Interference Management in Femtocell Networks and Capacity Maximization

By

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Approval

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Dedication

I dedicate this thesis to my parents and teachers.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

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Acknowledgment

This thesis is a milestone in my academic carrier. Extensive research has increased my knowledge in learning theories and concepts. I am grateful to Almighty Allah who gave me strength and support throughout the research work. It would not have been possible without His blessings.

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Syed Waqar Hasan

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List of Abbreviations

Abbreveation	**Description**
FBS	Femtocell Base Station
MBS	Macrocell Base Station
FUE	Femtocell User Equipment
MUE	Macrocell User Equipment
CCI	Co-Channel Interference
SINR	Signal-to-Interference Plus Noise Ratio
MCS	Modulation and Coding Scheme
ARUP	Annual Revenue per Unit
FAP	Femtocell Access Point
OFDMA	Orthogonal Frequency Division Multiple Access
FFT	Fast Fourier Transform

Abstract

Interference management is the biggest issue in successful deployment of femtocell networks. Efficient interference management scheme is required to minimize the effect of interference and to enhance network capacity. In this thesis, we have proposed a fuzzy logic-based dynamic subchannel allocation scheme for densely deployed femtocell networks affected by strong co-tier interference in order to enhance network capacity and manage interference effectively. The channel model includes Rayleigh fading with path loss and the femtocells use OFDMA-based channel access. The reported signal-to-interference plus noise (SINR) values at femtocell base stations are used to form a fuzzy superset, which in turn is utilized to allocate subchannels in an optimal way. The results are compared with the traditional user-oriented and channel-oriented subchannel allocation schemes. The proposed scheme provides almost the same system capacity with better fairness as compared to traditional channel-oriented scheme, while it also outperforms the traditional user-oriented scheme and improves the sum-rate capacity of the femtocell network. We have achieved upto 64% increase in capacity as compared to user-oriented subchannel allocation scheme and upto 22% increase in fairness factor as compared to the channel-oriented subchannel allocation scheme.

Chapter 1

Introduction

The demand for high data rates is increasing rapidly for next generation wireless systems. A study in [1] predicted a 39 fold increase in global wireless data traffic from 2009 to 2014. Because of the emergence of high data rate applications and multimedia services, it has become inevitable for the mobile operators to provide good quality links having higher capacity in modern cellular systems. The use of these highly sophisticated services cannot be restricted to open air only. Instead, for the mobility of modern society and with the independence in communication wherever people go, coverage of confined areas has become a key issue. Most of the 3G and 4G traffic is expected in confined areas where high data rate services cannot be accommodated efficiently because the signal quality is not good in these confined areas. Fig. 1.1 shows the growth of data demand and we can see that high data rate demand is increasingly rapidly.

In an outdoor environment, the provisioning of wireless signals with good signal strength is not a big problem for mobile operators. However, it becomes a challenging task to provide reliable indoor coverage. In an indoor

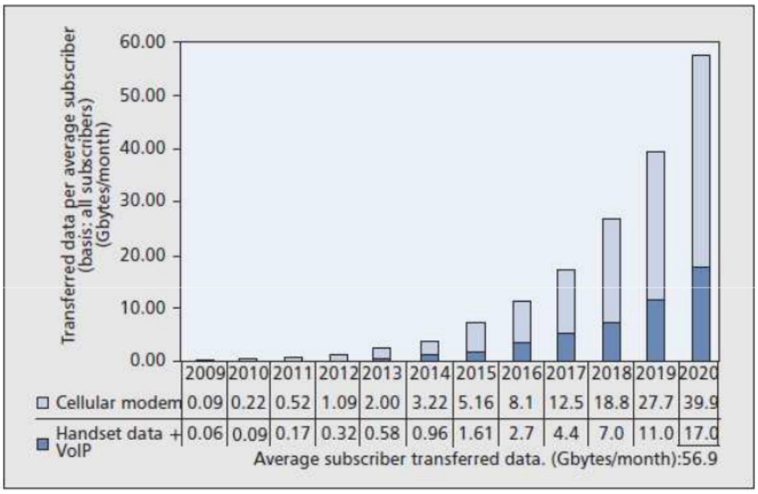

Figure 1.1: Growth of data demand [2]

environment, wireless signals are attenuated by different walls and floors due to which the signal strength is decreased significantly. According to ABI research [3], more than 50% voice calls and 70% percent of data traffic originates from the indoor environment. Another study claims that 45% household and 30% business users experience poor indoor coverage [4].

1.1 Indoor Coverage Problems due to Macrocell Base Station

Outdoor macrocell BTSs are deployed by the network operators to provide indoor and outdoor coverage but this deployment is not sufficient to provide good indoor signal strength and high data rates because this technique has a lot of drawbacks. Some of the drawbacks are mentioned below:

(1) For indoor coverage scenarios, macrocell BTS signals are degraded by free space losses as well as from penetrations in and out from the buildings and the metallic objects inside the building premises.

(2) There are also some issues related to the relative distance between the user and the macro-cell antenna. The users who are present at the far side of the building are at greater distance from the macro antenna and suffer badly from weak signals. They also have to transmit with more power to communicate with the base station which is also a problem.

(3) There are coverage problems at the base of the buildings which have macro antenna placed at the roof of the building because there are not many reflections from the adjacent buildings.

(4) For high traffic regions, large number of base stations are required. The deployment of these base stations has become very challenging for telecom operators due to huge expenses.

(5) Using macrocell BTS to provide services to indoor users for a high capacity network by increasing transmit power is not applicable practically because of large power consumption and interference issues.

(6) In case of a dense cellular network structure, the network planning becomes an important issue while using the macrocell base stations for providing coverage to the user equipment (UE).

(7) Turbo 3G, also known as HSDPA and HSUPA and 4G technologies offer substantially higher data rates. However, these services demand excellent RF-link conditions, which are typically not achieved when using macro cells to reach indoor users.

(8) Higher coding schemes are needed to achieve higher data rates. This requires better channel conditions for HSDPA, WIMAX and LTE, which are only available at windows facing macrocell BTS sites.

(9) Those buildings have usually better coverage which are served by more than one macro antenna. But there is a problem in this case, that whenever a user will connect to more than one base stations and enters in soft handover condition the interference and the load on the network will be increased.

(10) The penetration of signals inside the buildings become a major problem for the mobile networks which operate at 2 GHz or above.

1.2 Femtocell Technology

Recently, femtocell technology has been proposed to overcome the indoor coverage problem where femtocells increase both the coverage and capacity of wireless networks [5]. Femtocells are low-cost and low-powered indoor base stations with the functionality of providing standard mobile devices with an access method to mobile operator's network using the internet. Femtocells are aimed at providing good coverage in and around the immediate home environment for high performance voice and data communication. Femtocells have the potential to make indoor coverage for mobile communication truly persistent.

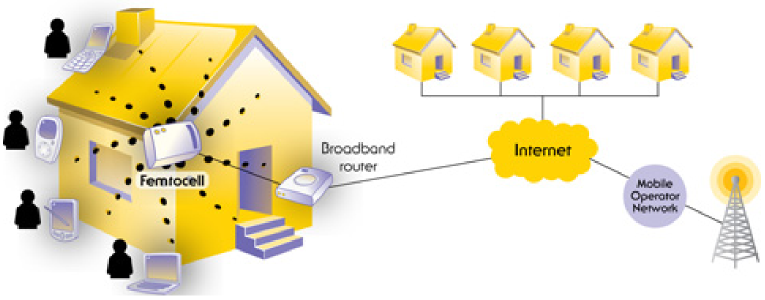

Figure 1.2: Deployment of femtocells inside buildings [6]

The operators are provided with complete indoor coverage solution by the implementation of femtocell network architecture. A femtocell is an easy to install base station that can be integrated into existing mobile networks. It starts providing efficient services within minutes of switching it on. Such platforms enable the operator to initiate new applications and generate new revenue opportunities. With the use of femtocells, operators are provided with the means to compete in the home market, increasing minutes of use and annual revenue per unit (ARUP) in the fixed mobile convergence market. Fig. 1.3, indicates the growth in femtocell deployment and its popularity amongst mobile users.

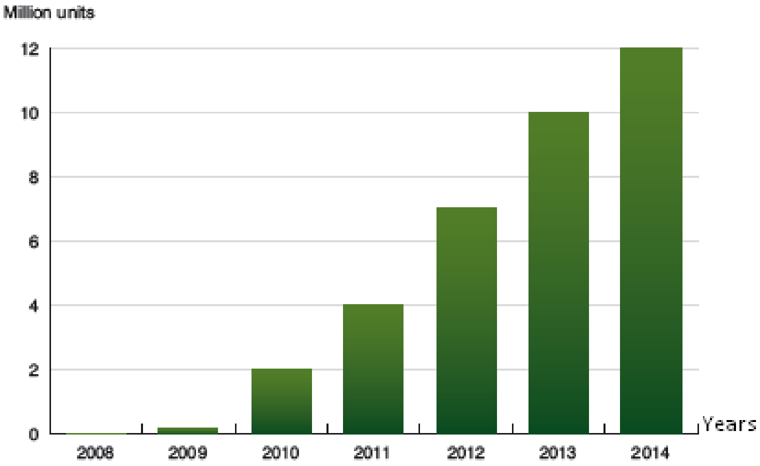

Figure 1.3: Annual shipment of femtocells, million units (Worldwide 2008-2014) [7]

1.3 Access Methods for Femtocells

Femtocells are user deployed devices. It depends on the user either he wants to utilize the femtocell resources personally by allowing some legitimate home users or he wants to share his femtocell resources with everyone in range of femtocell access point (FAP) to obtain better indoor coverage and high data rates. That is why there are two access methods available for connectivity with femtocells.

(1) Open Access

(2) Closed Access

1.3.1 Open Access

Open access is also referred as public access. In open access femtocells, every mobile station (MS) in the range of femtocell access point can make use of the femtocell resources. This access method is not likely to be adopted by the user who deployed femtocell because he is paying for the power consumption and internet connectivity charges but someone else from outside is making use of his resources.

1.3.2 Closed Access

Closed access is also referred as private access. In closed access femtocells, only some legitimate users can make use of the femtocell resources for improvement of wireless coverage and enhancement of data rates. All the other users are not allowed to connect with the femtocell access point (FAP). This access method gives rise to severe interference issues.

1.3.3 Choice Depending on the Scenarios

The subscriber who is using the femtocell services pays for the femtocell device as well as the charges for the broadband internet connection which is used to connect the user to the mobile network operator. This is the main problem which indicates the importance of access methods.

According to a survey, most people have shown their intention to use private access femtocells by restricting the users to use their femtocell facility and allowing only specific users to connect to the mobile network through their femtocell. This is because they are paying for the facility and they do not want all the people to use the facilities of femtocells in free.

In some scenarios where interference is the major problem, public access femtocells is the better choice for deployment. This is because in private access femtocells, there are a lot of interference issues which can affect the performance of the femtocell as only restricted users are allowed to use the femtocell services and the others are blocked.

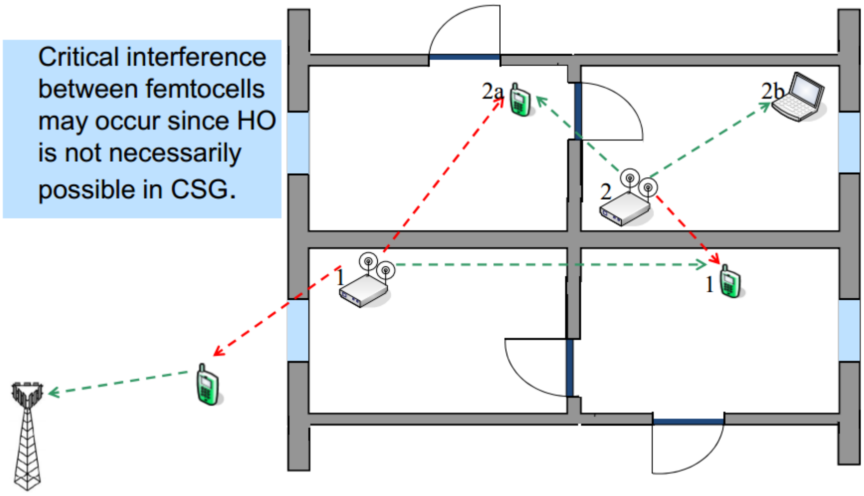

Figure 1.4: Interference scenarios due to closed access femtocells [6]

1.4 Advantages of Femtocells

The major advantage of a femtocell is the improvement in cellular coverage inside the building or some other places where the coverage is not much satisfactory. Some other advantages are mentioned below:

(1) There will be a reduction in the call charges if a user opts to use femtocell in his home, as it directly connects to the core network through the internet.

(2) To achieve utmost functionality, some vendors are also planning to bundle up all the three features WIFI, cellular and DSL in the same box/device.

(3) The femtocells will encrypt the voice calls processed through them and there will be an automatic switching process i.e. handover used by the femtocell, if a cell phone is detected in its range e.g. in homes.

(4) Femtocell units can handle up to 5 or 6 simultaneous calls (depends on the design), from the same operator. Also they can operate with conventional mobile handsets, without any technological enhancements.

(5) Femtocell units can boost up the use of cellular services like 3G and 4G as they provide better speed and data rates inside the buildings, where in general, the coverage is poor than outside.

(6) Generally, the cell towers are back-hauled by lines with bandwidth of around 2 Mbps, which may not be sufficient for 3G and 4G type services and hence will require an up gradation. But as subscribers internet connection is used in the case of femtocells, for that reason up gradation will not be an issue if femtocells are deployed at large scale.

(7) In a long term planning prospective, femtocells can also become the primary network if installed in a convenient manner. As a result, all the future upgrades can be done by the femtocells itself. Thus reducing the number of macro base stations required to cover an area.

1.5 Disadvantages of Femtocells

Some disadvantages of femtocells are mentioned below:

(1) Some internet service providers charge on the basis of the bandwidth consumed. So it will not be a convenient method as the user has to pay the additional charges.

(2) There are issues related to the access methodologies regarding femtocells i.e. either the access will be private or public which means that the neighboring subscribers may or may not be allowed to connect to them.

(3) All broadband packages cannot support the femtocells as they require minimum of 500 kbps to operate at their full capacity.

(4) As femtocells will use the internet connection for the purpose of calling and data transfer, there might be reduction in the call quality if large data files are being downloaded from the internet at the same time.

(5) Positioning of a femtocell within a building is also a very critical issue and is a major concern for the service providers.

1.6 Issues Related to Femtocell Technology

Femtocell technology is a very promising technology for mobile operators in order to increase the coverage and capacity of mobile network but there are some issues related to this technology. These issues are mentioned below:

(1) Frequent handovers

(2) Channel allocation

(3) Power control

(4) Placement of femtocells inside the building

(5) Access methods

(6) Stable internet connection

(7) Interference management

1.6.1 Frequent Handovers

Femtocells are deployed on an overlaid macrocellular layer. In case of open access, there are many handover issues generated due to deployment of femtocells. Inside the building, users are connected to femtocells however when a user moves outside the building it will be connected to macro base station. Due to frequent mobility of users, efficient handover algorithms are required to reduce the probability of call dropping. Similarly, if a user connected to macro BS passes by a building in which femtocell is deployed frequent handover from macro BS to femtocell BS will be required. These handovers create extra burden on the network.

1.6.2 Channel Allocation

Efficient channel allocation is required for the successful deployment of femtocells. Femtocells work in licensed spectrum provided to the network operator. If separate channel bands are allocated to macrocell BS and femtocell

BS, then spectral efficiency will be compromised. In case of co-channel deployment, spectrum efficiency will not be compromised but it will create interference issues.

1.6.3 Power Control

In case of closed access femtocell deployment, efficient power control techniques are required to minimize interference issues. If femtocell transmit power is high, it can effect the communication of any mobile user connected to macro BS because femtocell signals will act as an interference in case of co-channel deployment. Efficient power control algorithms are required so that femtocells will transmit data on minimum power keeping in view the rate requirements of the users.

1.6.4 Placement of Femtocells Inside the Building

Femtocells are plug and play devices which are deployed by users inside the buildings. There is random deployment of femtocells due to which the prediction of interference becomes a major issue. Research is required on the efficient placement of femtocells inside the buildings to minimize interference and maximizing indoor coverage.

1.6.5 Access Methods

Access methods for femtocells is another dilemma faced by mobile operators in successful deployment of femtocells. In case of open-access, interference issues are minimized but the users do not want to deploy femtocells in open access mode because the resources of user will be used by any other subscriber which is not a legitimate user. In case of closed-access, only legitimate users will be able to utilize the services of a specific femtocell BS but it will create severe interference issues.

1.6.6 Stable Internet Connection

Femtocells connect the user to the mobile operator by using internet. Stable internet connection is required for successful transfer of data without any delays. If the internet connection is not stable then it can cause disruption in voice calls and data transfer. Efficient protocols are required to prioritize the femtocell traffic so that the quality of service should not degrade during file downloads etc.

1.6.7 Interference Management

The biggest issue in the successful deployment of femtocells is interference management. Femtocell uses the licensed spectrum allocated to the mobile operator due to which careful resource allocation is required for interference management keeping in view the spectral efficiency. Efficient interference management techniques are required so that the users will not go in outage and maximum capacity can be achieved.

1.7 Research Gap and Problem Statement

A lot of research has been done in recent past on interference management techniques for femtocell networks. These techniques include power control, reverse frequency allocation, double frequency reuse and subchannel allocation. Usually subchannel allocation schemes are either user-oriented or channel-oriented. User-oriented schemes favor the users in selecting subchannels and provide good fairness. However, these schemes compromise the overall network capacity. Channel-oriented subchannel allocation schemes give preference to channels in order to select the user for which it can attain maximum data rate. These schemes provide very good network capacity but the fairness factor is compromised. There is a need to propose such subchannel allocation scheme which can provide better network capacity without compromising on fairness factor. In this thesis we have tried to overcome this problem and we have proposed a fuzzy logic-based dynamic subchannel allocation scheme for densely deployed femtocell networks affected by strong co-tier interference such that network capacity is enhanced without compromising on fairness factor.

1.7.1 Problem Statement

“Severe interference issues are caused due to co-channel deployment of femtocells over an already laid macrocell network. These interference issues degrade the overall network capacity and users face outage problems.”

1.8 Thesis Contribution

The contribution of our thesis is that we have developed an efficient interference management scheme for subchannel allocation in femtocell networks by using the concept of fuzzy logic. Our scheme outperforms the traditional user-oriented and channel-oriented subchannel allocation schemes and provides very good network capacity without compromising on fairness. The channel model includes Rayleigh fading with path loss and the femtocells use OFDMA-based channel access. The reported signal-to-interference plus noise (SINR) values at femtocell base stations are used to form a fuzzy superset, which in turn is utilized to allocate subchannels in an optimal way. Some of the major contributions of this thesis are mentioned below:

(1) We have achieved upto 64 % increase in capacity as compared to user-oriented subchannel allocation scheme.

(2) We have achieved upto 22 % increase in fairness factor as compared to the channel-oriented subchannel allocation scheme.

(3) It is shown that the performance of our proposed subchannel allocation scheme improves in dense femtocell deployment scenarios.

(4) We have suggested the number of subchannels required to attain specific data rate in dense deployment scenarios.

1.9 Thesis Organization

The rest of the thesis is organized as follows.

1.9.1 Chapter 2

In chapter 2, different interference scenarios are discussed which are caused due to deployment of femocells on already laid macrocell network.

1.9.2 Chapter 3

Chapter 3 describes the background and literature review. In this chapter, different techniques which are used by researchers for interference management in femtocell networks are discussed. Comprehensive analysis of each scheme has been done and the weaknesses have been pointed out.

1.9.3 Chapter 4

In chapter 4, network architecture which is used to implement the proposed scheme is described in details. Mathematical models which are used in the implementation of proposed scheme have been discussed.

1.9.4 Chapter 5

The proposed fuzzy logic based subchannel allocation scheme is described in chapter 5. A step by step process for allocation of subchannels is described in detail in this chapter. This chapter also contains the algorithm developed for the proposed scheme.

1.9.5 Chapter 6

Simulation results are shown in chapter 6 and performance analysis of the proposed scheme has been done with reference to user-oriented and channel-oriented subchannel allocation schemes.

1.9.6 Chapter 7

Chapter 7 contains the conclusion and the proposed future work.

Chapter 2

Interference Issues due to Femtocell Deployment

2.1 Introduction

The biggest issue in the successful deployment of femtocells is interference management. Femtocell uses the licensed spectrum allocated to the mobile operator due to which careful resource allocation is required for interference avoidance keeping in view the spectral efficiency. There can by femtocell-to-femtocell interference issues as well as femtocell-to-macrocell interference issues. These interference issues can be divided into two categories.

(1) Co-tier Interference

(2) Cross-tier Interference

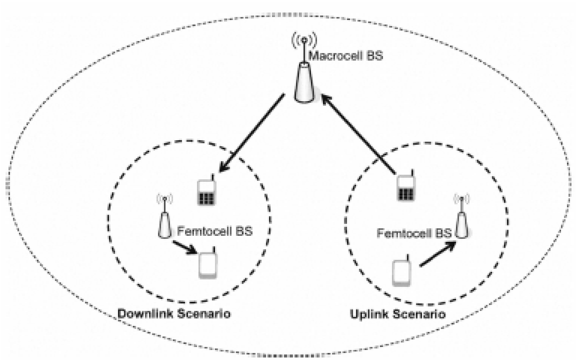

Figure 2.1: Interference scenarios in femtocell networks [8]

2.2 Co-tier Interference

It is the type of interference which occurs between the network elements which belong to the same tier in the network hierarchy. In our case co-tier interference can occur between different femtocell base stations (FBSs) and femtocell mobile station (FMS). The uplink transmission of the femtocell mobile station (FMS) can become the source of interference for the neighboring femtocell base stations (FBSs). Similarly the downlink transmission of femtocell base station (FBS) can become the source of interference for the femtocell mobile stations (FMSs) connected to another FBS. However in case of OFDMA-based femtocells, this type of co-tier interference can only occur when the aggressor (source of interference) and the victim use the same sub-channels. Co-tier interference affects the transmission in both uplink and downlink directions.

2.3 Cross-tier Interference

It is the type of Interference which occurs between the network elements which belong to different tiers in network hierarchy. In our case this is the interference which involves both macrocell and femtocell. The downlink transmission of femtocell base station can be a source of interference for the mobile station which is connected to the macro cell. Similarly the uplink of mobile station connected to the macro cell can become a severe source of interference for the nearby femtocell base station.

2.4 Interference Scenarios

Table 2.1 below shows different interference scenarios caused by the deployment of femtocell network.

Table 2.1: Interference Types in OFDMA Femtocell Networks

Sr. No	Aggressor	Victim	Interference Type	Transmissioin Mode
1	Macrocell UE	Femtocell BS	Cross-tier	Uplink
2	Macrocell BS	Femtocell UE	Cross-tier	Downlink
3	Femtocell UE	Macrocell BS	Cross-tier	Uplink
4	Femtocell BS	Macrocell UE	Cross-tier	Downlink
5	Femtocell UE	Femtocell BS	Co-tier	Uplink
6	Femtocell BS	Femtocell UE	Co-tier	Downlink

In wireless communications, we have a limited spectrum available and we have to utilize that spectrum efficiently to obtain maximum throughput. Due to scarcity of spectrum resources we have to reuse the same subchannels to enhance spectral efficiency. But reusing the same subchannels initiates interference issues which affect the network coverage greatly. Hence effective interference management scheme is required to overcome the interference issues in Femtocell Networks. Fig. 2.2 shows the interference issues caused by femtocell co-channel deployment without using efficient interference management techniques. We can observe that some users face severe interference due to inefficient resource utilization which also results in decreasing the overall network capacity.

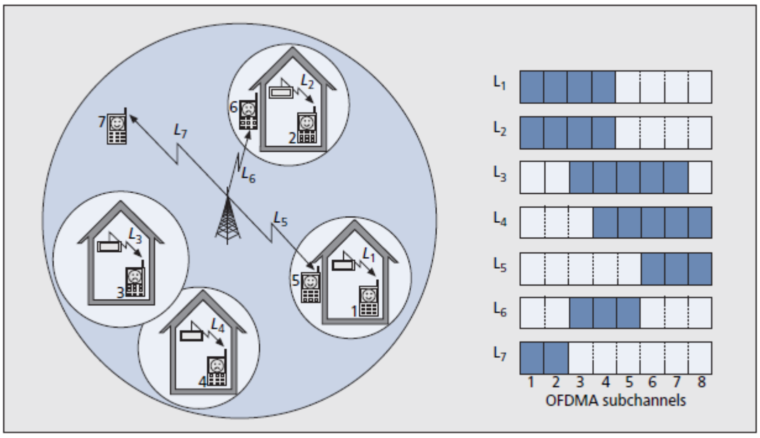

Figure 2.2: Downlink allocation of subchannels in macro/femto network with co-channel assignment [9]

2.5 Interference Management Methods

In order to achieve the required performance, femtocell design must incorporate the following interference management methods:

(1) Downlink transmit power calibration of FBS to provide good coverage to femtocell user while limiting the interference to macro network.

(2) Interference mitigation by adaptive UL attenuation so that the interference effect by macro and/or femtocell user can be minimized.

(3 Inter-frequency handover and carrier selection to avoid femto-to-macro and inter-femto interference.

(4) Minimization of uplink transmit power of femtocell user to limit the interference caused to the uplink of macrocellular network.

Chapter 3

Background and Literature Review

3.1 Introduction

A considerable amount of literature is available for femtocell interference mitigation or avoidance techniques such as power control [10-18], fractional frequency reuse [19-25], reverse frequency allocation [26,27,40] and the references therein. However, as this study deals with a specific type of orthogonal frequency division multiple access (OFDMA)-based heterogeneous network, we briefly discuss the subchannel allocation schemes devised in literature for interference management.

3.2 User-Oriented and Channel-Oriented Subchannel Allocation

In [28], user-oriented and channel-oriented subchannel allocation schemes have been proposed that allocate channels with respect to their respective priorities, however, these schemes compromise on network capacity and capacity fairness, respectively. The user-oriented subchannel allocation sheme gives priority to users for selection of subchannels. In this way it provides good fairness but network capacity is compromised. Channel-oriented subchannel allocation scheme provides good network capacity but it compromises on fairness. Using these schemes separately result in performance degradation either in terms of network capacity or fairness.

3.3 Stable Subchannel Allocation

In [35], authors proposed a stable subchannel allocation scheme to improve the fairness and capacity of OFDMA-based femtocell system. Deferred acceptance algorithm is used to allocate subchannels to users according to user's and subchannels's choice list. The priorities among subchannels are sorted according to CINRs in decreasing order. Number of subchannels allocated to users are limited to certain specific value to achieve better capacity fairness among users. Optimal femtocell capacity is calculated by using deferred acceptance algorithm with the maximum allowable number of subchannels.

The disadvantage of this scheme is that the achieved capacity is less than channel-oriented subchannel allocation scheme. In order to improve the fairness, stable subchannel allocation compromises on achieved capacity.

This is a great drawback of this scheme because the overall network capacity is compromised. As per Fig. 3.1, there is 15.3 % decrease in achieved capacity when number of femtocell users are 4.

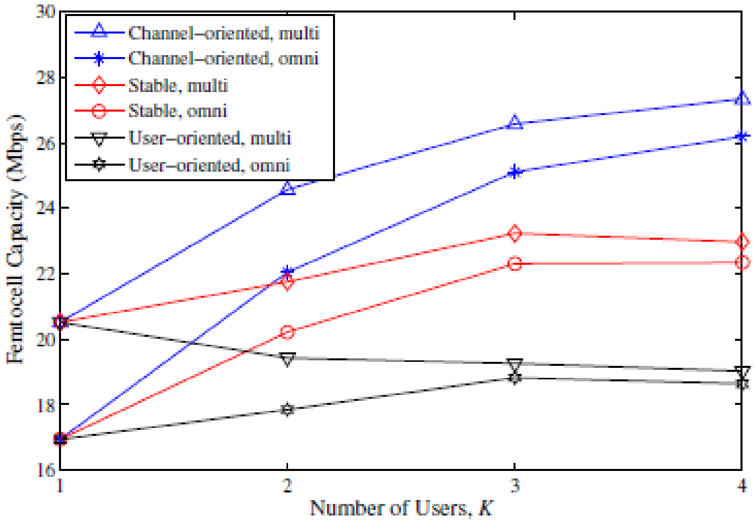

Figure 3.1: Femtocell capacity for different number of femtocell users [35]

Another disadvantage of this scheme is that the fairness achieved is quite less than the user-oriented subchannel allocation scheme. User-oriented subchannel allocation scheme provides very good capacity fairness but the capacity fairness achieved by stable subchannel allocation is very less as compared to user-oriented subchannel allocation scheme. According to Fig. 3.2, there is 20 % decrease in fairness factor when number of femtocell users are 4.

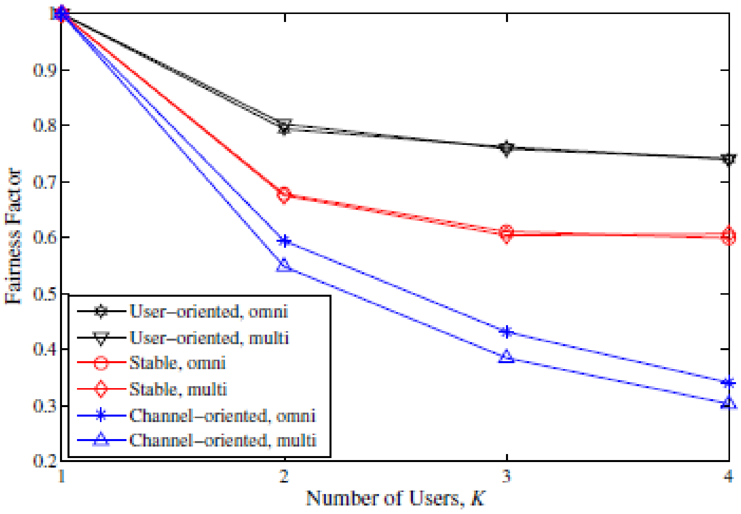

Figure 3.2: Fairness factor for different number of femtocell users [35]

3.4 Intercell Coordination

In [31], a centralized subchannel allocation scheme for interference avoidance is proposed by using intercell coordination but there are signaling overheads and computational complexities associated with this scheme. This scheme is too complex for implementation on practical grounds. This scheme is compromised of two algorithms which run simultaneously at the base station and central controller. A group of neighboring base stations are connected to the central controller. Dominant interferer information is gathered in dominant interferer set and dominant interferers are sorted out is descending order. If the data rate achieved by any user is less than the threshold then the most dominant interferer is restricted from that chunk. After that a Hungarian algorithm is run for allocation of subchannels for users.

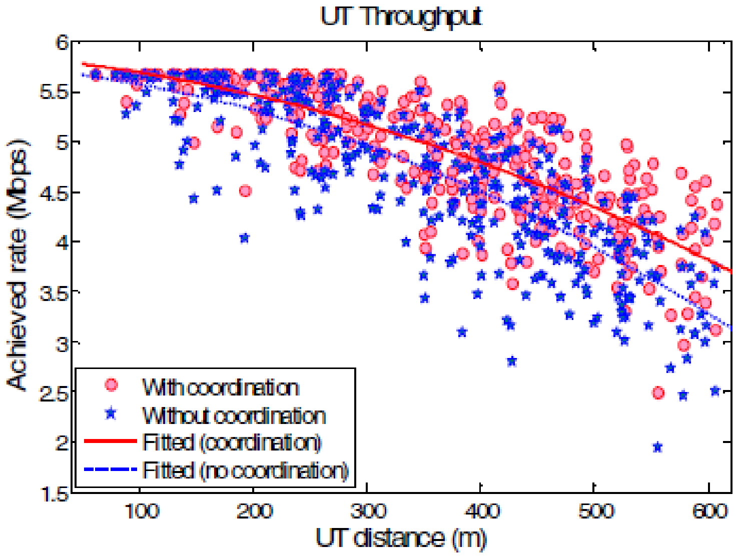

Figure 3.3: User throughput [31]

The disadvantage of the scheme is that central controller has a lot of computation overhead. Signaling overhead is one of the other issues associated with this scheme because the information about dominant interferers has to be conveyed to central controller after specific time interval. As per Fig. 3.3, there is not too much difference in the user throughput of intercell coordination scheme and the scheme without intercell coordination when the UT distance is small.

3.5 Stochastic Subchannel Allocation

A dynamic stochastic subchannel allocation scheme is proposed in [8]. This scheme is based on random selection of subchannels for FBS and the effect of co-channel interference (CCI) is dispersed on all subchannels. The probability of CCI is decreased by stochastic subchannel allocation. The femtocell base station allocates the available subchannels to each user after selection from stochastic methods and a greedy algorithm is used for subchannel allocation procedure. Transmit power control is also incorporated in this scheme to minimize the effect of interference and minimum transmit power is used keeping in view the rate requirements.

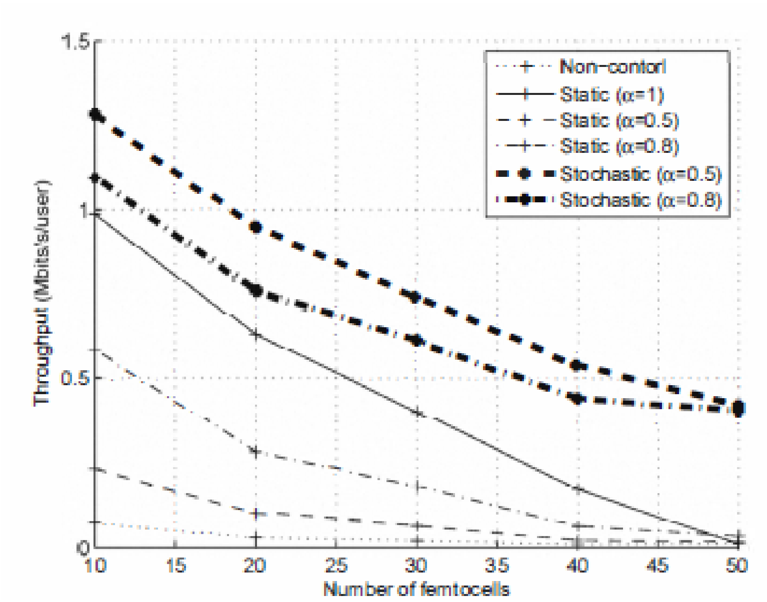

Figure 3.4: User throughput with different number of femtocell users [8]

The disadvantage of this scheme is that it compromises spectral efficiency. All the subchannels are not available for femtocell base station for allocation to users. Only a specific set of subchannels is available for femtocell base station for allocation to users based on stochastic selection. Therefore due to limited availability of subchannels, femtocell capacity is decreased. Another disadvantage is that there is still a possibility of co-channel interference although stochastic methods are applied because we cannot guarantee zero CCI with probabilistic methods.

3.6 Other Interference Management Schemes

Some other interference management schemes which are used to minimize the effect of interference due to femtocell deployment are mentioned below:

(1) A utility-based subchannel allocation scheme is proposed in [32] by using graph theory, however, it provides sub-optimal channel allocation. This schemes does not ensure the fairness among femtocell users.

(2) In [33], resource optimization has been done for downlink transmission of macro-femto network. In this scheme, per-user bandwidth is reduced in order to minimize the interference. This scheme compromises on capacity in order to minimize interference due to femtocell deployment.

(3) In [29], a decentralized spectrum allocation policy is proposed to increase the capacity of the network but capacity fairness is not considered.

(4) The authors developed the distributed channel-gain oriented subchannel selection scheme in [30] to maximize capacity but there is not much insight on the capacity fairness.

(5) A two-tier frequency reuse scheme is proposed by authors in [34]. This scheme allocates different set of subchannels for the macro BS and femtocell BS in one sector of a specific cell. By this disjoint allocation of subchannels, cross tier interference can be avoided easily. But the disadvantage of this scheme is that it does not provide a mechanism to deal with co-tier interference. Neighboring femtocell base stations share the same set of subchannels and it can cause severe co-tier interference issues. The performance of this scheme degrades significantly in dense femtocell deployment scenarios.

In this thesis, we have used the concept of fuzzy logic to develop a new fuzzy logic-based subchannel allocation scheme for interference management and capacity maximization in femtocell networks. Fuzzy logic deals with approximate reasoning instead of fixed and exact values. Fuzzy logic variables may have a range between 0 and 1 for truth value. In fuzzy mathematics this is represented by membership functions. Fuzzy logic handles the concept of partial truth in contrast to binary logic where variables may take on true or false value. Fuzzy logic is widely used for applications like fuzzy control systems [36], fuzzy neural networks [37], fuzzy soft computing [38] and fuzzy emitter recognition [39]. In our thesis, we utilized the concept of fuzzy logic for subchannel allocation based on memberships of user-wise and channel-wise priorities.

Chapter 4

Network Architechture

4.1 Introduction

In this chapter we describe the network architecture used to implement the the proposed fuzzy logic based subchannel allocation scheme. We consider a single cell heterogeneous network in which an arbitrary number of femtocell base stations (FBSs) are randomly deployed within a macrocell. The coverage radius of a femtocell is denoted by R_f. It is assumed that the macro base station (MBS) has either 120° or 60° sectors and that double frequency reuse scheme is used in all sectors [34]. This implies that the subchannels allocated to FBSs in one sector of the macrocell are different from the subchannels allocated to the MBS in that sector. The subchannels can be reused in any other sector of distant cell where the effect of co-channel interference is minimum. This will enable zero cross-tier interference and the system only has to deal with co-tier interference among FBSs in one sector of the macrocell. Let ξ represents the set of FBSs, which are deployed in one sector of the MBS. The index for FBS in a specific sector of MBS is denoted as f, such that $f = \{1, \cdots, \mid \xi \mid\}$ where $\mid \xi \mid$ represents the cardinality of set ξ. Minimum distance between two FBSs is denoted by d_{fmin}.

We have considered the scenario where all FBSs operate only in the closed-access mode, i.e., only legitimate users, which are part of the closed subscriber group (CSG) are allowed to use the services of a specific FBS. Any other user, which is not the part of CSG is denied service for that corresponding FBS. In this case, the effect of interference from neighboring FBSs is enhanced and the need for efficient interference management scheme becomes inevitable.

Without the loss of generality, we assume that a maximum of K legitimate FUEs can be connected to each FBS. Let k be the index to represent an FUE such that $k = \{1, \cdots, K\}$. Each FBS has N data subchannels available and each subchannel consists of N_d OFDMA subcarriers. A graphical illustration of 6 OFDMA subchannels with 2 subcarriers per subchannel is shown in Fig. 4.1. To provide a fair comparison, we also assume that the maximum subchannels allocated to any user k of a femtocell f are limited to M_f. For example, $K = 3$ implies 2 subchannels per user in Fig. 4.1, i.e., $M_f = 2$. By applying a threshold to maximum number of subchannels per user, we can improve the fairness factor otherwise if one user will avail too many subchannels to fulfill its data rate requirements, the remaining users will suffer due to deficiency of available subchannels and can result in outage.

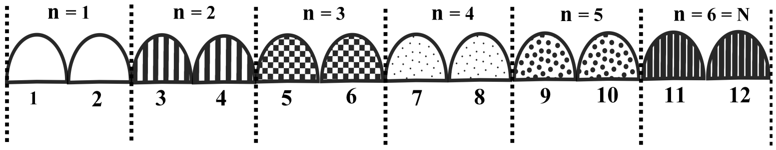

Figure 4.1: OFDMA Subchannels; $N = 6$, $N_d = 2$.

4.2 Binary Indicator Function

Let a binary indicator function, $I_{(f,k)}^{(n)}$, is used to denote the n^{th} subchannel allocated to user k of femtocell f such that

$$I_{(f,k)}^{(n)} = \begin{cases} 1 & if\ n^{th}\ subchannel\ is\ allocated\ to\ user\ k \\ 0 & if\ n^{th}\ subchannel\ is\ not allocated\ to\ user\ k \end{cases} . \tag{4.1}$$

Based on the above equation, we have

$$\sum_{k=1}^{K} I_{(f,k)}^{(n)} = 1 \quad \forall n \ . \tag{4.2}$$

The equation above guarantees that a subchannel cannot be shared by more than one user in the same FBS. Keeping in view the requirements of proposed subchannel allocation scheme, the maximum number of subchannels allocated to user k in femtocell f are limited to M_f such that

$$\sum_{n=1}^{N} I_{(f,k)}^{(n)} \leq M_f \leq N \ . \tag{4.3}$$

We consider equal transmit power for all the users in a femtocell and all FBSs also transmit with the same power. The transmit power for all subchannels of the FBS f is denoted as P_t. The recieved power at FUE k, for subchannel n, in the downlink of FBS f is given as

$$P_{r(f,k)}^{(n)} = \frac{P_t \mu_{(f,k)}^{(n)}}{d_{(f,k)}^{\beta}} \ , \tag{4.4}$$

where $\mu_{(f,k)}^{(n)}$ represents the channel gain for the subchannel n from FBS f to the user k. All channel gains are independent and exponentially distributed with unit mean, corresponding to Rayleigh flat fading. The distance between the FBS f and the user k is denoted by $d_{(f,k)}$ and β is the path loss exponent.

4.3 Calculation of SINR

For subchannel n, the downlink signal-to-interference plus noise ratio (SINR) at user k is given by

$$SINR_{(f,k)}^{(n)} = \frac{P_{r(f,k)}^{(n)} I_{(f,k)}^{(n)}}{I_{(f,k)}^{(n)} + N_o} \ , \tag{4.5}$$

where $I_{(f,k)}^{(n)}$ is the co-channel interference (CCI), introduced by the nearby FBSs communicating at the same subchannel, while the power spectral density of white Gaussian noise is given by N_o. As we have already considered that the subchannels used by the FBS situated in a specific macrocell sector are different from the subchannels used by the MBS in that sector, therefore there will be no downlink interference from MBS to femtocell users. Similarly, there will be no downlink interference from FBS to macrocell users. Hence, the CCI on subchannel n of user k, connected to FBS f is given as

$$I_{(f,k)}^{(n)} = \sum_{\acute{f} \in \xi / f} \frac{P_t \mu_{(\acute{f},k)}^{(n)}}{d_{(\acute{f},k)}^{\beta}} \ , \tag{4.6}$$

where $\acute{f}$ represents the interfering FBSs, $\mu_{(\acute{f},k)}^{(n)}$ is the channel gain for the subchannel n from FBS $\acute{f}$ to user k and $d_{(\acute{f},k)}$ is the distance between interfering FBS $\acute{f}$ and user k.

4.4 Femtocell Capacity

The total throughput of an OFDMA-based femtocell is defined by the achieved capacity. The achieved capacity of user k in a femtocell f is denoted by $C_{(f,k)}$. If there are K users and N data subchannels available in a femtocell f, then the achieved capacity of an OFDMA-based femtocell can be calculated by

$$C = \sum_{k=1}^{K} C_{(f,k)} \ , \tag{4.7}$$

$$C = \sum_{k=1}^{K} \sum_{n=1}^{N} I_{(f,k)}^{(n)} \frac{B}{M} \frac{N_d}{G+1} \eta_{(f,k)}^{(n)} \ , \tag{4.8}$$

where B is the system bandwidth, M is the Fast Fourier Transform (FFT) size and $\eta_{(f,k)}^{(n)}$ is the theoretical spectral efficiency of subchannel n allocated to user k, which is connected to FBS f. The value of $\eta_{(f,k)}^{(n)}$ is obtained from Table 4.1 [31].

Table 4.1: Modulation And Coding Schemes (MCS)

SINR Range (dB)	MCS mode	Efficiency, η
-1.76 $\leq \gamma$ ¡ 0.14	BPSK rate 1/2	0.5
0.14 $\leq \gamma$ ¡ 1.15	BPSK rate 2/3	0.67
1.15 $\leq \gamma$ ¡ 3.14	QPSK rate 1/2	1.0
3.14 $\leq \gamma$ ¡ 4.15	QPSK rate 2/3	1.33
4.15 $\leq \gamma$ ¡ 6.55	QPSK rate 3/4	1.5
6.55 $\leq \gamma$ ¡ 9.01	16-QAM rate 1/2	2.0
9.01 $\leq \gamma$ ¡ 10.22	16-QAM rate 2/3	2.67
10.22 $\leq \gamma$ ¡ 14.01	16-QAM rate 3/4	3.0
14.01 $\leq \gamma$ ¡ 15.33	64-QAM rate 2/3	4.0
$\gamma \geq$ 15.33	64-QAM rate 3/4	4.5

4.5 Fairness Factor

Capacity fairness is also considered along with the femtocell capacity in designing subchannel allocation method. The fairness factor is defined as

$$\alpha = \frac{C^2}{K \sum_{k=1}^{K} C_{(f,k)}^2} \ . \tag{4.9}$$

The value of α ranges between 0 and 1, i.e., $0 \leq \alpha \leq 1$. If all users in a femtocell achieve the same throughput then $\alpha = 1$.

Chapter 5

Fuzzy Logic-Based Subchannel Allocation

5.1 Introduction

In this chapter, we propose a low-complexity dynamic subchannel allocation scheme based on fuzzy logic. To make the subchannel allocation scheme practically implementable, a distributed network approach is applied instead of a centralized one. The former approach does not require a central control entity for subchannel allocations and hence the computational overhead on the central base station is minimized. In our scheme, the FUEs provide the information of received SINR on each subchannel to their respective FBS. The list of SINR values of each subchannel for every legitimate FUE is maintained by the FBS. Hence the problem in hand is to allocate the subchannels to the FUEs based on the reported SINR values. This is done optimally so that the effect of interference should be minimized and the overall capacity can be maximized keeping the fairness factor in consideration.

Traditional SINR-based subchannel allocation schemes are either user-oriented or channel-oriented. In the user-oriented approach, the users select the subchannels with the best SINR. In this way, the overall capacity of the femtocell network is compromised because the assigned subchannel cannot be allocated to another user, which may have better SINR on that specific subchannel and could achieve better capacity. The efficiency of this scheme depends on the sequence of users for which channels are assigned. There can be a subchannel on which another user can achieve more capacity instead of the user for which that subchannel is assigned and hence network capacity is compromised. Another widely used SINR-based subchannel allocation scheme is the channel-oriented scheme. This scheme improves the overall capacity of the network by assigning specific subchannel to the user that has maximum SINR for that subchannel but it compromises on fairness. The users who face more interference and have less SINR values for the available subchannels are badly affected by this scheme and may result in outage due to improper allocation of subchannels.

In our proposed subchannel allocation scheme, instead of considering only user-wise priority or channel-wise priority, we consider a mix of them and develop an algorithm that provides a better tradeoff between achievable capacity and fairness factor. The following sections provide a step-by-step process of our proposed scheme.

5.2 Formation of the SINR Matrix

From the reporting of FUEs, the FBS maintains the SINR values of every subchannel n for each user k. Let $\mathbf{S}$ be the SINR matrix such that $s_{(n,k)} \in$

S, where $n = \{1, \cdots, N\}$ and $k = \{1, \cdots, K\}$. In other words, the SINR values of all the subchannels for the k^{th} user are located in the k^{th} column of **S**. Similarly, the SINR values for all the users on the n^{th} subchannel are recorded in the n^{th} row of **S**. An example is shown in Table 5.1, where SINR values of 8 subchannels are shown for 4 users.

Table 5.1: SINR Values

Subchannels	U_1	U_2	U_3	U_4
Ch_1	-12.5	26.13	7.02	2.3
Ch_2	-6.1	22.08	4.81	-6.71
Ch_3	-5.7	30.79	10.83	5.36
Ch_4	2.3	35.74	15.39	6.99
Ch_5	-5.6	27.12	2.3	-3.88
Ch_6	-7.5	24.47	3.98	-0.007
Ch_7	6.07	32.56	11.36	11.22
Ch_8	-11.08	26.68	3.48	4.25

5.3 User-Wise Priority Matrix

Let $\mathbf{P}_u$ denotes the user-wise priority matrix such that $p_{u(n,k)} \in \mathbf{P}_u$. The matrix indicates the priority of users regarding the selection of available subchannels based on the SINR values. The priority value of any user k for subchannel n is calculated from a proportionate SINR value, which depends on the SINR of that specific subchannel and maximum SINR value achieved by that user on any subchannel from 1 to N. If the maximum SINR value achieved by user k is represented by $\Gamma_{max}^{(k)}$, then the priority value of user k

for subchannel n will be $p_{u(n,k)}$= $\frac{s_{(n,k)}}{\Gamma^{(k)}_{max}}$. Priority values in user-wise priority matrix can range from 0 to 1. If a user k has the best SINR for subchannel n among all other subchannels, then $p_{u(n,k)} = 1$. To better understand the calculation of priority values $p_{u(n,k)}$, for user-wise priority matrix $\mathbf{P}_u$, we consider the example shown in Table 5.1 where $K = 4$ and $N = 8$. Consider the SINR values for the first user ($k = 1$) for all 8 subchannels shown in Table 5.1. To calculate the user-wise priority values, we normalize the SINR values of user 1 for all 8 subchannels with the maximum SINR, i.e., $\Gamma^{(1)}_{max} = 6.07$. Normalization is done in linear scale and dB values are converted into linear values before normalization. Hence user 1 has the highest priority for subchannel 7, i.e., $p_{u(7,1)} = 1$ and the rest of the entries are calculated in the same manner. In our subchannel allocation scheme, $\mathbf{P}_u$ contributes in the capacity fairness. Table 5.2 shows the user-wise priority values of all 4 users for 8 subchannels accordingly.

Table 5.2: User-Wise Priority

Subchannels	U_1	U_2	U_3	U_4
Ch_1	0.013	0.109	0.145	0.128
Ch_2	0.06	0.043	0.087	0.016
Ch_3	0.066	0.32	0.349	0.259
Ch_4	0.42	1	1	0.377
Ch_5	0.066	0.137	0.049	0.03
Ch_6	0.043	0.074	0.072	0.075
Ch_7	1	0.48	0.395	1
Ch_8	0.0192	0.124	0.064	0.201

5.4 Channel-Wise Priority Matrix

Let $\mathbf{P}_c$ denotes the channel-wise priority matrix such that $p_{c(n,k)} \in \mathbf{P}_c$. It indicates the priority of subchannels regarding the selection of users based on the SINR values. The same procedure is repeated as described in the previous subsection and normalized values of $\mathbf{P}_c$ are calculated by dividing $s_{(n,k)}$ with the maximum SINR value for a particular subchannel n. If the maximum SINR value achieved by any subchannel n is represented by $\Gamma_{max}^{(n)}$, then the priority value of subchannel n for user k will be $p_{c(n,k)}= \frac{s_{(n,k)}}{\Gamma_{max}^{(n)}}$. Consider the SINR values for the first subchannel ($n = 1$) for all 4 FUEs shown in Table 5.1. After normalizing, the first subchannel ($n = 1$) has highest priority for user 2, i.e., $p_{c(1,2)}$=1, which is shown in Table 5.3. All the other values of channel-wise priority matrix will be calculated by adopting same procedure. In our proposed scheme, channel-wise priority will contribute in capacity maximization. Assignment of subchannels with better SINR results in Channel-wise priority values of all 8 subchannels for all users are shown in Table 5.3.

Table 5.3: Channel-Wise Priority

Subchannels	U_1	U_2	U_3	U_4
Ch_1	0.000137	1	0.012301	0.004142
Ch_2	0.001508	1	0.018745	0.001318
Ch_3	0.000223	1	0.010073	0.002859
Ch_4	0.000453	1	0.009213	0.001332
Ch_5	0.000524	1	0.003296	0.000792
Ch_6	0.000625	1	0.00893	0.003563
Ch_7	0.002245	1	0.007587	0.007346
Ch_8	0.000167	1	0.004792	0.005718

5.5 Formation of Fuzzy Subsets

The consideration of user-wise and channel-wise priority separately may result in suboptimal allocation. For instance, the subchannel, which is on the first priority for a particular user may have the least priority for that specific user. Therefore, instead of using binary decisions to allocate subchannels, we use the concept of fuzzy logic where probabilistic weights are assigned for the selection of subchannels according to user-wise or channel-wise priority. Let $F_{(n,k)}$ represents a fuzzy subset that contains the membership values of the subchannel n for user k and vice-versa. There are a total of NK fuzzy subsets that form the fuzzy superset $\mathbf{F}$, i.e., $F_{(n,k)} \subset \mathbf{F}$. The membership of any user k to acquire subchannel n is denoted by the membership function ϕ_u and its value is acquired from the user-wise priority matrix such that $\phi_{u(n,k)} = p_{u(n,k)}$. Hence ϕ_u denotes the membership function such that $\phi_{u(n,k)}$

: $s_{(n,k)} \rightarrow [0\ 1]$. Similarly, the membership of any subchannel n to acquire user k is denoted by the membership function ϕ_c and its value is attained from channel-wise priority matrix such that $\phi_{c(n,k)} = p_{c(n,k)}$. Thus we can write the fuzzy subset as a 2-tuple mathematical object such that $F_{(n,k)} = \left(\phi_{u(n,k)}, \phi_{c(n,k)}\right)$.

5.6 Cardinality of Fuzzy Subsets

Although $\phi_{u(n,k)}$ and $\phi_{c(n,k)}$ represent the membership degree of user k to subchannel n and vice versa, it is required to find a *measure* of suitability for this user-subchannel pair. In fuzzy mathematics, this measure is defined by the cardinality of fuzzy sets. In general, the cardinality can be calculated by using the l_1 norm of the fuzzy set, i.e.,

$$\mid F_{(n,k)} \mid = \sum_i \phi_{i(n,k)}; \;\; i \in \{u, c\}\,. \tag{5.1}$$

We have considered the l_1 norm because we are adding the weights of the membership values for fuzzy subset to select the favorable subchannel n for user k. In general, l_2 norm also provides the same result for the subchannel selection in this case. On the same lines, we compute the cardinality matrix, $\mathbf{C}$ that contains the cardinalities of all fuzzy subsets $F_{(n,k)}$ of $\mathbf{F}$ for $n = \{1, \cdots, N\}$ and $k = \{1, \cdots, K\}$.

Table 5.4: Cardinality Values

Subchannels	U_1	U_2	U_3	U_4
Ch_1	0.014021	1.109221	0.158124	0.132422
Ch_2	0.061721	1.043031	0.106295	0.0174
Ch_3	0.066339	1.320029	0.35996	0.262309
Ch_4	0.421159	2	1.009213	0.37915
Ch_5	0.067262	1.137372	0.052444	0.031655
Ch_6	0.043852	1.074589	0.081224	0.078921
Ch_7	1.002245	1.480119	0.402952	1.0073462
Ch_8	0.019412	1.124061	0.069322	0.206849

5.7 Allocation of Subchannels

Subchannels are allocated to the users on the basis of cardinality values. It can be noticed that the highest cardinality value for a user-subchannel pair represents the optimal combination. Thus the highest value of cardinality in matrix $\mathbf{C}$ is calculated and the corresponding subchannel is allocated to the corresponding user. As one subchannel can only be allocated to a single user, therefore, after this allocation of subchannel (*say* n) to the user, the cardinality values of subchannel n in $\mathbf{C}$ are set to zero for all K users, i.e., $\mathbf{C}_{(n,1:K)} = 0$. The maximum number of subchannels allocated to user k are bounded by M_f. If this condition is satisfied, then the cardinality values of the user k for all the subchannels from 1 to N become zero and the user cannot take part in further allocation of subchannels. Same process is repeated until all N subchannels are allocated among all K users and $\mathbf{C}$

becomes a null matrix. Subchannels are allocated dynamically to the users and the entire subchannel allocation process is repeated after specific interval of time for reallocation of subchannels.

Algorithm 5.1 Fuzzy Logic-Based Dynamic Subchannel Allocation Scheme

```
Initialization
  1. A set of $K$ users, where $k = \{1, \cdots, K\}$.
  2. A set of $N$ subchannels, where $n = \{1, \cdots, N\}$.
  3. Maximum $M_f$ subchannels allocated to user.
  4. Subchannel Allocation Matrix, $\mathbf{X} = 0_{(N \times K)}$.
Subchannel Allocation
  1. Create $\mathbf{S}$ from reported SINR values.
  2. Compute matrices $\mathbf{P}_u$ and $\mathbf{P}_c$.
  3. Form fuzzy subsets, $F_{(n,k)}$ and fuzzy superset $\mathbf{F}$.
  4. Compute the cardinality matrix, $\mathbf{C}$.
while $C \neq$ Null Matrix do
    5. Assign subchannel $n$ to user $k$ corresponding to the highest value in $\mathbf{C}$.
    6. Set $\mathbf{X}_{(n,k)} = 1$.
    7. Set $\mathbf{C}_{(n,\ 1:K)} = 0$.
    if $\sum_{i=1}^{N} X_{(i,k)} = M_f$ then
        8. Set $\mathbf{C}_{(1:N,\ k)} = 0$.
    else
        go back to step 5
    end
end
Output: The subchannels $n$ for which $\mathbf{X}_{(n,k)} = 1$ will be allocated to user $k$.
```

Chapter 6

Results and Performance Analysis

6.1 Introduction

In this chapter, we present the simulation results of our proposed scheme and compare them to the general user-oriented and channel-oriented schemes given in [28]. It is shown that our proposed scheme outperforms the user-oriented and channel-oriented subchannel allocation schemes specially in dense femtocell deployment scenarios. We consider a femtocell network with dense deployment where 50 FBSs are randomly distributed in an area of 300×300 m^2. The minimum distance between two nearest FBSs is kept at 20 m. In each FBS, there are 36 subchannels allocated to K authorized users. The maximum number of subchannels allocated to any user are $M_f = \frac{N}{K}$. We analyze a worst-case interference scenario such that all K FUEs of all 50 FBSs are active. Fig. 6.1 below shows the deployment of 50 femtocells in an area of 300×300 m^2 with 4 FUEs per FBS .

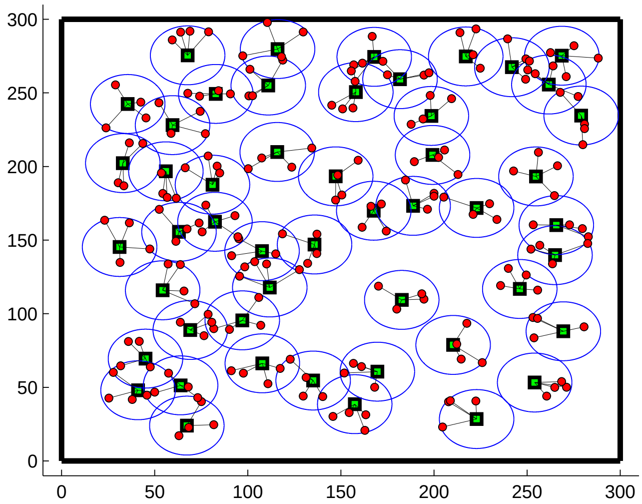

Figure 6.1: Femtocell deployment in given area

The simulation parameters for the considered OFDMA-based femtocell network are listed in Table 6.1.

Table 6.1: Simulation Parameters

Downlink OFDMA Parameters	Values
FBS transmit power (P_t)	15 dBm
System bandwidth (B)	10 MHz
FFT Size (M)	1024
Number of data subchannels (N)	36
Subcarriers for each data subchannel (N_d)	20
Path loss exponent (β)	2.5

6.2 Capacity and Fairness of Proposed Scheme

We have compared the results of proposed fuzzy logic-based subchannel allocation scheme with the channel-oriented and user-oriented subchannel allocation schemes and find out that the proposed scheme provides better tradeoff between the achieved capacity and fairness. Fig. 6.2 and Fig. 6.3 show the average femtocell capacity and fairness factor, respectively, for different number of femtocell users.

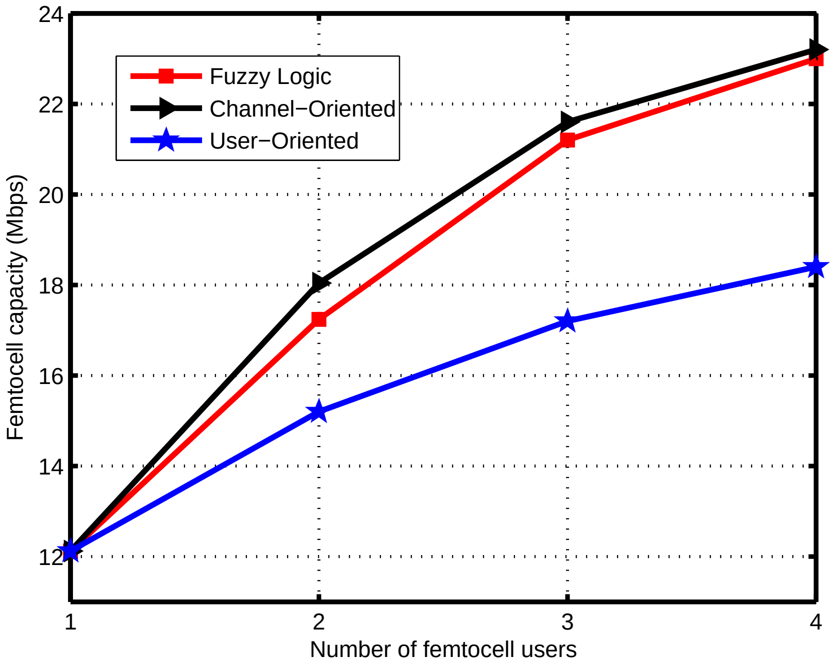

Figure 6.2: Femtocell capacity for different number femtocell users

For $K = 2$, the proposed scheme provides a 17% increase in fairness factor as compared to channel-oriented scheme, however there is 4.4% decrease in the achieved capacity. For $K = 4$, there is a 22% increase in fairness factor with only 0.86% decrease in the achieved capacity. This shows that the

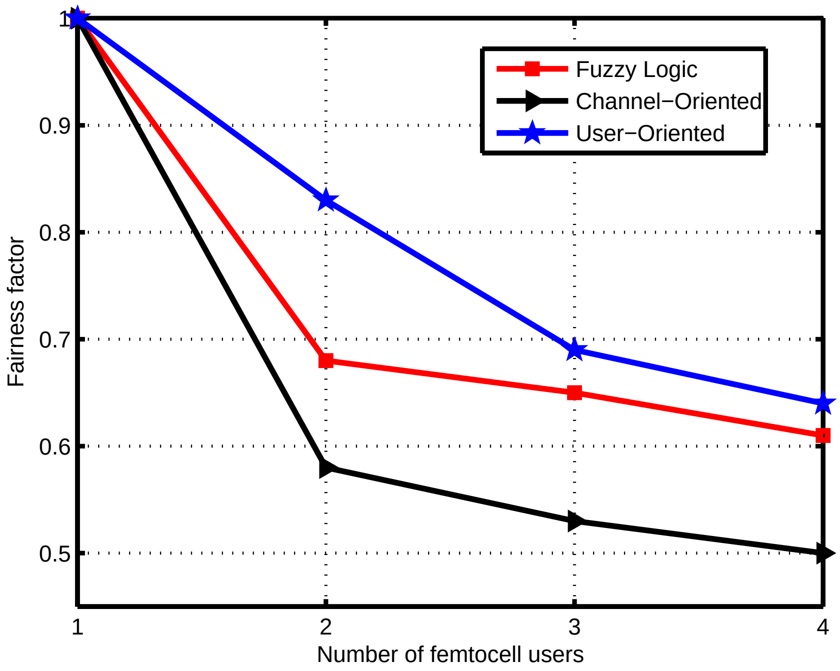

Figure 6.3: Fairness factor for different number of femtocell users

performance of proposed subchannel allocation scheme improves with the increase in the number of femtocell users. In comparison with the user-oriented subchannel allocation scheme, we can see that the proposed scheme provides a 25% improvement in achieved capacity with only 4.6% decrease in fairness factor for $K = 4$. These results indicate that the proposed scheme outperforms the user-oriented and channel-orieneted schemes. In [35], it can be seen that the scheme proposed by authors provides better fairness at the expense of capacity. However, our scheme not only provides almost the same maximum achievable capacity as that of channel-oriented scheme but also provides a fairly better performance on fairness factor.

6.3 Performance of Proposed Scheme in Dense Femtocell Deployment

It can be observed that the performance of the proposed subchannel allocation scheme improves in dense femtocell environment as compared to the other two schemes. Fig. 6.4 shows the comparison of three schemes for two different values of FBSs in the same area, which shows the effects of dense femtocell deployment. For 30 FBSs, the improvement in achieved femtocell capacity is 21% as compared to user-oriented scheme for $K = 4$. However, the achieved capacity improves from 21% to 25% when the number of FBS is increased to 50 in the same area. Similarly, the difference between the achieved capacity for proposed scheme and the channel-oriented scheme is reduced from 2.14% to 0.86% when the FBSs are increased from 30 to 50.

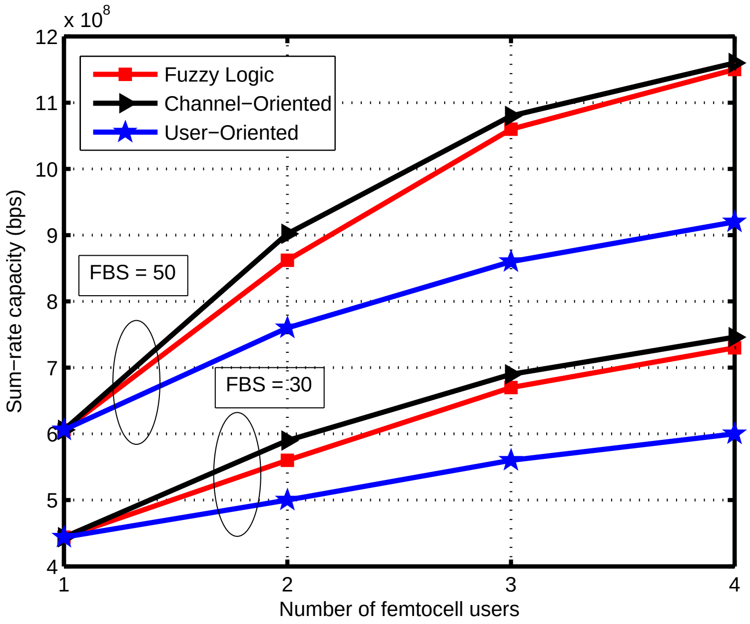

Figure 6.4: Sum-rate capacity for different number of femtocell users

Fig. 6.5 shows the results of femtocell capacity when 20 FBSs are randomly deployed in areas of different sizes. The deployment of femtocells in small-sized area refers to a rather dense deployment. The results show that there is 64% increase in achieved capacity of proposed scheme as compared to user-oriented scheme when the area under consideration in 200×200 m^2. We also notice that the difference in achieved capacity between proposed scheme and channel-oriented scheme is reduced from 2.8% to 0.8% when the area is reduced from 500×500 m^2 to 200×200 m^2. It shows that the performance of our proposed scheme improves in dense deployment scenarios, however, the other two schemes show performance degradation.

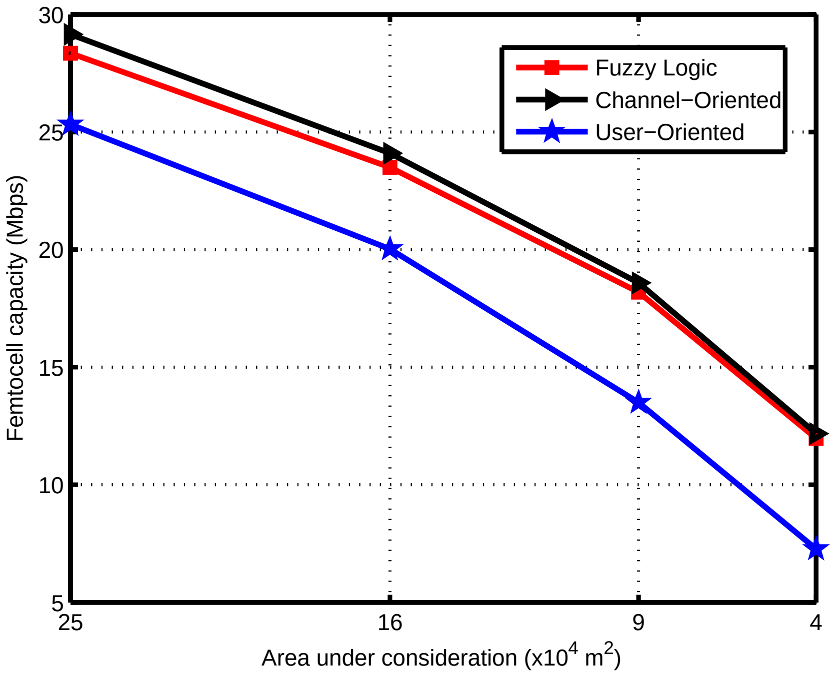

Figure 6.5: Femtocell capacity for different areas with 20 FBSs; $K = 4$ in each FBS.

6.4 Allocation of Subchannels According to Rate Requirements

Fig. 6.6 shows a contour plot of femtocell capacity for varying number of users and subchannels. The number of FBS is kept at 60 for an area of 300×300 m^2. This result can be used to allocate subchannels to femtocells based on the rate requirements. For instance, if each femtocell has 3 users and rate requirement in 9 Mbps, then 12 subchannels should be allocated to each femtocell. However, if the requirement exceeds to 15 Mbps, then 14 additional subchannels should be allocated to obtain the required quality of service. When the number of femtocell users increase, it increases the diversity and we can achieve more data rate with less number of subchannels. The results are consistent with results shown in Fig. 6.2, i.e., when number of femtocell users are increased the achieved capacity also increases.

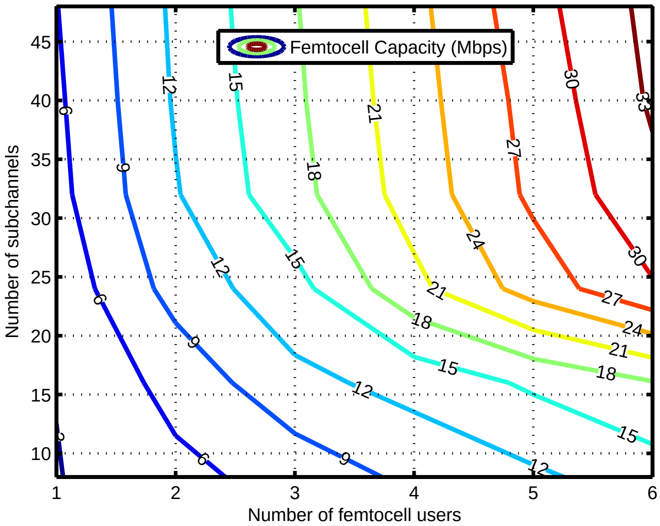

Figure 6.6: Femtocell capacity for different number of FUEs and subchannels.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

A novel fuzzy logic-based subchannel allocation scheme is proposed in this research thesis and its performance has been evaluated. The proposed scheme outperforms the user-oriented and channel-oriented subchannel allocation schemes, specially in dense femtocell deployment scenarios. Specifically, we introduced the concept of fuzzy memberships and applied it to the values obtained in the received SINR matrix at the FBS. The FBS then allocates channels based on the cardinality of fuzzy subsets. A significant improvement in network capacity as compared to user-oriented subchannel scheme has been quantified that also ensures capacity fairness as compared to the channel-oriented scheme. We have achieved upto 64 % increase in capacity as compared to user-oriented subchannel allocation scheme. We have achieved upto 22 % increase in fairness factor as compared to the channel-oriented subchannel allocation scheme. We have suggested the number of subchannels required to attain specific data rate in dense deployment scenarios. The performance of our proposed subchannel allocation scheme improves in dense femtocell deployment scenarios. The performance of the scheme improves with larger number of users per femtocell. The proposed scheme is simple and can be implemented for decentralized femtocell networks.

7.2 Future Work

For future work, we can assign scaling weights to the membership functions. In this way, the FBS can choose between improved data rate or fairness depending on the magnitude of interference. If the SINR values of subchannels are low and there is danger for users that they might go into outage then we can increase the weighting factor of user-wise priority. In this way, we can save the users from going into outage. Similarly if the interference is minimum, then we can increase the weight of channel-wise priority in order to enhance the network capacity by providing maximum data rates to users on best available subchannels.

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