macrocell network and so shares a common bandwidth with the macrocells. This dual-tier arrangement provides a substantial increase in system capacity, if as anticipated, the density of deployed low-powered nodes expands in *next generation* networks, with most importantly, higher capacity being available for indoor radio environments from where most future data demand is envisaged. The dual or multi-tier system means the traditional radio resource management techniques and architectures which have been used in cellular networks are either not applicable or operate inefficiently for this new scenario.

The dual-tier model developed in this thesis wherever possible, faithfully followed the 3GPP LTE standard. Since the femto-tier is a composition of unplanned deployments, uniform random distribution of both FAP and MS has been assumed. The femto-tier composition and performance however, varied considerably depending upon the density, distribution and location of the BS, FAP and MS, so equitably comparing and validating results with alternative solutions was challenging. To achieve an accurate estimation, theoretical modelling of the system is necessary and as most system parameter settings were specified in the LTE standard, the corresponding 3GPP LTE performance boundaries were adopted for validation purposes in evaluating the results and verifying the performance of the proposed system under various test scenarios.

New architectures and algorithms have been presented for managing radio resources in dual-tier, joint macro-femto deployments, with particular emphasis upon intra and cross-tier interference awareness. After initially providing a detailed review of the state-of-the-art in joint macro-femto network research, the spectrum sharing relationship between the macro and femto tiers has been rigorously investigated. Special emphasis has been given to maintaining, wherever possible, existing macro cellular resource management designs, while at the same time creating new opportunities for the femto-tier to access the same resources by exploiting these designs in the spatio-temporal domain.

The most significant of the contributions made is the *Generalised Virtual Clustering Framework* (GVCF) presented in Chapter 5 for managing cross and co-tier interference in a joint macro-femtocell deployment arrangement. Since co-tier interference mainly occurs because of random node deployment, a novel resource management model was developed as existing designs for managing planned cellular networks were not suitable.

The original virtual clustering architecture was proposed in Chapter 4 for managing resources in femtocell networks by introducing the concept of logically grouping together FAPs, with each group operating on the same frequency. Group membership is allocated based on firstly maintaining a prescribed safety distance threshold (at which the level of interference is deemed acceptable) and then maximizing the minimum distance between the cluster members. This ensures co-tier interference is always minimised. The initial *virtual clustering formation* (VCF) algorithm was developed for only a fixed set-up of radio resource availability before being subsequently generalised to afford enhanced flexibility and robustness in the GVCF architecture

Based upon a rigorous analysis of the GVCF model, especially in highly dense FAP scenarios, a formal framework has been developed which not only has the capability to flexibly manage interference under dynamic resource conditions, but also consistently provides superior performance across the range of FAP densities.

In a related contribution, the GVCF paradigm has been further enhanced by analysing FAP coverage range expansion as a strategy for combating excessive cross-tier handovers. Since FAP coverage is usually very low, there always exists the potential danger of an increased number of handovers occurring between tiers with correspondingly sudden load imbalances in the macrocells. To minimise these occurrences, the impact of FAP coverage range has been rigorously analysed. By gradually expanded the FAP coverage, the resulting effect upon overall system capacity and performance has been evaluated. Following extensive simulations, a look up table (LUT) approach has been implemented for the GVCF framework which enables the model to adaptively choose the best possible coverage range for both a particular FAP deployment density and a given set of resource constraints including: the number of clusters, the required minimum SINR and the average throughput.

In dense femtocell deployments, co-tier interference is the dominant source of interference. However, cross-tier interference remains a significant bottleneck. As the macro-tier is deployed after rigorous planning, the resource allocation for the macro-tier needs to remain as intact as possible. To ensure this, a new dynamic *fractional frequency reuse* (FFR) hybrid resource management scheme has been introduced. It minimises both cross and co-tier interference in low-to-moderate density FAP deployments.

A hybrid resource management architecture was developed to cope with new radio environments which consist of well-planned macrocell systems overlaid by randomly deployed FAP. A novel technique has been devised for sharing spectrum between the macro and femto tiers with dynamic updating between the tiers being realised to avoid any cross-tier interference. A femto-tier spectrum management technique has also been developed and tested to enable each FAP to maintain a neighbouring interferer list alongside their spectrum allocation so a FAP can independently allocate channels to its users in a distributed fashion. A dispute mechanism has been included to locally manage dispute amongst femtocells, and if this fails to resolve a dispute, then the additional assistance of the RNC is sought. An extensive evaluation has been undertaken which proved this new dynamic FFR-based approach significantly mitigated both cross and co-tier interference.

In summarising, this thesis has presented four original contributions to the field of radio resource management in cognitive and *next generation* networks, with the formal development of a generalised virtual clustering femtocell framework for cross and co-tier interference aware resource management. The system architecture is flexible and adaptive to network environment changes and has been rigorously analysed to ensure successful robust management of joint macro-femtocell deployments when sharing the same spectrum.

Appendix A: Received SINR and SE Performance of GVCF Algorithm

The following set of figures represent the SINR and SE performances of the GVCF paradigm and corresponding non-clustered system (NCS) for the FAP densities of 100 and 150 in the given area of *200m* squared.

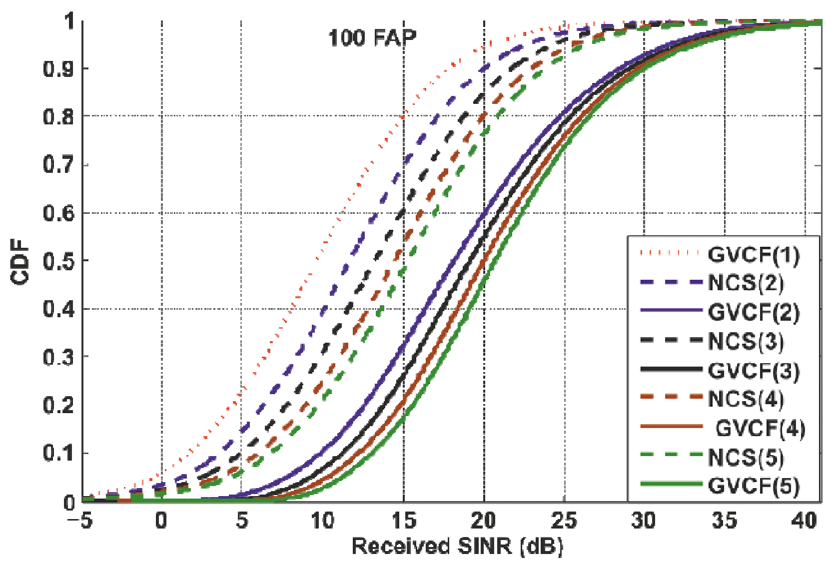


Figure A.1: CDF of received SINR with 100 FAP deployed

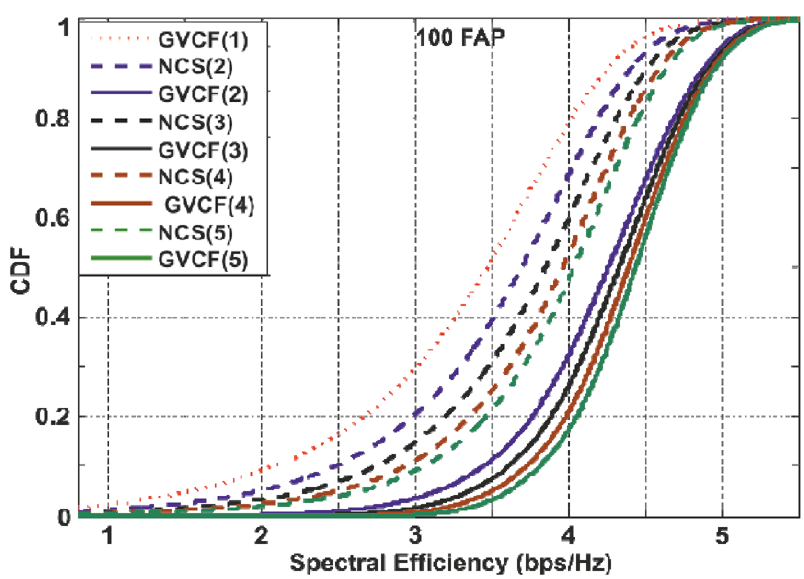


Figure A.2: CDF of received SE with 100 FAP deployed

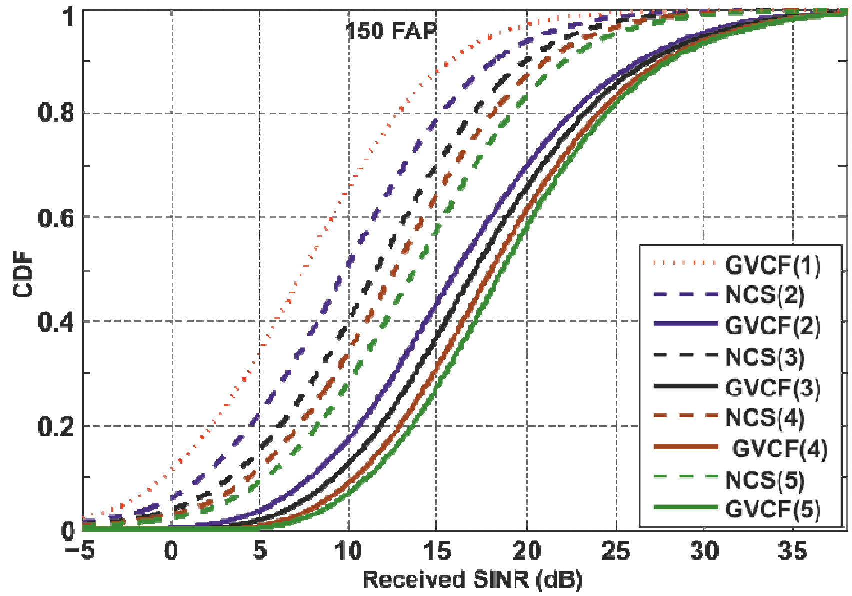


Figure A.3: CDF of received SINR with 150 FAP deployed

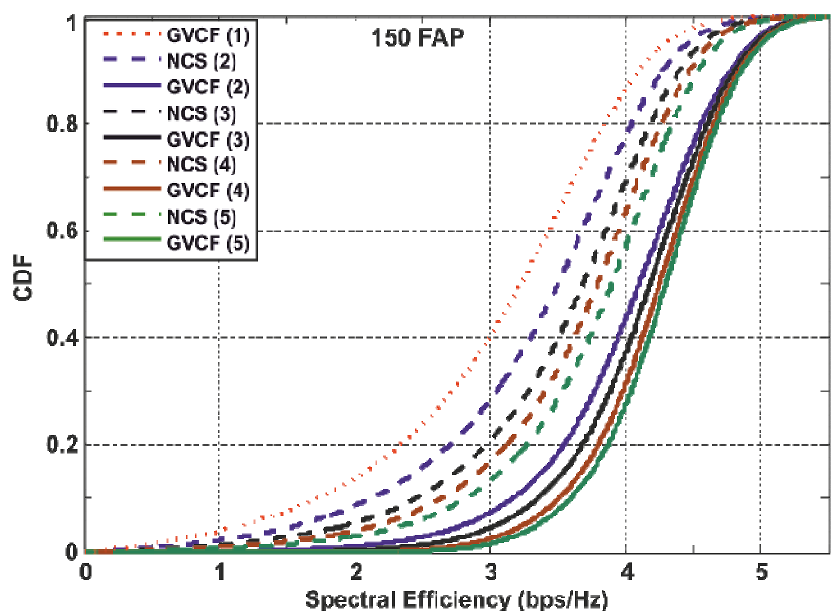


Figure A.4: CDF of received SE with 150 FAP deployed

Appendix B: Received SINR and SE Performance of GVCF Algorithm

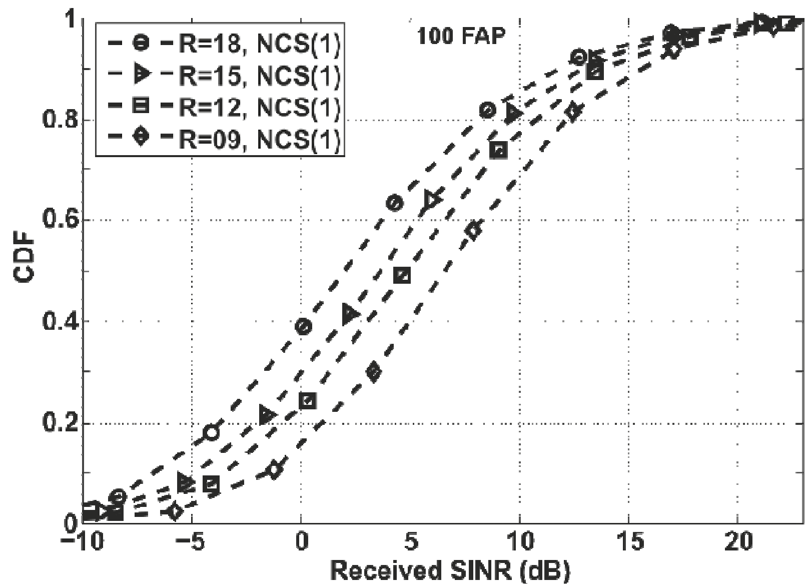


Figure B.1: Received SINR performance of NCS with 100 FAP deployed and using the same channels sets.

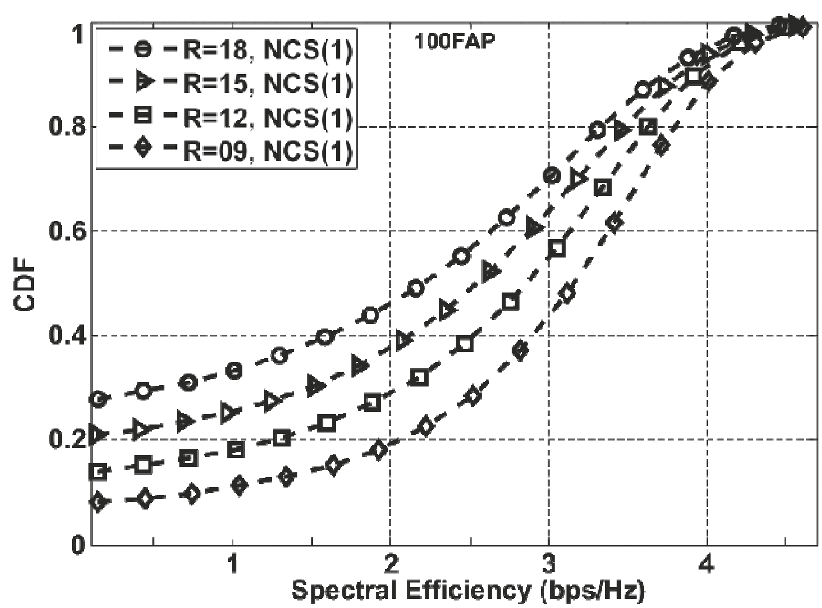


Figure B.2: Received SE performance of NCS with 100 FAP deployed and using the same channels sets.

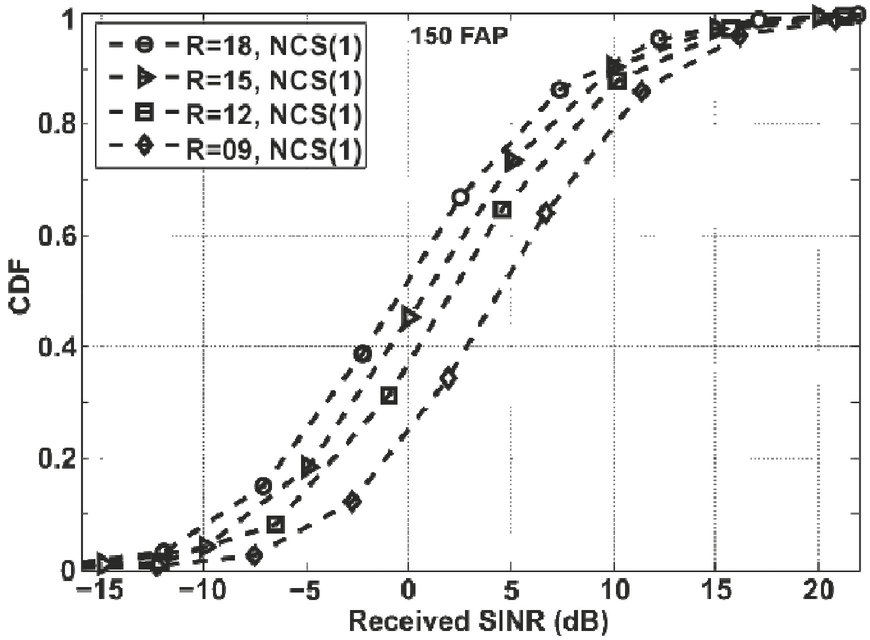


Figure B.3: Received SINR performance of NCS with 150 FAP deployed and using the same channels sets.

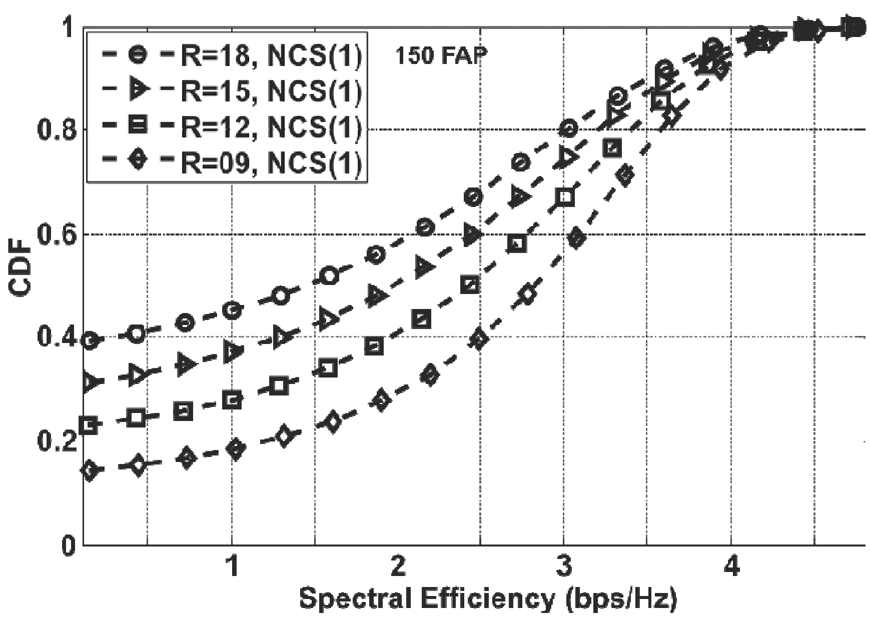


Figure B.4: Received SE performance of NCS with 150 FAP deployed and using the same channels sets.

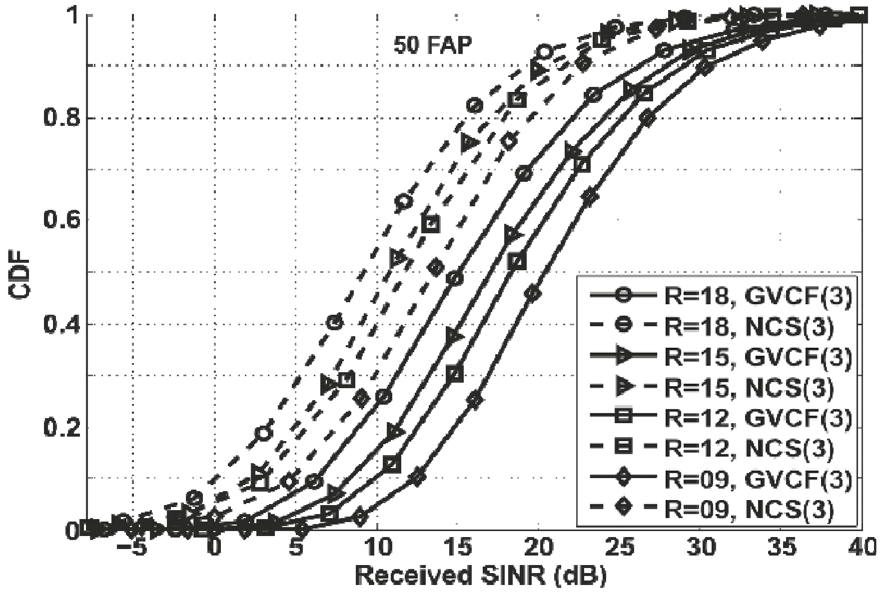


Figure B.5: Received SINR performance comparison for GVCF and NCS with 50 FAP deployed when VCC=3 (equivalent channel sets for NCS)

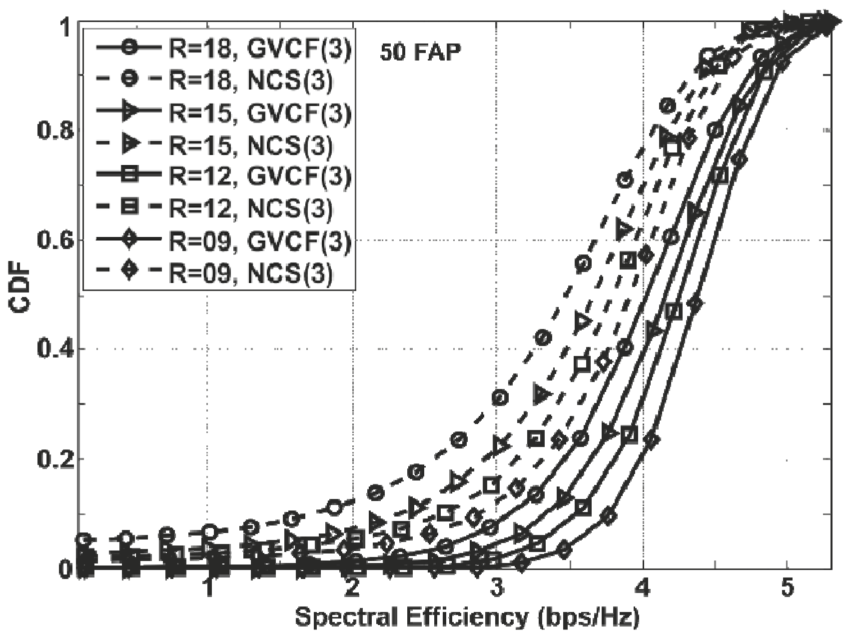


Figure B.6: Received SE performance comparison for GVCF and NCS with 50 FAP deployed when VCC=3 (equivalent channel sets for NCS)

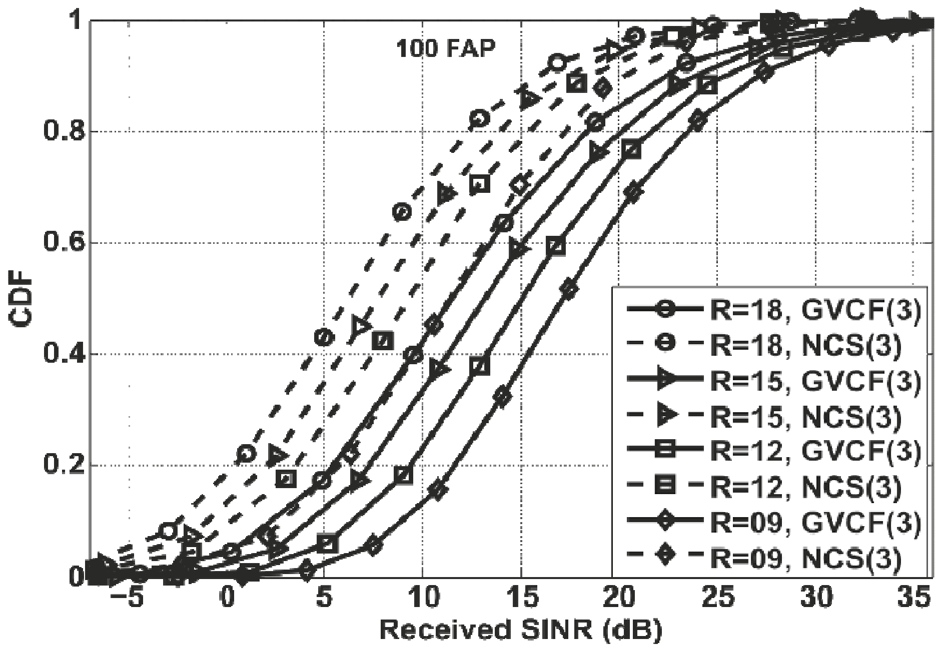


Figure B.7: Received SINR performance comparison for GVCF and NCS with 100 FAP deployed when VCC=3 (equivalent channel sets for NCS)

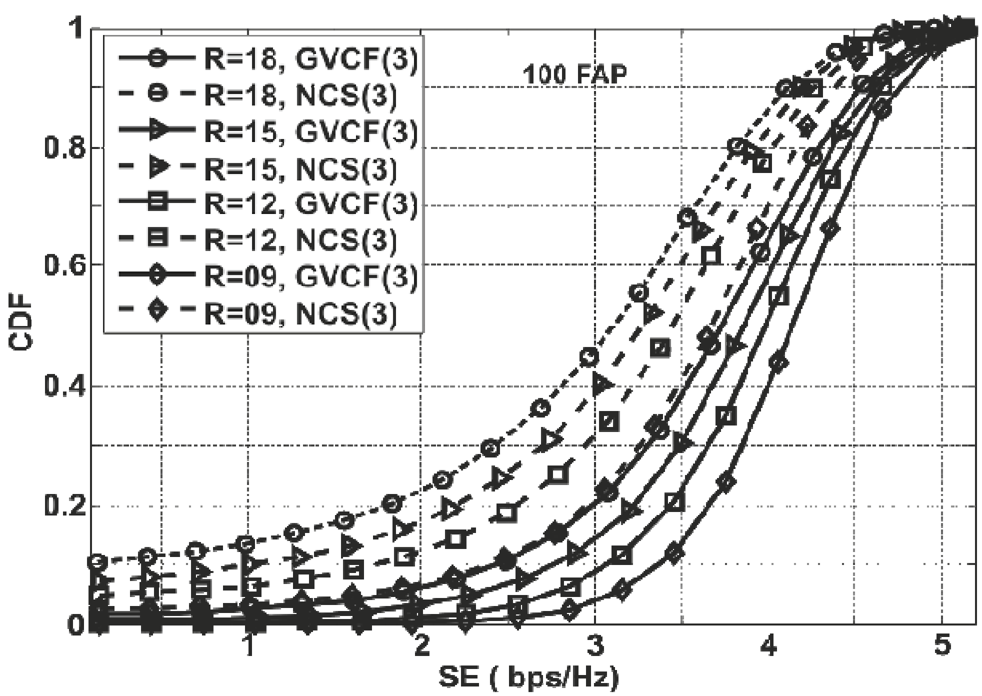


Figure B.8: Received SE performance comparison for GVCF and NCS with 100 FAP deployed when VCC=3 (equivalent channel sets for NCS)

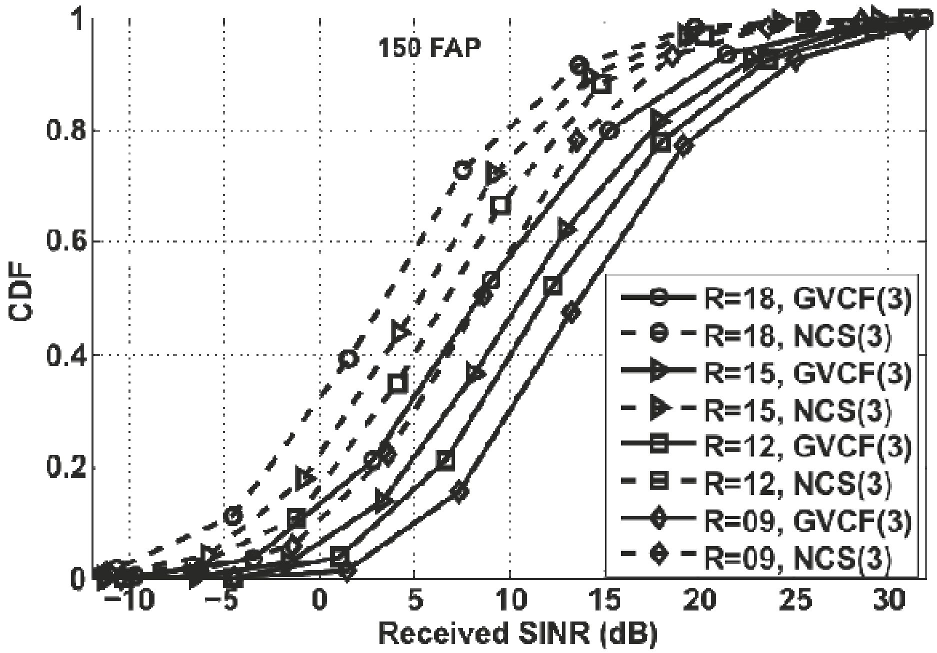


Figure B.9: Received SINR performance comparison for GVCF and NCS with 150 FAP deployed when VCC=3 (equivalent channel sets for NCS)

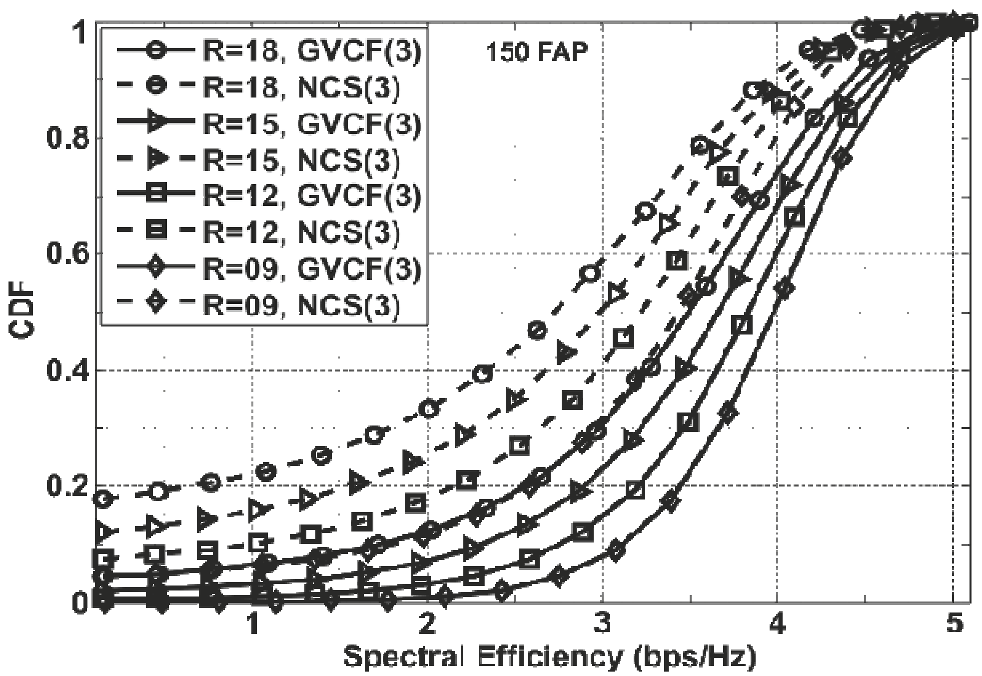


Figure B.10: Received SE performance comparison for GVCF and NCS with 150 FAP deployed when VCC=3 (equivalent channel sets for NCS)

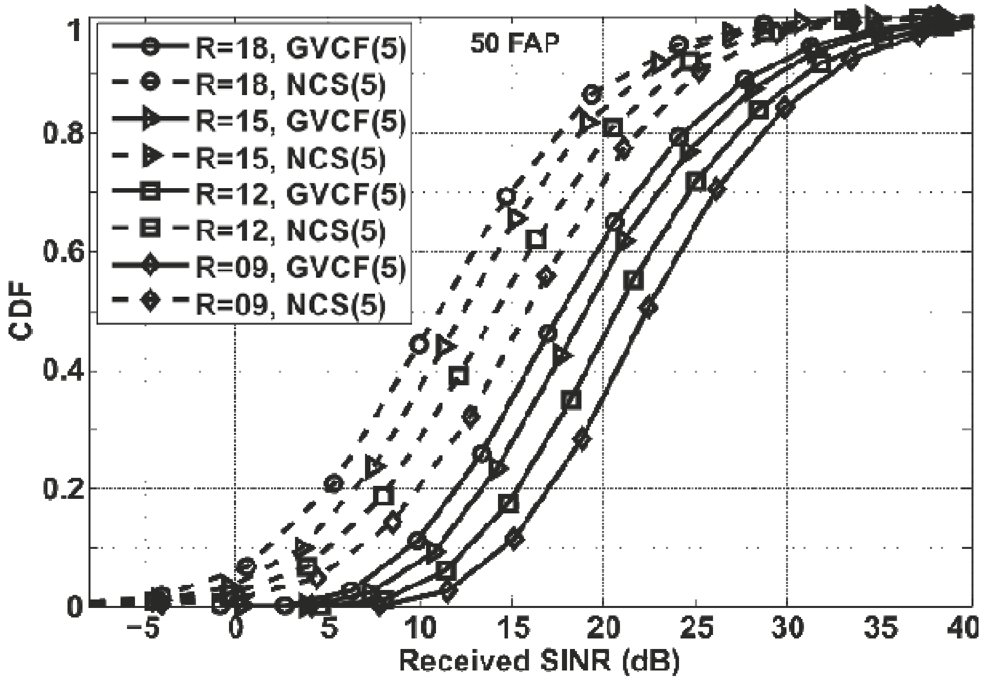


Figure B.11: Received SINR performance comparison for GVCF and NCS with 50 FAP deployed when VCC=5 (equivalent channel sets for NCS)

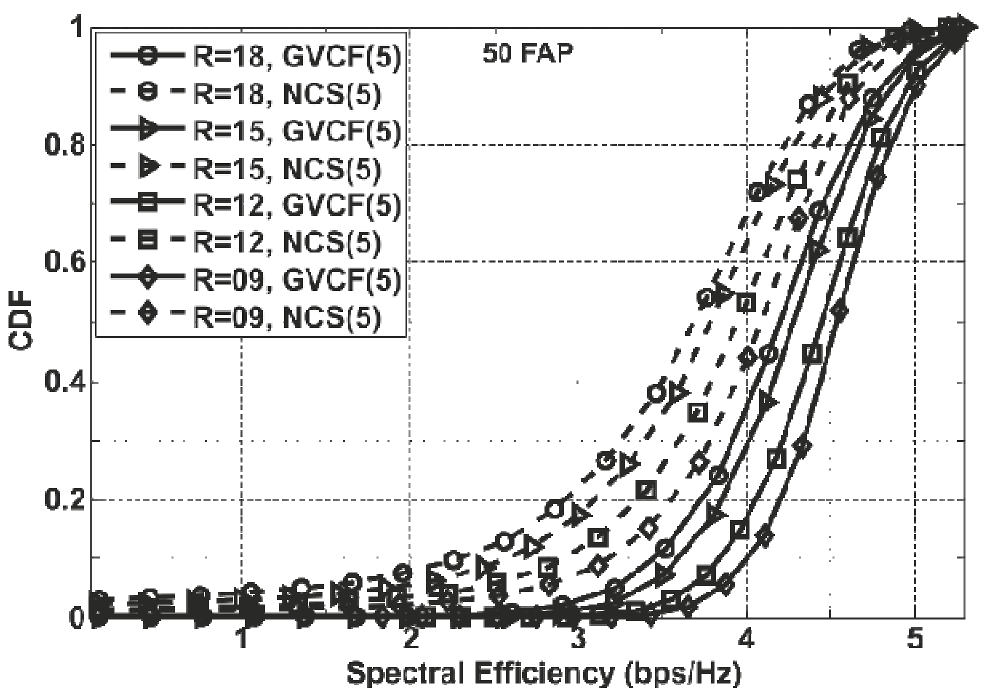


Figure B.12: Received SE performance comparison for GVCF and NCS with 50 FAP deployed when VCC=5 (equivalent channel sets for NCS)

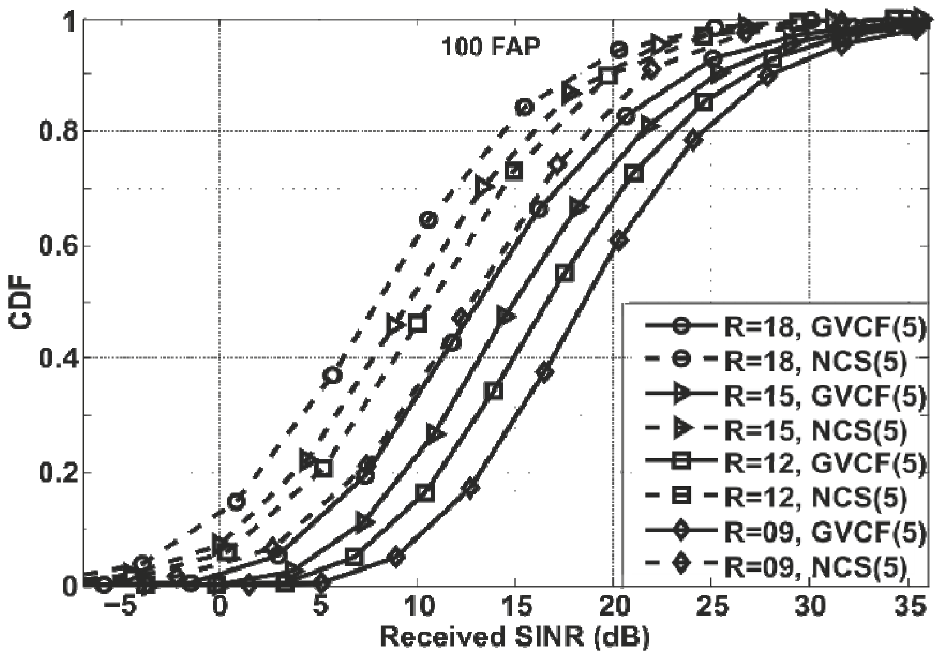


Figure B.13: Received SINR performance comparison for GVCF and NCS with 100 FAP deployed when VCC=5 (equivalent channel sets for NCS)

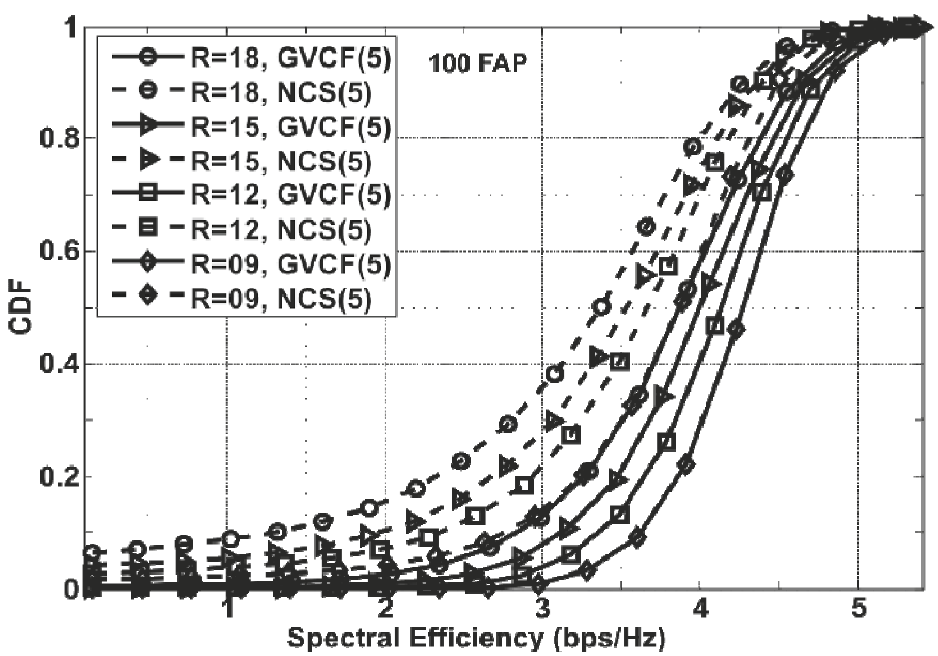


Figure B.14: Received SE performance comparison for GVCF and NCS with 100 FAP deployed when VCC=5 (equivalent channel sets for NCS)

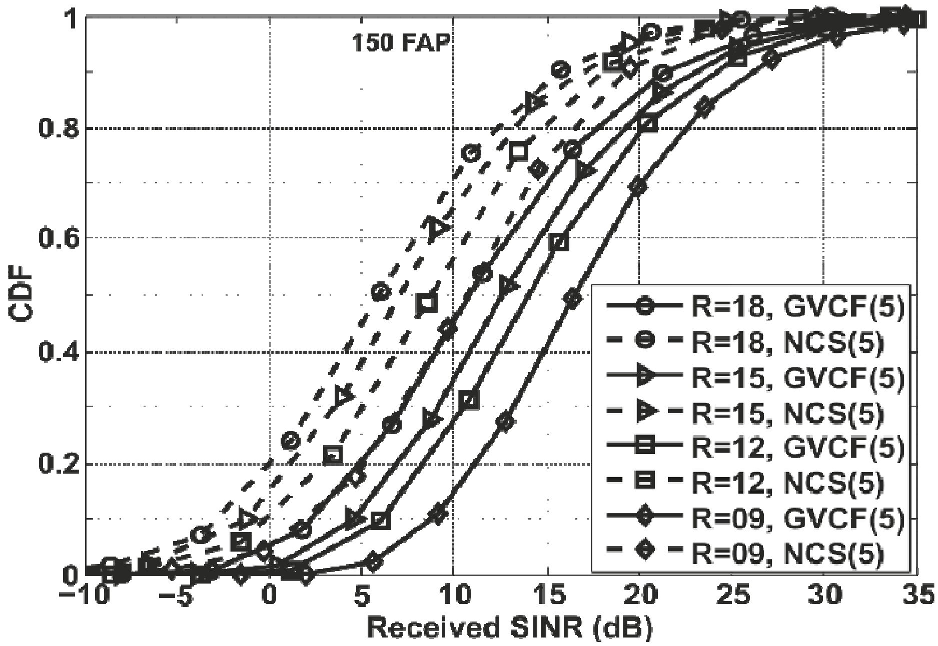


Figure B.15: Received SINR performance comparison for GVCF and NCS with 150 FAP deployed when VCC=5 (equivalent channel sets for NCS)

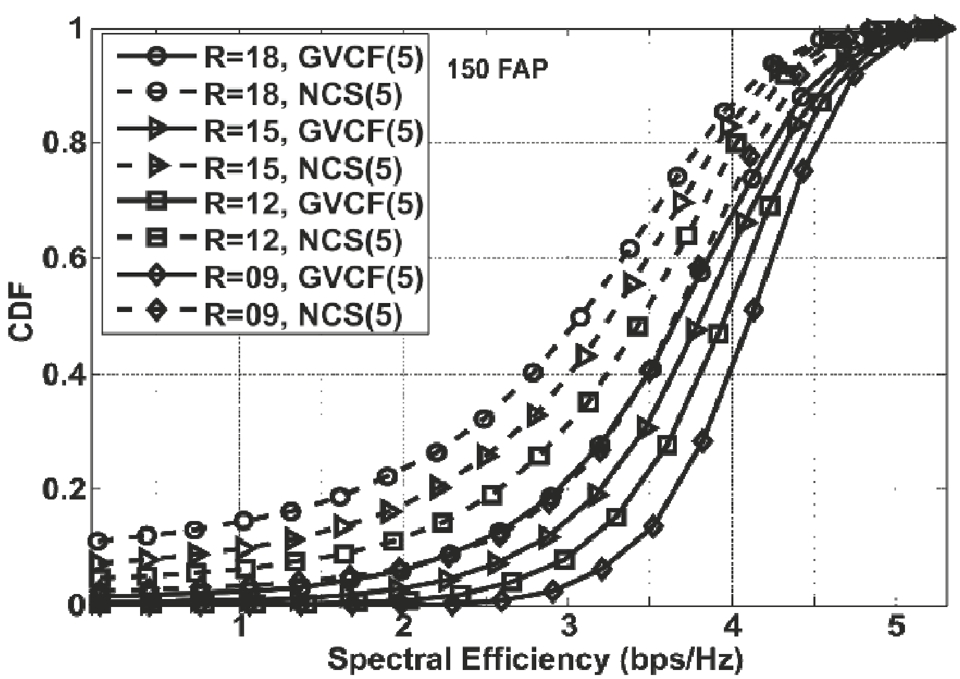


Figure B.16: Received SE performance comparison for GVCF and NCS with 150 FAP deployed when VCC=5 (equivalent channel sets for NCS)

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