ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC

MANUSCRIPT-BASED THESIS PRESENTED TO
ÉCOLE DE TECHNOLOGIE SUPÉRIEURE

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF
DOCTOR OF PHILOSOPHY
Ph.D.

BY
Rebeca Estrada Pico

OPTIMIZATION MODELS FOR RESOURCE MANAGEMENT IN TWO-TIER CELLULAR NETWORKS

MONTREAL, NOVEMBER 25, 2014

BOARD OF EXAMINERS

THIS THESIS HAS BEEN EVALUATED

BY THE FOLLOWING BOARD OF EXAMINERS:

M. Zbigniew Dziong, Thesis supervisor
Département de génie électrique à l'École de technologie supérieure

M. Hadi Otrok, Thesis co-supervisor
Department of ECE at Khalifa university of science, technology & research

M. Jean-Marc Robert, President of the board of examiners
Département de génie logiciel et des TI à l'École de technologie supérieure

M. Michel Kadoch, Examiner
Département de génie électrique à l'École de technologie supérieure

M. Chadi Assi, External examiner
Information Systems Engineering Department at Concordia University

THIS THESIS WAS PRESENTED AND DEFENDED

IN THE PRESENCE OF A BOARD OF EXAMINERS AND THE PUBLIC

ON NOVEMBER 19, 2014

AT ÉCOLE DE TECHNOLOGIE SUPÉRIEURE

ACKNOWLEDGEMENTS

First of all, i am grateful to God for giving me health and all the resources needed to complete this stage of my professional life. My gratitude is extended to my husband and children for all their support, great patience and comprehension at all times. I am also grateful to my parents who raised me with love and helped me to be the human being that I am now.

I wish to express my sincere thanks to my supervisor Professor Zbigniew Dziong for his support, valuable advices, and help. His encouragement and faith in me throughout have been very helpful. He was always available for my questions and he was very positive about my research work. I would also like to thank my co-supervisor Hadi Otrok, who showed me the road and helped me along the path of this degree. Working with both of them have added a valuable experience to my professional life.

Thanks to my colleagues of the LAGRIT Lab and especial thanks to Ph. D. Abdallah Jarray for his advices at the beginning of my doctoral studies.

Thanks to my friends of ESPOL that helped me when I arrived here and during my doctoral studies.

Last, but no least, I would like to acknowledge the financial support of the university Escuela Superior Politécnica del Litoral where I have been working during the last fourteen years.

MODÈLES D'OPTIMISATION POUR LA GESTION DES RESSOURCES DANS LES RÉSEAUX CELLULAIRES TWO-TIER

Rebeca Estrada Pico

RÉSUMÉ

L'architecture hiérarchique bi-niveau (c.à.d. *two-tier*) qui se compose d'une macrocellule et des femtocellules est la plus prometteuse pour les opérateurs des réseaux cellulaires, parce que cette architecture peut améliorer la capacité actuelle des réseaux cellulaires sans coûts additionnels. Toutefois, l'incorporation des femtocellules dans les réseaux cellulaires existants doit être habilement configurée en vue de l'amélioration de l'utilisation des ressources limitées. Dans cette thèse, nous abordons le problème de l'optimisation des ressources pour les réseaux bi-niveau utilisant la technologie OFDMA dans les scénarios où les femtocellules emploient la méthode d'accès hybride.

La méthode d'accès hybride est une technique qui fournit différents niveaux de service aux abonnés et aux utilisateurs non-autorisés et réduit les interférences perçus par les abonnés en octroyant des accès à des utilisateurs publics qui se trouvent dans les environs. Cette méthode devrait fournir un compromis entre l'impact sur la satisfaction des abonnés et le niveau d'accès accordé aux non-abonnés. L'impact sur les abonnés doit être minimisé en termes de performance ou doit être compensé par des avantages économiques.

Ce projet de recherche se concentre sur deux contraintes qui affectent le réseau cellulaire OFDMA bi-niveau. La première contrainte est constituée par le compromis à faire entre l'efficacité de l'utilisation des ressources de la macrocellule et la distribution équitable des ressources entre les macro-utilisateurs et les femtocellules. La seconde contrainte concerne les femtocellules, il s'agit du compromis à faire entre l'atténuation des interférences et l'octroi d'accès aux utilisateurs publics sans que les performances de la transmission descendante des abonnés ne soient affectées. Nous abordons ces contraintes par la mise en œuvre de plusieurs modèles d'allocation des ressources pour des déploiements de réseaux dense et non dense. La programmation linéaire et une méthode évolutionnaire d'optimisation sont les outils d'optimisation employées. En plus, les modèles d'allocation des ressources proposées déterminent conjointement la station base la plus appropriée a utiliser, la quantité de bande passante et la puissance de transmission de l'utilisateur dans le but d'améliorer la capacité globale du réseau.

Les deux premières parties de ce travail se concentrent sur l'optimisation des ressources pour les déploiements non-denses en utilisant l'assignation orthogonale et co-canaux entre la macrocellule et les femtocellules. Les deux parties aboutissent à la maximisation de la somme des débits pondérés des utilisateurs. Dans la première partie, deux ensembles de pondération sont introduits afin de prioriser l'utilisation des femtocellules par les abonnés et les utilisateurs publics qui se trouvent proche des femtocellules. En outre, nous avons introduit le réglage de la puissance dans la macrocellule en vue de l'amélioration de la distribution de la puissance entre les transmissions descendantes actifs et de l'amélioration de la tolérance au bruit. La deuxième partie permet la réutilisation spectrale et le réglage de la puissance. Cette réutilisation spectrale et le réglage de la puissance offrent une solution a trois volets qui améliore la distribution de la puissance entre les transmissions descendant actives, améliore la tolérance au bruit et à l'interférence et permet d'atteindre la qualité de service (QoS) exigée.

En vue de réduire la complexité du problème d'optimisation des ressources pour les déploiements de réseaux dense, la troisième partie de ce travail a divisé le problème d'optimisation en sous-problèmes. L'idée est de diviser les utilisateurs et les femtocellules en groupes distincts en se basant sur leurs localisations. Ainsi, le problème d'optimisation peut être résolu séparément dans chaque zone OFDMA. Cette solution permet la réutilisation des sous-porteuses d'une part entre une zone intérieure de la macrocellule et les femtocellules situées dans les zones extérieures de la macrocellule; et d'autre part entre les grappes des femtocellules situés dans la même zone. Le contrôle de la puissance est utilisé pour assurer la qualité de service (QoS) des utilisateurs et pour réduire l'interférence croisée entre la zone intérieure et les femtocellules situées dans les zones extérieures de la macrocellule.

Une autre méthode très commune pour réduire la complexité du problème de l'optimisation des ressources est le regroupement de femtocellules. Cependant, trouver la configuration optimale de regroupement en même temps que faire l'allocation de ressources est un problème d'optimisation complexe en raison du nombre de variables liées à toutes les configurations de regroupement possibles. Par conséquent, la quatrième partie de ce travail porte sur un modèle d'allocation des ressources heuristique basé sur les regroupements (c.à.d. *clusters*) et une méthode de motivation pour le regroupement des femtocellules à travers l'allocation de ressources supplémentaires aux transmissions de l'abonné et de l'utilisateur "visiteur". Le modèle d'allocation des ressources basé sur les regroupements maximise le débit du réseau tout en gardant les groupes équilibrés et en minimisant l'interférence inter-regroupements.

Finalement, les solutions proposées sont évaluées par de vastes simulations numériques et les résultats numériques sont présentées pour soutenir les solutions proposées, et pour fournir une comparaison plus éclairée avec d'autres modèles proposés dans la littérature.

Keywords: Réseau macro-femtocellule, Orthogonal Frequency Division Multiple Access, lèfemtocell d'accés hybride, le réglage de puissance, la grappe des femtocellules, la programmation linéaire, optimisation par essaim particulaire

OPTIMIZATION MODELS FOR RESOURCE MANAGEMENT IN TWO-TIER CELLULAR NETWORKS

Rebeca Estrada Pico

ABSTRACT

Macro-femtocell network is the most promising two-tier architecture for the cellular network operators because it can improve their current network capacity without additional costs. Nevertheless, the incorporation of femtocells to the existing cellular networks needs to be finely tuned in order to enhance the usage of the limited wireless resources, because the femtocells operate in the same spectrum as the macrocell. In this thesis, we address the resource optimization problem for the OFDMA two-tier networks for scenarios where femtocells are deployed using hybrid access policy.

The hybrid access policy is a technique that could provide different levels of service to authorized users and visitors to the femtocell. This method reduces interference received by femtocell subscribers by granting access to nearby public users. These approaches should find a compromise between the level of access granted to public users and the impact on the subscribers satisfaction. This impact should be reduced in terms of performance or through economic compensation.

In this work, two specific issues of an OFDMA two-tier cellular network are addressed. The first is the trade-off between macrocell resource usage efficiency and the fairness of the resource distribution among macro mobile users and femtocells. The second issue is the compromise between interference mitigation and granting access to public users without depriving the subscriber downlink transmissions. We tackle these issues by developing several resource allocation models for non-dense and dense femtocell deployment using Linear Programming and one evolutionary optimization method. In addition, the proposed resource allocation models determine the best suitable serving base station together with bandwidth and transmitted power per user in order to enhance the overall network capacity

The first two parts of this work cope with the resource optimization for non-dense deployment using orthogonal and co-channel allocation. Both parts aim at the maximization of the sum of the weighted user data rates. In the first part, several set of weights are introduced to prioritize the use of femtocells for subscribers and public users close to femtocells. In addition, macrocell power control is incorporated to enhance the power distribution among the active downlink transmissions and to improve the tolerance to the environmental noise. The second part enables the spectral reuse and the power adaptation is a three-folded solution that enhances the power distribution over the active downlink transmissions, improves the tolerance to the environmental noise and a given interference threshold, and achieves the target Quality of Service (QoS).

To reduce the complexity of the resource optimization problem for dense deployment, the third part of this work divides the optimization problem into subproblems. The main idea is to divide the user and FC sets into disjoint sets taking into account their locations. Thus, the optimization problem can be solved independently in each OFDMA zone. This solution allows the subcarriers reuse among inner macrocell zones and femtocells located in outer macrocell zones and also between femtocells belonging to different clusters if they are located in the same zone. Macrocell power control is performed to avoid the cross-tier interference among macrocell inner zones and inside femtocells located in outer zones.

Another well known method used to reduce the complexity of the resource optimization problem is the femtocell clustering. However, finding the optimal cluster configuration together with the resource allocation is a complex optimization problem due to variable number related to the possible cluster configurations. Therefore, the part four of this work deals with a heuristic cluster based resource allocation model and a motivation scheme for femtocell clustering through the allocation of extra resources for subscriber and “visitor user” transmissions. The cluster based resource allocation model maximizes the network throughput while keeping balanced clusters and minimizing the inter-cluster interference.

Finally, the proposed solutions are evaluated through extensive numerical simulations and the numerical results are presented to provide a comparison with the related works found in the literature.

Keywords: Macro-femtocell network, Orthogonal Frequency Division Multiple Access, Hybrid access femtocell, Power Adaptation, clustering, Linear Programming, Particle Swarm Optimization

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ALGORITHMS

LIST OF ABREVIATIONS

3GPP	Third Generation Partnership Project
ACO	Ant Colony Optimization
AMC	Adaptive Modulation and Coding
AMC-Band	Adaptive Modulation and Coding Band
BILP	Binary Linear Program
BPSK	Binary Phase Shift Keying
BS	Base Station
BSS-RAM	Base Station Selection and Resource Allocation Model
CSG	Closed Subscriber Group
CSI	Channel State Information
DE	Differential Evolution
DFP	Dynamic Frequency Planning
DL	Downlink
DSA	Dynamic Subcarrier Allocation
EC	Evolutionary Computation
EE-RAM	Energy-Efficient Resource Allocation Model
FBS	Femto Base Station
FC	Femtocell
FCRA	Femto-cluster based Resource Allocation
FFI	Femto-femto Interference
FFR	Fractional Frequency Reuse
FFT	Fast Fourier Transform
FT	Femto Tier
FUE	Femto User Equipment
FUSC	Full Usage Subcarrier

GA	Genetic Algorithm
ICIC	Inter-Cell Interference Coordination
IEEE	Institute of Electrical and Electronics Engineers
ILP	Integer Linear Program
IMBR	Interference Mitigation and Bandwidth Reduction
IMT	International Mobile Telecommunications
ITU	International Telecommunication Union
LBC	Load Balanced Cluster
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
LP	Linear Programming
MC	Memetic Algorithm
MAN	Metropolitan Area Network
MBS	Macro Base Station
MC	Macrocell
MCS	Modulation and Coding Scheme
MILP	Mixed Integer Linear Program
MIMO	Multiple Input Multiple Output
MR	Measurement Reports
MS	Mobile Stations
MSE	Mean Square Error
MT	Macro Tier
MU	Mobile User
MUE	Macro User Equipment
M-QAM	Quadrature Amplitude Modulation
NP	Non-Polynomial

OFDMA	Orthogonal Frequency Division Multiple Access
O-RAM	Orthogonal Resource Allocation Model
OP	Outage Probability
PAPR	Peak to Average Power Ratio
PCASO	Power and Channel Allocation using Swarm Optimization
PSO	Particle Swarm Optimization
PSO-RAM	Particle Swarm Optimization based Resource Allocation
PUSC	Partial Usage Subcarrier
PU	Public User
PWL	Piece Wise Linear
PWS	Piece Wise Segment
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
Q-FCRA	QoS-based OFDMA femtocell resource allocation
QP-FCRA	QoS-based power control and resource allocation
RA	Resource Allocation
RAM-SC	Resource Allocation Model and Subcarrier Control.
RF	Radio Frequency
RRM	Radio Resource Management
RPR	Resource Priority Region
RSRP	Reference Signal Received Power
SA	Stand Alone
SI	Swarm Intelligence
SC	Subcarrier
SFR	Soft Frequency Reuse
SFL	Shuffled Frog Leaping

SI	Swarm Intelligence
SINR	Signal to Interference plus Noise Ratio
SMDP	Semi-Markov Decision Process
SNR	Signal to Noise Ratio
SP	Spectrum Partitioning
SP-PSR	Spectrum Partitioning Partial Subcarrier Reuse
SS-FSR	Spectrum Sharing Full Subcarrier Reuse
SU	Subscriber
TTI	Transmission Time Interval
TU	Time Unit
UE	User Equipment
UL	Uplink
WIMAX	Worldwide Inter-operability for Microwave Access
WWF	Weighted Water Filling
WWF-LR	Link Rate based Weighted Water Filling Algorithm
WWF-DE	Demand based Weighted Water Filling Algorithm

LISTE OF SYMBOLS AND UNITS OF MEASUREMENTS

α_f	Attenuation factor of indoor environments
α_m	Attenuation factor of outdoor environments
a_k	Constant of the segment k of PWS linear approximation
b_i	Allocated bandwidth for user i
$b_i^{s,k}$	Variable indicating that subcarrier s is allocated to user i in base station k
B	Available bandwidth
B_C	Bandwidth per channel
B_m	Bandwidth allocated to macro tier
B_s	Bandwidth per subcarrier
BW^{Total}	Bandwidth usage
C_z^{max}	Maximum capacity allowed of zone z
C_{conf}^{Total}	Total number of possible ways of grouping a set of FCs into disjoint clusters
C	Set of Cluster
$Cluster_{Int}^i$	Set of clusters that interfere with a stand alone FC i
d_{if}	Distance from FBS f to the mobile user i
d_{im}	Distance from MBS to the mobile user i
γ_k	Spectral efficiency of BS k
f_c	Carrier frequency
F	Number of Femtocell in the network
FC	Set of femtocell
FC_u	Set of femtocell that have better link conditions than the macrocell for the user u
FC^z	Set of femtocell located in the coverage of MC zone z
FC_c	Set of femtocell member of cluster c
I_{th}^f	Interference threshold allowed in femtocell f

$I_i^{s,FC}$	Co-tier interference per subcarrier s allocated to user i
I_{th}^m	Interference threshold allowed in macrocell
$I_i^{s,k}$	Perceived Interference in subcarrier s allocated to user i in BS k
λ	Arrival rate of mobile stations
l_{avg}^{mod}	Average spectral efficiency required per user taking into account that macro users are served by MC and subscribers served by their own FCs
l_z^{mod}	Number of bits of modulation in MC's zone z
l_f^{mod}	Number of bits of modulation in FC f
LS_k^{max}	Maximum value of the range of the segment k of the second PWS linear approximation
LS_k^{min}	Minimum value of the range of the segment k of the second PWS linear approximation
MS	Set of mobile stations
MS^z	Set of mobile stations per MC zone z
m_k	Slope of the segment k of PWS linear approximation
M_f	Maximum number of users at the femtocell
μ	Average Service rate of mobile stations
N	Number of mobile users in the network
N^f	Maximum number of users at the femtocell
N_0	Average Thermal Noise Power
N_s	Number of Subcarriers
N_c^{MAX}	Maximum Cluster Size
N_{SU}^j	Number of subscribers in cluster j
N_{PU}^j	Number of public users in cluster j
N_s^k	Number of Subcarrier per channel in BS k
P_i	Transmitted power for downlink communication of user i
$P_i^{s,k}$	Transmitted power for downlink communication on subcarrier s between user i and base station k

PL_i^k	Path loss for outdoor/indoor between BS k and user i
P_i^f	Transmitted Power for DL between FBS f and user i
P_i^m	Transmitted Power for DL between MBS and user i
$P_i^{s,f}$	Transmitted Power per subcarrier s in the DL between FBS f and user i
$P_i^{s,m}$	Transmitted Power per subcarrier s in the DL between MBS and user i
P_m^{Total}	Total transmitted power in MC
P_k^{Total}	Total transmitted power in femtocell k
P_z^{max}	Maximum transmitted power per user in macrocell zone
P_f^{max}	Maximum transmitted power per user in FCs
P_u^m	Power consumption in macrocell
$P_z^{s,m}$	Maximum transmitted power per subcarrier in macrocell zone z,
$P_{max}^{s,f}$	Maximum transmitted power per subcarrier in FC
P^{Total}	Power consumption
r_i^k	Link rate between BS k and user i
r_s	Reuse factor per subcarrier s
R_m	Radius in macrocell
R_f	Radius in femtocell
R	User Satisfaction
S	Subscriber Satisfaction
S_i	Requested demand of mobile user i
S_{avg}	Average demand in a given BS
S_c^z	Set of allocated subcarriers to current zone z
S_p^z	Set of allocated subcarriers to precedent zones of zone z
$SC^{SU,j}$	Set of subcarriers allocated to subscribers in the cluster j
SC^j	Set of subcarriers allocated to the cluster j
SC^{FT}	Set of subcarriers allocated to the femto tier

SNR^k_{min}	Minimum SNR value of the range of the segment k of PWS linear approximation
SNR^k_{max}	Maximum SNR value of the range of the segment k of PWS linear approximation
SNR^k_i	Signal to noise ratio for the downlink between BS k and user i
$SINR^k_i$	Signal to interference plus noise ratio for the downlink between BS k and user i
$SINR^{s,k}_i$	Signal to interference plus noise ratio for the subcarrier s in the downlink communication between BS k and user i
SNR_{target}	Target Signal to noise ratio
θ^f_i	Angle between user i's location and FBS f's location
θ^m_i	Angle between user i's location and MBS
T	Network Throughput
T_u	Type of user (1 Public users, 2 FC Subscribers)
W_l	Wall Penetration losses
w^f_i	Weight for the link between femtocell f and user i
w^m_i	Weight for the link between macrocell f and user i
x^f_i	User i is assigned to FC f
x^m_i	User i is assigned to MC
X^k_f	Femtocell f is a member of the cluster c
Y^k_i	User i allocation to BS k
Z_i	Area of macrocell OFDMA zone
Z	Set of macrocell OFDMA zones

INTRODUCTION

Wireless communications have followed four different paths of evolution: (1) New modulation techniques such as Long Term Evolution (LTE) and Worldwide Inter-operability for Microwave Access (WIMAX), (2) spectral efficiency enhancement by means of beam-forming or cognitive radio, (3) the transformation of voice centric services to information based services and (4) implementation of hierarchical wireless network architecture that consists of a traditional macrocell (MC) and several underlaid small base stations (BSs) such as picocell or femtocell (FC).

The use of Orthogonal Frequency Division Multiplexing (OFDM) as the radio interface technology and OFDMA as the multiple access scheme in the downlink (DL) is one common characteristic of both 4G networks. This choice was driven by some particular characteristics of OFDM and OFDMA that make possible to get high speed mobile wireless systems.

Network operators continue deploying additional base stations to satisfy the user data rate demands. The trend of reducing the BS size has lead to the femtocell technology. In particular, the macro-femtocell network seems to be the most promising two-tier architecture for network operators as it improves the coverage and capacity of a macrocell without incurring additional costs.

Femtocells are end-user base stations with low-cost and short-range that operate in a licensed spectrum with the operator's approval and connect mobile devices to a cellular operator's network using broadband connections. Femtocells offer improved indoor coverage with increased performance and broadband services. Nevertheless, as femtocells are installed in an ad-hoc manner without any frequency planning by network operators and due to their rapid and uncontrolled deployment, resource allocation (RA) and interference management have been identified as key issues of this type of network.

From the service provider's perspective, the spectrum allocation should be performed by a central resource manager entity running in their macro BS since it is their spectrum being used. On the other hand, the network operators are not willing to perform any additional radio planning and network dimensioning every time a new femtocell is sold. This means that it is desirable for femtocells to have capabilities of self-configuration and self-planning, which requires a distributed scheme. Therefore, the resource allocation for OFDMA macro-femtocell networks should find a compromise between centralized approach and distributed one. We believe that there is still an open research area, which consists of establishing a win-win scheme that addresses three important concerns in macro-femtocells networks, which are:

- resource allocation regarding hybrid access femtocells to improve network throughput and therefore the revenue of network operator;
- trade-off between macrocell resource usage efficiency and the fairness of the resource distribution among macro mobile users and femtocells;
- design a compensation mechanism based on the level of granted access to non-authorized users that encourage femtocell to form clusters in order to increase their throughput and to reduce the perceived interference.

In order to better understand these concerns, we describe the problems that we are going to address in this research in Section 0.2.

0.1. Motivation

Network operators are interested in deploying as many femtocells as possible with two main objectives: (i) improve indoor coverage and (ii) grant access to public users through them. However, current access control policies do not allow getting full benefit from FCs. Open access femtocells are usually deployed by the network operator because there is a lack of appropriate incentives that motivates the customers to buy open or hybrid access femtocells.

Most important issues related to femtocell deployment in a cellular network are presented in (Zhang and De la Roche, 2010), such as synchronization, security, access method, location, new applications and health issues. In this research work, we focus on three major critical issues that can be found in the literature as: resource allocation, interference mitigation and hybrid access mechanisms. We believe that there is still an open research area for resource management in two-tier cellular networks that provides a win-win scheme for the network operator and FC owners.

Nowadays, some research groups have focused on the mechanisms to motivate femtocells owners to deploy their FC using hybrid access policy because it can be used to solve several problems in the traditional cellular macrocell networks such as:

- providing high data rate service where macrocell cannot guarantee;
- reduction of macro-femto and femto-macro interference through the avoidance of having mobile users close to femtocell served by macrocell;
- reduction of dead zones for macro users created by the use of closed access femtocells.

Moreover, hybrid access policy should find a trade-off between the impact on the performance of FC subscriber transmissions and the level of access granted to non-subscribers (3GPP-TR-36.921, 2011). Therefore, FC resource sharing between subscribers and non-subscribers needs to be finely tuned. Otherwise, FC owners might feel that they are paying for a service that is being exploited by others.

Regarding hybrid access femtocells, the resource allocation problem becomes more complex because under this consideration any approach should also select the best suitable base station that can provide the required service by the mobile user based on some criteria such as the distance between BS and mobile users, link rate or signal strength. In any case, a centralized approach can provide an optimal solution while a decentralized approach has the advantage of running locally in each femtocell and making the decision faster.

In summary, this research work is motivated by the following:

- resource management should improve the area spectral efficiency;
- power control should be performed in both tiers in order to guarantee high data rates in FC;
- dense FC deployment requires changes in the current macro BS configuration to guarantee the quality of service (QoS) of femtocells transmissions.

0.2. Problem Overview

Resource allocation for OFDMA macro-femtocells network has been widely studied under different scenarios for FC networks with closed access control policy. The main concern of prior research work is the bandwidth allocation and power control in the femtocell network. There are few resource allocation approaches that take into account hybrid access femtocells. Some approaches are oriented on the benefits of having femtocells with this type of access such as interference reduction and network throughput maximization (Valcarce *et al.*, 2009). Another approach has considered a compensation mechanism that motivates femtocell to grant access to nearby public users (Chun-Han and Hung-Yu, 2011). However, none of these approaches perform the estimation of the data rate that femtocells can potentially provide to non-authorized users.

Some issues that need to be addressed with the introduction of hybrid access femtocells are: lack of appropriate BS selection if the public user is close to several femtocells, inefficient resource usage (i.e. bandwidth and power), lack of compensation mechanisms for femtocell that guarantees the subscriber satisfaction while granting access to public users, and the bandwidth starvation when the users are not fairly treated. In the following, we explain each one of these problems.

0.2.1 Lack of appropriate Base Station selection mechanisms

BS selection procedure is usually performed before running the resource allocation algorithm. Basically, this procedure chooses the BS with the best link conditions between the BS and the mobile user among all BSs (including the macro BS). In large FC deployment, the link conditions between FCs and mobile equipment might constantly be changing due to the interference of surrounding FCs or nearby macro users. Therefore, the resource allocation should include BS selection or at least some re-selection mechanism needs to be implemented in order to avoid blocking users due to the resources starvation in a particular BS, especially the FCs since they have limited capacity in terms of number of connected users.

0.2.2 Inefficient resource usage

The traditional power distribution among the macro users can lead to an inefficient power usage owing to the fact that the bandwidth allocated to macro tier might be less than the total available bandwidth depending on the spectrum allocation technique used for the two tier such as spectrum partitioning or sharing. For non-dense FC deployment, the enhancement of MC power distribution can be seen as the trade-off between the bandwidth allocated to femtocells and the requested demand of public users satisfied by each indiviual femtocell. In such a way, the MC transmitted power is distributed among the active downlink transmissions, which might use a portion of the available bandwidth.

As the market of femtocells is expected to grow rapidly in the few coming years (Infonetics, 2012), network operators have to deal with dense FC deployment and the spectrum partitioning is not longer a viable solution. Thus, universal subcarrier reuse needs to be investigated. Under this scenario, the cross-tier and co-tier interference will be present and both macrocell and femtocells should perform power adaptation to satisfy the signal to interference plus noise ratio (SINR) required in their downlink communications.

0.2.3 Lack of compensation mechanisms for FC

Hybrid access control policy is now included in (3GPP-TR-36.921, 2011). The hybrid access means that FCs can grant different access level for public users while keeping priority for their own subscribers. Thus, the unused resources can be shared with nearby public users. This can potentially benefit the overall system performance by reducing the interference caused by nearby public users due to their high transmitted power during the connection to the macrocell.

Nevertheless, FC should have the appropriate motivation to avoid denying the access to public user while keeping the QoS of subscriber transmissions. This can be any type of reward that depends on the level of access granted to public users. For example, adding extra resources for the subscriber transmissions as well as the resources to be allocated to the "visitor users".

0.2.4 Bandwidth Starvation

Clustering techniques have been recently introduced to reduce the complexity of resource optimization problem (Moon and Cho, 2013; Hatoum *et al.*, 2011) or to enhance the coverage area of the femtocell network (Huang *et al.*, 2012). Within a cluster, the co-channel interference is avoided by applying orthogonal subcarrier allocation among its members. If the bandwidth allocated to femto tier is fixed, then a higher cluster size implies the reduction of the bandwidth allocated per cluster member leading to the bandwidth starvation in femtocells. On the other hand, if the bandwidth allocated to femto tier is dynamically adapted as the cluster size increases, then the femto tier requires more subcarriers, which can lead to the resource starvation for macro users transmissions. Therefore, new clustering techniques should be investigated to balance the traffic load from public users among several clusters and to avoid the bandwidth starvation in any BS.

In summary, the resulting work should answer the following questions:

- How to enhance the power distribution efficiency in BSs under the non-dense FC deployment?
- How to improve area spectral efficiency for non-dense FC deployment enabling the full subcarrier reuse?
- How to motivate femtocells to form clusters in order to guarantee their own subscribers downlink transmissions?
- How to enable the bandwidth reuse among the two tiers or among FC clusters without starving the macrocell resources?

These questions will be answered by developing different models using different theories and working environments.

0.3. Objectives

The general objective of this research work is to contribute with practical solutions for resource allocation problem for OFDMA macro-femtocell networks. Therefore, the first main objective is to conceive, evaluate and develop optimal resource allocation models that are able to jointly perform BS selection and resource allocation (RA) per user in a two-tier network for non-dense and dense FC deployment. Resource allocation models should allocate bandwidth and power taking into account the user requirements and femtocell proximity. Moreover, such models should also satisfy the goals of maximizing the operator's profit while maintaining the QoS guarantees of femtocell subscribers.

The second main objective is to evaluate and develop practical solutions that reduce the complexity and the processing time of the resource allocation problem for dense deployment taking into account the user and femtocell locations and cluster formation. Thus, the resource optimization problem can be divided into subproblems and independently applied.

The two main objectives are decomposed into the following specific objectives:

- study and analyze the resource allocation problem for two-tier networks when hybrid access femtocells are involved and evaluate the trade-off between the contrasting performance metrics that are affected;
- develop a resource allocation model that optimizes the two-tier network throughput while enhancing the power distribution in BSs under the non-dense FC deployment using orthogonal bandwidth allocation among the two tier and between femtocells belonging to the same cluster;
- develop a resource allocation model that maximizes the network throughput while enhancing spectral reuse for non-dense FC deployment enabling full subcarrier reuse;

- develop a resource allocation model that maximizes the sum of the MC zone throughput while enhancing the spectral reuse for dense FC deployment taking into account user and FC locations;

- develop a low-complexity resource allocation model using alternative optimization tools and its integration with compensation mechanism for femtocells to form clusters if they grant access to public users.

0.4. Methodology

In this research, we study the problem of resource allocation using hybrid access femtocells. The resource allocation problem is addressed in two phases, as shown in Fig. 0.1.

In the first phase, we address the problem of optimizing resources for downlink transmission in a macro-femtocell network under non-dense femtocell deployment. The RA model should determine together the optimal serving BS, allocated bandwidth and the transmitted power per mobile user while satisfying their QoS. This phase consist of two components: the spectrum partitioning and spectrum sharing approaches. The former is appropriate non-dense deployment with orthogonal channel allocation or what we call noisy scenario and the latter is useful under the scenario with co-channel allocation. In a noisy scenario, we determine the total transmitted power required at the macrocell that enables the model: (1) to perform the power adaptation in order to maximize the two-tier network throughput, (2) to enhance the macrocell power distribution over the active DL transmissions taking into account the allocated bandwidth in the macro tier, and (3) to improve the tolerance to the noise. In the case of interference mitigation, we first analyze the two-tier network using fixed BS transmitted power and estimate the interference threshold that can be allowed in macrocell and femtocells without degrading the target SINR. Thus, the second resource allocation model determines the total transmitted power required in macrocell to perform the power adaptation in order to maximize the network throughput, to guarantee the target SINR for both tiers (i.e. macro and femto users) and to mitigate the interference in both tiers assuming full subcarrier reuse and femtocells deployed with hybrid access policy.

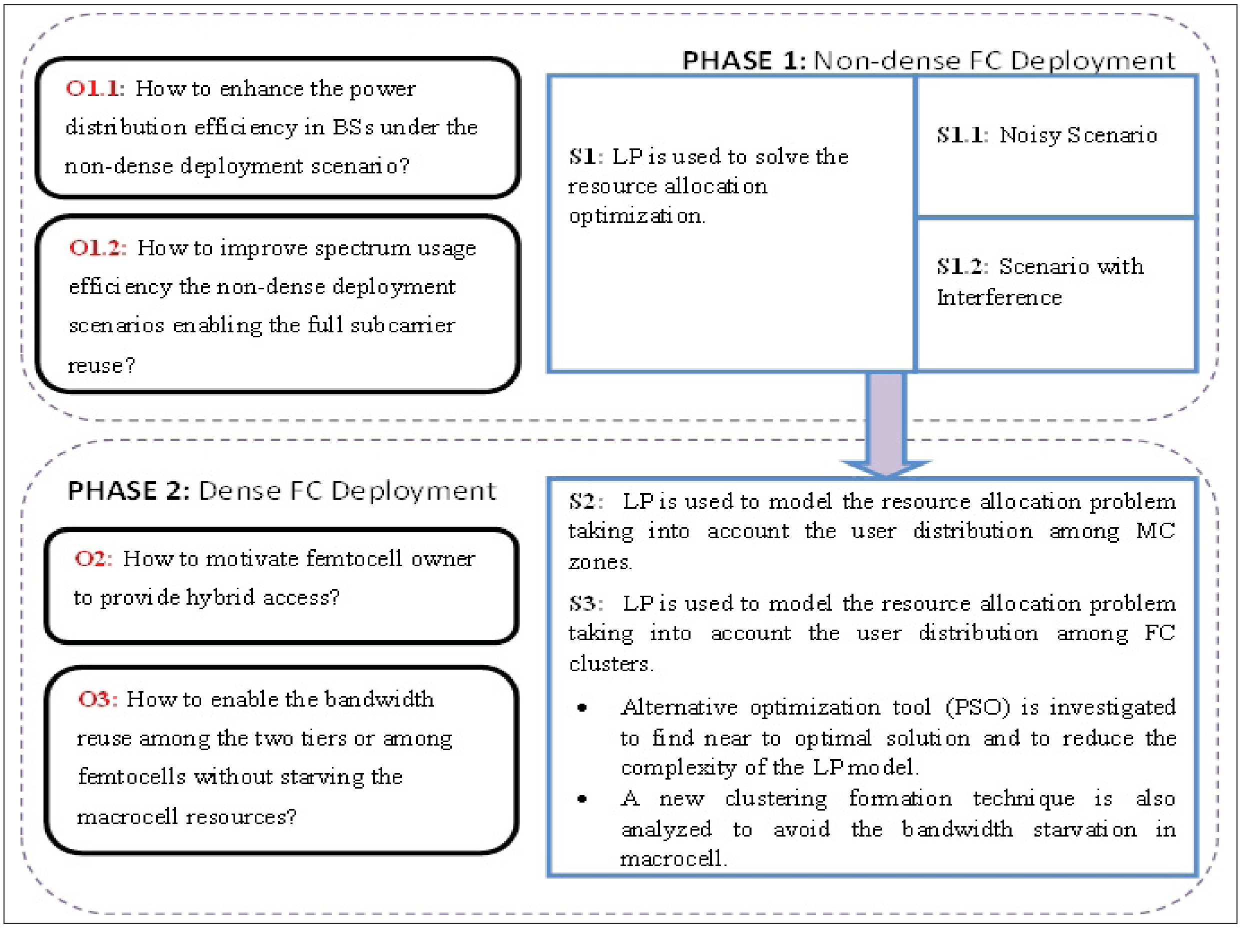


Figure 0.1 Mapping Objectives to Stages of Methodology

We propose to formulate every resource optimization problem using Linear Programming (LP), since this optimization theory has successfully been proved to deliver optimal metric in several fields. In fact, LP is considered a powerful tool that can be used to solve almost everything from airline scheduling to simple pricing problems. Moreover, our resource allocation problem can be modeled as a constrained optimization problem and LP is considered the most commonly applied form of constrained optimization (Chinneck, 2001).

The second phase attempts to reduce the complexity of the LP based resource allocation models. Therefore, additional techniques such as the division of the resource allocation problem into subproblems corresponding to each particular OFDMA macrocell regions are analyzed. Moreover, for each MC region, the RA subproblems can still be divided into smaller subproblems if FCs are associated to clusters. Thus, clustering techniques are also investigated in order to find or propose an appropriate clustering technique that motivates the FC owner to deploy their FC using hybrid access policy.

The cluster based resource allocation model should determine the optimal cluster configuration, base station selection and the amount of bandwidth and power allocation per mobile user. In this case, the optimization problem becomes more complex and requires higher processing time. Therefore, we propose the use of alternative optimization tools such as evolutionary methods, which have become a very popular research topic for solving real-time convex problems in recent years. The most commonly used methods are genetic algorithm (GA) and particle swarm optimization (PSO). GA has the advantage of being well-established due to its earliest introduction while PSO algorithm have started to attract more attention for continuous optimization problems. According to most recent research works, PSO outperforms GA on most of the continuous optimization problems (Kachitvichyanukul, 2012).

LP models are implemented using Visual Studio 2008, ILOG CPLEX 12.1 and Concert Technology 2.9. Matlab R12.a is used to implement the RA models using the alternative optimization tools.

In particular, the following elements are investigated and used throughout this research project:

a. Linear Programming to model the resource allocation problem that dynamically allocates bandwidth per tier, per cluster, per FC and per user;

b. Piece wise segment (PWS) linear approximation to convert the real-time convex problem into a linear problem.

c. Prioritization and fairness among the two types of user (femto subscribers and public users).

d. Power adaptation in both tiers to achieve the target SINR and to avoid depriving other DL transmissions.

e. Particle Swarm Optimization (PSO) as an alternative optimization tool for resource allocation model.

f. Cluster formation as a mechanism to reduce the complexity and running time of the RA model and also to motivate femtocells to become a cluster member.

0.5. Contributions and Novelty of the Thesis

Guided by the objectives presented in Section 0.3 and using the methodology proposed in Section 0.4, this thesis makes the following important novel contributions:

- joint BS selection and resource allocation models for non-dense deployment that performs orthogonal channel allocation or co-channel allocation among the two tiers and neighboring femtocells; prioritizes the use of FC for subscribers and public users close to FCs; and performs power adaptation to reach the SINR and to increase the tolerance to the noise and a given interference threshold;
- a low-complexity resource allocation model that fairly distributes the MC resources to the OFDMA zones given a particular user distribution and enables the subcarrier reuse between MC inner zone and FC located in outer MC zones and also between FC and macro users located in the same OFDMA zone;
- a heuristic resource allocation model that distributes the resources among macro users and the femto tier taking into account the average off-loaded traffic to the clusters at femto tier; and a novel clustering technique that keeps balanced clusters and motivates FC to become a member of a cluster.

0.6. Publications

Some of the contributions listed in Section 0.5 have been published, accepted or submitted for publication in different journals. The complete list of publications associated with this research work is presented below.

0.6.1 Journals

The two published journals (J1 and J2) corresponds LP models developed during the first phase of this research work and are presented in Chapters 2 and 3 respectively. As a result of the second phase, we have the accepted journal (J3) and the submitted journal (J4) that correspond to the low-complexity RA models and are included in Chapter 4 and 5.

Published

[J1] Estrada R., Jarray A., Otrok H. , Dziong Z., *Base station selection and resource allocation in macro-femtocell networks under noisy scenario*, Wireless Networks, Volume 20, Issue 1, January 2014, Pages: 115-131. (Impact Factor: 1.055, 5-year: 1.167)

[J2] Estrada R., Jarray A., Otrok H. , Dziong Z., Barada H., *Energy-Efficient Resource-Allocation Model for OFDMA Macrocell/Femtocell Networks*, IEEE Transactions on Vehicular Technology, Volume 62, Issue 7, September 2013, Pages: 3429-3437. (Impact Factor: 2.642, 5-year 2.667)

Accepted

[J3] Estrada R., Otrok H. , Dziong Z.,Barada H., *Spectrum Sharing Model for OFDMA Macro-Femtocell Networks*, Accepted at the special issue "Dynamism and Mobility Handling in Mobile and Wireless Networking" of the International Journal of Ad hoc and Ubiquitous Computing, March 2014, Inderscience. (Impact Factor: 0.900, 5-year 0.981).

Submitted

[J4] Estrada R., Otrok H. , Dziong Z., *Load Balanced Clusters and Resource Allocation for macro-femtocell networks*, Submittted to IEEE Transactions on Vehicular Technology, August 2014.

0.6.2 Conferences

The conference paper (C1) presents the performance evaluation of the RA model described in Chapter 3 with mobility incorporation under a FC dense scenario in one macrocell zone.

As an initial step for the RA model developed in Chapter 5, we demonstrated that for given BS selection, PSO can enhance the network throughput in comparison with Weighted Water Filling and the results were published in the conference paper (C2).

The RA approaches published in the conference papers (C3 and C4) are the results of the collaboration with a master student of the university where the co-director of this thesis currently works. In these conference papers, two resource allocation algorithms based on Genetic Algorithm (GA) were presented using orthogonal and co-channel allocation. To validate the results of GA based RA models, the models presented in Chapter 2 and 3 were used as reference.

Finally, the accepted paper (C5) proposes and evaluates a novel clustering technique that aims at balancing the public users and FC among the existing clusters taking into account the available FC capacity in terms of number of connected users. This clustering technique is modified and included in the proposed solution in Chapter 5.

Published

[C1] Estrada, R., Otrok, H., Dziong, Z., Barada, H., *Joint BS selection and resource allocation model for OFDMA macro-femtocell networks incorporating mobility*, International Conference on Selected Topics in Mobile and Wireless Networking (MoWNeT), Pages: 42-47, 19-21 Aug. 2013, Montreal,Canada.

[C2] Estrada, R., Otrok, H., Dziong Z., *Resource allocation model based on Particle Swarm Optimization for OFDMA macro-femtocell networks*, IEEE International Conference on Advanced Networks and Telecommuncations Systems (ANTS), 15-18 Dec. 2013, Chennai, India

[C3] Marshoud H., Otrok H. , Barada H., Estrada R., Jarray A., Dziong Z., *Resource allocation in macrocell-femtocell network using genetic algorithm*, WiMob, Pages: 474-479, 8-10 Oct. 2012, Barcelona, Spain.

[C4] Marshoud H., Otrok H. , Barada H., Estrada R., Dziong Z., *Genetic algorithm based resource allocation and interference mitigation for OFDMA macrocell-femtocells networks*, WMNC, Pages: 1-7, 23-25 Apr 2013, Dubai, United Arab Emirates

Accepted

[C5] Estrada R., Otrok H. , Dziong Z., *Clustering and Dynamic Resource Allocation for Macro-Femtocell Networks*, Networks 2014, Accepted July 2014.

0.7. Thesis Outline

The thesis is organized as follows: Chapter 1 presents the methodology tools and literature review related to the addressed problem, and explains how the chosen tools and theories were deployed in the prior works. Chapters 2-5 show the contribution of this research work.

Chapter 2: Base Station Selection and Resource Allocation model (BSS-RAM) [J1]

Chapter 2 studies the problem of optimizing resources for downlink transmission in a macro-femtocell network under non-dense FC deployment. In this part, we focus on the following issues: efficient MC power distribution and the impact of noise. This RA model maximizes the sum of the weighted user data rates. Two set of weights are evaluated: one related to the link conditions and one related to the demand. Both sets are used to prioritize the use of femtocells for subscribers and nearby public users. Two main issues are found in the LP model, which are: (1) the objective function contains the product of two variables, one binary and one real and (2) some nonlinear constraints. These issues are solved through the conversion of the real variable as the sum of binary variables and replacing the convex function by a linear approximation (Imamoto and Tang, 2008). A performance comparison with Weighted Water Filling (WWF) based resource allocation algorithm (Chun-Han and Hung-Yu, 2011) is presented.

Chapter 3: Energy-Efficient Resource Allocation model (Controlled-SC) [J2]

In Chapter 3, the problem under study is the resource allocation for non-dense FC deployment with co-channel allocation among the tiers. We focus on the following issues: (1) subcarrier granularity of the OFMDA technology, (2) enabling universal subcarrier reuse among the tiers and between neighboring FCs, and (3) adaptive power control to reach the target SINR per subcarrier and to minimize the cross-tier and co-tier interference. Here, a joint resource allocation with BS selection is proposed to maximize the network throughput enabling the subcarrier reuse subject to several constraints. Two important constraints of this model are related to the total transmission power per BS and a maximum transmitted power per subcarrier. This model presents one common issue with our previous model presented in Chapter 2, which is having nonlinear constraints. This inconvenience is solved using the same method.

For comparison purposes, three benchmark models are analyzed and developed using LP as well. The first model is the underlay spectrum sharing, which assumes the same value of transmitted power per subcarrier in each BS (including the macro BS). The second one is the controlled-underlay spectrum sharing that performs adaptive power control per subcarrier at femto tier. The third one corresponds to the model presented in Chapter 2.

Chapter 4: Spectrum Sharing Resource Allocation model (SS-RAM) [J3]

In Chapter 4, an approach based on the "divide and conquer" principle is presented. This approach divides the resource optimization problem into subproblems related to each OFDMA zone. To do so, the MC resources (i.e. bandwidth and power) are first distributed among the MC zones in accordance to the user distribution. Then, the set of users and femtocells is divided into disjoint subsets per MC zone. Thus, each MC zone runs independently RA algorithm that maximizes the sum of the achievable data rate of the users located in each OFDMA zone. By doing so, the time required to find the optimal solution is reduced. Subcarrier are shared among femtocell located in the same zone if they belong to different cluster, and between inner MC zone and femtocells located in outer MC zone such as the soft frequency reuse proposed in (Li *et al.*, 2012a). The LP algorithm is similar to the model presented in Chapter 3 with additional constraints for the subcarrier reuse inside FCs and the upper bound for the transmitted power per subcarrier for each MC zone to avoid the cross-tier interference over the reused subcarrier inside these FCs. The performance comparison is carried out with pure spectrum partitioning (i.e. the BSS-RAM model) and spectrum partitioning with partial subcarrier reuse under mobility incorporation.

Chapter 5: Load Based Clusters and Resource Allocation model (LBC-PSO) [J4]

Chapter 5 presents a resource allocation model using Particle Swarm Optimization technique and clustering scheme to balance the traffic load of public users and FCs among established clusters. We assume that the operator is willing to compensate FCs that grant access to public users. Thus, several subcarriers can be allocated to the FC cluster if a public user can be served by its members. The number of allocated subcarrier should be less than the required subcarrier number in macro tier due to the short-range transmission and higher than the required subcarriers in femto tier in order to distribute the remaining subcarriers among the FC subscribers. Subcarriers are orthogonally allocated between the two tiers and among the cluster members to avoid the cross/co-tier interference. The proposed solution consists of three components: BS selection algorithm to balance the traffic load among the clusters, cluster formation algorithm using a merging metric based on the available FC capacity, and heuristic RA algorithm that takes into account the cluster configuration and determine the number of required subcarriers per tier. The cluster formation algorithm is carried out if there are FCs working without joining any cluster (i.e. stand-alone mode) until the cluster members cannot obtain more extra subcarriers for subscribers. In this part, the benchmark model consists is a decentralized WWF based resource allocation and clustering technique takes into account the interference mitigation and bandwidth reduction of the cluster members.

Table 0.1 summarizes the RA models developed in this thesis and the mapping with the objectives, the novelty, the methodology used and results.

Finally, the thesis ends by conclusions that provide a summary of the addressed problems, the proposed solutions and the future research works.

Table 0.1 Summary of the Thesis Outline

Chapter(Model)	Objectives	Novelty	Methodology	Results
2 (BSS-RAM)	– Enhance the MC power distribution for spectrum partitioning approaches. – Increase the tolerance to the Noise. – Evaluate set of weights that prioritizes the use of FCs.	– BS Selection as a part of resource allocation algorithm. – MC power adaptation. – Estimation of the required MC transmitted power.	– PWS linear approximation to convert the RA problem into a LP. – Evaluation under scenarios with variable MC transmitted power and variable noise levels. – Complexity Analysis and MSE error estimation due to PWS linear approximation. – Estimation of the theoretical required MC transmitted power.	– Between 5% and 16% less power than WWF model to achieve the same user satisfaction. – 4 dBm noise increase degrades the user satisfaction in WWF model by 6% more than BSS-RAM model. – MSE error introduced is about 0.4 Mbps, which corresponds to 0.13 % of the total throughput for 50 users. – Weight set to prioritize the use of FCs indeed reduces the running time.
3 (Controlled-SC)	– Enhance the power distribution and spectrum reuse per subcarrier. – Increase the tolerance to the Noise. – Minimize the cross-tier and co-tier interference.	– BS Selection as part of resource allocation algorithm. – Power adaptation in both tiers. – Subcarrier Granularity. – Universal subcarrier reuse among all BSs.	– Interference threshold estimation for both tiers. – PWS linear approximation that convert the problem into to LP. – Limitation of the cross-tier and co-tier interference to the first segment of PWS linear. – Evaluation under scenarios with incremental capacity and different FC user density. – Complexity Analysis and MSE Error estimation.	– A throughput gain around 14% and 31% compared to underlay and controlled-underlay models. – 5dB less MC power consumption in comparison underlay and controlled-underlay models. – A user satisfaction gain between 5% and 9% compared to the controlled-underlay model. – Femto tier is able to reuse up to 48% of the available bandwidth.
4 (SS-RAM)	– Combine spectrum partitioning and spectrum sharing to improve the spectrum reuse in femto tier. – Enhance the power distribution per subcarrier to achieve the target SINR. – Reduce the complexity and running time of the LP algorithm.	– BS Selection included in resource allocation algorithm per zone. – Subcarrier Granularity. – Orthogonal subcarrier allocation among the MC zone and FC located in the same zone. – Subcarrier reuse among inner MC zones and FC located in outer MC zones controlling the maximum power transmitted per zone.	– RA problem is divided into sub problems taking into account users distribution per zone. – PWS linear approximation to convert the problem into to LP. – New constraint to ensure the subcarrier reuse of inner MC zones inside FCs. – New constraint to perform full subcarrier reuse of the subcarrier allocated to the zone. – Mobility incorporation. – Evaluation under scenarios with incremental capacity and different FC user density. – Complexity Analysis.	– 75% of throughput gain compared to pure SP. – Around 32% more connected users. – Reduces the handover ratio and call dropping ratio by up to 3% and 2% respectively. – Running time around 3 sec for 30% of mobile users in the vicinity of 40 FCs.
5 (LBC-PSO)	– Improve the bandwidth usage by means of adaptive bandwidth allocation per tier. – Avoid the cross-tier and co-tier interference within a FC cluster. – Minimize the inter-cluster interference. – Enhance the subcarrier reuse for FC belonging to different clusters. – Incorporate incentives for FC to form part of a cluster.	– Base Station Selection procedure to balance the traffic load of public users among the clusters. – Subcarrier Granularity. – Resource allocation algorithm based on alternative optimization tools. – Clustering based on the satisfied demand of public users served by FCs and number of femtocells in current clusters.	– BS selection based on the link conditions and current cluster configuration. – RA algorithm is divided into two subproblems per tier. – PSO based RA algorithms with a parameter-less scheme. – Bandwidth adaptation per tier taking into account the maximum resources required by clusters. – Evaluation under scenarios with incremental traffic load and variable FC density. – Complexity Analysis	– MC power consumption is reduced by 3 dB due to access granted to public users by FC. – Improves the bandwidth usage efficiency in 9% compared WWF. – Improves the throughput in about 28 % – Enhance the SU satisfaction up to 40%. – Between 20% and 100% more extra resources when compared to IMBR-PSO.

CHAPTER 1

LITERATURE REVIEW

This chapter provides a brief presentation to the tools and theories used to achieve the research objectives, and the related work in the literature.

1.1 Optimization Tools

Resource allocation models can be formulated as constrained optimization problems, with an objective function that should be maximized or minimized subject to several constraints that correspond to physical restrictions of the network. Some possible objective functions are: capacity, coverage, energy consumption, QoS, fairness, spectrum usage, etc. To solve the RA optimization problem, some optimization tools are more suitable than others, which depends on several factors, such as the formulation itself, the possibility of the linearization of the objective function and the possibility of relaxation of the constraints. We mainly target the resource optimization problem as the maximization of the two tier network using Linear Programming in Chapters 2-4. In Chapter 5, an alternative optimization tool is used due to the complexity of the mathematical modeling. Below, we present brief high-level definitions of the optimization tools and theories that are used in this work.

1.1.1 Linear Programming

Linear Programming (LP) has successfully proved to deliver optimal solutions in various field that include economics, energy, manufacturing, routing, etc. In fact, LP has been widely used to solve resource optimization problems for different types of networks.

For constrained optimization problems, LP is the most-widely applied optimization theory. Compared to the unconstrained problems, solving a constrained optimization problem is more challenging, as it adds more restrictions to the desired optimality point (Chinneck, 2001). Hence, the optimal solution in a constrained problem does not necessarily mean a point of the peak or the valley, as it could be at somewhere in between bounded by the objective functions and the constraints.

Building up a constrained optimization model requires the clear definition of the following five components:

Decision Variables or Output Parameters: These variables are unknown when you start the problem. They usually represent things that can be adjusted or controlled. The goal is to find the best values that optimize the objective function.

Problem Data or Input Parameters: These are values that are either given or can be simply calculated from what is given.

Objective Function: This is a mathematical expression that combines the variables to express the goal. It will be required to either maximize or minimize the objective function. This objective function can be subject to several constraints.

Constraints: These are mathematical expression that combine the variables to express limits on the possible solutions. LP cannot handle arbitrary restrictions: the restrictions have to be linear. This means that a linear function of the decision variables can be related to a constant, where related can mean less than or equal to, greater than or equal to, or equal to.

Variables Bounds: This corresponds to the upper bound or lower bound of the decision variables, which can be also written as restrictions or constraints.

Linear Programming is not successful solving - problems with large number of variables and non-linear objective functions. Solving such problems may be time-consuming and impose high complexity. These difficulties related to mathematical optimization on large-scale problems have contributed to the development of alternative solutions. Below we present a brief description of the most commonly used evolutionary optimization methods and the reason for the selection of the alternative optimization method used in Chapter 5.

1.1.2 Evolutionary Optimization Methods

Evolutionary optimization methods are based on the principles of natural evolution and genetics. Owing to their efficiency and simple underlying principles, these methods are used in the context of problem solving and optimization. The common principle behind any evolutionary method is the same: given a population of individuals, the environmental pressure causes natural selection and the fitness of the population is growing. Thus, given an objective function to be maximized, we can randomly create a set of candidate solutions and use the objective function as an abstract fitness measure (Blum, 2013). In (Kachitvichyanukul, 2012), three similar and popular evolutionary methods are compared. These methods are genetic algorithm (GA), particle swarm optimization (PSO), and differential evolution (DE). GA has the advantage of being well-established because of its earlier introduction while PSO and DE algorithms are recent and have attracted the attention especially for continuous optimization problems. From their work, PSO and DE presents several advantages in comparison with GA. Moreover, it can be noticed that PSO presents two advantages over DE, which are the high influence of best solution over the population and the ability of homogeneous sub-grouping that can improve convergence time.

The authors of (Elbeltagi *et al.*, 2005) presented a comparison of five evolutionary-based optimization methods, which are: GA, PSO, Ant colony optimization (ACO), memetic algorithm (MA) and shuffled frog leaping algorithm (SFL). However, MAs is a variation of GAs that applies local search on chromosomes and offsprings, ACO is suitable for discrete problems and SFL is combination of two techniques: the local search of the PSO technique and the competitiveness mixing of information of the shuffled complex evolution technique (Amiri *et al.*, 2009). According to their results, PSO method was generally found to perform better than other algorithms in terms of success rate and solution quality, while being second best in terms of running time.

In the following sections, we briefly describe the basic concepts of the evolutionary methods that are combined and used in the cluster based resource allocation presented in Chapter 5.

1.1.2.1 Genetic Algorithm (GA)

In genetic algorithm, the solutions are represented as chromosomes. Each chromosomes is evaluated for fitness values and they are ranked from best to worst based on fitness value. The process to produce new solutions is accomplished through repeated applications of three genetic operators: selection, crossover, and mutation (Blum, 2013). The best chromosomes are selected to become parents to produce new chromosomes for the next iteration population. To simulate the survivor of the fittest, the chromosomes with better fitness are selected with higher probabilities than the chromosomes with poorer fitness. The selection mechanism chooses individuals for reproduction according to their fitness. Thus, the crossover operator combines the chromosomes of the parents to produce perturbation of old solutions. Since stronger individuals are being selected more often, there is a tendency that the new solutions may become very similar after several generations, and the diversity of the population may decline. In order to avoid this effect, the mutation mechanism serves to inject diversity into the population (Zalzala and Flemming, 1997).

There are several variants of GA, which are basically related to the chromosomes representation, how the operators are applied to the populations, and variation on any of the operations involves in the process of new solutions generation (Zalzala and Flemming, 1997). Despite GA is well-established because of its earlier introduction, PSO algorithm has attracted more attention especially for continuous optimization problems such as the resource allocation in OFDM cellular systems presented in (Gheitanchi *et al.*, 2010) or for femtocell networks in (Shahid *et al.*, 2013).

1.1.2.2 Particle swarm optimization (PSO)

Particle Swarm Optimization is a population-based search approach that depends on information sharing among the population members to enhance the search processes using a combination of deterministic and probabilistic rules (Bratton and Kennedy, 2007).

PSO has three main components: particles, social and cognitive components of the particles, and the velocity of the particles. In a problem space where there may be more than one possible solution and the optimal solution of the problem is required, a particle represents an individual solution to the problem. The learning of the particles comes from two sources, one is from the particle's own experience called cognitive learning and the other source of learning is the combined learning of the entire swarm called social learning. Cognitive learning is represented by personal best solution and social learning is represented by the global best value. The personal best solution is the best solution the particle has ever achieved in its history. The global best value is the best position the swarm has ever achieved. The swarm guides the particle using parameter global best value. Together cognitive and social learning are used to calculate the velocity of particles to their next position.

When applied to optimization problems, the PSO algorithm starts with the initialization of a number of parameters. One of the important initializations is selecting the initial swarm. The number of particles in the swarm depends upon the complexity of the problem. An initial choice of solutions can be randomly generated. However, an initial guess that spreads the particles uniformly in the solution space can speed up the emergence towards an optimal solution.

There are also several variations of the basic PSO algorithm, which corresponds to parameters changes (i.e. inertia, cognitive or social learning) or combination of PSO with other evolutionary optimization technique. These variations are intended to improve the convergence speed, solution quality, convergence ability or search space exploration and exploitation (Santos *et al.*, 2012; Blum, 2013). A study of the diverse variations of PSO applied to real world complex optimization problems is presented in (Geetha, 2013).

In summary, PSO has the following advantages:

- there are not many parameters to be adjusted;
- PSO is faster and can deal with many kinds of optimization problems with constraints;
- there is no limit to the objective and constraints.

1.2 OFDMA Technology Overview

Nowadays, two proposals for 4G standards are accepted by ITU as fully compliant with IMT-Advanced specifications, which are 3GPP LTE-Advanced and IEEE WirelessMAN-Advanced (Alden, 2012). A common characteristic is the use of Orthogonal Frequency Division Multiplexing (OFDM) as the radio interface technology and OFDMA as the multiple access scheme in the downlink.

OFDM divides a broadband channel into multiple parallel narrowband subcarriers. Each subcarrier carries a low data rate stream. This has two main advantages: the system has higher immunity to frequency selective fading, and if the system bandwidth is large enough, the sum of data rate streams lead to a high data rate transmission. In addition, the reception of an OFDM signal requires only a Fast Fourier Transform (FFT), which can be implemented with reasonable computational complexity in the user equipment (Yang, 2010).

OFDM based systems have the multiuser diversity capability, which means that the users have different channel qualities with respect to the subcarriers. This diversity can be fully exploited by OFDMA, because it allows multiple users to transmit simultaneously on different subcarriers. Besides that, OFDMA takes advantage of the frequency diversity, allowing each subcarrier to use a different Modulation and Coding Scheme (MCS) or a particular power level. Since OFDMA resources are also fragmented in the time domain, users can access the system in different time slots. Finally, the parallel nature of the OFDM multiplexing is specially suitable for Multiple Input Multiple Output (MIMO) schemes.

To exploit the flexibility offered by OFDMA and to achieve the challenging requirements of 4G systems, efficient resource management techniques play an important role. If the base station knows the channel state information (CSI) of the different users, then, adaptive allocation mechanisms can be used to allocate the limited resources, e.g. bandwidth and power, in an intelligent and dynamic way that maximizes the performance metrics. Therefore, the problem of allocating time slots, subcarriers, rates, and/or power to the different users in an OFDMA system has been an active area of research.

In downlink, the subcarriers are divided into resource blocks which empower the system to be able of arranging the data across standard numbers of subcarriers compartment wise. Resource blocks consists of 12 adjacent subcarriers in LTE, one slot in the time frame irrespective of the general LTE-A femtocell signal bandwidth. For LTE-A, it can be understood that dissimilar signal bandwidths will have diverse numbers of resource blocks. Furthermore, the sub-frames are assembled in 10 ms radio frames, which holds two 5 ms halves containing the signals essential to acquire the physical identity of the cell (3GPP-TR-136.913, 2011).

1.3 Femtocell Overview

Femtocells are low cost and short range base stations. They can be installed by the consumer for better indoor voice and high-rate data services. Femtocells provide cellular service to mobile users with the network operator's approval and connect them to the core network through broadband connections (e.g, ADSL, fiber, etc.). They require short range wireless communications between mobile user and femtocell as shown in Figure 1.1. In addition, femtocells off-load traffic from macrocell, releasing capacity to offer to incoming users and decrease the capital and operating expenditure for the network operator (Zhang and De la Roche, 2010).

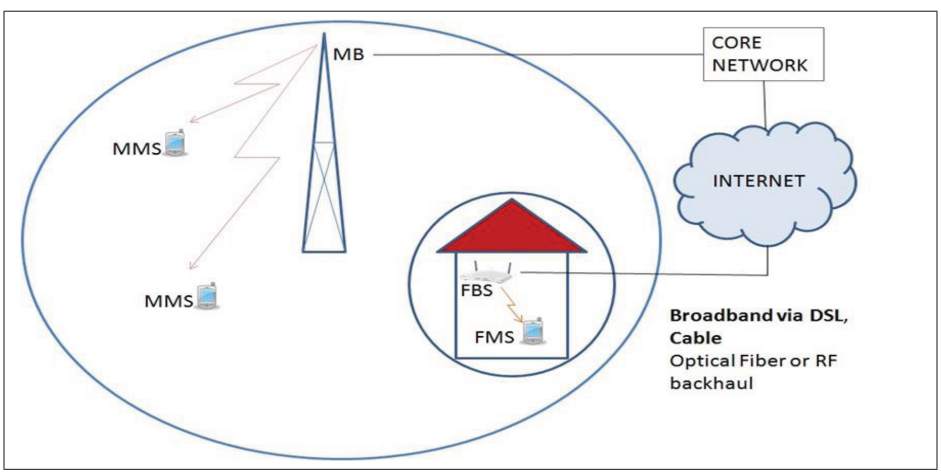


Figure 1.1 Two-tier cellular Network

Nowadays, cellular providers deal with two-tier hierarchical networks. The first tier corresponds to conventional cellular network consisting of multiple macrocells and second tier comprises the femtocell network.

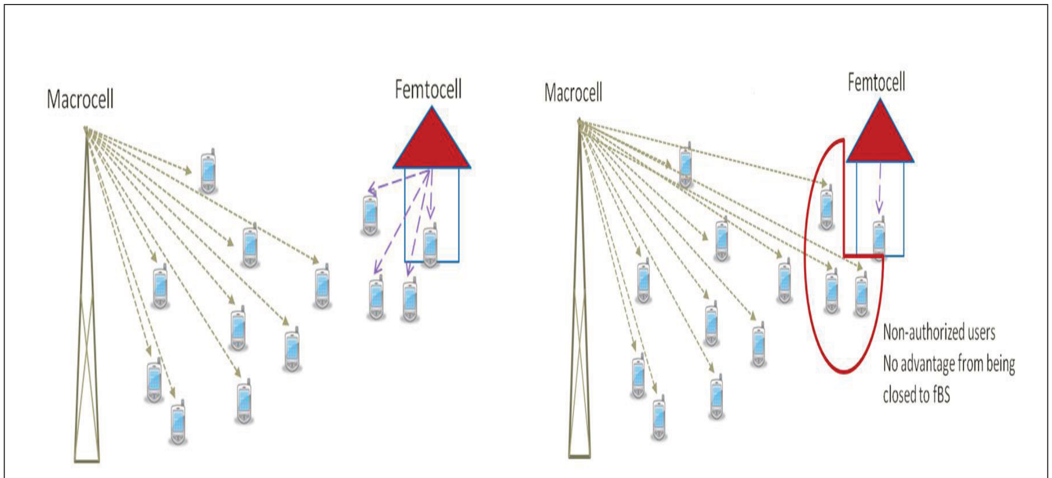
The most important issues related to femtocell are introduced in (Zhang and De la Roche, 2010; Boccuzzi and Ruggiero, 2011). We summarize them as synchronization, security, access method, location, new applications and health issues and proposes several possible solutions. Nevertheless, this work focuses only on three major critical challenges which are strongly related such as: resources allocation, interference mitigation and hybrid access policy.

In the following section, we describe some basic concepts about femtocells which are required to understand the basics of the access control policy.

1.3.1 Access Control Policies

There are three main different access control policies: Open Access, Closed Access and Hybrid Access. In the first one, every client of the cellular operator can connect to the femtocell. In the second one, only authorized clients can connect to the femtocell. Figure 1.2 depicts how the connections are carried using the first two access modes. According to the closed access femtocell, users can be classified as subscribers (i.e. authorized FC user) and non-subscribers or public users.

The third access policy is the hybrid one, which is a promising technique that allows to reduce the interference perceived by femto users by granting access to nearby public users. However, it requires that resource allocation model also determines the best suitable serving base station per user in order to enhance the wireless network capacity. Femtocell research groups are still working on the specifications of the necessary mechanisms to incentivize the femtocells owners to grant access to public users (3GPP-TR-36.921, 2011).



a) Open Access Femtocell b) Closed Access Femtocell

Figure 1.2 Access Control Policies for Femto Base Stations

1.3.2 Hybrid Access Femtocells

Hybrid access femtocells are included in (3GPP-TR-36.921, 2011) and they may provide different service levels to mobile users that are members of the femtocell and non-authorized users. For the scenario where femtocell shares subcarriers with macrocell, the interference management considerations are different between closed and hybrid access modes. For closed access mode, the femtocell resources (e.g. resource blocks) are selected as a trade-off between performance of the femtocell/subscriber transmissions and interference caused to the macrocell/macrousers transmissions. For the hybrid access mode the trade-off is between overall system performance, and resources consumed at the femtocell by public users (i.e. non-authorized users).

For hybrid access femtocells, non-authorized users can consume some resources which depend on the number of non-authorized users and the service level provided to them. One possible method of managing the resources used at a FC for non-authorized users is to reserve some FC resources for use by non-authorized users as in (Valcarce *et al.*, 2009). For close access mode, femtocells should reduce their transmitted power in order to mitigate the interference caused to nearby macro users, which degrades the FC subscribers capacity. Regarding the hybrid access mode, femtocell that accepts public users as temporary users, degrades also the subscribers capacity in terms of the bandwidth reduction. In the case that femtocells fulfill their capacity, non-authorized users should be blocked first or handover to macro BS. These diverted public users that are still within the vicinity of the hybrid access femtocell may experience strong interference from the femtocell transmissions if they are sharing the licensed spectrum.

In order to manage resource and mitigate the DL interference of the hybrid access femtocells, a method called Resource Priority Region (RPR) can be used which guarantees a small percentage of femtocell resources for non-authorized users as shown in Fig. 1.3.

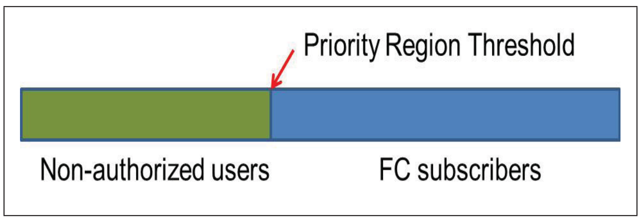


Figure 1.3   Resource Priority Region

The Priority Region Threshold (PRT) serves to separate resources between two priority regions, which means that non-authorized users have priority access over the green part of Fig. 1.3 whereas subscribers have priority access to the blue part. Moreover, the PRT could be time or physical resource block, and PRT could be statically or dynamically adjusted by exchanging Inter-Cell Interference Coordination (ICIC) messages between femtocell and macro BS (3GPP-TR-36.921, 2011).

The optimum power settings for hybrid access femtocells is set as a compromise between the overall system performance versus resources used at the femtocell by non-authorized users. Measurements from neighbor femtocells can be made by each femtocell to set the appropriate downlink transmitted power. However, the propagation conditions between a neighboring FC and its associated mobile users may differ significantly from the propagation conditions where the measurement took place. In addition, the propagation conditions between the femtocell and nearby non-served users are not known by femtocells. These differences introduce uncertainty when estimating the coverage of femtocell and neighboring femtocells to non-served users.

Hybrid access femtocell can obtain accurate measurements of their local environment by means of requesting measurement reports of reference signal received power (RSRP) from both the source and target FCs when the mobile user hands-in or registers with the FC. In this way, the femtocell can determine if the hand-in or re-selection is due to (1) the poor signal from the source femtocell or (2) high interference from the femtocell. This would allow the femtocell to determine its maximum transmitted power appropriately. In the case with the poor signal from source BS, femtocells could use a relatively high power or provide relatively high access priorities for non-authorized users in femtocell (3GPP-TR-36.921, 2011).

1.4 Resource Allocation for OFDMA system

The resource allocation for OFDMA based cellular networks corresponds to a multidimensional problem, since different domains such as time, frequency, power and spatial, should be efficiently used. Efficient resource allocation algorithms are essential to provide considerable gains in coverage, capacity and QoS for OFDMA based wireless networks. From the network operators' point of view, the benefits are improved coverage, capacity and QoS represent higher profit and better investment return rates. For the customers' perspective, this will improve the mobile services, including fairness and QoS levels with availability at lower prices.

A resource allocation algorithm is responsible for the efficient resources usage of the air interface of a given cellular network. Its functionalities are decisive to guarantee the QoS requirements of different service classes, the coverage optimization, the maximization of the network throughput, the capacity increase and the provision of acceptable fairness in the resource and QoS distribution among the mobile users.

There are many RA algorithms available for OFDMA based cellular systems. Below, we present a brief description of the most well known approaches:

Adaptive or Dynamic Subcarrier Allocation (DSA): The spatial selectivity of the subcarriers is related to the multiuser diversity and gives the opportunity of assigning different subcarriers to different users. DSA algorithm explores this flexibility and determines the pairs users/subcarriers according to a given resource allocation policy, which can be related to the service class or users priority (Bohge *et al.*, 2007).

Adaptive Power Allocation: Each subcarrier can present different channel gain depending on frequency, time and multiuser diversity. Therefore, it is worth to dynamically adapt the power of each subcarrier taking into account all these parameters, (Zhang and Leung, 2009).

Adaptive Modulation and Coding (AMC): This technique exploits the time and frequency diversities in order to allocate the most suitable MCS to each subcarrier according to its SNR. This technique is also know as bit loading (Fantacci *et al.*, 2009).

Dynamic Frequency Planning (DFP): This approach was proposed to mitigate the inter-cell interference in hierarchical macrocell networks as Fractional Frequency Reuse (FFR) (Assaad, 2008). It is also possible to use frequency planning in order to determine the amount of sub-carriers to be allocated to users or base stations as a prior step before the final assignment of sub-carriersśubsets to the end-users. This scheme is also applied in a macro-femtocell network since they can be seen as a hierarchical networks in (Kim and Jeon, 2012; Tariq *et al.*, 2011).

Interference Management: This strategy consists of low-level RA algorithms in order to manage the interference in the system. In the particular case of a two-tier macro-femtocell network, the possible types of interference to be managed are: macro-to-macro, macro-to-femto, femto-to macro and femto-to-femto.

1.5 Resource Allocation for OFDMA Macro-femtocell Networks

A classification of the different approaches that can be adopted to manage the OFDMA sub-channels in a macro-femtocell network are schematized in Fig. 1.4, which is a modified version of the original classification given in (Lopez-Perez *et al.*, 2009).

To completely eliminate the cross-tier interference, an approach that divides the licensed spectrum into two dedicated parts is proposed in (Chandrasekhar and Andrews, 2008). This approach is known as spectrum partitioning approach. In this way, a fraction of the subcarriers

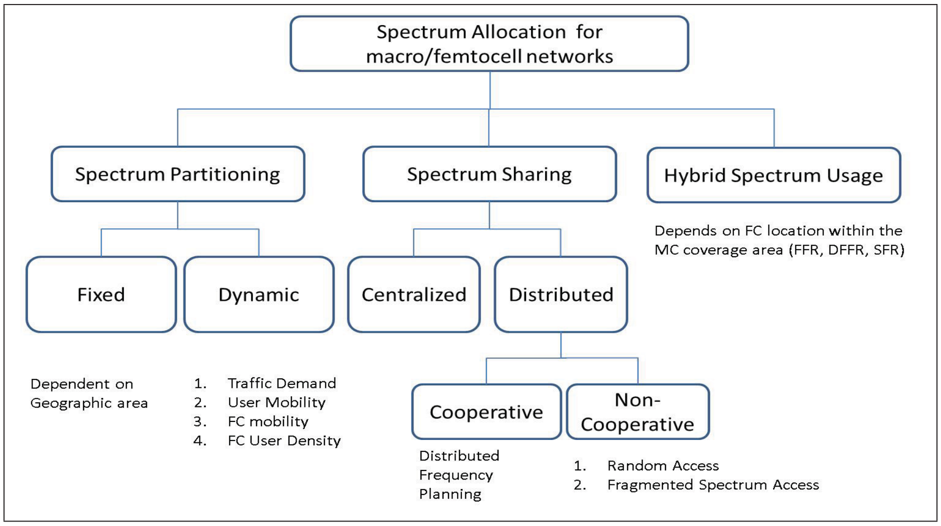


Figure 1.4 Classification of subcarrier allocation techniques for OFDMA macro/femtocells

would be used by the macro tier while another fraction would be used by the femtocells as shown in Fig. 1.5a. However, this approach is inefficient in terms of spectrum reuse. In fact, the main concerns of this type of approaches are the efficient power distribution over the active DL transmissions per BS and the prioritization of the macro communications over femto communications.

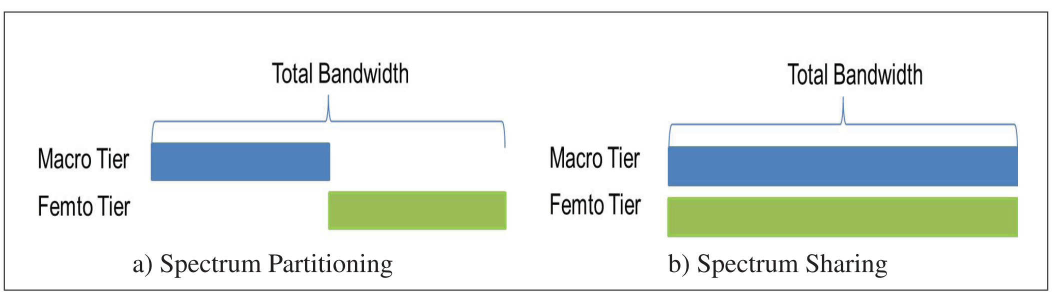


Figure 1.5 RA allocation categories

Co-channel allocation for both tiers seems to be more efficient and profitable from operators' perspective, although more challenging from the technical point of view. This means that the whole license spectrum can be simultaneously used among the tiers as shown in Fig. 1.5b (Kang *et al.*, 2012). This approach is also known as spectrum sharing and is recommended for dense FC deployment but it requires interference management schemes to uphold Quality of Service (QoS) of downlink (DL) or uplink (UL) communications and to improve the spectrum efficiency.

Hybrid spectrum usage approaches combine the spectrum sharing and spectrum partitioning approaches depending on the FC location. Some examples of hybrid spectrum usage are:

- Fractional Frequency Reuse (FFR) divides the entire frequency spectrum into several sub-bands, which are differently assigned to each macrocell or femtocells located in a subarea of the macrocell in such a way that the resources for femtocell are not overlapped with the overlaid macrocell resource (Lee *et al.*, 2010b).
- Dynamic or Adaptive FFR determines the frequency reuse for femtocells coupled with pilot sensing to reduce cross-tier/co-tier interference between macrocell and femtocells. The macrocell uses a frequency reuse factor of three or above and each femtocell sense the pilot signals from the macrocell and discard the sub-band with the largest received signal power, and thus FCs use the rest of the frequency sub-bands resulting in an increased SINR for macro UEs. The overall network throughput is enhanced by adopting high order modulation schemes (Kim and Jeon, 2012).
- Soft frequency reuse (SFR) divides also the system bandwidth into sub-bands. The frequency bands are assigned to FCs using a soft frequency reuse technique in inner regions of multiple macrocells. The distance to the boundary of the MC inner region is adaptively determined to the achieve the required demand of the cell-edge user (Li *et al.*, 2012a).

One important concern of a RA approach for OFMDA macro-femtocell networks is its complexity, which can be categorized into two types: (1) computational complexity and (2) implementation complexity. The computational complexity of an RA algorithm refers to the processing time required to execute the algorithms at the BS. On the other hand, the implementation complexity refers to the amount of signaling overhead and information exchange between BSs (Lee *et al.*, 2014). As dense FC deployment is expected in wireless networks in the near future, traditional RA approaches may not be feasible due to excessive signaling overhead between BSs. Moreover, the computational time of an RA algorithm should be kept within a resource block period, since resource allocation among UEs is performed for every TTI in the OFMDA systems (Yang, 2010).

In the following, we provide a detailed analysis for the related work in the literature that intersects with the addressed problems, and the proposed methodology.

1.5.1 Linear Programming based Resource Allocation models

In this section, we present the related work using linear programming found in the literature.

The optimal distance for the inner region of macrocell using fractional frequency reuse RA approach was deduced in (Assaad, 2008). In this scheme, fixed transmitted power per macrocell and femtocell is assumed. However, this scheme solve the resource allocation for an environment with multi-macrocells, where the neighboring macrocell are restricted to use only a sub-band of the whole licensed spectrum which means a reduction of spectrum reuse for multicell environments.

In (Le *et al.*, 2012), a joint load balancing and admission control scheme for OFDMA-Based Femtocell Networks is presented. In their work, the admission control problem is formulated based on a Semi-Markov Decision Process (SMDP) and a Linear Programming (LP) solution is proposed to address the minimization of the blocking probability to obtain the optimal admission control policy and the traffic load for each femtocell. Then, a power adaptation algorithm is applied in each FC to reduce the co-tier interference achieving better femtocell throughput and more energy-efficient operation of the femtocell considering the variety of traffic load in the femtocell network. The authors claim that efficient admission control policy is needed to coordinate spectrum sharing and admission control decisions for both types of users (public users and subscribers), which should find a trade-off between achieving high spectrum utilization and protecting QoS subscriber requirements. However, the main disadvantages of this scheme are the lack of the motivation for FC to grant access to public users, the power adaptation is not performed together with the bandwidth allocation in the femtocell network, and the BS re-selection procedure is not established for the case when public users are blocked by the femtocell network.

A hierarchical three-stage RA solution is presented by (Sadr and Adve, 2012) that consists of: (1) the load of each FC is estimated considering the number of connected users, their average channel gain and required data rates; (2) the physical resource blocks (PRBs) are allocated to FCs taking into account each FC load in such a way that minimizes the interference by coloring the modified interference graph; and (3) the resource allocation is formulated as a convex max-min fair optimization problem. This optimization problem is converted to linear program by using a simplified alternative that equally distributes the total FC transmitted power among the channels. However, equal power distribution among the channels converts the problem into the bandwidth optimization problem.

Subcarrier/Subchannel allocation has been investigated with several objective functions for OFDMA macro-femtocell network under the assumption of equal power distribution per bandwidth unit. For example, the work in (Hatoum *et al.*, 2011) solves the subchannel allocation within a cluster using Linear Programming for a given cluster configuration using equal power distribution among the DL channels.

In (Hatoum *et al.*, 2012a), two joint power and bandwidth allocation algorithms are proposed for femtocell networks and implemented using Linear Program, one for subscribers and one for visitor users in a FC cluster. The first model minimizes the power consumption while guarantee the QoS of subscriber while the second model minimizes the power consumption and the degradation of the public user demands. Their research work focuses only on the femtocell network having the subscribers as high priority users and public users as best effort users with different types of applications.

It can be noticed that the optimization problem for the BS selection together with joint bandwidth and power allocation has not been investigated.

1.5.2 Resource Allocation models using alternative optimization tools

In this section, we describe some approaches that utilize an evolutionary technique as optimization tool to reduce the computational complexity of the resource allocation problem in OFDMA two-tier networks.

In (Reddy and Phoha, 2007), one approach that applies genetic algorithm in multi-user OFDMA systems and performs adaptive power and subcarrier allocation. In this scheme, the subset of subcarriers to be assigned to each user and the spectral efficiency per each assigned subcarrier on downlink transmission are determined aiming at the minimization of total transmission power.

Genetic Algorithm is applied for the resource allocation in multi-user cellular OFDMA networks aiming at the maximization the average system throughput over a given period of time while guaranteeing the variety of QoS user request (Zhou *et al.*, 2011). However, GA had not been applied for the resource optimization problem in OFDMA macro-femtocell networks before we started to work with it. This work was a collaboration with a master student from Khalifa University. The results were published in two conference papers in (Marshoud *et al.*, 2012, 2013) regarding the spectrum partitioning and spectrum sharing respectively.

In (Li *et al.*, 2012b), a power and channel allocation using swarm optimization (PCASO) algorithm is proposed. This scheme is applied to a joint optimization of resource allocation in a femtocell network through the maximization of the minimal throughput of the femtocell network. The authors claim that this goal simultaneously reflects the improvement of the capacity of whole network and fairness among different femtocells, which is true for deployment of closed access femtocells and the orthogonal subcarrier allocation among the two-tiers. However, we believe that with the introduction of hybrid access policy, the resource allocation models should solve together the BS selection and the resource allocation for the whole macro-femtocell system, adaptively determine the dedicated bandwidth for both tiers and allow the spectrum reuse.

We presented a novel resource allocation based on Particle Swarm Optimization in (Estrada *et al.*, 2013b) assuming that femtocells are deployed using hybrid access policy. In this previous work, it is demonstrated that for a given BS selection, PSO can indeed enhance the network throughput in comparison with Weighted Water Filling algorithm proposed in (Chun-Han and Hung-Yu, 2011). Nevertheless, the main disadvantages of this proposal are: (1) BS selection procedure is solved before running the resource allocation algorithm, and (2) the lack of BS re-selection mechanism when public users are blocked by a femtocell.

A comparison among two heuristic algorithms, PSO and GA, for joint power assignment and bandwidth allocation in femtocell network is presented in (Shahid *et al.*, 2013). The authors present two variants of each algorithm for PSO and GA. The resource optimization is carried out in a decentralized fashion, which means that the optimization procedure is executed by each FC. Then, each FC shares its best solution with neighboring FCs. Their objective function is to minimize the maximum throughput of the femtocell network. In their work, it is demonstrated that PSO outperforms the GA under high-traffic and low-traffic scenarios. Nevertheless, the scenarios analyzed do not consider the hybrid access femtocells and the spectrum partitioning is assumed among the two tier. Thus, the problem is reduced to improve the throughput of the isolated femtocell networks by means of appropriate subcarrier selection and FC power control.

In summary, there is still an open research area involving specialized techniques that allow to find near to optimal solution and reduce the computational complexity of a joint BS selection and resource allocation optimization problem for OFDMA macro-femtocell networks as well as multi-user cellular OFDMA networks while guaranteeing the QoS of the mobile user demands.

1.5.3 Cluster based Resource Allocation Algorithm

Some cluster based resource allocation approaches are proposed to reduce the complexity of the resource allocation problem. Cluster formation technique involves the grouping of femtocells that interfere with each other. Then, RA algorithm runs independently within each cluster. Typically, the RA algorithm assigns orthogonal channels among the cluster members, which eliminates the co-tier interference within each cluster. This technique is attractive because it makes the RA algorithm scalable to any network size, while the implementation complexity remains reasonable. There are several cluster formation techniques that has been proposed regarding closed access femtocell and none of them consider the concept of hybrid access policy. In the following, we present the main objectives of some of the clustering technique found in the literature.

A femtocell cluster-based resource allocation scheme (FCRA) that aims at the maximization of FC network throughput is presented in (Hatoum *et al.*, 2011). The RA scheme consists of three stages: Neighboring discovery, cluster formation and resource allocation. Initially, each femtocell creates an interfering neighbor list with one-hop distance, and this list is sent to all of its own one-hop neighbors. Then, each femtocell computes the interference degree as the number of interfering FCs from its one-hop neighboring FC. The selection of cluster head is based on interference degree. Each femtocell is attached to the cluster head with highest interference degree in their own neighboring list. Finally, the RA algorithm is solved using Linear Program within each cluster. Here, orthogonal spectrum allocation between macro and femto tiers is employed to avoid cross-tier interference.

Nevertheless, FCRA model fails to guarantee the QoS of the own FC subscribers transmission and therefore, the same authors proposed an enhanced approach that maximizes the sum of subscribers data rate and upholds the QoS for subscribers transmission (Q-FCRA) in (Hatoum *et al.*, 2012b, 2014). Their objective is to satisfy a maximum number of subscribers users while serving public users as well as possible. Therefore, FC subscribers and public users are considered as high priority service and best-effort service respectively. The joint resource allocation and admission control problem is formulated as a multi-objective optimization problem. The first objective is to maximize the set of admitted subscribers in order to guarantee the feasibility of the allocation problem. The second objective is to allocate as better as possible the remaining resources to BE users.

QP-FCRA model is proposed in (Hatoum *et al.*, 2012a) to additionally minimize the power consumption in the femtocell network. In this scheme, the resource allocation problem is also divided into two subproblems, which corresponds to: (1) the joint power and bandwidth allocation that minimizes the power consumption in the cluster while guaranteeing the QoS of subscriber demands, and (2) the joint power and bandwidth allocation for public users with the multi-objective function that minimizes the power consumption and the users requirements degradation. Linear Programming is used to solve both subproblems.

In (Lin and Tian, 2013), a cluster based resource allocation approach is presented aiming at minimizing the co-tier interference (FFI) as well as guaranteeing subscriber QoS in term of outage probability (OP). In this work, the maximum cluster size is deduced to guarantee the target OP for femto users. Then, disjoint femtocell clusters with dynamic size lower than the maximum cluster size are formed using a graph method that minimize the co-tier interference. Finally, the subchannel allocation algorithm is executed within each cluster in order to maximize system capacity while ensuring (QoS) of each femto user in terms of the outage probability.

A bankruptcy game theory based approach is proposed in (Hoteit *et al.*, 2012) assuming the spectrum partitioning among the tiers. In this scheme, femtocells belonging to the same interference set, share information about respective demands, their interaction is modeled as a cooperative game. Thus, if a coalition of femtocells belonging to an interference FC set, decide to group apart, then, they will be able to share what the other femtocells have left after getting what they claimed. In such a way, the best coalition should be the grand coalition grouping all femtocells in the same interference set.

Universal subcarrier reuse is allowed at femto tier if femtocell belongs to different cluster in (Abdelnasser *et al.*, 2014). Femtocell are motivated to form a cluster through the reduction of the perceived co-tier interference. Then, the cluster head attaches the femtocell causing the lowest FC bandwidth reduction of current FC members. After the FC are organized into disjoint clusters, each cluster head performs sub-channel and power allocation within its cluster. Joint subchannel and power allocation is a iterative process, which is performed in two phases until it converges: (1) for a given power allocation, sub-channel allocation is performed, and (2) for a given the subchannel allocation, the power allocation is performed. In addition, the subchannel and power allocation is performed for each possible cluster configuration and the cluster configuration yielding the highest data rate will be selected as the optimal one.

In summary, the majority of the prior cluster based resource allocation approaches take into account the scenarios with femtocells deployed with closed access policy for a fixed amount of bandwidth allocated to femto tier. Moreover, if the cluster size is a high value, then the subscriber satisfaction can be affected due to the reduction of the bandwidth allocated to each cluster member. On the other hand, if cluster size is a low value, then the subscriber satisfaction is affected due to the level of inter-cluster interference. Therefore, we believe that cluster based resource allocation models should perform bandwidth adaptation per tier taking into account the level of granted access to public users. Moreover, the clustering technique should find a compromise between the cluster size and the BS selection for public users in order to avoid the resources starvation at the macro tier.

CHAPTER 2

BASE STATION SELECTION AND RESOURCE ALLOCATION IN MACRO-FEMTOCELL NETWORKS UNDER NOISY SCENARIO

Rebeca Estrada[1] , Abdallah Jarray[1] , Hadi Otrok[2] , Zbigniew Dziong[1] ,

[1] Département de Génie Eléctrique, École de Technologie Supérieure,

1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3

[2] Department of ECE, Khalifa University of Science, Technology & Research, UAE

An Article submitted to the Springer Journal Wireless Networks in June 2012

and published in January 2014 (vol. 20, issue 1, pp. 115-131)

http://dx.doi.org/10.1007/s11276-013-0594-9

2.1 Abstract

In this paper, we address the problem of optimizing resources for downlink transmission in a macro-femtocell network under non-dense femtocell deployment. In the literature, some approaches perform bandwidth or power optimization depending on the air interface technology and others optimize both types of resources, but only in femtocell network. However, the following limitations can be noticed: (i) Equal distribution of transmitted power among all subcarriers, even if they are not used, leads to resource underutilization, (ii) femtocell data rates are reduced in order to minimize the interference from femto base stations to macro users, and (iii) the impact of noise has not been evaluated. Moreover, there is lack of optimal selection of users that can be served by femtocells. To overcome these limitations, we propose a model that finds a tradeoff between bandwidth and power to reduce the bandwidth usage per user and to minimize the impact of noise. By means of Linear Programming, our solution maximizes the sum of weighted data rates and provides the optimal serving base station, power and bandwidth for each mobile user taking into account its location and demand. Furthermore, we present a performance analysis under changes of signal to noise ratio. Simulations were conducted and a comparison with a modified version of Weighted Water Filling algorithm is presented.

2.2 Introduction

Femtocells (FCs) are end-user base stations (BSs) with low-cost and short-range that guarantees good indoor coverage and enhances data rates. In traditional cellular networks, macrocell (MC) must satisfy the requirements of indoor and outdoor users, which leads to poor indoor coverage and dead zones appearance. Therefore, there are several economical factors that encourage network providers to use femtocells such as capacity improvements, traffic offload and power reduction in mobile equipment to transmit to a nearby femtocell instead of a farther macrocell (Zhang and De la Roche, 2010). Nevertheless, the main challenge of such overlaid networks is the resource allocation due to the uncontrolled deployment of femtocells and their ad-hoc nature.

In literature, several resource allocation approaches have been proposed. Some approaches perform only bandwidth optimization (Chun-Han and Hung-Yu, 2011), or power optimization (Chandrasekhar and Andrews, 2009) depending on the air interface technology of the network, i.e. CDMA or OFDMA. Other approaches attempt to jointly optimize bandwidth and power but only in femtocell network by means of the maximization of femtocells throughput instead of the entire network (Torregoza *et al.*, 2010; Zhang *et al.*, 2010a).

In the case of OFDMA technology, equal distribution of maximum transmitted power among subcarriers has been assumed in most of the research work (Torregoza *et al.*, 2010; G. He, 2010). Therefore, bandwidth optimization approaches reduce the problem to subcarriers allocation with equal power. The main goal of these approaches is to maximize network throughput taking into account sparse or dense femtocells deployment. In sparse deployment, dedicated portion of subcarriers is assigned to each tier as in (Chandrasekhar and Andrews, 2008). Conversely, in dense deployment, subcarriers should be shared among macrocell and femtocells and interference management schemes need to be implemented to enhance network throughput, such as: power control (Chandrasekhar *et al.*, 2009), hybrid access femtocell scheme (Li *et al.*, 2010), fractional frequency reuse (Dalal *et al.*, 2011), soft frequency reuse (Jeong *et al.*, 2010) and the use of cognitive radios (Torregoza *et al.*, 2010; Cheng *et al.*, 2012; Bennis and Perlaza, 2011).

It is well known that femtocells offload traffic from MC, since some users are served by FCs instead of MC leading to a scenario with underloaded macrocell. In (Alsawah and Fijalkow, 2008), it was shown that equal power distribution per bandwidth unit leads to the resource underutilization in a framework with one underloaded macrocell. In their work, two solutions are suggested to improve the performance of active users in MC, which are: (i) to redistribute unused subcarriers over active users to offer higher data rates or (ii) to redistribute the power excess over the active subcarriers and leave the subcarriers unused. This latter fits perfectly in a macro-femtocells network since unused subcarriers can be allocated to FCs without introducing interference to macro users and the power margin on active subcarriers in MC yields a better immunity to fading. This motivates us to investigate how the power excess can be efficiently distributed over active subcarriers to improve the network throughput when there is no need to deal with the interference problem.

Furthermore, it would be good for femtocells to have capabilities of self-configuration and self-planning, which requires a distributed Resource Allocation (RA) scheme. In literature, there are few distributed RA approaches that consider providing access to public users through femtocells. For example, in (Valcarce *et al.*, 2009), channel reservation to provide service to public users close to femtocells is investigated assuming a fixed number of channels per femtocell. In (Chun-Han and Hung-Yu, 2011), an adaptive bandwidth allocation is proposed and it is based on pre-fixed user selection and Weighted Water Filling Algorithm. However, determining which public users can be served by each femtocell itself is not an easy task, especially considering high mobility users and surrounding femtocells.

The main justification for using distributed schemes is the unpredictable delay in communications between macrocell and femtocells over the internet backhaul, which can negatively influence centralized schemes. Nevertheless, studies on wireless traffic have shown that more than 50 percent of all voice calls and more than 70 percent of data traffic occurs indoors (Infonetics, 2012; FemtoForum, 2010). Therefore, since this traffic has low mobility, a centralized resource allocation decision can be used. In this case, the allocation is updated over a period of several resource block time slots while subcarrier exchange techniques, e.g. (Chen *et al.*, 2010), between base stations can be implemented to improve mobile users transmission during this period.

In addition, it is important to notice that the most important capacity-limiting factor in spectrum partitioning approaches is the noise. Therefore, it is worth analyzing the performance of such resource allocation models under scenario with different noise levels.

Based on the previous arguments, the following limitations from prior works can be noticed:

- power control that reduces FC transmitted power to avoid disturbing macro user transmissions also reduces FC coverage area and data rates. Moreover, it limits the possibility of serving public users through FCs;
- inefficient power usage in MC due to the equal distribution of maximum transmitted power among all subcarriers even though some subcarriers are not used, which leads to resources underutilization in the entire network;
- selection of the set of public users served by femtocells may not be optimal;
- performance of resource allocation model has not been evaluated under conditions where the signal to noise ratio degrades.

To overcome these limitations, we propose a spectrum partitioning model that pursues a trade-off between bandwidth and power assignment in both tiers. This model aims to maximize the sum of data rates assigned to mobile users in the network. To the best of our knowledge, our work is the first effort that carries out joint power and bandwidth allocation together with base station selection taking into account noises.

The proposed model is based on *Integer Linear Program* (ILP) and is able to optimally:

- utilize the maximum transmitted power in both macrocell and femtocells;
- allocate the available bandwidth into dedicated portions for each tier taking into account power assignment;
- select the set of users that need to be served by femtocells based on their traffic demand and locations;
- minimize the impact of the noise in order to maximize the network capacity.

We consider only downlink (DL) transmission since for uplink transmission there are interference cancelation techniques that can be applied at base stations. These techniques are not suitable for mobile devices due to their hardware limitations such as the number of antennas and circuitry (Zhang and De la Roche, 2010).

To evaluate the performance of our model, we use as a benchmark one centralized scheme that uses Weighted Water Filling (WWF) algorithm to allocate first resources in macro tier and then in each femtocell (Chun-Han and Hung-Yu, 2011). The algorithm has been modified to assign also the power in both tiers using the same constraints as in our model. Simulations were conducted to compare performance of our model with the benchmark model for scenarios where the signal to noise ratio changes.

The rest of the chapter 2 is organized as follows: Section 2.3 presents the problem statement. Section 2.4 describes our model. Section 2.5 presents the performance measurements. Section 2.6 shows the results obtained for our model in comparison with the Weighted Water Filling Algorithm. Finally, Section 2.7 concludes the paper.

2.3 Problem Statement

In the spectrum partitioning scenario, Shannon's link capacity is given by

$$c_i = b_i log_2 \left(1 + \frac{P_i}{N_0 PL(d_i)}\right), \tag{2.1}$$

where N_0 is the noise power assumed equal for all users, $PL(d_i)$ is the path loss due to the signal propagation and d_i is the distance between user i and the base station. It is worth noting that noise is the only capacity-limiting factor in the spectrum partitioning scenario. Distances and noise are measurable parameters, while bandwidth, b_i, and power, P_i, can be variable and should be allocated to meet the users requirements taking into account their locations.

For example, to satisfy one user asking for 2 Mbps, who is located about 80 meters from macrocell, resources can be allocated with different pairs of bandwidth and power that satisfy (2.1). Let us consider only the following two options: (i) bandwidth equal to 250 kHz and power equal to 19 dBm, or (ii) bandwidth equal to 300 kHz and power equal 16 dBm using a non-line of sight propagation model in (ITU-TR-36.921, 1997). Both options assume a noise level of -145 dBm. Then, first allocation needs less bandwidth and second uses less power reducing the interference. Note that interference is not a concern in spectrum partitioning approaches. Therefore, the first challenge that we are addressing in this paper is to determine the increase of power that can be applied without trespassing the allowable maximum transmit power per user in order to improve the network capacity.

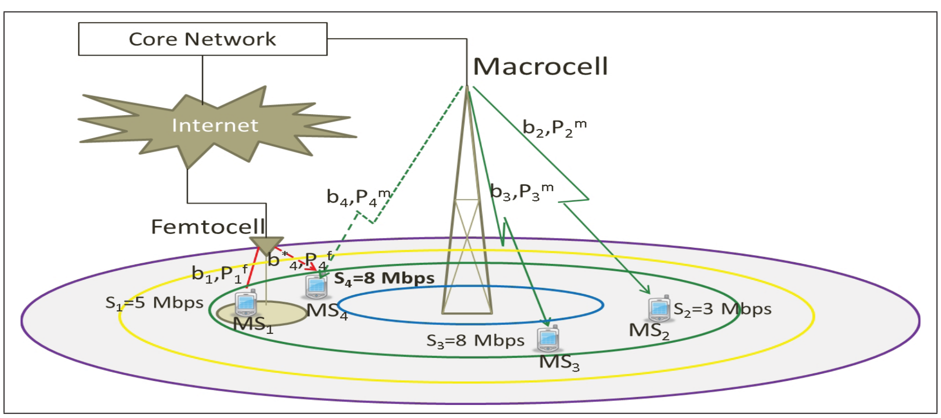


Figure 2.1 A OFDMA macro-femtocell network with four mobile users

Figure 2.1 shows the macrocell coverage area in OFDMA, which is divided into four zones (Tarhini and Chanjed, 2007; Alsawah and Fijalkow, 2008). Each zone is differentiated by the modulation scheme, in such way that the closest zone to macro BS uses the highest number of bits per symbol. Table 2.1 depicts physical layer assumptions such as modulation technique, signal to noise ratio (SNR) target and percentage of surface.

Table 2.1 IEEE802.16 Physical Layer Assumptions

Zone	**Modulation Technique**	**Bits/Sym**	**SNR Target (dB)**	**Surface [%]**
Z_1	64-QAM	6	22.4	2.64
Z_2	16-QAM	4	16.24	9.21
Z_3	QPSK	2	9.4	48.75
Z_4	BPSK	1	6	39.40

The surface percentages from Table 2.1 and their radii are defined by the SNR specified per zone. We consider the maximum transmitted power per user, P_z^{max}, as the required transmitted power at the zone edge to achieve SNR target in the zone. Therefore, P_z^{max} is given by

$$P_z^{max} = SNR_{Target} \times PL(R_z) \times N_0. \tag{2.2}$$

Let's assume a network with one macrocell and one femtocell. Femtocell and four users are located in zone Z_2 as shown in Figure 2.1. One subscriber, MS_1, is located inside the femtocell and one public user, MS_4, is placed near to the femtocell. Public users MS_2 and MS_3 can only be served by macrocell because they are not close enough to the femtocell. If we assume that femtocell can serve public users using Quadrature Phase Shift Keying ($QPSK$) owing to the fact that the wall penetration losses reduce their SNR. Then, there are two possible options for serving user MS_4, which are: (i) by femtocell, assigning low power P_4^f and high bandwidth b_4^* or (ii) by macrocell, allocating high power P_4^m and low bandwidth b_4. These two options are shown in Figure 2.1 by dashed and dotted lines respectively. The available bandwidth will be exhausted faster using the femtocell than macrocell. Thus, we present the second challenge addressed in this paper, which is how to determine the appropriate base station to serve public users taking into consideration the tradeoff between power and bandwidth to enhance the network throughput?

2.4 Base Station Selection and Resource Allocation Model (BSS-RAM)

In this section, we describe the proposed model that performs base station selection together with resource allocation (BSS-RAM) which aims to maximize the sum of user achievable data rates.

2.4.1 ILP Formulation

The case under study consists of several femtocells and mobile users located in the coverage area of one macrocell. Certain percentage of users are located in the proximity of femtocells. Each mobile user can be served either by MC or one nearby FC. In addition, femtocells must prioritize their own subscribers transmissions and if they have enough capacity, then, they provide service to public users.

We want to maximize the sum of the achievable user data rates in the network. According to Shannon's Law, the sum of the achievable data rates can be formulated as:

$$\max_{\mathbf{x},\mathbf{b},\mathbf{P}} \sum_{i\in\{M\}} x_i^m b_i log_2(1+SNR_i^m) + \sum_{i\in\{M\}} \sum_{f\in\{F\}} x_i^f b_i log_2(1+SNR_i^f), \tag{2.3}$$

where vectors $\mathbf{x}$, $\mathbf{b}$ and $\mathbf{P}$ correspond to user-base station association, bandwidth and power assignment for each user. In other words, $\mathbf{b}$ consists of real variables, b_i, that determine the bandwidth assigned to each user in the associated base station given by vector $\mathbf{x}$. SNR_i^m and SNR_i^f are the signal to noise ratio perceived by macro and femto users and depend on the transmitted power assigned in the associated base station.

Equation (2.3) is a non-linear function and this type of optimization problem has been proven to be NP-hard (Hong and Garcia, 2012), which means that finding the optimal solution is extremely hard and not applicable in practice. For this reason, we propose to maximize instead the sum of the weighted data rate given by (2.9) described in Section 2.4.1.3, assuming that the log term should be at least equal to the number of bit per symbol required in the MC's zone, l_z^{mod}, or FC, l_f^{mod}. To ensure this, we add a constraint that replaces the log function with the respective segment of a piece wise segment linear approximation obtained using the algorithm in (Imamoto and Tang, 2008), which is described in Section 2.4.2.

2.4.1.1 Model Parameters

The parameters used in BSS-RAM model are described in Table 2.2. They are classified as system, input, and output parameters. System parameters represent the network features, such as available bandwidth, maximum power per user in a given sector, maximum transmitted power in macrocell, attenuation factors, carrier frequency, maximum capacity allowed per sector, average noise, and so on. Input parameters specify the requirements of the mobile users and femtocells, such as demands, distances and weights. The output parameters are the ILP model variables. These parameters are described in Table 2.2.

2.4.1.2 Model Variables

BSS-RAM determines the following variables: serving base station, (x_i^m, x_i^f), assigned bandwidth , b_i, and transmitted power in each serving base station, (P_i^m, P_i^f) for each user i in the network. These variables are given by the following equations:

$$x_i^m = \begin{cases} 1 & \text{if MC serves the user } i \\ 0 & \text{otherwise} \end{cases}, \tag{2.4}$$

$$x_i^f = \begin{cases} 1 & \text{if FC } f \text{ serves the user } i \\ 0 & \text{otherwise} \end{cases}, \tag{2.5}$$

$$0 \leq b_i \leq B, \tag{2.6}$$

$$0 \leq P_i^m \leq P_z^{max}, \tag{2.7}$$

$$0 \leq P_i^f \leq P_{max}^f. \tag{2.8}$$

Table 2.2 Model Parameters of BSS-RAM

System Parameters	
Name	**Description**
B	Available bandwidth
B_C	Bandwidth per subcarrier
P_m^{Total}	Maximum transmitted power in MC
P_z^{max}	Maximum transmitted power per user in MC's zone
P_f^{max}	Maximum transmitted power per user in FCs
R_m, R_f	Radii in macrocell and FCs
α_f, α_m	Attenuation factor of indoor and outdooor environments
C_z^{max}	Maximum capacity allowed of zone z
l_z^{mod}	Number of bits of modulation in MC's zone z
l_f^{mod}	Number of bits of modulation in FC f
W_l	Wall Penetration losses
N_0	Average Thermal Noise Power
f_c	Carrier frequency
N	Number of mobile users in the network
N^f	Maximum number of users at the femtocell
Input Parameters	
S_i	Requested demand of mobile user i
w_i^m	Weight assigned to mobile user i at macro tier
w_i^f	Weight assigned to mobile user i at femtocell f
d_{if}	Distance from FBS f to the mobile user i
θ_i^f	Angle between user i's location and FBS f's location
d_{im}	Distance from MBS to the mobile user i
θ_i^m	Angle between user i's location and MBS
Output Parameters (Variables)	
b_i	Assigned Bandwidth to a femto/macro user i
P_i^f	Transmitted Power for DL between FBS f and user i
P_i^m	Transmitted Power for DL between MBS and user i
x_i^f	User i is assigned to FC f
x_i^m	User i is assigned to MC

2.4.1.3 Objective Function

BSS-RAM aims to maximize the sum of the weighted users data rates and is given by:

$$\max_{\mathbf{x},\mathbf{b},\mathbf{P}} \sum_{i\in\{N\}} w_i^m x_i^m b_i l_z^{mod} + \sum_{i\in\{N\}} \sum_{f\in\{F\}} w_i^f x_i^f b_i l_f^{mod}, \tag{2.9}$$

where the parameters l_z^{mod} and l_f^{mod} represents the number of bits per symbol in zone z or in femtocell f. And w_i^m and w_i^f are weights that provide a base station selection mechanism for each user i. These weights should enable the model to prioritize subscriber transmissions inside femtocells and the use of femtocells for public users close to them.

2.4.1.4 Model Constraints

For the objective function presented in (2.9), we have the following constraints:

- Bandwidth capacity constraint is given by

$$\sum_{i \in \{N\}} b_i \leq B, \tag{2.10}$$

which means that the sum of the assigned bandwidth must be less than or equal to the available bandwidth B.

- Clash constraint is expressed as follows:

$$x_i^m + \sum_{f \in \{F\}} x_i^f \leq 1 \qquad ; i \in N, \tag{2.11}$$

i.e. a user i can at most be served by one base station, either one femtocell or the macrocell.

- Femtocell capacity constraint is given by

$$\sum_{i \in \{N\}} x_i^f \leq N^f \qquad ; f \in F, \tag{2.12}$$

which indicates that the sum of assigned users to a femtocell should be less than or equal to the number of allowed users in FCs, i.e. N^f.

- Maximum assigned transmit power in the macrocell is limited by:

$$\sum_{i \in \{N\}} P_i^m \leq P_m^{Total}. \tag{2.13}$$

In other words, the sum of power assigned to the users served by macrocell must be less than or equal to the maximum transmitted power, P_m^{Total}.

- Spectral efficiency constraint in macrocell: The achievable spectral efficiency must be greater than or equal to the number of bits per symbol required for modulation scheme applied in zone z. This constraint is given by

$$\log_2(1+SNR_i^m) \geq l_z^{mod} x_i^m \qquad ;i \in N \tag{2.14}$$

where l_z^{mod} is the target spectral efficiency in zone z and SNR_i^m is the signal to noise ratio of mobile user i at macro tier and is given by

$$SNR_i^m = \frac{P_i^m}{PL_i^m N_0} \qquad ;i \in N. \tag{2.15}$$

N_0 is the average noise in the network, P_i^m is the power assigned to user i if he is served by macrocell and PL_i^m is the path loss for outdoor environments taking into account the non-line of sight (NLOS) propagation model in (ITU-TR-36.921, 1997), given by

$$PL_i^k(dB) = \begin{cases} 10log_{10}(d_{ik}^{\alpha_m}) + 30log_{10}(f_c) + 49 & Outdoor \\ 10log_{10}(d_{ik}^{\alpha_f}) + 37 & Indoor \end{cases}. \tag{2.16}$$

- Spectral efficiency constraint in femtocells: The FC spectral efficiency must be greater than or equal to number of bits per symbol required for modulation scheme used in femtocell f. This can be expressed as follows:

$$\log_2\left(1+SNR_i^f\right) \geq l_f^{mod} x_i^f \qquad ;i \in N, f \in F, \tag{2.17}$$

where SNR_i^f is the signal to noise ratio perceived by mobile user i in femtocell f and is given by

$$SNR_i^f = \frac{P_i^f}{PL_i^f N_0} \qquad ;i \in M, f \in F. \tag{2.18}$$

PL_i^f is the path loss for indoor environments given in (4.3) and P_i^f is the power assigned to user i in femtocell f.

- Maximum Data Rate per User: In OFDMA technology, it is defined maximum allowed capacity per zone, C_z^{max}, which is increasing with respect to the proximity of MC's zone to macro BS (Alsawah and Fijalkow, 2008). Therefore, data rate assigned must be less than or equal to the minimum among the maximum allowed capacity per zone, C_z^{max}, and user demand in macro tier. Due to the short range DL transmission in femtocells, we are assuming that there is no data rate limitation in femtocells. Thus, data rate assigned to user i should be less than or equal to his demand, S_i in femto tier. Thus, the maximum data rate per user constraint is expressed as follows:

$$b_i \leq x_i^m \left(\frac{\min\left(S_i, C_z^{max}\right)}{l_z^{mod}} \right) + \sum_{f \in \{F\}} x_i^f \frac{S_i}{l_f^{mod}} \qquad ; i \in N, f \in F. \tag{2.19}$$

- Upper bound for assigned bandwidth per user:

$$b_i \leq B \left(\sum_{f \in \{F\}} x_i^f + x_i^m \right) \qquad ; i \in N. \tag{2.20}$$

- Upper bound for transmitted power per user at macro tier:

$$P_i^m \leq P_z^{max} x_i^m \qquad ; i \in N; z \in Z. \tag{2.21}$$

- Upper bound for transmitted power per user at femto tier:

$$P_i^f \leq P_f^{max} x_i^f \qquad ; i \in N, f \in F. \tag{2.22}$$

The general BSS-RAM model has been defined for base station selection together with joint power and bandwidth allocation in a macro-femtocell network. However, two important issues are presented in the proposed model, which are: i) the objective function (2.9), contains the product of two variables, one binary and one real, which cannot be solved using CPLEX (IBM, 2011), and ii) the log terms in (2.14) and (2.17) are not linear functions. These issues are handled in Sections 2.4.2 and 2.4.3.

2.4.2 Linear Approximation of Log Term

According to (Imamoto and Tang, 2008), any convex function can be approximated by a K segment continuous piecewise segment (PWS) linear function $g(x)$ defined over the range $x_0 \leq x \leq x_K$ by a set of points or knots K $(x_k, y_k)_{k=0}^{N}$ connected by K segments given by:

$$g^k(x) = \begin{cases} m_k x + a_k & x_k \leq x \leq x_{k+1} \\ 0 & \text{Otherwise.} \end{cases}, \tag{2.23}$$

where m_k is the slope of the linear segment k and a_k is a constant value added to it.

For a given set of pivots (x_0,x_1,...x_K), a piece wise segment linear approximation of any function $f(x)$ can be written as the sum of several linear segments given by

$$g^k(x) = \max_{k=0}^{K} f'(x_k)(x - x_k) + f(x_k) - \varepsilon, \tag{2.24}$$

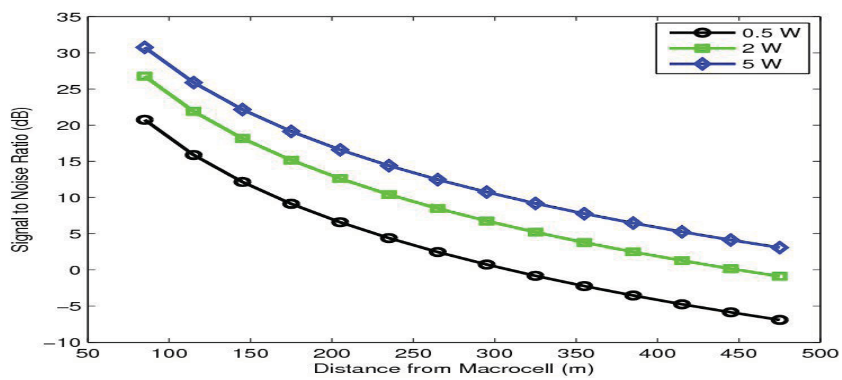
where $f'(x)$ is the first-order derivative. In our case, $f(x)$ is $log_2(1+x)$. Accordingly, the slope m_k and the constant a_k for each linear segment k are given by

$$m_k = f'(x_k) \qquad ;k \in K, \tag{2.25a}$$

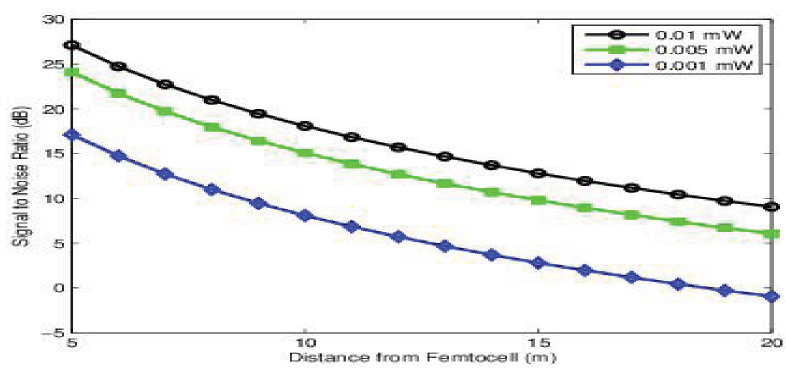
$$a_k = f(x_k) - f'(x_k)x_k - \varepsilon \qquad ;k \in K, \tag{2.25b}$$

respectively. In (Imamoto and Tang, 2008), the idea is to find the appropriate values of pivots that minimize the error for each given segment.

First, we inspect SNR values of mobile users in the network. We use the propagation model for outdoor and indoor environments from (ITU-TR-36.921, 1997), varying transmitted power and keeping the rest of parameters fixed such as noise level, attenuation factor and carrier frequency. Several SNR curves for one mobile user with different location in macrocell and femtocell are shown in Figures 2.2a and 2.2b. It can be observed that SNR values are in the range of (0, 1200) for distances greater than 85 m in macrocell and (0, 600) for distance greater than 5 m in femtocell.



a) SNR vs distance from MC



b) SNR vs distance from FC

Figure 2.2 Signal to Noise Ratio in macrocell and femtocells vs distance

Then, we use the recursive algorithm proposed by *Imamoto* in (Imamoto and Tang, 2008) to find a PWS linear approximation of the log_2 term. Figure 2.3 shows both functions $log_2(1+SNR)$ and $5-PWS$ linear approximation. This approximation was obtained after 16 iterations with minimum and maximum SNR values equal to -20 dB and -32.6 dB.

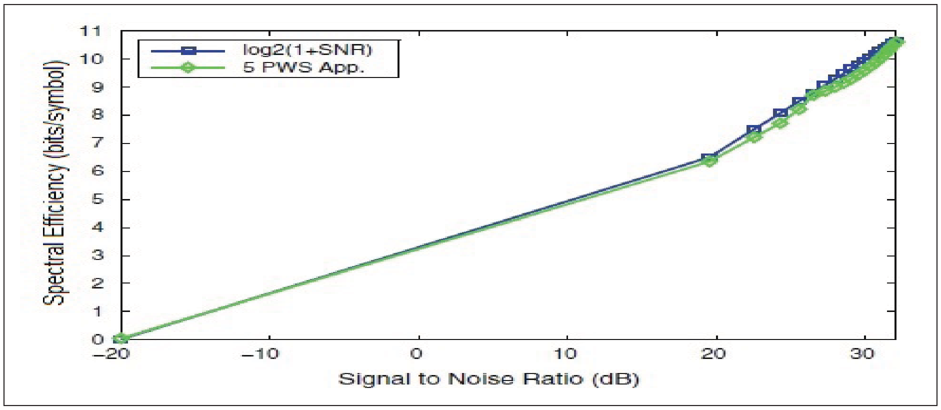


Figure 2.3 5-PWS Linear Approximation of Log Term

Table 2.3 shows the number of iterations that Imamoto's algorithm needs to converge with respect to the number of segments required in the PWS linear approximation using *SNR* values between 0.01 and 1800.

Table 2.3 Algorithm Convergence

Number of Segments	**Number of Iterations**	**Mean Error**
2	5	2.54
3	8	1.12
4	11	0.59
5	16	0.37
6	21	0.26
7	28	0.19

A high number of linear segments introduces more complexities to the model while a low number gives less accuracy. For convenience, we have decided to work with a 6 PWS-linear approximation owing to the fact that only one segment includes SNR target for each modulation technique. Thus, BSS-RAM solves the resource allocation problem using the corresponding segment for each user in macro or femto tier.

Therefore, Equation (2.14) can be replaced by

$$(m_k SNR_i^m + a_k) \geq x_i^m l_z^{mod} \qquad ; i \in N, k \in K, \tag{2.26}$$

but SNR values should be in the range of the segment, i.e. $(SNR^k_{min}, SNR^k_{max})$. Therefore, two new constraints are added to BSS-RAM model as the upper and lower bound of SNR^m_i and are given by

$$SNR^k_{min} \leq SNR^m_i \leq SNR^k_{max} \qquad ; i \in N, k \in K. \tag{2.27}$$

For femtocells, (2.17) is replaced by

$$\left(m_k SNR^f_i + a_k\right) \geq x^f_i l^{mod}_f \qquad ; i \in N, f \in F, \tag{2.28}$$

and the upper and lower bound of SNR^f_i and are given by

$$SNR^k_{min} \leq SNR^f_i \leq SNR^k_{max} \qquad ; i \in N, f \in F. \tag{2.29}$$

as in 2.27.

The curves of SNR perceived by users in femtocells differ from those in macrocell, due to the short distance, lower attenuation factor and different propagation model. For simplicity, we have used the same PWS linear approximation for both tier and placed the mobile users inside femtocells to meet SNR in the range of the PWS linear approximation.

In summary, for each mobile user in MC or FCs, the corresponding segment is selected to satisfy the SNR target required by the modulation scheme of MC's zone or in femtocell.

2.4.3 Conversion of real variable to binary variable

The objective function (2.9) contains the product of two variables, one real and one binary. This cannot be solved using CPLEX. However, as we use Concert Technology Environment, it is possible to solve LP model in the special case where the objective function contains quadratic term of binary variables (IBM, 2011). Therefore, the real variables should be converted into binary variables. The solution is simple such as the available bandwidth is divided into small pieces with a fixed amount of bandwidth. Thus, the bandwidth assigned to one user, b_i, can be represented as a integer number multiplied by the fixed amount of bandwidth per small piece.

Then, the integer number can be represented using binary notation, which means using a binary vector combined with power of two. Thus, the bandwidth per user, b_i is given by

$$b_i = B_C \sum_{j=0}^{j=T} \beta_j^i 2^j \qquad ; i \in N \qquad ; i \in N, \tag{2.30}$$

where T is equal to the total number of small pieces of bandwidth that comprise the available bandwidth, i.e. $\frac{B}{B_C}$. T can be seen as the number of subcarriers in the OFDMA network and B_C is the bandwidth per subcarrier. The coefficients β_j^i determine if the j-th power of two is part of the sum or not.

$$\beta_j^i = \begin{cases} 1 & j\text{-th power of two is used to represent } b_i \\ 0 & \text{Otherwise.} \end{cases} . \tag{2.31}$$

We have replaced all the approximations on the general BSS-RAM model and the details of the Mixed Integer Linear Programming (MILP) model can be found in the appendix I. This model is implemented using IBM ILOG CPLEX and Concert Technology (IBM, 2011). Algorithm 2.1 presents the MILP based RA algorithm that determine the optimal serving BS and optimal amount of resources for each user in the macro-femtocell network.

2.4.4 Weights applied in RA models

The weights w_i^m and w_i^f are parameters that depend on input parameters. They allow the BSS-RAM model to implement one mechanism to select the serving base station for each user. In this paper, we propose to use weights that prioritize:

- subscriber's DL transmission over public users' transmission inside femtocells;
- the use of femtocells for public users close to them.

We limit our analysis to two types of weights. They are related to link conditions and user demand and described in Sections 2.4.4.1 and 2.4.4.2 respectively. However, other set of weights

Algorithm 2.1 BS Selection and RA Algorithm

Data: MS Set of users, FCSet of Femtocell, m represents Macrocell
(X_i, Y_i) User Locations
(X_f, Y_f) FC Locations,
(l^f_{mod}) FC Modulation Technique
(D_i) User Demands.
Result: BS selection for the set of users, $\mathbf{bs_i}$,
Bandwidth allocated per subcarrier per user $\mathbf{b_i}$,
Power allocated per subcarrier per user $\mathbf{P_i}$.

begin
At each interval of time t, MC Resource Manager **do**;
Collect from each mobile user i, its demand and location (S_i, d^m_i, θ^m_i);
Collect from femtocell f, its location and the scheme of modulation (d^m_f,θ^m_f,l^{mod}_f);
Calculate the weights of the links between macrocell and each user i;
Calculate the weights and distances of the links between femtocell f and each user (w^f_i,d^f_i,θ^f_i);
Formulate the problem as an ILP;
Solve the ILP, and find the optimal resource allocation;
end

can be investigated, which is related to the service plan that mobile users are paying for, providing preferential treatment to user paying more over other users.

2.4.4.1 Link Rate

The proposed algorithm in (Chun-Han and Hung-Yu, 2011) uses a set of weights taking into account the link rate from macrocell or femtocell. Thus, w^m_i and w^f_i are calculated based on the link rate between base stations and mobile user and given by

$$w^k_i = (1/r^k_i)^{1/2} \qquad k \in \{m, F\}; i \in N, \tag{2.32}$$

where r^m_i and r^f_i are links rate in DL from macro BS and femto BS f respectively. In (Chun-Han and Hung-Yu, 2011), it was proved that this set of weights have better performance than a set of equal weights. In their work, the link rate was randomly generated but the link rate depends strongly on several wireless impairments such as path loss, shadowing, noise and the power assigned to the user. In this work, link rate corresponds to the log term of Shannon's Law capacity and is given by

$$r_i^k = log_2(1 + SNR_i^k) \qquad k \in \{m, F\}; i \in N, \tag{2.33}$$

where SNR_i^k is the signal to noise ratio of user i, which corresponds to the received signal from BS k, belonging to the set of base stations, i.e. macrocell (m) and deployed femtocells (F). In macrocell, link rate r_i^m is calculated considering the maximum transmitted power per user in the zone, P_z^{max}. In femtocell, link rate r_i^f is calculated using the maximum transmitted power per user, P_f^{max}.

2.4.4.2 Demand

In macrocell, weights are inversely proportional to user demand to prevent denial of service to certain users due to those users who request high data rates (Zhang and De la Roche, 2010). However, in femtocells, it is possible to serve users with high demand. Therefore, the proposed weights regarding the demand are given by

$$w_i^k = \begin{cases} \frac{1}{S_i} & \text{in Macrocell} \\ \frac{2S_i}{S_{avg}} & \text{for own subscriber in Femtocell}, \\ \frac{S_i}{S_{avg}} & \text{for public user in Femtocell} \end{cases} \tag{2.34}$$

where S_i is the demand of the user i and S_{avg} is the average demand of the mobile users in the network.

2.4.5 Benchmark Model

In (Chun-Han and Hung-Yu, 2011), bandwidth allocation is performed using Weighted Water Filling (WWF) algorithm taking into account pre-fixed user selection per BS and no power limitation. This latter means that the bandwidth is assigned assuming that user data rates can be provided without limitation of maximum transmitted power per BS. However, the total power assigned to users should be less than or equal to the maximum transmitted power in base stations (Yang, 2010). On the other hand, pre-fixed user selection takes into account the higher link rate from MC or FC to assign the user to one of them. This approach considers only one femtocell that competes for the resources with mobile users assigned to macrocell. Then, femtocell RA algorithm is carried out using its allocated bandwidth.

The authors recommend a user selection procedure for more femtocells, which consists of two steps:

- determine the femtocell with better link conditions for user i;
- if link conditions from femtocell is better than link from macrocell, then, the user i is considered as femto user, otherwise, is considered as macro user.

However, the following issues can be noticed:

- femtocell with maximum link rate might not have enough assigned resources to serve the demand of a public user;
- if the public user is blocked in the pre-fixed femtocell, which mechanism can be used to reassign that user to be served by MC or even by other nearby FC.

Nevertheless, we have used their algorithm and changed it in order to assign the transmitted power assuming equal power distribution per unit of bandwidth in MC. This means that the power assigned to a mobile user is proportional to the bandwidth assigned to each user in every round, as it is stated in step 5 of macrocell algorithm in Algorithm 2.2. The fraction of resources calculated in each round is assigned to mobile user only if the power assigned to the user is less than or equal to the maximum transmitted power per user in MC's zone, P_z^{max}. However, the transmitted power is calculated based on the SNR target without trespassing the maximum transmitted power per user in femtocells, P_f^{max}. Algorithm 2.2 and 2.3 present the WWF algorithms for macrocell and femtocells respectively.

Algorithm 2.2 MC WWF Algorithm

Data: MS Set of users and Femtocells MC,FC,
(X_i, Y_i) User Locations,
(X_f, Y_f) FC Locations,
(w_i^k) Weights for link rates between base station k and users i,
(D_i) User Demands.
Result: Bandwidth per mobile user or femtocell $\mathbf{b_i}$,
Power allocated per mobile user served by macrocell $\mathbf{P_i^m}$.

begin
Sorting the users according to the bandwidth required divided by the weight;
For each user $i = 1, \ldots, M+F$, it is obtained the bandwidth to be assigned as:;
$b_i = \min\left(\frac{b_i^{required} - b_i^{k-1}}{w_i^m}, \frac{B - \sum_{k=1}^{i-1}\sum_{j=k}^{M+F} b_j}{\sum_{j=i}^{M+F} w_j^m}\right)$;
Bandwidth Assignment: For every user j starting from i, bandwidth is equal to bw_i multiplied by its corresponding weight;
$b_j^k = b_j^{k-1} + w_j^m b_i$;
Power Assignment: For every user j assign the power proportionally to the bandwidth assigned to user j as follows:;
$p_j^k = p_j^{k-1} + \min\left(\frac{w_j^m b_i P_{max}^m}{B}, P_z^{max} - p_j^{k-1}\right)$;
This process stops when the total bandwidth available is exhausted or for macrouser i, assigned bandwidth is equal to the required bandwidth.;
end

2.5 Performance Measurements

We use the metrics described in this section to evaluate and compare the performance of both resource allocation models.

Achievable Throughput: The total achievable throughput is calculated based on Shannon's Law Capacity. Accordingly, the network throughput can be expressed as

$$T = \sum_{i \in \{N\}} x_i^m b_i log_2(1 + SNR_i^m) + \sum_{i \in \{N\}} \sum_{f \in \{F\}} x_i^f b_i log_2(1 + SNR_i^f). \tag{2.35}$$

Algorithm 2.3 FC WWF Algorithm

Data: MS Set of users MC^f
(X_i^f, Y_i^f) User Locations
(w_i^f) Weights for link rates between femtocell f and users i,
(D_i) User Demands.
Result: Bandwidth allocated per user in femtocell f $\mathbf{b_i^f}$,
Power allocated per user in femtocell f $\mathbf{P_i^f}$.
begin
Sorting the users according to the bandwidth required divided by the weight;
For each user $i = 1, ..., N_f$, it is obtained the bandwidth to be assigned as:;
$b_i = \min\left(\frac{b_i^{required} - b_i^{k-1}}{w_i^f}, \frac{B - \sum_{k=1}^{i-1}\sum_{j=k}^{N_f} b_j}{\sum_{j=i}^{N_f} w_j^f}\right)$;
Bandwidth Assignment: For every user j starting from i, bandwidth is equal to bw_i multiplied by its corresponding weight;
$b_j^k = b_j^{k-1} + w_j^f b_i$;
Power Assignment: For every user j to be served by femtocell f, the assigned power is calculated as follows:;
$p_j^f = \min\left(SNR_{th}^f N_0 PL_j^f, P_{max}^f\right)$;
This process stops when the bandwidth assigned to femtocell f is exhausted or for femto user i, the assigned bandwidth is equal to the required bandwidth. ;
end

Power used in MC: The power used in MC corresponds to the sum of power assigned to the DL transmissions between macro base station and macro mobile users and is given by

$$P_u^m(dBm) = 10log_{10}\left(\frac{\sum\limits_{i\in\{N\}} x_i^m P_i^m}{1mW}\right). \tag{2.36}$$

User Satisfaction: This is defined as the ratio between the sum of assigned data rates and the sum of users demand and given by:

$$R = \frac{\sum\limits_{i\in\{N\}} x_i^m b_i l_z^{mod} + \sum\limits_{i\in\{N\}}\sum\limits_{f\in\{F\}} x_i^f b_i l_f^{mod}}{\sum\limits_{i\in\{N\}} S_i}. \tag{2.37}$$

2.6 Simulation Results

System parameters and assumptions considered in simulations are described in Section 2.6.1. Simulation results were conducted using: (1) Visual C++ Studio 8.0 and (2) IBM ILOG Cplex 12.1: Concert Technology Environment. These results for different scenarios are analyzed in Sections 2.6.2 , 2.6.3, 2.6.4, 2.6.5, 2.6.6 and 2.6.7.

2.6.1 Simulation Scenario

Table 2.4 shows the applied network and environment parameters used, which are similar to the scenarios used in (Bharucha *et al.*, 2010; Cheng *et al.*, 2012). In the following, the main assumptions are described.

Table 2.4 System Parameters
(Network & Environment)

Name	**Description**
B	100 MHz
B_C	100 kHz
P_m^{Total}	(46.9 dBm - 51.03 dBm)
R_m, R_f	500 m, 20 m
α_f, α_m	3, 3.7
C_z^{max}	(10, 7, 5, 1)
l_z^{mod}, l_f^{mod}	(6, 4, 2, 1)
W_l	(-3 dB)
N_0	(-105 dBm, -100.9 dBm)
f_c	2.3 MHz
N	10-50
N^f	4

OFDMA physical layer assumptions per zone are the same as in (Tarhini and Chanjed, 2007). Therefore, the number of bits used for modulating the signal can be 6, 4, 2 or 1 if the mobile user is on the surface of Z_1, Z_2, Z_3 or Z_4 respectively, as shown in Figure 2.1.

Femtocells should modulate with the number of bits per symbol equal to 6, 4 or 2 depending on where they are located. In such way, the system can reduce bandwidth usage by means of serving public users through them instead of the macrocell. For example, if femtocells are deployed in zone Z_2, they should modulate at least with 4 bits per symbol. Table 2.5 presents the relative position of femtocells with respect to macrocell, number of bits of modulation and final number of subscribers for the set of simulations.

Simulation runs for different set of mobile users increasing from 10 to 50 with 10 user increment. The location of mobile users is limited to the same zone as femtocells in every simulation. 30 % of the mobile users are public users near femtocells and FC subscribers.

Table 2.5 Femtocell Locations

Femtocell	**Location X**	**Y**	**Subscribers**	l_f^{mod}
1	-283	-186	3	2
2	-258	229	1	2
3	-308	229	1	4

The demand of FC subscribers and public users close to femtocells are randomly generated from 1 to 10 Mbps. For the remainder users, their demand are randomly generated from:

- 1 to 7 Mbps on the second zone;
- 1 to 5 Mbps on the third zone;
- 1 to 3 Mbps on the last zone.

Table 2.6 shows the total demand of mobile users in the network.

The PWS linear approximation is composed of six piece wise linear segments, which were obtained using the algorithm from (Imamoto and Tang, 2008). The minimum value of SNR is equal to 10^{-2} and maximum value is equal to 1800. Table 2.7 lists all the segments with their values of slope, m_k, constant, a_k, and interval (SNR^k_{min},SNR^k_{max}) where each segment is valid.

Table 2.6 Total Demand of Mobile users

Mobile Users	Total Demand	SUs & PUs
10	38	3
20	77	6
30	102	9
40	137	12
50	172	15

Table 2.7 PWS Linear Approximation

Segment	m_k	a_k	SNR^k_{min}	SNR^k_{max}
1	0.6997	0.0071	0.01	2.68
2	0.1905	1.3750	2.68	12.47
3	0.0525	3.0974	12.47	47.73
4	0.0146	4.9042	47.73	173.78
5	0.0043	6.7042	173.78	546.10
6	0.0003	8.3800	546.10	1800.00

The performance analysis of resource allocation models was carried out using measurements of throughput, power used in macrocell and user satisfaction described in Section 2.5.

2.6.2 Impact of Signal to Noise Ratio

The performance of both resource allocation models is analyzed under SNR changes using the two types of weights described in Section 2.4.4. We use the abbreviation LR to specify that weights are related to link rate and DE if the weights are related to user demand. Two conditions affect the signal to noise ratio: i) maximum transmitted power in base station and ii) different noise levels.

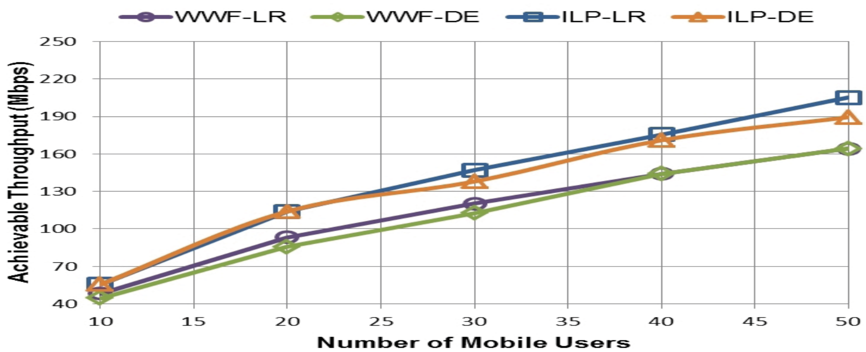
2.6.2.1 Throughput and Power Usage

Usually in OFDMA technique, the maximum transmitted power per macrocell, P_m^{Total}, is equally distributed among all subcarriers even if some subcarriers are not used. In (Alsawah and Fijalkow, 2008), equal power distribution per bandwidth unit was studied in a framework with one underloaded macrocell. In their work, it was shown that equal power distribution among subcarriers with underloaded system leads to the excess of unused resources, both power and bandwidth. Femtocells offload traffic from MC, since some users are served by FCs instead of MC leading to a scenario with underloaded macrocell. For this reason, BSS-RAM has been developed to allow adaptive power per user taking into account its demand and location without trespassing the maximum transmitted power per user in a given zone, P_z^{max}.

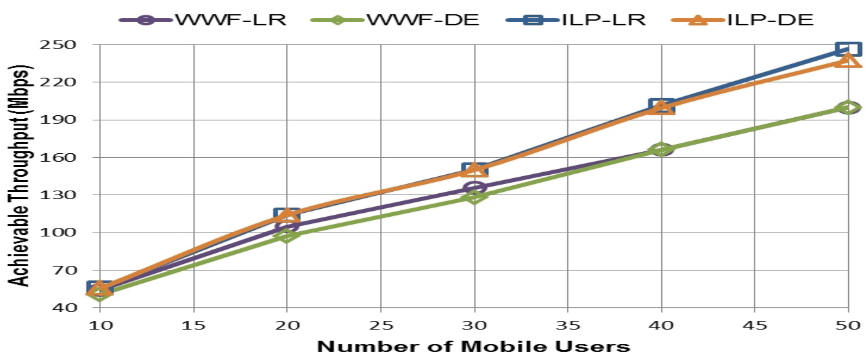
In BSS-RAM, the maximum transmitted power in macrocell, P_m^{Total}, limits the total power to be assigned to DL transmissions in macro BS by means of the constraint in (2.13). Moreover, P_m^{Total} has also indirect influence on the SNR at macro tier, which has been considered by means of the constraint in (2.14). The performance of ILP and WWF models are analyzed using two different P_m^{Total} values (i.e. 46.9 and 50 dBm) and also the two set of weights related to the link rate (LR) and demand (DE).

Figure 2.4 shows the achievable throughput in the macro-femtocell network with two different values of maximum transmitted power in macrocell, P_m^{Total}. One can observe that the best throughput values are obtained using the weights related to the link rate (LR) for both models. This is owing to the fact that the LR weights are dependent on the allocated power to the users which is adaptively changing whereas the DE weights do not take into account the power control. On the other hand, the throughput tends to be equal for both models if the maximum transmitted power in MC is increased. This tendency can be appreciated in Figures 2.4a and 2.4b where the gap between the achievable throughput is bigger for lower P_m^{Total}. In fact, the network throughput has the same value for both RA allocation models when the total transmitted power in macrocell is equal to 51.76 dBm. In other words, the modified WWF requires at least 51.76 dBm as the total transmitted power in macrocell to achieve the same throughput as BSS-RAM.

BSS-RAM model assigns more power to mobile users than modified WWF algorithm as shown in Figure 2.5. However, when the value of maximum transmitted power, P_m^{Total}, is increased, the power usage in WWF model is also increased as seen in Figure 2.5b. This is owing to the



a) P_m^{Total} equal to 46.9 dBm

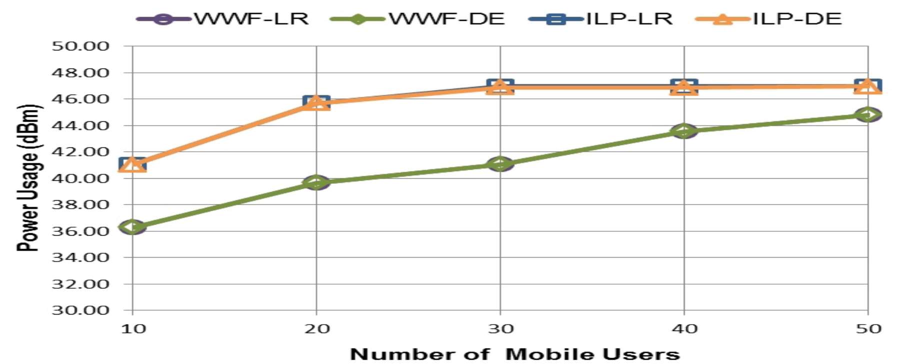


b) P_m^{Total} equal to 50 dBm

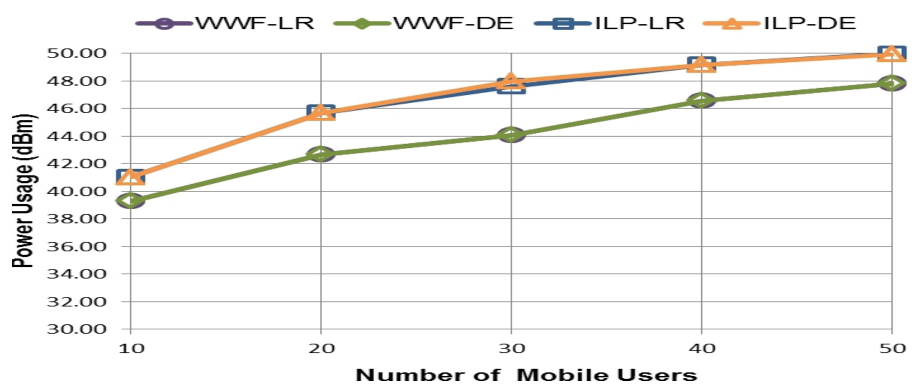
Figure 2.4 Achievable Throughput for different P_m^{Total}

fact that higher power per user allows macro mobile users to have better signal to noise ratio, SNR_i, and therefore higher number of bits per symbol can be used in the modulation technique.

BSS-RAM exhibits a network throughput gain with a number of users higher than 10 users. For example, 40 users have a total throughput of 175.5 Mbps with P_m^{Total} equal to 46.9 dBm, while there is 15% of throughput gain with P_m^{Total} equal to 50 dBm. However, the throughput for 20 users is not improved with this power increase. This indicates that there must be a maximum transmitted power threshold from which BSS-RAM model can not provide a further throughput increase. This threshold is shown in Figure 2.8a and described in Section 2.6.4.



a) P_m^{Total} equal to 46.9 dBm



b) P_m^{Total} equal to 50 dBm

Figure 2.5 Assigned Power in MC for different P_m^{Total}

It can be noticed that weights related to link rate provide better throughput than the weights related to demand for both resource allocation models. For that reason, we use only weights related to link rate in the following sections.

2.6.2.2 Impact of Noise

Based on the conditions under which both resource allocation models, i.e. BSS-RAM and modified WWF, reach the same throughput, we want to show how an increase in the noise level affects the performance of both RA models. Equation (2.2) in Section 2.3 indicates that higher noise level requires higher maximum transmitted power per user in each zone, P_z^{max}.

Figure 2.6 shows the user satisfaction for two noise levels: -105 dBm (solid lines) and -100.9 dBm (dashed lines). It can be seen that BSS-RAM model exhibits user satisfaction between 97% and 100% with a noise level of -105 dBm while the user satifaction applying WWF model goes from 91% and 97%. One can observe that if the noise increases by 4 dB, the user satisfaction degrades up to 18% in WWF model while in BSS-RAM the maximum degradation is 12%.

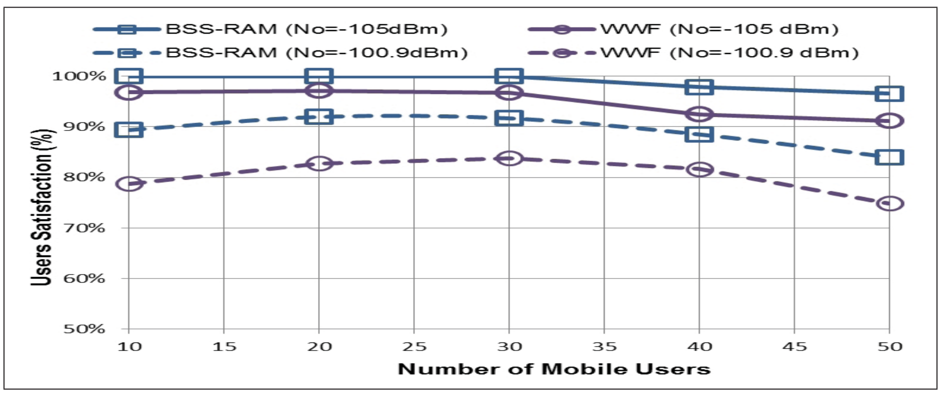


Figure 2.6 User Satisfaction for different N_0

In summary, equal power distribution per bandwidth unit assumed in WWF requires higher maximum transmitted power in MC than in BSS-RAM model in order to tackle higher noise levels. Therefore, adaptive power per user enables BSS-RAM model to reduce the impact of noise. In fact, adaptive power per subcarrier can be investigated to reduce the impact of the interference in dense deployment of femtocells. We will target this problem in our future research work since in such a case, bandwidth needs to be associated to base stations due to the subcarrier reuse.

2.6.3 Impact of users density in FC neighborhood

In this section, we want to show how the user density affects the performance of both resource allocation models. To do so, we fix the number of users to 30 and we change the percentage of mobile users within the FCs coverage area from 30% to 60%. Figures 2.7a, 2.7b and 2.7c show the performance measurements for both RA approaches versus the percentage of users in femtocells neighborhood.

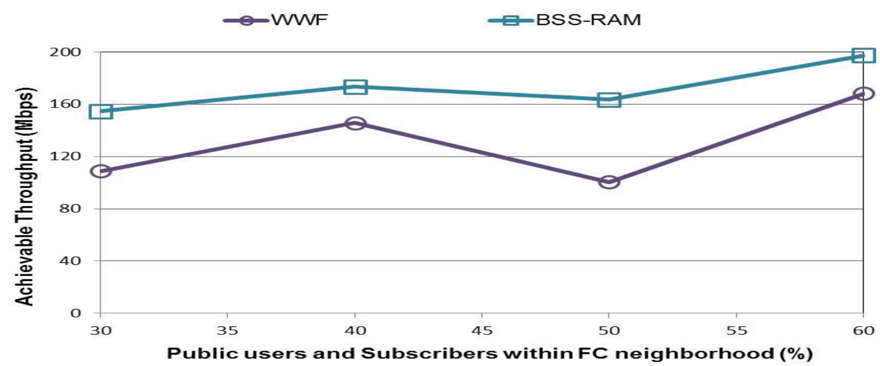
Figure 2.7a indicates that BSS-RAM model provides higher throughput than WWF model and Figure 2.7b shows that higher user satisfaction is obtained using BSS-RAM model than WWF model. This gain can be attributed to the adaptive power usage and the optimal serving BS selection. Moreover, it can be noticed that the power used in MC decreases for BSS-RAM model as the user density increases as shown in Figure 2.7c. Therefore, BSS-RAM model selects the public users that should be served by FCs better than modified WWF model. This is owing to the fact that pre-fixed BS selection in WWF is carried out before the resource allocation algorithm and public users are assigned to each FC until the total number of allocated users is equal to its capacity, N_f.

In summary, it is worth noting that both RA approaches are centralized but the main difference is that WWF assumes pre-fixed user selection and equal power distribution per bandwidth unit. This indicates that in order to maximize the network throughput, a RA approach for macro-femtocell networks should determine user assignment to base stations together with joint bandwidth and power allocation.

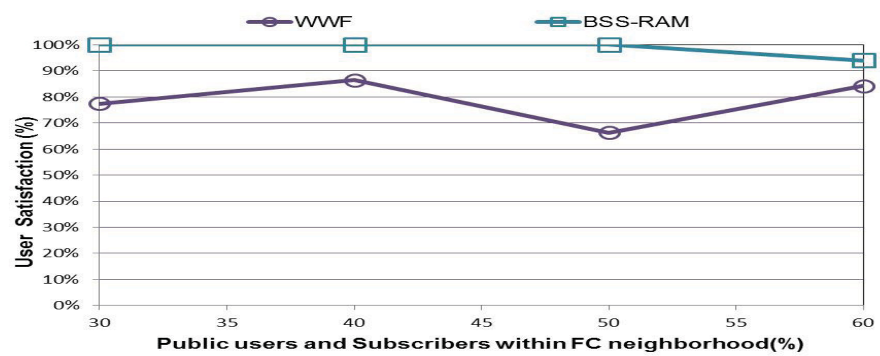
2.6.4 User Satisfaction and Maximum Transmitted Power Required in MC

We want to determine the maximum transmitted power required in macrocell, P_m^{Total}, for a fixed number of mobile users. Simulations were performed changing P_m^{Total} from 46.98 to 55 dBm, to obtain the maximum user satisfaction for two different percentages of mobile users within the FCs coverage area: 30% (solid lines) and 40% (dashed lines). Figure 2.8a shows the user satisfaction versus P_m^{Total} with 30 mobile users located in zone Z_3 and Figure 2.8b depicts the power assigned to macro users.

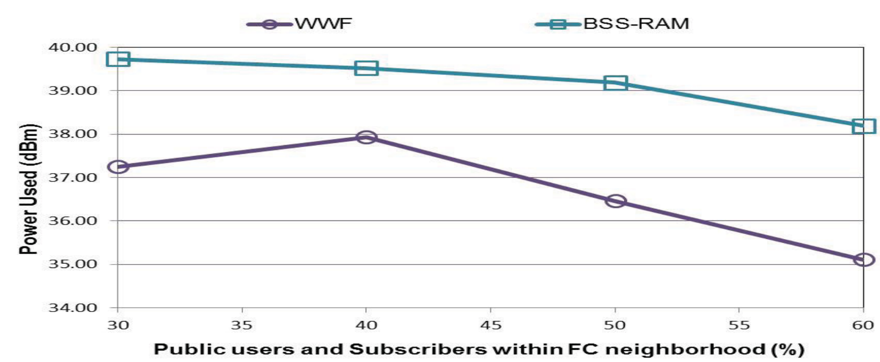
It can be noticed that BSS-RAM model requires at least 49.98 dBm as maximum transmitted power to achieve the maximum user satisfaction in both scenarios, while WWF model requires



a) Throughput



b) User Satisfaction

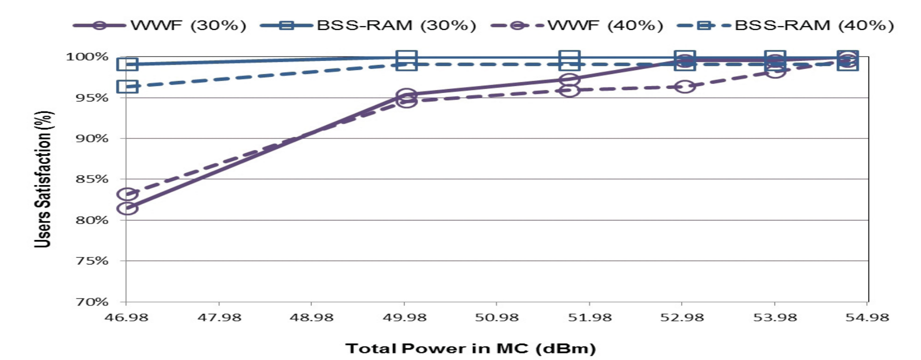


c) Power Assigned in MC

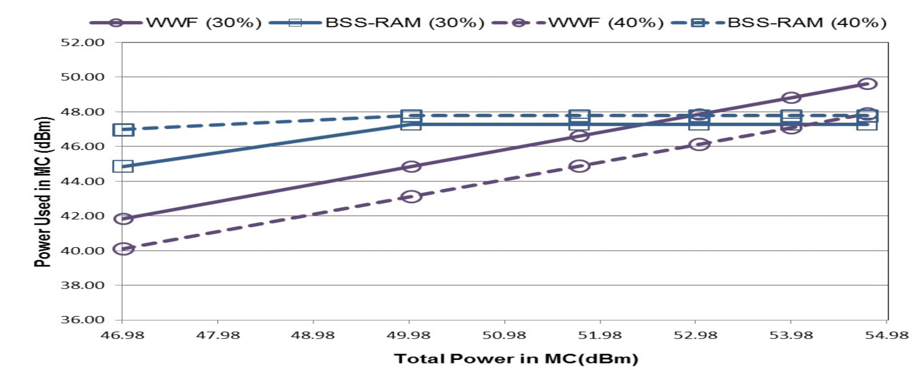
Figure 2.7 Performance Metrics for different users density in FCs

52.9 dBm to provide the maximum user satisfaction in the scenario with 30% and 54.98 dBm with 40%.

In summary, the use of adaptive power per user enables the BSS-RAM model to reduce maximum transmitted power required in MC with high satisfaction levels.



a) User Satisfaction vs P_m^{Total}



b) Power Assigned in macrocell vs P_m^{Total}

Figure 2.8 Maximum transmitted power required for 30 mobile users

2.6.5 Maximum Transmitted Power Required in MC vs number of mobile users

In this section, the maximum transmitted power required in MC is determined for different number of users in the network with a fixed percentage of users in FC neighborhood. We analyze both resource allocation models and look for the maximum transmitted power required in macrocell to achieve the maximum user satisfaction. We derived the total transmitted power required in MC for modified WWF model by equating the network throughput from both models. The throughput is given by:

$$Th = B_m \times log_2\left(1 + \frac{\overline{P_u^m}}{PL(\overline{d_u^m}) \times N_0}\right) + B_f log_2\left(1 + \frac{\overline{P_u^f}}{PL^f(\overline{d_u^f}) \times N_0}\right), \tag{2.38}$$

where B_m and B_f correspond to the bandwidth assigned to macro tier and femto tier respectively. $\overline{P_u^m}$ is the average assigned power per user and is differently calculated by the models and PL^k is the path loss for indoor (k=f) or outdoor environments (k=m). We assume that the spectral efficiency in FCs for both models is achieved, therefore, we can replace the log_2 of the second term as the average spectral efficiency ($\overline{l_f^{mod}}$) in femto tier as follows:

$$Th = B_m \times log_2 \left(1 + \frac{\overline{P_u^m}}{PL^m(\overline{d_u^m}) \times N_0} \right) + B_f \overline{l_f^{mod}}, \tag{2.39}$$

and the average spectral efficiency in femto tier can be expressed as:

$$\overline{l_f^{mod}} = \frac{\sum\limits_{f \in \{F\}} l_f^{mod}}{|F|}. \tag{2.40}$$

In LP model, the average power per user can be calculated as mean of uniform distribution between P_{min}^m and P_{max}^m. These values correspond to the power required to reach the SNR target in both edges of the zone. P_{min}^m and P_{max}^m are determined using the following equation:

$$P_m = SNR_{target} \times PL^m(d_i^m) \times N_0, \tag{2.41}$$

evaluated for distances equal to 172 and 376 m, their values are equal to 25 and 37.88 dBm respectively. Thus, $\overline{P_u^m}$ is equal to 35 dBm. Therefore, total power required is easily calculated as $\overline{P_u^m}$ multiply by the number of users assigned to macrocell, which is:

$$P_m^{Total} = \overline{P_u^m} \times \sum_{i \in N} x_i^m. \tag{2.42}$$

In the case of WWF, the average power per users is simply calculated as:

$$\overline{P_u^m} = \frac{P_m^{Total} \times B_M^{WWF}}{\sum\limits_{i \in N} x_i^m \times B}, \tag{2.43}$$

where B is the available bandwidth of the network. Then, equating the network throughput of both models and replacing known parameters such as $\overline{P_u^m}$ of LP model, $\overline{d_u^m}$, N_0 and B, we can determine the total power required in MC using WWF to reach the same throughput as the BSS-RAM model for any bandwidth allocation and number of users in the network. Thus, P_m^{Total} for WWF RA model is given by

$$P_m^{Total} = \frac{B \times PL^m(\overline{d_u^m}) \times N_0 \times \sum_{i \in N} x_i^m}{B_m^{WWF}} \times \left(2^{\frac{B_m^{LP}}{B_m^{WWF}} \times log_2\left(1 + \frac{\overline{P_u^m}}{PL^m(\overline{d_u^m}) \times N_0}\right) + (B_f^{LP} - B_f^{WWF})\overline{l_f^{mod}}} - 1 \right). \tag{2.44}$$

It can be noticed that the number of users assigned to MC tends to be $N - F \times N_f$, when N is a high value. However, the bandwidth allocation depends on the number of bits per symbol required in FCs and the user demands.

Figure 2.9 shows the analytical results (dashed lines) and the results obtained from running several simulations with increasing P_m^{Total} values until the same throughput is reached for both models (solid lines). This figure indicates that our approach requires less maximum transmitted power in macrocell, P_m^{Total}, than WWF model. In particular, the gap is bigger with a number of users lower than 30, but it remains constant and equal to 3 dB for more than 30 users. It can be observed that simulation results present higher power value than the theoretical one. This is owing to the fact that we run the simulation changing the total power in MC with steps of 20 Watts, therefore the exact value of total power required should be between the total power values used for last two simulations.

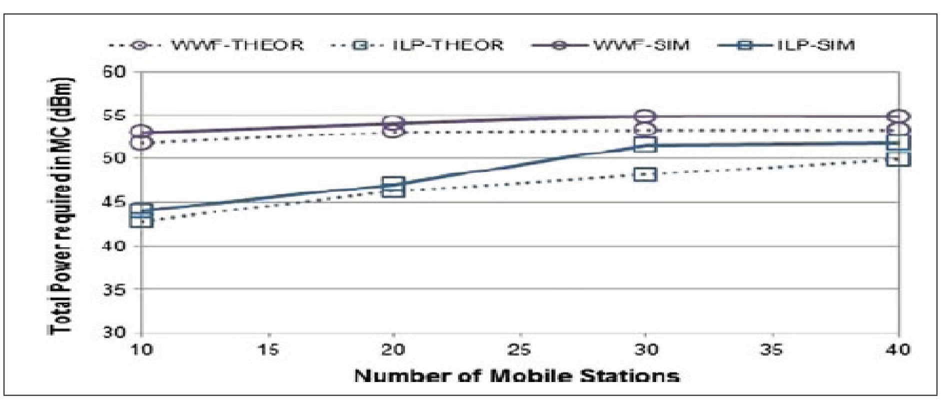


Figure 2.9 Total Power Required in macrocell

In general, BSS-RAM model requires less transmitted power in macrocell to provide good user satisfaction. This is owing to the fact that equal power distribution among all subcarriers leads to a certain disadvantage in OFDMA macro-femtocell networks. Since femtocells offload traffic from macrocell, the maximum transmitted power in MC, P_m^{Total}, should be efficiently distributed over its active subcarriers. However, it is difficult to know a priori which users are going to be served by MC or FCs and the number of subcarriers to be assigned to each BS depends on this.

2.6.6 Throughput MSE

In this section, we analyze the mean square error of the network throughput caused by the applied PWS linear approximation of log term in Shannon's Law Capacity. The mean square error can be expressed by

$$e_T = \sqrt{\frac{\sum_{i \in N} b_i^2 \left(log_2(1+SNR_i) - (m_k SNR_i + a_k)\right)^2}{N}}. \tag{2.45}$$

The average error between log_2 function and its corresponding linear segment function is equal to 0.2623, which is taken from Table 2.3 in Section 2.4.2. Using this value, we can provide an estimate of the mean square error by

$$e_T = \sqrt{\frac{0.0676 \sum_{i \in N} b_i^2}{N}}, \tag{2.46}$$

which depends on the bandwidth assigned to each user and the number of users in the network, N. Figure 2.10 shows the mean square error as function of the number of mobile users. It is important to notice that the MSE error tends to converge to 0.4 Mbps, which is only 0.13 % of the total throughput assigned to 50 users.

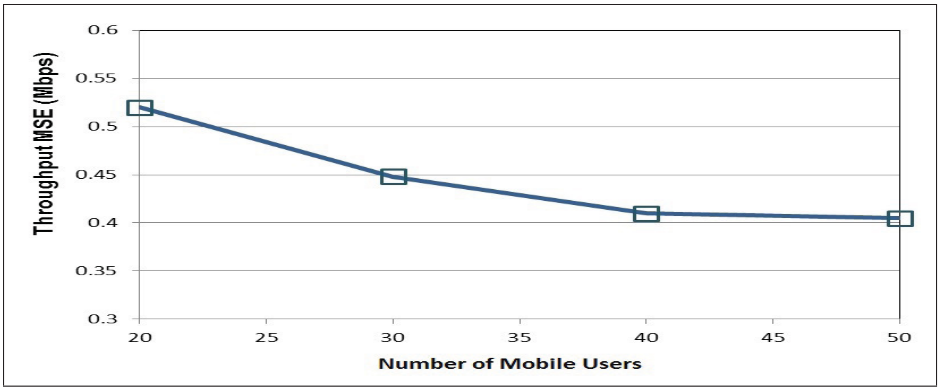


Figure 2.10 Throughput Mean Square Error

2.6.7 Complexity

The complexity of our model depends on the number of small pieces of fixed amount bandwidth that comprise the licensed spectrum, mobile user density within FC coverage area, the number of femtocells in the cluster and the total transmitted power in MC. In this paper, we have used two set of weights, i.e. LR related to link rate and DE related to user demand. Table 2.8 shows running time of BSS-RAM using the two types of weights for different number of mobiles users, 3 femtocells, bandwidth equal to 100 MHz divided into small pieces of 100 kHz and total power equal to 51.76 dBm.

Table 2.8 Running Time

Users	LR	DE
10	0.04	0.04
20	0.14	0.03
30	0.42	0.20
40	1.06	0.29
50	2.07	1.59

Although the weights related to the demand provide lower running time, the throughput is lower than the one achieved using weights related to link conditions. Both models can handle the same number of user but the main difference is the user satisfaction that is improved by using the LR based weights since the are adaptively changed taking into to the allocated power to the users.

Our ILP model can connect a maximum number of users equal to the capacity of the FC cluster (i.e. 12) multiply by the number of clusters in the network plus the remaining bandwidth that can be used for macro user transmission divided by the average bandwidth per macro user. As we are prioritizing the use of FC, the bandwidth that should be allocated to femtocells is equal to the total demand for the 12 users multiply by the average demand per user (7.5 Mbps) divided into the average spectral efficiency for FCs (2.66 bits/symbol from Table 2.5). In the particular case under study, the FCs bandwidth should be equal to 34 MHz, leaving 66 MHz for the macrocell. Therefore, the maximum number of user is equal to 12 plus 66 divided by the average bandwidth per user (1.25 MHz), this gives as a maximum capacity of 64 users.

2.7 Conclusion

We introduced a RA model that is able to determine optimal serving base station together with the optimal amount of bandwidth and power for each user taking into account its demand and location. We presented a performance comparison of the proposed model with a modified version of Weighted Water Filling algorithm. Simulation results showed that WWF model requires between 5% and 16% more power than BSS-RAM model to achieve the same user satisfaction. In addition, a noise increase of 4 dBm degrades the satisfaction level in WWF model by 6% more than BSS-RAM model. The main disadvantages of modified WWF model are the pre-fixed user selection and equal power distribution per bandwidth unit. Therefore, we can conclude that bandwidth allocation together with adaptive power per user and base station selection enable the BSS-RAM model to enhance the network throughput and to reduce the impact of noise. Moreover, BSS-RAM model makes the macro-femtocell network more compliant with the Green Communication Technologies trends since the proposed model required less transmitted power in MC than modified WWF.

CHAPTER 3

ENERGY-EFFICIENT RESOURCE ALLOCATION MODEL FOR OFDMA MACRO-FEMTOCELL NETWORKS

Rebeca Estrada[1] , Abdallah Jarray [2] , Hadi Otrok[3] , Zbigniew Dziong[1] , Hassan Barada[3] ,

[1] Département de Génie Eléctrique, École de Technologie Supérieure,

1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3

[2] University of Ottawa, Ottawa, ON, Canada

[3] Department of ECE, Khalifa University of Science, Technology & Research, UAE

An Article submitted to the IEEE Transactions on Vehicular Technology in September 2012

and published in September 2013 (vol. 62, issue 7, pp. 3429-3437)

http://dx.doi.org/10.1109/TVT.2013.2253693

3.1 Abstract

Femtocells are introduced to enhance the indoor coverage and system capacity of traditional cellular network. However, the network performance could be significantly deteriorated due to the increase of co-channel interference in dense deployment. In literature, three spectrum usage schemes have been proposed that deal with the cross-tier interference, which are orthogonal assignment, underlay and controlled underlay using mainly closed access femtocells. This paper targets the optimization of resource allocation together with base station selection in two-tier networks assuming hybrid access femtocells to reduce the cross-tier interference. Moreover, this model aims to achieve effective spatial reuse between macrocell and femtocells while guaranteeing Quality of Service transmissions by means of joint power control in both tiers. Simulations are conducted to show a comparison with the other three approaches.

3.2 Introduction

Femtocells (FCs) are low cost base stations (BSs) with short range that guarantees good indoor coverage and enhances data rates. In traditional cellular networks, macrocell (MC) must satisfy the requirements of indoor and outdoor users, which leads to poor indoor coverage and dead zones appearance. Hence, there are several economical factors that encourage network providers to use FCs such as capacity improvements and power consumption reduction due to transmission to a nearby femtocell instead of a farther macrocell (Zhang and De la Roche, 2010). Nevertheless, one main challenge of such a network is the resource allocation in dense FC deployment due to the ah-hoc nature of femtocell locations.

In conventional cellular networks, three subchannel formation schemes are specified in the physical Orthogonal Frequency Division Multiple Access (OFDMA) standard: Partial Usage Subcarrier (PUSC), Full Usage Subcarrier (FUSC) and Adaptive Modulation and Coding Band (AMC-Band) (IEEE-802.16, 2004). AMC-Band uses adjacent subcarriers per subchannel while PUSC and FUSC assign distributed subcarrier abroad the spectrum using permutation algorithms. The distributed subcarrier approach provides immunity to selective fading. FUSC also provides interference diversity and allows the subcarrier reuse in neighbor MCs (Yang, 2010). One concern in a co-channel deployment of FCs is the high level of interference caused to MC downlink (DL) transmissions. This problem motivates us to investigate how the subcarrier reuse can improve the resource allocation in an OFDMA macro-femtocell network.

Another concern is the definition of FC access mode that controls which users are authorized or not to connect to FCs. Closed access mode allows only authorized users (i.e. subscribers) to connect to their own femtocells. In open access mode, all users are considered equal and able to connect to either FCs or MC. In (Choi *et al.*, 2008), a hybrid access mode for femtocells was evaluated, where public users are allowed to connect to FCs according to different levels of open access.

Most of the previous research work assumed equal power distribution among subcarriers, which reduce the resource allocation problem to subcarrier allocation and BS selection, i.e. (Bharucha *et al.*, 2010). Their goal is to maximize network throughput taking into account sparse or dense FCs deployment. In sparse deployment, a dedicated portion of bandwidth is assigned to each tier (Chun-Han and Hung-Yu, 2011). Conversely, in dense deployment, subcarriers can be shared among MC and FCs and interference management schemes need to be implemented to enhance network throughput, such as: power control (Torregoza *et al.*, 2010), hybrid access femtocell scheme (Li *et al.*, 2010), fractional frequency reuse (Dalal *et al.*, 2011), soft frequency reuse (Jeong *et al.*, 2010) and the use of cognitive radios (Bennis and Perlaza, 2011).

The limitations of prior work can be summarized as: (i) power control in FCs mitigates the interference perceived by macro users but also reduces the data rates provided by FCs, (ii) Data rate depends on mobile user (MU) location and requires a higher number of subcarriers if the transmitted power is fixed and the interference increases, and (iii) as FC density increases, orthogonal subcarrier allocation limits the number of MU that can be connected to the network. To overcome these limitations, bandwidth reuse with granularity subcarrier is investigated in this paper as the subcarrier is the smallest unit of bandwidth in OFDMA transmissions.

In this paper, we target to maximize the network performance by reusing subcarrier and prioritizing the use of femtocells for own subscribers and public users in their vicinity. To do so, we propose to jointly perform power adaptation in both tiers. The proposed solution aims to: (1) find the optimal selection of users to be served by each BS taking into account their demands and locations,(2) determine the optimal subcarriers allocation and their transmitted power guaranteeing Quality of Service (QoS), (3) enhance the throughput by serving more users, and (4) improve the power usage in both tiers.

To evaluate the performance of our approach, we use as benchmark three approaches: one spectrum partitioning model and two spectrum sharing models. First approach assigns orthogonal subcarriers among tiers and between neighbor FCs to avoid cross-tier (Chun-Han and Hung-Yu, 2011) and co-tier interference (Chandrasekhar and Andrews, 2008). Second approach performs power control in FC to avoid depriving macro DL transmissions (Hatoum *et al.*, 2011) and third model attempts to exploit resources occupied in MC to increase the spatial reuse as long as they do not trespass an interference threshold (Liu *et al.*, 2012).

The rest of the chapter 3 is organized as follows: Section 3.3 presents the problem statement. Section 3.4 describes the proposed model. In Section 3.5, we present three benchmark models. The performance measurements are described in Section 3.6. Section 3.7 presents the simulation scenario and analyzes results obtained in our model compared with the benchmark models. Finally, Section 3.8 concludes the paper.

3.3 Problem Statement

In a scenario with interference, transmitted power from any interfering BS should be reduced to minimize the interference caused to nearby mobile users served by other BSs. This power reduction decreases the spectral efficiency in interfering BSs and may reduce data rates unless bandwidth usage is increased to satisfy user demands. Conversely, the transmitted power in each BS should be maximized to tackle the interference level when subcarrier reuse is allowed. Therefore, there is a complex dependency between power, bandwidth and interference.

To uphold the signal to interference plus noise ratio (SINR) required in BS, an interference threshold can be easily determined using fixed transmitted power per BS. In the following, we show some limitations of using fixed transmitted power per subcarrier.

Analogously to (Tarhini and Chanjed, 2007), we consider the MC coverage area divided in four different zones shown in Fig. 3.1, each with a specific modulation technique related to the spectral efficiency that can be achieved due to the propagation losses. Few research work has been dedicated to solve the resource allocation problem among the MC zones as in (Tarhini and Chanjed, 2007). However, this issue is out of the scope of our paper.

In general, the achievable spectral efficiency in MC or FCs can be estimated as

$$\gamma_k = log_2\left(1 + \frac{P_i^k}{PL_i^k(N_0 + I_i)}\right), \qquad k \in \{m, FC\} \tag{3.1}$$

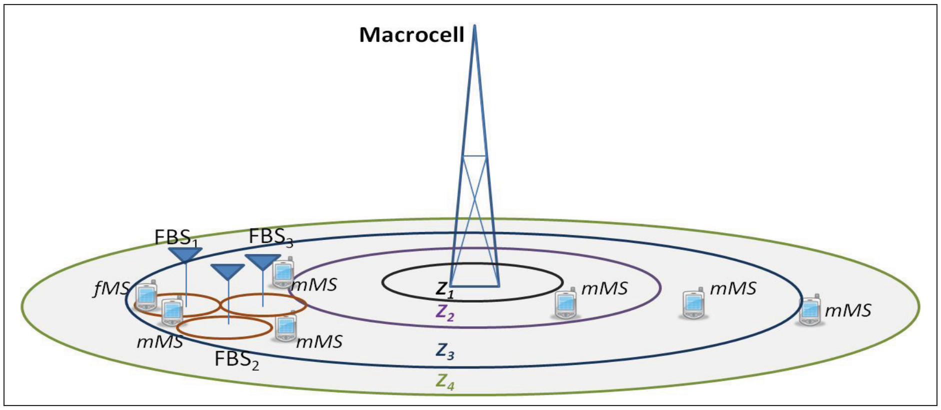


Figure 3.1 Example of macro-femtocell network

The index k stands for user association with the BS k. PL_i^k is the path loss for wireless channel and P_i^k is the power assigned to user i in BS k. I_i is the interference perceived per subcarrier from the interfering BSs.

All channel models used in this paper are based on the ITU-R M.1225 model (ITU-TR-36.921, 1997). Accordingly, the path loss between BS and mobile user is given by

$$PL_i^k(dB) = \begin{cases} 10log_{10}(d_{ik}^{\alpha_k}) + 30log_{10}(f_c) + 49 & k = m \\ 10log_{10}(d_{ik}^{\alpha_k}) + 37 & k \in FC \end{cases} \tag{3.2}$$

where d_{ik} is the distance from BS k to user i, which should be given in meters for femtocells and kilometers for macrocell. f_c is the carrier frequency adopted by the MC (in MHz). α_k is the outdoor/indoor attenuation factor, which are assumed to be equal to 3.7 and 3 for outdoor and indoor environments respectively in accordance with the carrier frequency (K., 2007).

We perform an interference analysis only in one MC zone. The idea is to locate both macro users and FCs in the same zone to deal with the interference. We select zone Z_3 because it has a wide area according to the OFDMA physical assumptions in (Tarhini and Chanjed, 2007) but any zone can be analyzed following this procedure. The modulation technique is Q-PSK in zone Z_3. Noise is equal to -174 dBm/Hz (Fehske *et al.*, 2009) and the number of subcarriers assigned to the zone is equal to 128.

3.3.1 Interference perceived in Femto Tier

In femto tier, a MC transmission and several neighbor FCs transmissions can interfere with a given wireless link between a femto BS and a mobile user. Assuming equal power distribution among subcarriers in FCs, the transmitted power per subcarrier, P_i^f, can be determined by dividing FC total power, P^f, by the number of subcarriers. We use P^f equal to 10 mW (3GPP-TR-36.921, 2011). In general, FCs can be deployed with different modulation techniques. For simplicity, we only analyze QPSK and 16-QAM. Replacing the known parameters (i.e. α_f, d_{if}, P_i^f) in (3.1), we obtain the interference thresholds equal to 5x10^{-12} watts/subcarrier and 1.2x10^{-12} watts/subcarrier for Q-PSK and 16-QAM respectively.

We can derive the distance between a macro BS and a mobile user, d_{im}, from which femto BSs can reuse his assigned subcarriers replacing these interference thresholds in the following equation:

$$\frac{P_i^m}{PL_i^m} \leq I_{th}^f, \tag{3.3}$$

where P_i^m is MC transmitted power per subcarrier assigned to user i, PL_i^m is the path loss for outdoor channel given by (3.2) and I_{th}^f is the interference threshold allowed in FC. Commercial macro BS utilizes transmitted power of 10W (Dufková *et al.*, 2011). Thus, the total MC transmitted power, P_m^{Total}, is equal to 316.5 W, including the antenna gain (15 db). P_i^m is equal to 2.47 W assuming equal power distribution. Then, we replace this power in (3.3) and obtain the distance equal to 128 and 189 meters for QPSK and 16-QAM respectively. Therefore, FC with higher data rate requirements needs to be deployed farther from macro BS to avoid high interference levels.

Since FCs might not use all the subcarriers belonging to MC zone, it would be good to have adaptive power distribution over active subcarriers to satisfy femto user demands and to provide immunity to interference perceived per subcarrier instead of the fixed transmitted power.

3.3.2 Interference perceived in Macro Tier

In macro tier, the interference threshold is determined to achieve the SINR target in the zone using the following equation:

$$P_i^m = SINR_{target} \times PL_i^m \times (N_0 + I_{th}^m), \tag{3.4}$$

where $SINR_{target}$ is equal to $9.4dB$ and zone's radius is calculated based on the OFDMA physical layer assumptions in (Tarhini and Chanjed, 2007). Thus, I_{th}^m results to be equal to 1.09x10^{-14} using P_i^m value as in Section 3.3.1.

The achievable spectral efficiency is calculated using (3.1) and plotted in Fig. 3.2 using 15 dB as wall penetration losses and assuming that the macro user i is equidistant from each interfering femto BS. Horizontal line shows the target spectral efficiency (i.e 2) and the other curves represent the spectral efficiency obtained for 1 to 3 nearby interfering femto BS. The crossing points between the horizontal line and the spectral efficiency curves shows that for distance d_{im}:

- between 176 and 280 meters, three nearby FCs can reuse these subcarriers, or;
- between 176 and 320 meters, two nearby FCs can reuse them;
- less than 376 meters, subcarriers can be reused by only one nearby FCs.

without degrading the QoS transmission. In other words, subcarrier reuse also depends on macro user location.

In summary, we determined the interference thresholds for both tiers assuming equal power distribution in MC and FCs for a given modulation technique. In addition, we estimated the distance from macro BS where macro users DL transmissions allows nearby FCs to reuse the subcarriers assigned to their DL transmissions.

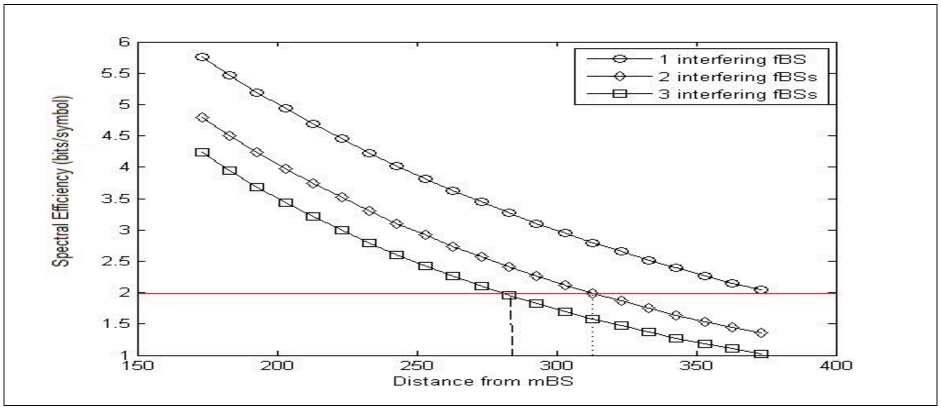


Figure 3.2 Achievable spectral efficiency in MC zone Z_3

OFDMA technology allows having different power levels per subcarrier as long as the peak to average power ratio (PAPR) is lower than 21 dB with 128 subcarriers (IEEE-802.16, 2004). Then, the challenge is to jointly allocate subcarriers in each BS and their respective power to tackle a given interference threshold without degrading the target SINR taking into account the transmission environments and demands.

3.4 Controlled per subcarrier Model (Controlled-SC)

OFDMA physical layer standard specifies maximum data rates offered to mobile users, which are decreasing according to remoteness of the zone where the users are located owing to the propagation losses (IEEE-802.16, 2004; Yang, 2010). In a macro-femtocell network, user data rate should be limited to the maximum MC data rate per zone or available capacity in nearby FCs. We propose to adapt the transmitted power per subcarrier without trespassing a maximum transmitted power per subcarrier in each BS. This maximum value is obtained from (3.3) for a user located in the zone edge (or FC edge in femto tier). The use of this maximum power can reduce MC power consumption and also enable the reuse of subcarriers assigned to zone closer to macro BS in FCs located in zones farther from MC. Let's assume one macro user located in zone Z_1 of Fig. 3.1, who uses subcarriers $(S_1 - S_{12})$. Then, FCs located in any remote zone can reuse his subcarriers with low interference levels. Moreover, these subcarriers can also be reused by FCs inside the same zone by means of joint power control in both tiers.

This additional power control would make the two-tier networks more compliant with green communication technologies trends.

3.4.1 Problem Formulation

The proposed solution aims to maximize the network throughput evaluated as the sum of user data rates. The sum of achievable data rates according to Shannon's Law Capacity is given by

$$\max_{\mathbf{b},\mathbf{P}} \sum_{k\in\{m,FC\}} \sum_{i\in\{MS\}} \sum_{s\in\{S\}} b_i^{s,k} log_2(1+SINR_i^{s,k}), \tag{3.5}$$

where the vectors **b** and **P** correspond to subcarrier assignment and their respective power in each BS. In other words, **b** consists of binary variables $b_i^{s,k}$, which determine if the subcarrier is used or not in BS $k \in \{m, FC\}$. The index k represents the association with MC m or FC f from the set of deployed femtocells FC and MS is set of mobile users. $SINR_i^{s,k}$ is the signal to noise plus interference ratio perceived by macro users or femto users and is given by

$$SINR_i^{s,k} = \frac{b_i^{s,k} P_i^{s,k}}{PL_i^k \left(N_0 + I_i^{s,k}\right)} \qquad k \in \{m, FC\} \tag{3.6}$$

$P_i^{s,m}$ and $P_i^{s,f}$ are the components of the power vector **P**, N_0 is the average noise per subcarrier and PL_i^k is the path loss, which is given by (3.2) in Section 3.3. $I_i^{s,k}$ is the interference perceived by mobile user i caused by macrocell and/or neighboring femtocells using the same subcarrier s, which is given by

$$I_i^{s,k} = \begin{cases} \sum\limits_{f\in\{FC\}} \sum\limits_{j\in\{MS\}} \frac{b_j^{s,f} P_j^{s,f}}{PL_i^f}, & k = m \\ \sum\limits_{j\in\{MS\}} \frac{b_j^{s,m} P_j^{s,m}}{PL_i^m} + \sum\limits_{f\in\{FC\backslash k\}} \sum\limits_{j\in\{MS\}} \frac{b_j^{s,f} P_j^{s,f}}{PL_i^f}, & k \in FC \end{cases} \tag{3.7}$$

In particular, the interference perceived by macro users only corresponds to cross-tier interference while for femto users, it consists of: (i) cross-tier interference related to the reuse of the subcarriers already assigned in MC and (ii) co-tier interference due to the use of the same subcarriers in neighbor FCs.

From (3.5-3.7), it can be seen that our problem is a nonlinear optimization problem and and it has been proven to be NP-hard (Hong and Garcia, 2012). Therefore, we replace (3.5) by

$$\max_{\mathbf{b},\mathbf{P}} \sum_{i\in\{MS\}} \sum_{s\in\{S\}} w_i^m b_i^{s,m} l_z^{mod} + \sum_{f\in\{FC\}} \sum_{i\in\{MS\}} \sum_{s\in\{S\}} w_i^f b_i^{s,f} l_f^{mod}, \tag{3.8}$$

assuming that the log_2 term should be at least equal to the spectral efficiency required in the MC zone, l_z^{mod}, or FC, l_f^{mod}. The spectral efficiencies (l_z^{mod}, or FC, l_f^{mod}) are given parameters that identify the target spectral efficiency in the MC zone or a given femtocell f. Weights (w_i^m, w_i^f) are included to prioritize the use of FCs for subscribers and public users in FC vicinity.

Based on Linear Programming (LP) (Karloff, 2009), the proposed solution aims to maximize the network throughput by means of performing jointly power and bandwidth assignment together with BS selection. We also incorporate joint power control in macro tier and femto tier to reduce all kinds of interference perceived by mobile users.

3.4.2 LP Parameters

LP parameters are classified as system, input, and output parameters. System parameters determine the network features, such as: Number of subcarriers, N_s, bandwidth per subcarrier, B_s, maximum number of subcarriers per channel, $N_s^k, k \in \{m, FC\}$, maximum power per sector, $P_z^{s,m}$, maximum transmitted power per subcarrier in FC, $P_{max}^{s,f}$, total power available in MC, P_m^{Total}, attenuation factors, (α_m, α_f), carrier frequency, f_c, spectral efficiency required per modulation technique, (l_z^{mod}, l_f^{mod}), average noise, N_0, radius of FC, $R_f, f \in \{FC\}$, FC Capacity, in terms of number of users, M_f.

Input parameters specify the requirements of the mobile users, such as demands,D_i, user locations (d_{im}, θ_{im}) and FC locations $(d_f, \theta_f), f \in \{FC\}$. Output parameters are the LP model variables, which are described in next section.

3.4.3 Model Variables

The proposed model determines the following variables: BS assignment, Y_i^k, subcarrier assignment, $b_i^{s,k}$, power per subcarrier in each BS, $(P_i^{s,m}, P_i^{s,f})$, and reuse per subcarrier r_s. The values for these variables are as follows:

$$Y_i^k = \begin{cases} 1 & \text{if user } i \text{ is assigned to BS } k \in \{m, FC\} \\ 0 & \text{otherwise} \end{cases}, \tag{3.9}$$

$$b_i^{s,k} = \begin{cases} 1 & \text{if subcarrier } s \text{ is assigned to user } i \text{ in BS } k \in \{m, FC\} \\ 0 & \text{otherwise} \end{cases}, \tag{3.10}$$

$$0 \leq P_i^{s,m} \leq P_z^{s,max}, \tag{3.11}$$

$$0 \leq P_i^{s,f} \leq P_{max}^{s,f}, \tag{3.12}$$

$$0 \leq r_s \leq |FC|, \tag{3.13}$$

$|FC|$ indicates the cardinality of the set of femtocells FC. The proposed LP model consists of two types of variables (one real and one integer), then, the throughput maximization is solved by means of a Mixed Integer Linear Programming (MILP) based algorithm 3.1.

3.4.4 Objective Function

Our objective is to maximize the network throughput given by (3.8) in Section 3.4.1. For convenience, we use weights that prioritize the use of FCs for own subscribers and public users in their vicinity. In particular, w_i^m is equal to 1 for public users and subscribers, w_i^f is equal to 3 for subscribers of FC f and w_i^f 1.25 for public users close to FC f.

3.4.5 Model Constraints

For the objective function presented in (3.8), we have the following constraints:

Algorithm 3.1 Controlled-SC Resource Allocation algorithm

Data: MS Set of users,
FC,m Set of Femtocell and m represents Macrocell,
(X_i,Y_i) User Locations,
(X_f,Y_f) FC Locations,
$(l_m^f od)$ FC Modulation Technique,
(D_i) User Demands.
Result: BS selection for the set of users, $\mathbf{Y_i^k}$,
Bandwidth allocated per subcarrier per user $\mathbf{b_i^{s,k}}$
Power allocated per subcarrier per user $\mathbf{P_i^{s,k}}$.
begin
Macrocell resource management entity **do**;
Collect from each mobile user i, its demand and location (D_i, d_{im}, θ_{im});
Collect from femtocell f, its location and modulation scheme (d_f,θ_f,l_f^{mod});
Assign weights
$$w_i^f = \begin{cases} 3 & \text{for SU } i \text{ close to FC } f \text{ to prioritize their transmission in their own FC} \\ 1.25 & \text{for PU } i \text{ close to FC } f \text{ to prioritize the use of FC} \end{cases};$$
$w_i^m = 1$ for all the mobile users;
Calculate distances of links between femtocell f and each user (d_i^f,θ_i^f);
Formulate the problem as an MILP;
Solve the MILP, and find the optimal RA solution;
end

Upper bound for number of assigned subcarriers per BS: The sum of assigned subcarriers per BS must be less than or equal to the number of subcarriers.

$$\sum_{i\in\{MS\}} \sum_{s\in\{S\}} b_i^{s,k} \leq N_s \qquad ;k \in \{m,FC\}, \tag{3.14}$$

Subcarrier clash constraint: One subcarrier can be assigned only to one user in each BS.

$$\sum_{i\in\{MS\}} b_i^{s,k} \leq 1 \qquad ;s \in S, k \in \{m,FC\}, \tag{3.15}$$

Upper Bound for subcarrier reuse: One subcarrier can be assigned to one user in macro-tier and also to F users in femto-tier, i.e. one user in each FC.

$$\sum_{f\in\{m,FC\}}\sum_{i\in\{MS\}} b_i^{s,f} \leq 1+r_s \qquad ;s\in S, \tag{3.16}$$

Upper Bound bandwidth satisfaction: Number of assigned subcarriers must be less than or equal to the minimum between the number of subcarriers allowed par the technology, N_k^s, and number of subcarriers required to satisfy the user demand, D_i.

$$B_s \sum_{s\in\{S\}} b_i^{s,k} \leq \min\left(B_s N_s^k, \frac{D_i}{l_k^{mod}}\right) \qquad ;i\in MS, k\in\{m,FC\}, \tag{3.17}$$

User clash constraint: One user can only be assigned to one BS at each time.

$$\sum_{k\in\{m,FC\}} Y_i^k \leq 1 \qquad ;i\in MS, \tag{3.18}$$

Maximum capacity in femtocells: The number of users assigned to FC f must be less or equal to its capacity, i. e. number of allowed femto users, M_f.

$$\sum_{i\in\{MS\}} Y_i^f \leq M_f \qquad ;f\in FC, \tag{3.19}$$

Enabling Subcarrier Reuse Constraint: Subcarrier reuse should not be allowed if the sum of the users demand, i.e $\sum D_i$, is less than or equal to the sum of data rate provided to macro users and subscribers in the network.

$$r_s = \begin{cases} 0 & \sum\limits_{i\in\{MS\}} D_i \leq N_s \times B_s \times l_{avg}^{mod} \\ F & \text{otherwise} \end{cases} \tag{3.20}$$

l_{avg}^{mod} is the average spectral efficiency required per user taking into account that macro users are served by MC, subscribers are served by their own FC and orthogonal assignment is used among tiers and between neighboring FCs. In other words, if the orthogonal subcarrier assignment can not satisfy the user demands, then, the subcarrier reuse is allowed and interference will be present.

$$l_{avg}^{mod} = \frac{\sum_{i \in \{MS \setminus \cup_f MS_f\}} l_z^{mod} + \sum_{f \in \{FC\}} \sum_{i \in \{MS_f\}} l_f^{mod}}{M}, \tag{3.21}$$

Total transmitted power per BS: The sum of power assigned to each subcarrier must be less than or equal to maximum transmitted power in each BS.

$$\sum_{i \in \{MS\}} \sum_{s \in \{S\}} P_i^{s,k} \leq P_k^{Total}, k \in \{m, FC\}, \tag{3.22}$$

Variables linking constraints

- Upper bound for number of subcarriers assigned to users per BS if the user i is assigned to the BS k:

$$\sum_{s \in \{S\}} b_i^{s,k} \leq N_s Y_i^k \qquad ; i \in MS, k \in \{m, FC\}, \tag{3.23}$$

- Maximum transmitted power per subcarrier

$$P_i^{s,k} \leq b_i^{s,m} P_z^{s,k} \qquad ; i \in MS, s \in S, k \in \{m, FC\}, \tag{3.24}$$

- Zero bandwidth for power equal to zero:

$$b_i^{s,k} \leq P_i^{s,k} Q_k \qquad ; i \in MS, s \in S, k \in \{m, FC\}, \tag{3.25}$$

Q_k is a big constant at least equal to the maximum amount of power in BS k that can be assigned to a given user on a given subcarrier in macro and femto tiers respectively. This constant is used in (3.25) to express the relationship between assigned bandwidth and power to users. In other words, (3.25) ensures that an amount of bandwidth can be assigned to one user only and only if a non-zero power is assigned.

Spectral Efficiency Lower Bound: Spectral efficiency must be greater than target spectral efficiency in zone Z_r or in FC f.

$$\log_2\left(1+SINR_i^{s,k}\right) \geq l_k^{mod} b_i^{s,k} \qquad ; i \in MS, s \in S, k \in \{m, FC\}, \tag{3.26}$$

$SINR_i^k$ is the signal to interference plus noise ratio of the user i and is given by (3.6).

Interference Constraint: The interference level must be less than or equal to the interference threshold, γ_{Th}.

$$I_i^{s,k} \leq \gamma_{Th} \qquad ; i \in MS, k \in \{m, FC\}, \tag{3.27}$$

$I_i^{s,k}$ depends on the BS selection and was given by (3.7).

Equation (3.26) can be decomposed into the sum of two log_2 terms as follows:

$$\log_2\left(N_0 + I_i^{s,k} + \frac{P_i^{s,k}}{PL_i^k}\right) - \log_2\left(N_0 + I_i^{s,k}\right) \geq l_k^{mod} b_i^{s,k}. \tag{3.28}$$

Equation (3.28) can be replaced by linear segments of a PWS linear approximation. However, it is necessary to evaluate the received power and interference values in order to use an appropriate linear approximation. This issue is handled in next section.

3.4.6 Linear Approximation of Log Term

According to (Imamoto and Tang, 2008), any convex function can be approximated by a L segment continuous piecewise linear function $g(x)$ defined over the range $x_0 \leq x \leq x_L$ by a set of points or knots L $(x_l^{min}, x_l^{max})_{l=0}^N$ connected by L segments. Using this basis, we propose to use a PWS linear approximation to convert our non-linear programming problem in linear program model. The composed PWS linear approximation using three segments is defined in Table-A II-1 of the Appendix II.

The linear segments are calculated using the algorithm in (Imamoto and Tang, 2008). This algorithm requires a high number of iterations to converge as the number of segments increases. A high number of linear segments involves more power variables and requires determining the corresponding segment. For simplicity, we use a 3-segment PWS linear approximation since the received power and interference values can be evaluated in only one segment for each modulation technique. The details of the PWS linear approximation and the mean square error introduced due to the linear approximation can be found in Appendices II and III respectively.

Interference values plus noise are confined to the first linear segment. To do so, two more constraints are added in each tier. The upper bound and lower bound of interference plus noise is given by (3.32) and (3.33). Thus, Equation (3.28) can be replaced using the corresponding segment l of PWS linear approximation to (3.29-3.33).

$$m_l\left(N_0+I_i^{s,k}+\frac{P_i^{s,k}}{PL_i^k}\right)+a_l-m_0\left(N_0+I_i^{s,k}\right)-a_0 \geq l_k^{mod} b_i^{s,k} \tag{3.29}$$

$$N_0+I_i^{s,k}+\frac{P_i^{s,k}}{PL_i^k} \leq LS_l^{max} \qquad ;k\in\{m,FC\}, i\in MS, s\in S, \tag{3.30}$$

$$N_0+I_i^{s,k}+\frac{P_i^{s,k}}{PL_i^k} \geq LS_l^{min} \qquad ;k\in\{m,FC\}, i\in MS, s\in S, \tag{3.31}$$

$$I_i^{s,k} \leq b_i^{s,k}(LS_0^{max}-N_0) \qquad ;k\in\{m,FC\}, i\in MS, s\in S, \tag{3.32}$$

$$I_i^{s,k} \geq b_i^{s,k}(LS_0^{min}-N_0) \qquad ;k\in\{m,FC\}, i\in MS, s\in S. \tag{3.33}$$

Controlled-SC determines transmitted power per subcarrier in each base station and subcarrier assignment taking into account users demand, user locations and interference threshold per modulation technique used in MC zone or in FCs.

3.5 Benchmark Resource Allocation models

In this section, we describe the benchmark models. Section 3.5.1 describes the underlay model that performs bandwidth allocation and fixed power assignment per subcarrier in each BS. Section 3.5.2 presents the controlled-underlay model that carries out bandwidth assignment, fixed power assignment per subcarrier in MC and adaptive power per subcarrier in FCs. Finally, a model that avoids interference through the orthogonal subcarrier assignment among BSs is presented in Section 3.5.3.

3.5.1 Underlay Model

This model reduces the resource allocation problem to the subcarrier allocation, the determination of one transmitted power per BS and BS selection. To do so, we assume that the transmitted power in MC zone and FCs is a fixed value given by, $P^{s,m}$ and $P^{s,f}$ respectively without limitation of maximum transmitted power per BS. We keep the same objective function in (3.8) and replace the new power variables in (3.6-3.7). Constraints (3.22 - 3.25) are not used since the transmitted power per subcarrier is the same value for all the users in a given BS and we do not need the linking constraint between subcarrier assignment and its power.

Constraint (3.26) with the new power variables are changed into the sum of two log_2 terms and replaced using the PWS linear approximation. A MILP based algorithm is used to solve the throughput maximization as in the Controlled-SC model. However, this algorithm is not included due to the paper length limitation.

It is important to notice that this model assumes no limitation in the total transmitted power per BS. However, this value can be determined by multiplying the number of subcarrier assigned to the BS by the optimal transmitted power per BS.

3.5.2 Controlled-underlay model

This benchmark model is a combination between the two previous models since we assume the same transmitted power per subcarrier in MC, $P^{s,m}$, and adaptive transmitted power in FCs, $P_i^{s,f}$, to prioritize macro user DL transmissions. Thus, MC transmitted power per subcarrier needs to be changed without the user index i in (3.6,3.7). Most of the constraints of the Controlled-SC model are valid except for (3.22,3.25,3.24), which are only required for femtocells.

3.5.3 Orthogonal Resource Allocation model(O-RAM)

This model performs orthogonal subcarrier assignment among tiers and also between neighbor FCs. To do so, we use the idea from (Chandrasekhar and Andrews, 2008; Chun-Han and Hung-Yu, 2011) and change Controlled-SC model to have complete subcarriers partitioning. This means that (3.16) is replaced by

$$\sum_{k\in\{m,FC\}}\sum_{i\in\{MS\}} b_i^{s,k} \leq 1 \qquad ;s\in S. \tag{3.34}$$

By doing so, we want to avoid the interference instead of mitigating it.

3.6 Performance Measurements

To evaluate the performance of the models, we use the following metrics:

Throughput: Network throughput is calculated as the bandwidth assigned multiplied by the number of bits per symbol used by the modulation technique in MC zone or FC instead of the theoretical achievable throughput given by Shannon's Law.

$$T = B_s\left[\sum_{i\in\{MS\}}\sum_{s\in\{S\}} b_i^{s,m} l_z^{mod} + \sum_{i\in\{MS\}}\sum_{f\in\{FC\}}\sum_{s\in\{S\}} b_i^{s,f} l_f^{mod}\right], \tag{3.35}$$

User Satisfaction: User satisfaction is defined as the ratio between the sum of assigned user data rates and the sum of user demands.

$$R = \frac{B_s \left[\sum_{i \in \{MS\}} \sum_{s \in \{S\}} b_i^{s,m} l_z^{mod} + \sum_{i \in \{MS\}} \sum_{f \in \{FC\}} \sum_{s \in \{S\}} b_i^{s,f} l_f^{mod} \right]}{\sum_{i \in \{MS\}} D_i}. \tag{3.36}$$

3.7 Simulation Results

System parameters and assumptions considered are described in Section 3.7.1. Simulation results were conducted using: (1) Visual C++ Studio 8.0 and (2) IBM ILOG Cplex 12.1: Concert Technology Environment (IBM, 2011). These results are analyzed for the different scenarios in Sections 3.7.2 and 3.7.3.

3.7.1 Simulation Scenarios

We analyze the performance of the proposed solution and the benchmark models under two different scenarios:

Incremental Traffic Load: Simulation runs with set of 10 to 140 mobile users with increment of 10 users in each period.

Variable FC User Density: Simulation runs for 40 mobile users with fixed percentage of subscribers (i.e. 10%) and increases public user percentage within the FC vicinity from 0 to 60% with 20% steps.

In our scenarios, a cluster of seven FCs is randomly placed in zone Z_3. FCs are separated by a distance equal to a factor of 2.25 times FCs radius. FC modulation techniques are QPSK or 16-QAM, therefore, l_{mod}^{f} can be equal to 2 or 4 and is generated randomly with the same probability for each option.

User distribution is as follows: 20% are public users (PU) close to FC cluster, 10% are FC subscribers (SU) and 70% are public users randomly located far from the FC cluster. The demand of subscribers and public users close to FCs is randomly generated between 128 to 512 Kbps, and the demand of other users from 64 to 256 Kbps.

We run the simulation 10 times for each set of users and averaged the results to smooth the performance metric curves. In each simulation run, user locations, user demands and the FC modulation technique are randomly generated. Table 3.1 shows the network and environment parameters used.

Table 3.1 System Parameters
(Network & Environment)

Name	**Description**	**Value**
B_s	Bandwidth per subcarrier	15 Khz
N_s	Number of subcarriers	128
N_s^k	Number of subcarriers per user	24
P_m^{Total}	Total transmitted power in MC	43 dBm
P_f^{Total}	Total transmitted power in FC	10 dBm
R_m, R_f	Macrocell and Femtocell radius	500 m, 20 m
α_k	Attenuation factor for indoor and outdoor	3,3.7
l_z^{mod}	Spectral efficiency in MC zone	2
l_f^{mod}	Spectral efficiency in FC	2, 4
N_0	Noise per subcarrier	-174 dBm/Hz
f_c	Carrier Frequency	2.3 GHz
M_f	Maximum number of femto users	4

Performance metrics described in Section 3.6 and the complexity of the models are analyzed in the following sections.

3.7.2 Throughput, Bandwidth and Power Usage

Table 3.2 shows the numerical results for the scenario of incremental traffic load. Bandwidth usage per tier is presented in the 7th and 8th columns. It can be observed that the three spectrum sharing models begin to reuse bandwidth with 30 mobile users where the sum of these two columns is greater than 100%. Moreover, macrocell utilizes 100% of the bandwidth with 40 mobile users in the network for the spectrum sharing models.

Table 3.2 Simulation Results for Incremental Traffic Load Scenario

MS	**Served MS**	**User Dist. (%)**			B (%)	**Bandwidth (%)**		**MC Power (dBm)**	
		MU	**SU**	**PU**		**MC**	**FC**	**Total**	**Avg/SC**
O-RAM									
10	10	89	10	1	0	40	7	31.72	14.59
20	20	84	10	6	0	77	15	34.44	14.51
30	28	70	10	14	6	71	29	34.03	14.47
40	34	61	10	14	15	61	39	33.18	14.29
50	36	48	10	14	28	50	50	32.16	14.05
Underlay									
10	10	92	5	3	0	44	2	35.95	18.43
20	20	90	7	3	0	88	6	39.30	18.78
30	30	75	8	17	0	98	19	40.39	19.39
40	39	69	10	20	1	100	30	40.52	19.45
50	48	66	10	20	4	100	36	40.72	19.64
Controlled-Underlay									
10	10	93	5	2	0	44	2	35.98	18.44
20	20	91	7	2	0	89	5	39.37	18.81
30	30	76	8	16	0	98	18	40.42	19.42
40	39	70	10	19	1	100	29	40.61	19.54
50	47	65	10	19	6	100	35	40.8	19.73
Controlled-SC									
10	10	90	9	1	0	41	6	31.75	14.57
20	20	85	10	5	0	80	14	34.60	14.51
30	30	73	10	17	0	90	27	35.03	14.41
40	40	70	10	20	0	100	39	35.64	14.57
50	48	65	10	20	5	100	48	35.30	14.23

It can be noticed that the three spectrum sharing models have more connected users, allow the macrocell to use the whole available bandwidth and require more transmitted power than O-RAM model. However, Controlled-SC model assigns 5 dB less power than the other two spectrum sharing models and 3 dB more than the spectrum partitioning model (O-RAM) in the macro tier and assigns similar values of transmitted power compared to the O-RAM model in the femto tier. In particular, O-RAM model assigns a maximum value of 34.44 dBm in the scenario with 20 mobile users. This power reduction in O-RAM is due to the prioritization of the use of FCs for public users and subscribers. In other words, the percentage of users served by FCs increases while the percentage of users served by MC decreases as the number of mobile users increases. In addition, power and bandwidth usage in MC are reduced whereas in FC they are increased, as it can be observed on the 3rd, 4th and 5th columns of Table 3.2. Nevertheless, the throughput is enhanced thanks to the use of hybrid access FCs as shown in Fig. 5.4a.

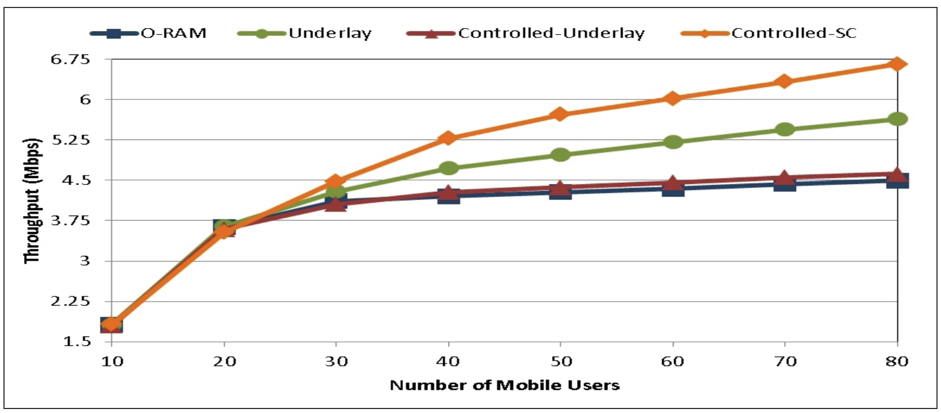


Figure 3.3 Network Throughput for Incremental Load Traffic Scenario

The 10th column of Table 3.2 presents the average transmitted power per subcarrier in MC. This was calculated as the total assigned power to macro users divided by the number of assigned subcarriers to MC. O-RAM and Controlled-SC assign less power in MC (15 dBm) than the other two models (20 dBm) but only Controlled-SC model improves the network throughput through the additional adaptive power allocation per subcarrier in both tiers. Typical values of transmitted power per subcarrier of commercial macro BS is approximately 21 dBm (Group, 2009; 3GPP-TR-36.921, 2011). These models use between 14 dBm to 20 dBm in MC, which mean a reduction of 1dB for Underlay and Controlled-Underlay and 7 dB in the case of O-RAM and Controlled-SC.

Figure 5.4a shows the throughput for the scenario of incremental traffic load. As expected, controlled-underlay model increases the throughput compared to O-RAM. Underlay model presents better throughput than controlled-underlay model because the power variables for MC and FCs are jointly determined. Nevertheless, Controlled-SC presents the best throughput among all the models due to the joint power adaptation in both tiers.

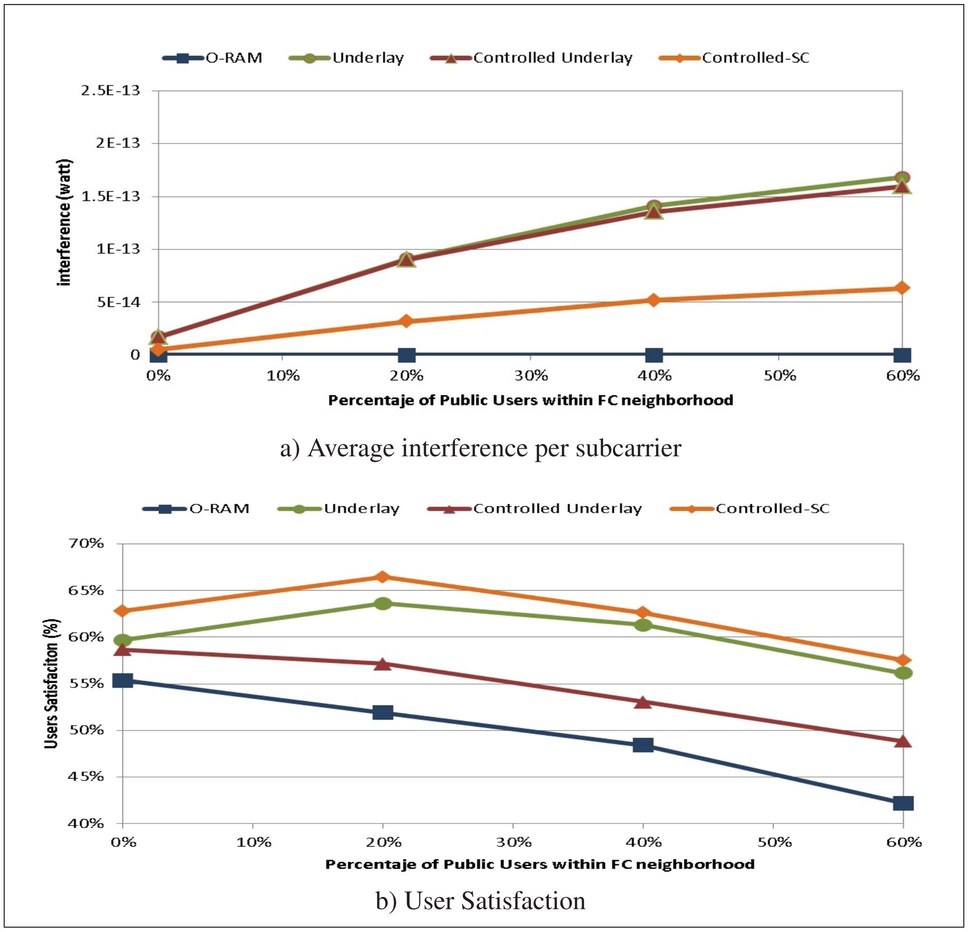
For variable FC user density scenario, the number of users is set to 40 since the three spectrum sharing models present a significant subcarrier reuse among the tiers from this point as can be appreciated in the 7th and 8th columns of Table 3.2. Fig. 3.4a shows the average interference per subcarrier as a function of the FC public user density. Controlled-SC model has lower average interference per subcarrier than underlay and controlled-underlay models. This is owing to the fact that the underlay model finds the same transmitted power value for all the subcarriers assigned to a BS, which increases the interference levels perceived by users being served by other BSs. The difference between the interference levels obtained for underlay and controlled-underlay models can not be appreciated due to high influence of MC DL transmissions.

In summary, Controlled-SC model uses an enhanced power distribution among the assigned bandwidth in each BS with lower interference level and higher subcarrier reuse.

3.7.3 Blocking Ratio and User Satisfaction

For the incremental traffic load scenario, ORAM has a rapid growth in the blocking ratio (in the range of 0 to 28%) while the spectrum sharing models achieve less than 6% as presented in the 6th column of Table 3.2. Therefore, orthogonal subcarrier assignment limits the number of connected users.

Fig. 3.4b presents the user satisfaction for the variable FC user density scenario. In general, the user satisfaction of the underlay and controlled-SC models exceeds the user satisfaction of the O-RAM and controlled-underlay models. In particular, it is shown that jointly power adaptation in BS provides a gain in the user satisfaction as FC public user density increases



a) Average interference per subcarrier

b) User Satisfaction

Figure 3.4 Interference and User Satisfaction for the variable FC user density scenario

from 0 to 20% for the underlay and controlled-SC models. However, controlled-SC model presents the highest user satisfaction equal to 66.4% with 20% of public users close to FCs.

In summary, controlled-SC model outperforms the O-RAM model in terms of throughput, power usage and capacity (i.e. number of connected users). Moreover, controlled-SC model performs better than other two spectrum sharing models, in terms of throughput, power usage and interference mitigation. This can be attributed to the fact that the proposed model considers a tradeoff between interference mitigation, power adaptation and subcarrier reuse.

3.7.4 Complexity

The running time of a MILP model grows exponentially with the number of variables. The complexity of the presented models depends on the number of subcarriers, number of users, FC user density and the number of deployed FCs. The difference between the spectrum sharing models is the assumption of one or several power variables in each BS. In particular, underlay model requires one power variable per BS, i.e. $F+1$ variable besides the bandwidth, subcarrier reuse and user assignment variables. Controlled-underlay model performs power control in FC, which introduces new variables associated to power per subcarrier per user in each FC but keeps one power variable in MC, i.e $N_s \times F \times M + 1$ power variables. The proposed solution requires a higher number of power variables to carry out the additional power control per subcarrier in MC, i.e $N_s \times (F+1) \times M$ power variables. For example, Controlled-SC model requires around three times and twice the running time of underlay and controlled-underlay models respectively with a set of 40 mobile users.

3.8 Conclusion

We proposed a joint power and bandwidth allocation with BS selection intended to maximize the network throughput enabling the subcarrier reuse with constraints on the total transmission power per BS, maximum transmitted power per subcarrier for mobile users in each BS and an interference threshold. The proposed model (Controlled-SC) is compared to other two spectrum sharing models (underlay and controlled-underlay) and a spectrum partitioning model (O-RAM) in two different scenarios. The underlay model jointly determines the transmitted power per BS and the controlled-underlay allocates adaptive power per subcarrier in femtocells. The proposed solution includes power adaptation per subcarrier in MC. In the incremental load traffic scenario, controlled-SC model reaches a throughput gain around 14% and 31% compared to underlay and controlled-underlay models respectively with approximately 5 dB less power consumption in macrocell. In the variable FC user density scenario, the user satisfaction of the underlay and controlled-SC models exceeds the user satisfaction of the O-RAM and controlled-underlay models. The gain is in the range of 5% to 9% with respect to controlled-underlay model. Hence, the jointly power adaptation per subcarrier in all the BSs that comprise the network allows to increase the number of public users that can be connected to FCs improving the overall user satisfaction. However, this improvement is limited by FC capacity and the interference threshold. As a future work, we plan to incorporate user mobility to study its impact on the proposed scheme. Specifically, we will study resource reservation considering the variation in time of user locations as well as the network load.

CHAPTER 4

SPECTRUM SHARING MODEL FOR OFDMA MACRO-FEMTOCELL NETWORKS

Rebeca Estrada[1] , Hadi Otrok[2] , Zbigniew Dziong[1] , Hassan Barada[2] ,

[1] Département de Génie Eléctrique, École de Technologie Supérieure,

1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3

[2] Department of ECE, Khalifa University of Science, Technology & Research, UAE

An Article submitted to the Inderscience International Journal of Ad Hoc and Ubiquitous Computing in November 2013 and accepted by March 2014

4.1 Abstract

Enhancing the network throughput while supporting non-uniform user distribution and dense femtocell deployment is a challenge in OFDMA networks. Previous research works provide approaches based on spectrum partitioning and spectrum sharing for macro-femtocell networks. Few proposed interference management approaches have been investigated without considering user mobility. In this paper, we target the optimization of resource allocation in macro-femtocell networks taking into account the user distribution over macrocell coverage area and femtocells dense deployment. We propose a spectrum sharing approach that aims to maximize the network throughput based on Linear Programming. Interference mitigation is performed through the power adaptation in both tiers while guaranteeing the QoS transmission requirements. Our solution is able to: (1) fairly allocate macrocell resources to each zone taking into account the user distribution over the macrocell coverage area, (2) optimally reuse of the bandwidth allocated to inner zone inside the femtocells located in outer zone, and (3) optimally determine the serving base station, subcarriers and respective transmitted power for downlink transmissions per zone taking into account user locations and demands in any given period. Performance analysis is presented under incremental traffic load and realistic scenarios where user mobility is considered. Simulations are conducted to show a comparison of the

proposed model with two spectrum partitioning approaches with and without partial bandwidth reuse.

4.2 Introduction

Several economical factors encourage wireless network providers to use femtocells (FCs) such as capacity improvements, traffic offload, power consumption reduction and minimal installation and operation costs. Femtocells are low cost base stations (BSs) with short range transmissions that guarantee good indoor coverage and enhances data rates. As they are installed in an ad-hoc manner without any frequency planning by network operators and due to their rapid and uncontrolled deployment, resource allocation and interference management have been identified as key issues since femtocells use the same spectrum as macrocell (MC) (Mhiri *et al.*, 2013).

Resource allocation approaches can be classified as spectrum partitioning (SP) and spectrum sharing (SS). In spectrum partitioning, dedicated portion of subcarriers is assigned to each tier (Chun-Han and Hung-Yu, 2011) while in spectrum sharing approach, subcarriers are shared among the two tiers (Cheng *et al.*, 2012). The former has been used for sparse FC deployment whereas the latter is recommended for dense deployment but requires interference management schemes to uphold Quality of Service (QoS) of downlink (DL) or uplink (UL) communications and to improve the spectrum efficiency (Hanm *et al.*, 2009; Torregoza *et al.*, 2010).

Interference is classified as cross-tier and co-tier interference. The first type occurs among elements that belong to different tiers (i.e. between macro BS and femto BS) while the second type occurs between elements of the same tier, i.e. between neighboring femto BS. In the literature, several interference management techniques can be found, such as power control (Torregoza *et al.*, 2010), frequency reuse (Dalal *et al.*, 2011; Jeong *et al.*, 2010), frequency scheduling (Bennis and Perlaza, 2011), or hybrid access mechanisms (Li *et al.*, 2010).

Hybrid access mode is a promising technique that allows to reduce the interference perceived by femto users by granting access to nearby public users. However, it requires a resource allocation model which also determines the best suitable serving base station per user in order to enhance the wireless network capacity.

Handover and mobility management constitute other challenges of considered overlaid network. In the literature, the majority of the proposed resource allocation approaches do not consider user mobility. In general, the impact of user mobility on the resource allocation model performance has been omitted under the assumption that all the users are fixed or have low mobility. This latter is not necessarily true for public users. This motivates us to present the respective performance analysis of the proposed solution where user mobility is taken into account.

Our previous research work in (Estrada *et al.*, 2014) introduced a spectrum partitioning approach using linear programming that finds a tradeoff between bandwidth and power to reduce the bandwidth usage per user and to minimize the impact of noise. Namely, the available bandwidth is divided between MC and FCs in such a way that only one BS can use one subcarrier at any given instant and the power is assigned to achieve the target signal to noise ratio (SNR). This model is suitable for non-dense FC deployment, however, the network throughput is limited as the FC density increases.

In this paper we expand significantly the model and addressed problems by considering the following issues: $1)$ subcarrier reuse is allowed in femto tier if the perceived interference is below a given threshold, $2)$ FC power control is used to find a tradeoff between bandwidth and the interference, $3)$ Random Walk, (Nain *et al.*, 2005), is implemented to model user mobility, and $4)$ FC are grouped into clusters such the interference can be mitigated between neighboring FCs.

Some cluster formation algorithms can be found in the literature such as a simple algorithm using neighbor discovery technique, (Hatoum *et al.*, 2011), discovering interfering neighbor FCs (Pantisano *et al.*, 2011), minimizing the co-tier interference and guaranteeing the outage probability for FC mobile user, (Lin and Tian, 2013) or maximizing femto users SINR, (Moon and Cho, 2013). Nevertheless, cluster formation is out of the scope of this paper. We assume that FC clusters are already formed and MC resource manager has the required information such as their required demand, number of FCs in each cluster, number of macro users close to them and so on.

The limitations of prior resource allocation approaches can be summarized as:

- spectrum partitioning limits network capacity, i.e. number of connected users;
- power control in FCs mitigates interference perceived by macro users and also reduces FC data rates;
- QoS Cellular Parameters have not been analyzed when user mobility is considered;
- users Distribution over MC coverage area has not been considered.

To overcome above limitations, we propose a resource allocation model that uses the principle of divide and conquer. The main idea is to divide the set of users and femtocells into disjoint subsets according to their locations. Thus, the resource allocation problem is solved as four independent resource allocation problem per OFDMA zone. The proposed model finds a sub-optimal solution by means of: (1) fair resource allocation per zone taking into account user distribution over the MC coverage area, (2) an optimal resource allocation per zone including BS selection, bandwidth and power allocation aiming to maximize the throughput per zone based on Linear Programming, and (3) power adaptation per subcarrier basis is performed to avoid unnecessary handovers as the FC user density increases.

To evaluate the performance of the proposed model, we consider two benchmark models: a spectrum partitioning and a spectrum partitioning with a partial bandwidth reuse. The former approach assigns orthogonal subcarriers among tiers and between neighboring FCs to avoid cross-tier (Chun-Han and Hung-Yu, 2011) and co-tier interference (Chandrasekhar and Andrews, 2008) respectively. The latter allows reusing bandwidth allocated to inner MC zones for DL transmission within the coverage area of femtocell located in outer MC zones. Simulations are conducted to show a comparison of their performances for different traffic load and variable FC user density when macro users mobility is taken into account.

Our contribution is a spectrum sharing model based on linear programming that is able to:

- fairly distribute the MC resources to its zones given a particular user distribution;
- bandwidth Reuse in FC located in outer MC zones;
- optimally select serving BS and allocate subcarriers and their transmitted power for each user per MC zone and guaranteeing QoS DL transmissions;
- enhance the throughput while reducing the power consumption in macro tier;
- enable subcarrier reuse while incurring least possible number of handovers and dropped calls.

The rest of the chapter 4 is organized as follows: Section 4.3 presents the problem statement. Section 4.4 introduces the generalized optimal resource allocation model for an overlaid network with interference mitigation. Section 4.5 describes the Spectrum Sharing model with full subcarrier reuse taking into account a particular MC zone division. Section 4.6 describes the benchmark models: spectrum partitioning and spectrum partitioning with partial bandwidth reuse. Section 4.7 presents simulation scenarios and obtained results. Finally, Section 4.8 concludes the paper.

4.3 Problem Statement

Macrocell resources should be allocated to the communication links between mobile users and whether macro BS or a femto BS within MC coverage. In a scenario with dense FC deployment, several challenges are created such as the orthogonal frequency assignment among macrocell and the underlaid femtocells for spectrum partitioning and interference management for spectrum sharing.

In the case of spectrum sharing approaches, transmitted power from any interfering BS should be reduced to minimize the interference caused to nearby mobile users served by other BSs. This power reduction decreases the spectral efficiency in interfering BSs and may reduce data rates unless bandwidth usage is increased to satisfy user demands. Conversely, the transmitted power in each BS should be maximized to tackle the interference level when subcarrier reuse is allowed. Therefore, there is a complex dependency between power, bandwidth and interference.

To uphold the signal to interference plus noise ratio (SINR) required in BS, an interference threshold can be easily determined using fixed transmitted power per BS.

As in (Tarhini and Chanjed, 2007), we use the same OFDMA physical layer assumptions for a particular MC zone division, which are described in Table 2.1 in Section 2.3. In particular, the number of bits used for modulating the signal is 6, 4, 2 or 1 for users is in Z_1, Z_2, Z_3 or Z_4, respectively.

Since FCs can grant access to nearby public users and offload traffic from macrocell, several technical challenges are addressed in this paper, such as:

How to reduce the complexity of a resource allocation model with dense FC deployment and non-uniform user distribution? It is well known that the complexity of a centralized resource allocation approach increases as the FC density and the user number increases (Estrada *et al.*, 2014). As the user distribution within MC coverage area and FC user density play an important role in the resource allocation for macro users and underlaid femtocell, a simple approach proposed in (Tarhini and Chanjed, 2007) for resource allocation among the MC zones can be applied to reduce the complexity. The main idea is to distribute the MC resources, i.e. bandwidth and power, proportional to the number of users in each zone regardless of the number of deployed femtocells within the zone. It is worth to notice that an orthogonal subcarrier allocation among MC zones will be performed.

What should be the optimum power setting for each MC zone to allow the bandwidth reuse in femtocell located in outer MC zones? Since FCs use the same spectrum as the overlaid macrocell, the transmitted power in MC zone can be restricted to achieve the SINR target at the edge of each zone in such way that the interference caused by macro users DL transmission to femto users located in outer zones is negligible.

This means that the bandwidth allocated to macro users in zone:

- Z_1 can be reused for DL transmissions inside femtocells located in zones Z_2, Z_3 and Z_4;
- Z_2 can be reused inside femtocells within MC zones Z_3 and Z_4;
- Z_3 can be reused inside femtocells in MC zone Z_4.

Fig. 4.1 shows an illustrative example. We can see that the bandwidth allocated to MC zone Z_1 is also used for DL transmissions of subscriber MU_2 in Fig. 4.1b. The MC transmitted power P_1^m should be less than the transmitted power P_2^m in such a way macro user MU_1 located in zone Z_1 will not interfere with the DL transmission in femtocell FBS_1. Thus, this scenario requires less power than the one with the macrocell shown in Fig. 4.1a and allows the bandwidth reuse.

Femtocells have the wireless impairment of wall penetration loss for transmitted signal coming in or out. Therefore, neither FC transmitted signal will cause interference for macro users DL transmission in inner MC zones nor MC transmitted signal affects the femto users DL transmissions. Thus, the cross-tier interference will be eliminated and the co-tier interference will be minimized due to the wall penetration losses.

How to select the appropriate BS and the amount of resources per user in each zone? In order to consider the FC deployment per zone, the serving BS should be the one that provides better data rate to the user by allocating less interfered subcarrier with an appropriate level of transmitted power in each zone.

What is the impact of user mobility on the resource allocation model? SINR degradation and call drop occur if there are insufficient subcarriers with lower interference levels than a

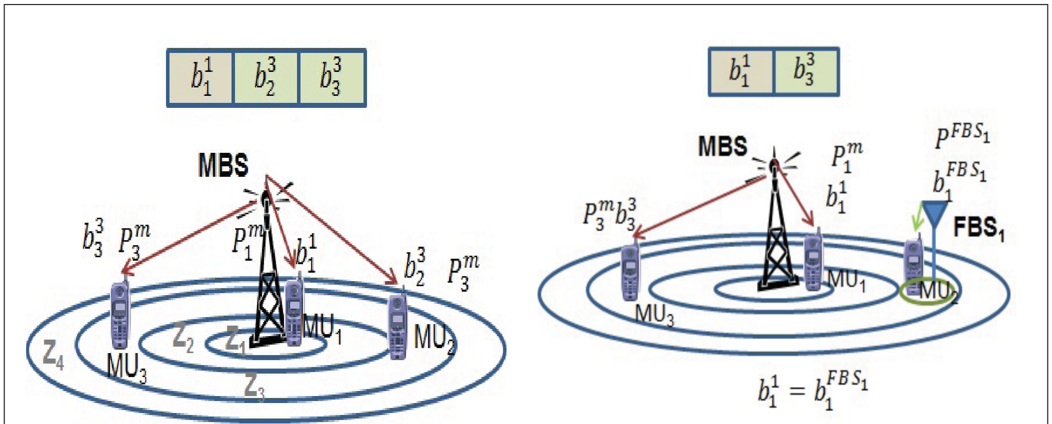
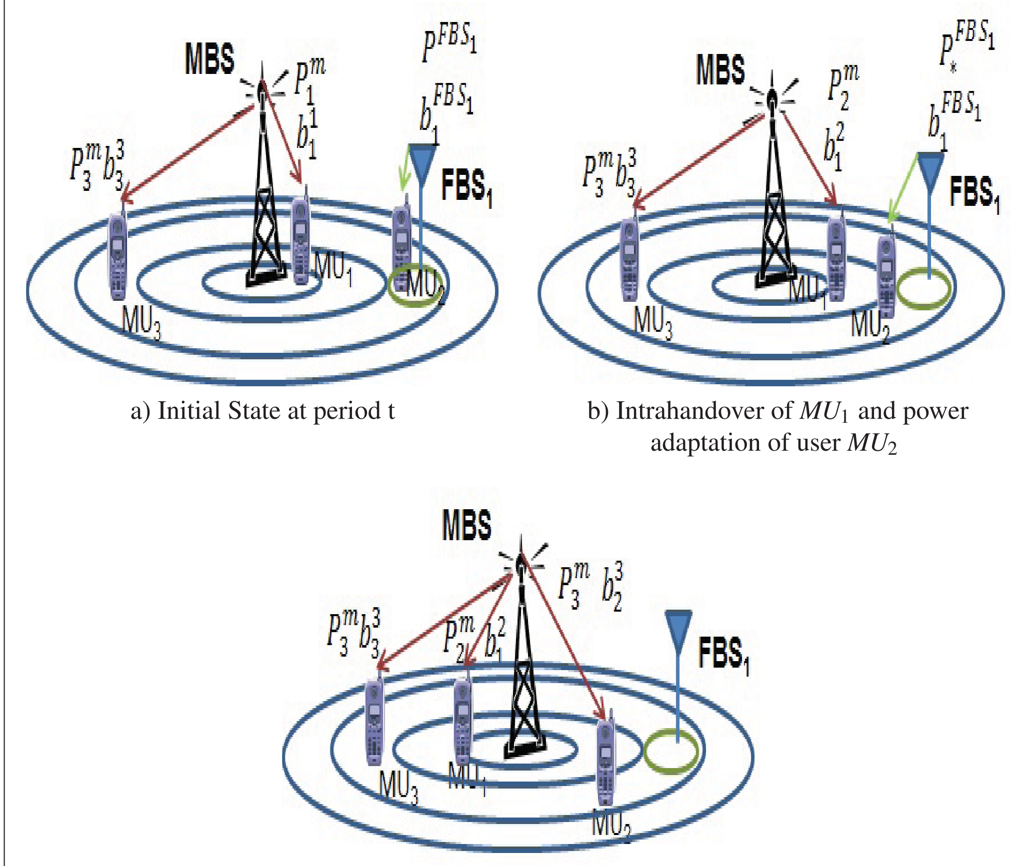


Figure 4.1 Illustrative example of resource allocation. Parameters b_i^j and P_i^j correspond to bandwidth and power allocated to user i in femtocell j or macrocell represented by m

given threshold during a call or a transfer of call. Hence, handover calls should have priority than a new call, since the blocking of a handover call is more annoying as compared to blocking a new call. One way to solve this is to adaptively change the transmitted power to reach the required SINR target without trespassing a given interference threshold over the interfered DL transmission.

To uphold signal to interference plus Noise ratio (SINR) target per subcarrier in each BS when mobility is incorporated, one of following actions must be done:

- handover, which means change of current serving BS, i.e. MU_2 in Fig. 4.2c;
- intrahandover, i.e. change of assigned subcarriers in the current serving BS, if there were any available with less interference perceived, or change of allocated subcarriers belonging to different MC zone when a mobile user cross a zone edge, for example user MU_1 in Fig. 4.2b;
- power adaptation to allow the mobile user staying connect to the current serving BS, i.e. MU_2 in Fig. 4.2b.



a) Initial State at period t

b) Intrahandover of MU_1 and power adaptation of user MU_2

c) Handover of user MU_2

Figure 4.2 User mobility impact on resource allocation models

In summary, our objective is to find a reduced complexity spectrum sharing model for an OFDMA two-tier network to deliver user data rate, minimize interference, enable bandwidth reuse and at the same time ensure the required QoS, i.e. in terms of SINR, and analyze the mobility impact on the proposed model.

4.4 Resource Allocation Problem Formulation

In our model, we consider that network operators want to maximize the network throughput, which can be evaluated as the sum of user data rates and is given by

$$\max_{\mathbf{b},\mathbf{P}} \sum_{z\in\{Z\}} \sum_{k\in\{m,FC^z\}} \sum_{i\in\{MS^z\}} \sum_{s\in\{S\}} b_i^{s,k} log_2(1+SINR_i^{s,k}), \tag{4.1}$$

where the vectors **b** and **P** correspond to subcarrier assignment and their respective power in each BS. In other words, **b** consists of binary variables $b_i^{s,k}$, which determine if the subcarrier s is allocated to user i in BS k. Z represents the set of OFDMA macrocell zones (3 in LTE or 4 in WIMAX). The index k stands for the association with macrocell m or femtocell f. FC^z and MS^z are the set of femtocells and mobile users located within the coverage area of MC zone z. $SINR_i^{s,k}$ is the signal to noise plus interference ratio perceived by macro users or femto users and is given by

$$SINR_i^{s,k} = \frac{b_i^{s,m} P_i^{s,k}}{PL_i^k \left(N_0 + I_i^{s,k}\right)} \tag{4.2}$$

$P_i^{s,k}$ are the components of the received power vector **P**, N_0 is the average noise per subcarrier and PL_i^k is the path loss in outdoor or indoor environments (ITU-TR-36.921, 1997) and given by

$$PL_i^k(dB) = \begin{cases} 10log_{10}(d_{ik}^{\alpha_k}) + 30log_{10}(f_c) + 49, & k = m \\ 10log_{10}(d_{ik}^{\alpha_k}) + 37, & k \in FC \end{cases} \tag{4.3}$$

where α_m and α_f are the path loss exponents for outdoor and indoor environments, d_{ik} is the distance between BS $k \in FC, m$ and the user i, and f_c is carrier frequency. $I_i^{s,k}$ is the interference perceived by the mobile user i in BS k caused by macrocell and/or nearby femtocells DL transmissions using same subcarrier s, and is given by

$$I_i^{s,k} = \begin{cases} \sum\limits_{f \in \{FC\}} \sum\limits_{j \in \{MS\}} \frac{b_j^{s,f} P_j^{s,f}}{PL_i^f}, & \text{macrousers} \\ \sum\limits_{j \in \{MS\}} \frac{b_j^{s,m} P_j^{s,m}}{PL_i^m} + \sum\limits_{f \in \{FC \backslash k\}} \sum\limits_{j \in \{MS\}} \frac{b_j^{s,f} P_j^{s,f}}{PL_i^f}, & \text{femtousers} \end{cases} \tag{4.4}$$

The interference perceived by macro users only corresponds to cross-tier interference and for femto users, it consists of two components: (i) cross-tier interference related to the reuse of the subcarriers already assigned in MC and (ii) co-tier interference due to the use of the same subcarriers in neighbor FCs. From (4.1-4.4), it can be seen that our problem is a nonlinear optimization problem and there is no polynomial-time algorithm to obtain the optimal solution.

4.5 Spectrum Sharing model

In (IEEE-802.16, 2004), the air interface for wireless access system using OFDMA technique specifies maximum data rates offered to mobile users, which are decreasing according to remoteness of the zone where the users are located owing to the propagation losses. According to this, user data rates should be limited to the maximum MC data rate per MC zone or available capacity in nearby FCs in a two-tier network. Our proposal is to adapt the transmitted power per subcarrier in MC and FC without trespassing a maximum transmitted power per subcarrier. This maximum power is defined as the required transmitted power per subcarrier for a user located in the zone edge (or FC edge in femto tier) to meet the SINR target. The use of maximum transmitted power per subcarrier can reduce MC power consumption and also enable the reuse of subcarriers assigned to zone closer to macro BS in FCs located in zones farther from MC. For convenience, the propagation channel models are dependent mainly on the path loss. However, shadowing and fast fading effect may be considered and we suggest to determine the maximum transmitted power using the expected value of the received power variables at FC cell edge or MC zone edge. In (Kelif and Coupechoux, 2010), the probability density functions for the received power variables are derived from channels that include only shadowing or both shadowing and fast fading.

4.5.1 Optimal Resource Allocation model

Taking into account the division of macrocell coverage area into zones, we propose to replace (4.1) presented in Section 4.4 as follows:

$$\max_{\mathbf{b},\mathbf{P}} \sum_{z\in\{Z\}} \sum_{i\in\{MS^z\}} \sum_{s\in\{S_c^Z\}} b_i^{s,m} l_z^{mod} + \sum_{z\in\{Z\}} \sum_{k\in\{FC^z\}} \sum_{i\in\{MS^z\}} \sum_{s\in\{S_c^Z \cup S_p^Z\}} b_i^{s,k} l_k^{mod} \tag{4.5}$$

assuming that the log term should be at least equal to the spectral efficiency required in the MC's zone, l_z^{mod}, or FC, l_f^{mod}. We decompose equation (4.1) in two terms: First term corresponds to MC throughput and the second one is the femto tier throughput. The binary variables $b_i^{s,k}$ and $b_i^{s,m}$ determine if the subcarrier s is assigned to user i in femtocell k or macrocell m. Z represents the set of OFDMA macrocell zones (3 in LTE or 4 in WIMAX). FC^z and MS^z are the set of femtocells and mobile users located within the coverage area of MC zone z. S_p^Z and S_c^Z represent the subcarrier set allocated to precedent zones and current zone respectively. For example, the set of subcarriers of precedent zones for zone Z_3, is equal to S_c^1 and S_c^2.

Our objective function is subject to:

$$\sum_{i\in\{MS^z\}}\sum_{s\in\{S\}} b_i^{s,k} \leq \begin{cases} |S_c^Z \cup S_p^Z|, & k \in \{FC\} \\ |S_c^Z|, & k = m \end{cases}, \tag{4.6}$$

$|.|$ stands for the cardinality of the set of subcarrier.

$$\sum_{i\in\{MS^z\}} b_i^{s,k} \leq 1 \qquad ; s \in S_c^z, k \in \{m, FC^z\}, z \in Z \tag{4.7}$$

$$B_s \sum_{s\in\{S\}} b_i^{s,k} \leq \sum_{k\in\{m,FC^Z\}} Y_i^k \min\left(B_s N_s^k, \frac{D_i}{l_k^{mod}}\right) \qquad ; i \in MS^z, z \in Z, \tag{4.8}$$

$$\sum_{i\in\{MS^z\}}\sum_{s\in\{S\}} P_i^{s,k} \leq P_k^{Total}, k \in \{m, FC^z\}, z \in Z, \tag{4.9}$$

$$\sum_{s\in\{S_c^Z\}} b_i^{s,k} \leq |S_c^Z| Y_i^m \qquad ; i \in MS^z, z \in Z, \tag{4.10}$$

$$\sum_{s\in\{S_p^Z \cup S_c^Z\}} b_i^{s,k} \leq |S_p^Z \cup S_c^Z| Y_i^k \qquad ; i \in \{MS^z\}, k \in \{FC^z\}, z \in Z, \tag{4.11}$$

$$\sum_{k\in\{m,FC^z\}} Y_i^k \leq 1 \qquad ; i \in MS^z, z \in Z \tag{4.12}$$

$$\log_2\left(1 + SINR_i^{s,m}\right) \geq b_i^{s,m} l_z^{mod} \qquad ; i \in MS^z, s \in S, z \in Z, \tag{4.13}$$

$$\log_2\left(1 + SINR_i^{s,f}\right) \geq b_i^{s,f} l_f^{mod} \qquad ; i \in MS^z, s \in S, f \in \{FC^z\}, z \in Z, \tag{4.14}$$

$$I_i^{s,k} \leq b_i^{s,k} \gamma_{Th} \qquad ; i \in MS^z, s \in S_p^Z \cup S_c^Z, k \in \{m, FC^z\}, c \in Z, \tag{4.15}$$

$$\sum_{f\in\{m,FC\}}\sum_{i\in\{MS\}} b_i^{s,f} \leq 1 + r_s \qquad ; s \in S. \tag{4.16}$$

The model variables are: (1) an integer variable r_s that determines the number of BS sharing the subcarrier s, (2) a binary variable $b_i^{s,k}$, which indicates that subcarrier s is allocated to user i in BS k, (3) a binary variable Y_i^k determines the serving BS k is associated to user i and real variable $P_i^{s,k}$ representing the power allocated to subcarrier s in BS k for user i.

Constraints can be briefly described as follows: Constraint (4.6) is the upper bound of the total number of allocated subcarrier to a BS or a MC zone, where S_C^Z is the set of subcarriers allocated to the zone C and S_P^Z is the set of subcarriers in the precedent zones. Constraint (4.7) indicates that one subcarrier can be assigned only to one user in each BS. The upper bound of total bandwidth and power allocated in each BS is given by constraints (4.8) and (4.9). Constraint (4.10) and (4.11) establish the upper bound for the number of allocated subcarriers to a user in a BS. $|.|$ stands for the cardinality of the subcarriers subset S_C^Z and S_P^Z. This upper bound corresponds to the available number of subcarriers in FCs or MC zone if the user is allocated for service to FCs or MC. For this reason, the right term of equations (4.10) and (4.11) is equal to the number of available subcarriers multiply by the binary variable that associates the user with the serving base station (Y_i^k, Y_i^m). Constraint (4.12) establishes that one user can be served by one BS. The subcarrier capacity is limited to a maximum capacity value as presented by constraint (4.13). Constraint (4.15) determines an upper bound for the interference level allowed. Finally, constraint (4.16) indicates that the subcarrier can be use one time in MC and r_s times in femto tier (i.e. one time in each femtocell).

One important issue of the proposed model is that the log term in (4.13) is not a linear function. However, (4.13) can be decomposed into the sum of two log_2 terms. Doing so, each log_2 term can be replaced by segments of a PWL approximation. In order to use an appropriate linear approximation, it is necessary to evaluate the power and interference values. This is issue is handle in next section.

4.5.2 Piecewise segment linear approximation

According to (Imamoto and Tang, 2008), any convex (or concave) function over a finite range can be optimally approximated by a L segment continuous piecewise linear (PWL) function $g_l(x)$ defined over the range $x_0 \leq x \leq x_L$ by a set of points or knots $(x_{l-1}, x_l)_{l=1}^{L}$ connected by L segments. Using this basis, we propose to use a PWL approximation of three segments to convert our non-linear programming problem in linear program model. The composed (PWL) approximation function using three segments is given by

$$g_l(x) = \begin{cases} 2.15 \times 10^{13} \times x - 46.41 & 3.11 \times 10^{-14} \leq x \leq 2.2 \times 10^{-13} \\ 9.96 \times 10^{11} \times x - 41.87 & 2.2 \times 10^{-13} \leq x \leq 4.66 \times 10^{-12} \\ 4.63 \times 10^{10} \times x - 37.76 & 3.09 \times 10^{-12} \leq x \leq 1 \times 10^{-10} \end{cases} \tag{4.17}$$

High number of segments requires more power variables to be determined in the corresponding segment. For simplicity, we decided to use a 3-segment PWL approximation since the received power values and interference can be evaluated in only one segment of the linear approximation for each modulation technique. In addition, interference values plus noise are confined to the first segment of PWL approximation. To do so, we need to add two more constraints in each tier related to upper bound and lower bound of interference plus noise given by maximum and minimum values of range of the first segment. Thus, SS-FSR determines transmitted power per subcarrier in each BS and subcarrier assignment taking into account user demands, their locations and interference threshold per modulation technique used in MC zone or in FCs. Other details such as convergence time and error caused by this linear approximation can be found in our previous work in (Estrada *et al.*, 2013a).

It is important to remark that the channels models take into account the path loss and a deterministic wall loss penetration. In other words, the received power is mainly affected by path loss due to the distance. In the case that the effect of shadowing and fast fading need to be considered, an appropriate PWL approximation should be found, since the received power values in both tiers might be different from those obtained for the current channel models.

4.5.3 Sub-optimal Spectrum Sharing Model with full subcarrier reuse (SS-FSR)

The proposed model in Section 4.5.1 has a high complexity, which depends on the number of zone (i.e. 4 for WIMAX or 3 for LTE), number of deployed femtocells, number of available subcarriers and number of users in network. Therefore, we propose a suboptimal model to reduce the complexity separating the optimal resource allocation per MC zone. Since mobile user locations can be determined by macrocell, a suboptimal model can determine first the user number in each MC zone taking into account the user distribution regardless the FC density.

Our proposed solution consists of three components: (1) fair distribution of macrocell resources into disjoint sets of subcarriers among its OFDMA zones taking into account the user distribution, (2) MILP based algorithm for allocation of shared subcarriers among inner MC zones DL transmissions and DL transmissions femto of mobile users inside femtocells located in outer MC zones and (3) MILP based algorithm for optimization of MC zone resource allocation.

Resource algorithms can run in parallel in the MC resource manager entity to allocate the bandwidth and transmitted power to the mobile users per zone.

4.5.4 MILP Resource Allocation per zone

In (Estrada *et al.*, 2013c), we proposed a MILP Resource Allocation per zone and target the maximization of network throughput. Our previous work showed that spectrum sharing per subcarrier basis (RAM-SC) allows to increase the network throughput per zone. Here, we use the same idea but first the resource manager allocates transmitted power and bandwidth to each MC zone based on the user distribution. Thus, the resource optimization problem is reduced to a linear optimization problem with the following objective function:

$$\max_{\mathbf{b},\mathbf{P}} \sum_{f\in\{m,FC^z\}} \sum_{i\in\{MS^z\}} \sum_{s\in\{S_c^z\}} b_i^{s,k} l_k^{mod} \tag{4.18}$$

Algorithm 4.1 Spectrum Sharing Model

Data: MS Set of users,
FC, m Set of Femtocell and m represents Macrocell
(X_i, Y_i) User Locations
(X_f, Y_f) FC Locations
(D_i) Demands.
Result: BS selection for the set of users **bs**
Bandwidth allocated per subcarrier per user $\mathbf{b_i^{s,k}}$
Power allocated per subcarrier per user $\mathbf{P_i^{s,k}}$.

begin
Determine the user sets in each zone, MS^1, MS^2, MS^3, MS^4 according to user locations;
Determine the FC set in zone z, FC^1, FC^2, FC^3, FC^4 according to FC locations;
Compute the maximum transmitted power per subcarrier in MC zone edge as;
$P_z^m \leftarrow SINR_{Target} \times (N_0 + I_{th})$;
Determine resources for each MC zone as follows:;
$B^z \leftarrow \frac{|MS^z| \times B}{|MS|}$;
$P_z^{Total} \leftarrow \frac{|MS^z| \times P_m^{Total}}{|MS|}$;
for $z \leq Z$ **do**
    if $z \geq 1$ **then**
        Run MILP based spectrum sharing resource allocation algorithm per zone z with the user set equal to FC subscribers and public users within FC coverage area in zone z and subcarriers allocated to precedent zones $h \in 1, ..z-1$, $P_m^{Total} \leftarrow 0$;
        Remove FC subscribers and public users assigned from the set of user MS^Z in zone z;
    end
    Run MILP spectrum sharing resource allocation algorithm per zone with MS^Z as the set of mobile users in the network, B^z and P_z^{Total} as the available bandwidth and power in MC;
end
end

and subject basically to the same constraints defined in Section 4.5.1 and one additional constraint that determines maximum transmitted power per subcarrier in MC zone precedent given by

$$P_i^{s,m} \leq b_i^{s,m} P_z^{s,m} \qquad ; i \in MS^z, s \in S_c^Z \tag{4.19}$$

This is owing to the fact that our solution allows the subcarrier reuse of precedent zones in FC located in outer MC zone. $P_z^{s,m}$ can be determined as the one required to satisfy the SINR target of the MC zone and to avoid the cross-tier interference inside of FC coverage area in outer MC zone and is given by

$$P_z^{s,m} = SINR_z^{Target} \times (N_o + I_{Th}) \tag{4.20}$$

4.5.5 MILP Resource allocation of shared resource among mobile users in inner zones and femtocells in outer zone

Owing to the limitation of MC transmitted power in inner zones, bandwidth reuse can be allowed among macro or femto users DL transmissions in inner zones and mobile users within the coverage area of femtocells located in outer MC zones as in (Bai *et al.*, 2009). Thus, the objective function will be

$$\max_{\mathbf{b},\mathbf{P}} \sum_{f \in \{m, FC^z\}} \sum_{i \in \{MS^z\}} \sum_{s \in \{S_p^z\}} b_i^{s,k} l_k^{mod} \tag{4.21}$$

where S_p^z is equal to $\cup_{h=1}^{Z-1} S^h$ and MS^z includes only FC subscribers and public users inside the FC coverage area. To ensure that all users are associated to a femtocell, the total power in macrocell P_m^{Total} is set up equal to 0. Therefore, we run the same MILP based algorithm as in previous section with different input and system parameters.

4.6 Benchmark models

Here, we describe two benchmark models proposed for comparison analysis.

4.6.1 Spectrum Partitioning model (SP)

This model performs orthogonal subcarrier assignment between MC and FCs and also between neighbor FCs. To do so, we use the idea from (Chandrasekhar and Andrews, 2008) and (Chun-Han and Hung-Yu, 2011) and change general MILP model to have complete subcarriers partitioning. This means that (4.16) is replaced by

$$\sum_{k\in\{m,FC\}}\sum_{i\in\{MS\}} b_i^{s,k} \leq 1 \qquad ; s \in S. \tag{4.22}$$

By doing so, we want to avoid the interference instead of mitigating it. Therefore, the dedicated portion of subcarriers per tier is adaptively determined by the model depending on the FC user density in each time unit. This model assigns the maximum transmitted power per subcarrier to reach the maximum throughput and allocates the user to the BS providing higher data rate to the users.

4.6.2 Spectrum Partitioning model with partial bandwidth reuse (SP-PSR)

This model performs orthogonal subcarrier assignment between MC and FCs and also between neighbor FCs in the same zone. To do so, we use the idea from (Chandrasekhar and Andrews, 2008) and (Chun-Han and Hung-Yu, 2011) and change general MILP model to have complete subcarriers partitioning. This means that (4.16) is replaced by

$$\sum_{k\in\{m,FC^z\}}\sum_{i\in\{MS\}} b_i^{s,k} \leq 1 \qquad ; s \in S, z \in Z. \tag{4.23}$$

In this model, MC transmitted power per zone is also obtained using (4.20) to allow the bandwidth reuse among macro and femto users located in inner zones and femto users served by FC in outer MC zones. The algorithm 4.2 describes the steps for the spectrum partitioning approach with partial subcarrier reuse.

Because this model enables subcarriers reuse between neighboring FCs, it is expected the presence of co-tier interference, which is limited by the interference threshold.

4.7 Simulation Results

System parameters and assumptions considered in simulations are described in Section 4.7.1. Simulation results were obtained using: (1) Visual C++ Studio 8.0 and (2) IBM ILOG Cplex

Algorithm 4.2 Spectrum Partitioning Algorithm with partial bandwidth reuse

Data: MS Set of users,
FC, mSet of Femtocell and m represents Macrocell
(X_i, Y_i) User Locations
(X_f, Y_f) FC Locations
(D_i) Demands.
Result: BS selection for the set of users **bs**
Bandwidth allocated per subcarrier per user $\mathbf{b_i^{s,k}}$.
Power allocated per subcarrier per user $\mathbf{P_i^{s,k}}$.

begin
Determine the user sets in each zone, MS^1, MS^2, MS^3, MS^4 according to user locations;
Determine the FC set in zone z, FC^1, FC^2, FC^3, FC^4 according to FC locations;
Compute the maximum transmitted power per subcarrier in MC zone edge as ;
$P_z^m \leftarrow SINR_{Target} \times (N_0 + I_{th})$;
Determine resources for each MC zone as follows:;
$B^z \leftarrow \frac{|MS^z| \times B}{|MS|}$;
$P_z^{Total} \leftarrow \frac{|MS^z| \times P_m^{Total}}{|MS|}$;
for $z \leq Z$ **do**
if $z \geq 1$ **then**
Run MILP based spectrum sharing resource allocation algorithm per zone z with the user set equal to FC subscribers and public users within FC coverage area in zone z and subcarriers allocated to precedent zones $h \in 1, ..z-1$ and $P_z^{Total} \leftarrow 0$;
Remove FC subscribers and public users assigned from the set of user MS^Z within zone z;
end
Run MILP based spectrum partitioning resource allocation algorithm per zone with MS^Z as the set of users, B^z and P_z^{Total} as the available bandwidth and power in MC;
end
end

12.1: Concert Technology Environment (IBM, 2011). These results are analyzed for the different scenarios in Sections 4.7.2, 4.7.3 and 4.7.4.

4.7.1 Simulation Scenario

Several clusters of a random number of FCs are randomly located within the upper region of zones Z_1, Z_2, Z_3, Z_4 as illustrated in Fig. 4.3. By doing so, we keep certain percentage of users being served by MC. Mobile users are represented by letters (**S** for FC subscribers and **O** for public users). Femtocells are indicated by small circles and separated by a distance equal to a factor of 2.25 times FCs radius. Femtocells use QPSK, 16-QAM or 64-QAM, which means that the spectral efficiency in FCs, l^f_{mod}, can be equal to 2, 4 or 6 and is generated randomly with the same probability for each option.

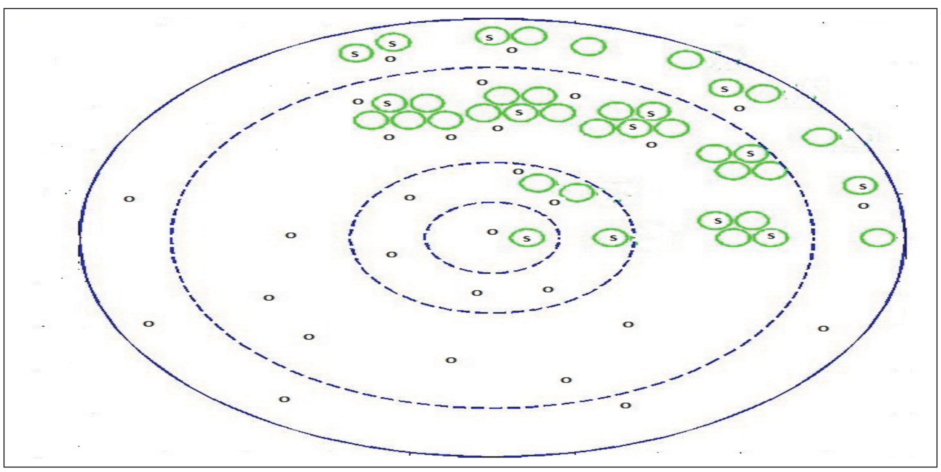


Figure 4.3 Network Configuration with a dense FC deployment in the upper region of macrocell coverage

The call arrival process is model as a Poisson process and service time in BS follows an exponential distribution. From each set of new users, a given percentage of them are located within the coverage of femtocells. We analyze the performance of the proposed solution and the benchmark models under three different scenarios:

Incremental Traffic Load Scenario: Simulation runs for different set of mobile users increasing from 10 to 100 with 10 user increment keeping a fixed percentage of user within the FCs vicinity.

Variable arrival rate: The average number of arriving users per TU is changed from 4 to 20 mobile stations per time unit (MS/TU) and a fixed percentage (30%) of new users are located within the FC neighborhood. We run the simulation for 50 TUs and measure the expected throughput, total number of handover, blocking and call dropping ratio.

Variable FC user density: Simulation runs for a given arrival rate (i.e. 20 MS/TU), fixed percentage of FC subscribers (i.e. 10 %) and the percentage of public user within FC vicinity changes from 20 and 50%.

In last two simulations scenarios, we incorporate random walk to model the macro user mobility (Nain *et al.*, 2005). Thus, user directions and speeds are randomly generated between 0 and 2π and 0 and 50 Km/h respectively.

Table 4.1 indicates the network and environment parameters used.

Table 4.1 System Parameters
(Network & Environment)

Name	**Description**	**Value**
B_s	Bandwidth per subcarrier	15 Khz
N_s	Number of subcarriers	256
N_s^m,N_s^f	Number of subcarriers per user in MC and FC	12
P_m^{Total}	Total transmitted power in MC	43 dBm
P_f^{Total}	Total transmitted power per FC	10 dBm
R_m, R_f	Macrocell and Femtocell radius	500 m,20 m
α_f, α_m	Attenuation factor for indoor and outdoor	3,3.7
l_m^{mod}	Spectral efficiency in MC zone	6, 4, 2, 1
l_f^{mod}	Spectral efficiency in FC	2, 4
N_0	Noise per subcarrier	174 dBm/Hz
f_c	Carrier Frequency	2.3 GHz
M_f	Maximum number of femto users	8
λ	Arrival rate of mobile users	4-20 MS/TU
μ	Mean service time	5 TU
TU	Time unit	1 s

Our model run the LP based algorithm every time unit (TU), which is defined as a fixed period of time where RA decisions are taken. The resource manager should be able to detect user and FC locations within the time unit to perform handovers and/or to change the assigned power subcarriers.

4.7.2 Performance analysis under the incremental traffic load scenario

Here, we present performance analysis as result of simulations under incremental traffic load scenario. Figure 4.4 shows the network throughput as a function of number of mobile stations. As expected, SP model presents the lowest throughput, which is due to the subcarrier reuse allowed in the other two models. SP-PSR model has a maximum throughput gain of 25% whereas SS-FSR has 75% gain. This is owing to the fact that SS-FSR model uses power adaptation to tackle interference and reach the SINR target of each mobile user in each zone.

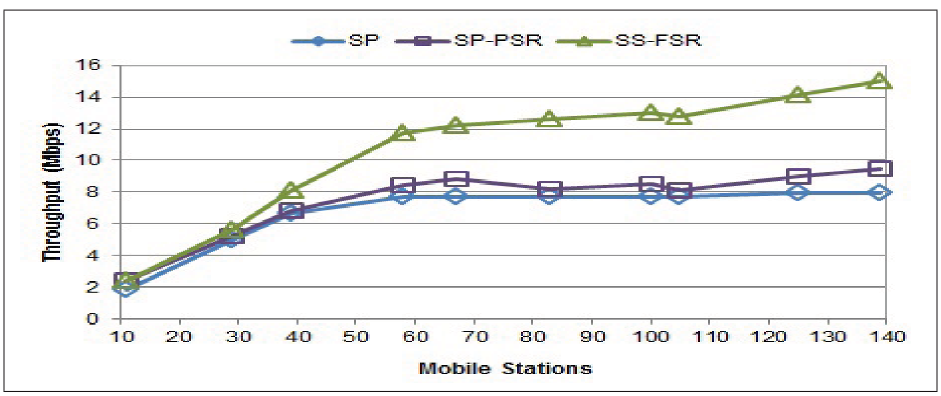


Figure 4.4 Maximum Throughput achieved in a incremental traffic load scenario

Table 4.2 presents subcarrier distribution per tier and per zone. It is worth to notice that the subcarrier distribution per zone depends on the user distribution. In the case of the SP-PSR and SS-FSR models, the number of subcarriers used in the outer zone is cumulative due to the reuse of the inner MC zone subcarriers inside of femtocell in outer zones. This means that for zone Z_2, SP-PSR and SS-FSR models add 22 or 18 subcarriers, respectively, of its corresponding inner zone (i.e. Z_1) to 66 or 50 subcarriers, respectively, that were assigned to be used in its zone coverage. It is also presented the subcarrier reuse factor in femto tier, which is given by

$$R_{FT} = \frac{\sum\limits_{f \in FC} \sum\limits_{s \in SC} b_i^{s,f}}{\sum\limits_{s \in SC} \cup_f^{FC^Z} \left[b_i^{s,f} \right]} \tag{4.24}$$

where $\cup[.]_f^{FC^Z}$ indicates the *OR* operation among the binary variables $b_i^{s,f}$ for femtocells in the zone Z. In other words, it represents the number of subcarriers allocated to femto tier in zone Z without considering its reuse. As expected, the SS-FSR model presents higher subcarrier reuse factor than SS-PSR model.

Table 4.2 Subcarrier Distribution

Zone	Macro Tier			Femto Tier			FT Reuse Factor	
	SP	SP-PSR	SS-FSR	SP	SP-PSR	SS-FSR	SP-PSR	SS-FSR
1	17	16	4	7	8	14	1.0	1.0
2	46	66	50	20	36	33	1.0	1.1
3	69	46	125	29	91	89	1.5	2.5
4	24	12	47	10	46	43	1.1	1.3

Table 4.3 indicates the user distribution among the two tiers per zone. The user distribution among the two tiers can be used to adaptively change the subcarrier distribution per zone in the next algorithm run. Thus, the proposed model can be easily modified to adapt the MC resources distribution over the MC zones based on FC density and user distribution, which means only MC user distribution. This will enhance the efficiency of the MC power usage. However, the model consider the user distribution per zone regardless of the FC density at the initial state because the MC user distribution per zone is not known.

In Fig. 4.5, we present a comparison with our previous model (Estrada *et al.*, 2013c) under the incremental traffic load scenario. For this comparison, 256 subcarriers are available for the two-tier network, which corresponds to less than 128 subcarriers allocated to zone Z_3. The arrival rate is equal to 16 MS/TU and corresponds approximately 8 MS/TU in zone Z_3.

Table 4.3 User Distribution

Zone	Macro Tier			Femto Tier		
	SP	SP-PSR	SS-FSR	SP	SP-PSR	SS-FSR
1	90	89	50	10	11	50
2	80	96	76	20	4	20
3	45	40	53	45	40	41
4	10	0	36	50	69	48

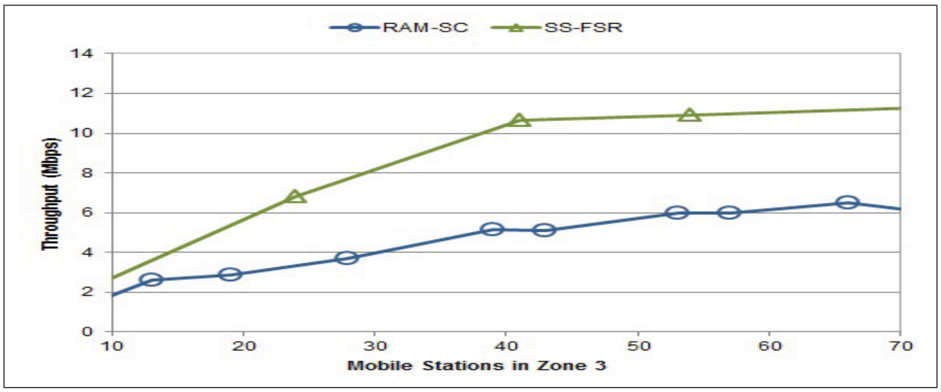
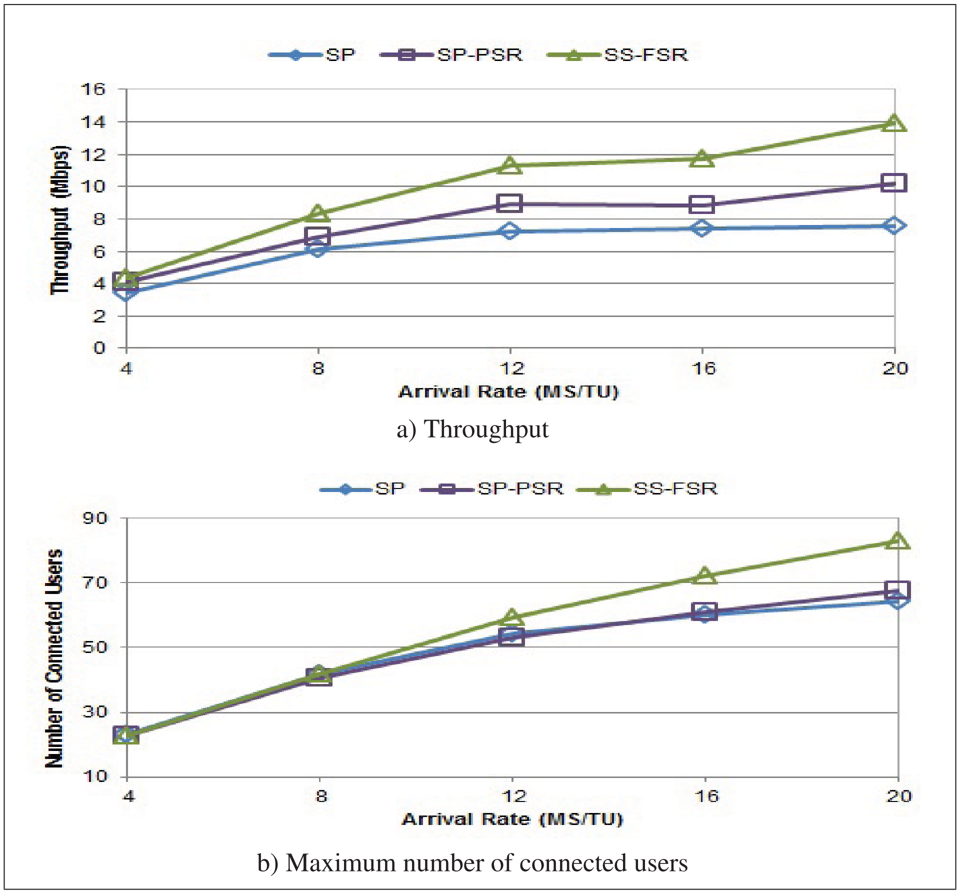


Figure 4.5 Throughput in zone 3 under a incremental traffic load scenario (allocated subcarriers in zone Z_3 for SS-FSR model is around 122 compared to 128 subcarrier used in RAM-SC only for zone Z_3)

4.7.3 Performance analysis in the variable arrival rate and FC user density scenarios

Figure 4.6 shows the expected throughput and the maximum number of connected users as a function of arrival rate. As expected, the spectrum sharing that allows full subcarrier reuse presents the highest throughput, see Fig. 4.6a. This is owing to the availability of the reuse of assigned subcarriers to DL transmissions of inner MC zones inside of FCs located in outer zones. Moreover, the proposed approach SS-FSR performs power adaptation in each MC zone and in femtocells. It can be observed that the SS-FSR present the highest system capacity, in terms of number of connected users, as shown in Fig. 4.6b, while SP and SP-PSR models presents similar capacity values.

Table 4.4 presents the total power consumption per tier for different arrival rates with 30% of users within FC vicinity. SP and SP-PSR models require less power consumption in both tiers than when compared with SS-FSR. On the other hand, the power consumption in femto



a) Throughput

b) Maximum number of connected users

Figure 4.6 Performance Measurements as a function of arrival rate in the scenario with variable arrival rate

tier for SP is the lowest since it does not require increasing the power in any BS to tackle the interference.

Table 4.4 Power Consumption per Tier

Arrival Rate	**Macro Tier**			**Femto Tier**		
	SP	**SP-PSR**	**SS-FSR**	**SP**	**SP-PSR**	**SS-FSR**
4	51.9	52.0	52.1	-8.5	-4.98	-0.1
8	53.5	52.5	53.3	-2.5	1.4	8.0
12	52.8	52.4	54.2	-0.9	4.3	10.3
16	51.8	51.8	54.1	-0.6	5.9	12.5
20	51.4	51.2	54.3	0.5	5.9	12.6

Network throughput is shown in Fig. 4.7 for the variable FC user density scenario. As expected, the throughput of the proposed solution increases as the FC user density increases unlike both spectrum partitioning models where the maximum throughput is the same regardless of the FC user density. However, the throughput gain of the proposed model is limited by the interference threshold used and the number of mobile users that can be connected to a femtocell.

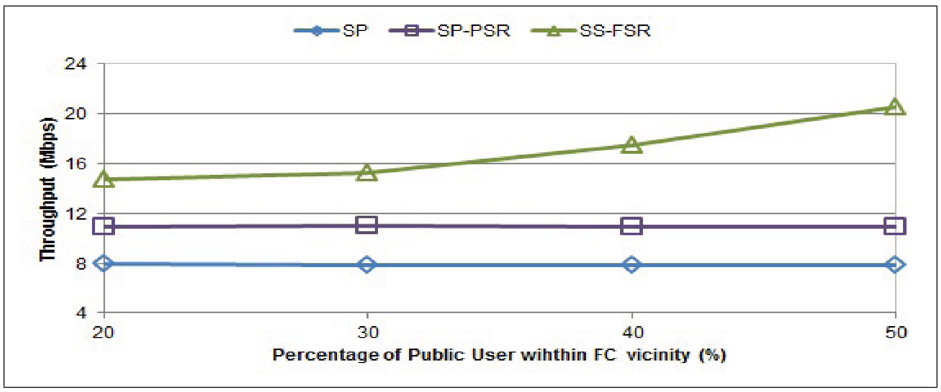


Figure 4.7 Throughput for the Variable FC User Density scenario, arrival rate equal to 16 MS/TU and 10% of FC subscribers

4.7.4 Mobility analysis

In this section, we want to analyze the performance metrics related to the mobility such as call dropping and handover ratios. Tables 4.5 and 4.6 presents the handover and call dropping ratios for different arrival rates and variable FC user density respectively. It can be noticed that our model has lower handover and call dropping ratio in comparison with spectrum partitioning model and SP-PSR model presents the highest call dropping ratio for different values of arrival rate. In the case of variable FC user density, it can be observed that the call dropping ratio increases as the FC user density increases for the three models. However, the lowest call dropping ratio is obtained using the proposed solution. In summary, the SS-FSR model provides the best throughput for different MS arrival rates and variable FC user densities and performs less number of handovers compared to spectrum partitioning approaches with or without partial subcarrier reuse.

Table 4.5 Handover and Call Dropping
Ratio for variable arrival rate scenario

Arrival Rate	Average HO (%)			Average Call Drop (%)		
	SP	SP-PSR	SS-FSR	SP	SP-PSR	SS-FSR
4	6	4	3	0	0	0
8	4	4	4	0	1	0
12	5	4	4	2	2	1
16	4	3	3	3	8	3
20	4	3	3	5	8	3

Table 4.6 Handover and Call Dropping
Ratio for variable FC user density

Percentage PU	Average HO (%)			Average Call Drop (%)		
	SP	SP-PSR	SS-FSR	SP	SP-PSR	SS-FSR
20	6	4	3	0	0	0
30	4	4	4	0	1	0
40	5	4	4	2	2	1
50	4	3	3	3	8	3

4.7.5 Complexity

The complexity of the proposed solution depends on the number of subcarriers that comprise the licensed spectrum, mobile user density within FC coverage area, the number of femtocells in each zone and the total transmitted power in MC. The idea of considering the OFDMA zones in the macrocell is to have disjoint subsets of both femtocells and users, so that the complexity and runtime of a MC zone resource allocation algorithm is reduced as it considers less number of users and femtocells. Since the zone algorithms can run in parallel, the total time required to solve the RA problem is equal to the maximum time required to find the optimal solution of all four zones. In our simulation scenarios, this maximum running time corresponds to the zone Z_3 because this zone has the higher FC and user densities. Fig. 4.8 shows the required time to solve the RA allocation problem using the three models as a function of the number of users in the network with a fixed number of deployed FC. As we can see, all the models have running time below 3 sec for 80 users in the network but only SS-FSR is able to connect all of them as shown in Figure 4.6b.

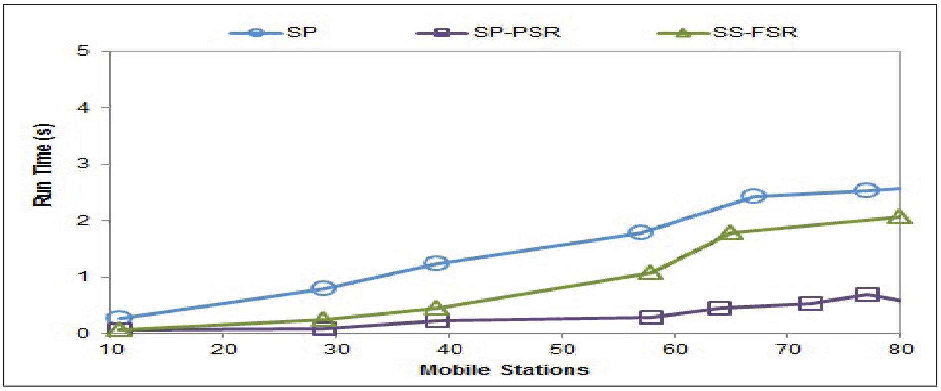


Figure 4.8 Running Time vs number of mobile stations for an incremental scenario with 30% of mobile user within FC vicinity and 40 deployed femtocells

4.8 Conclusion

Based on the "divide and conquer" principle, we proposed a suboptimal model that independently maximizes each MC zone throughput of an OFDMA two-tier network with interference mitigation per subcarrier basis by means of linear programming. The set of users and femtocells is divided into disjoint subsets per zone in such way that the resource allocation algorithm complexity is reduced. Moreover, each zone algorithm can be executed in parallel thereby reducing the time required to find an near to optimal solution. Simulation results were conducted based on CPLEX environment and showed that the proposed SS-FSR model reaches 75% of throughput gain, serves around 32% more users and reduces the handover ratio and call dropping ratio by up to 3% and 2%, respectively, when compared to spectrum partitioning approach. The advantages of the proposed model lie in: (1) its ability to enhance the power distribution over active subcarriers in each BS, (2) its ability to assign the best set of public users to femtocells, (3) bandwidth reuse among the BSs located in the same zone for a given interference threshold, and (4) reuse of bandwidth allocated in inner MC zones among FCs located within outer zone coverage by means of power control of MC transmitted power per zone. As future work, dynamic changes on MC zones can be analyzed as well as the impact of cluster formation techniques on the performance of the resource allocation model.

CHAPTER 5

LOAD BALANCED CLUSTERS AND RESOURCE ALLOCATION FOR MACRO-FEMTOCELL NETWORKS

Rebeca Estrada[1,3] , Hadi Otrok[2] , Zbigniew Dziong[1] ,

[1] Département de Génie Eléctrique, École de Technologie Supérieure,

1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3

[2] Department of ECE, Khalifa University of Science, Technology & Research, UAE

[3] Electrical Engineering and Computer Science Faculty, Escuela Superior Politécnica del Litoral, Ecuador

An Article submitted to IEEE Transactions on Vehicular Technology in August 2014

5.1 Abstract

Femtocells have been deployed to enhance indoor coverage, to improve the system capacity of cellular networks, and to increase the spectrum efficiency by means of full subcarrier reuse among macrocell and femtocells. Nevertheless, the introduction of hybrid access mode imposes new challenges for the resource allocation in a macro-femtocell network such as: (1) granting access to public users while guaranteeing QoS subscriber transmission, (2) trade-off between level of offloaded traffic from macrocell and bandwidth allocated to femto-tier and (3) appropriate power settings that finds a compromise between the overall system performance and the bandwidth allocated to femtocells. In this paper, we propose a cluster formation technique together with a centralized resource allocation algorithm based on Particle Swarm Optimization technique. Our algorithm aims at the maximization of network throughput and determines the serving base station and the amount of resources per user taking into account user locations and demands, femtocell proximity and traffic load of existing clusters. Simulations are conducted to show the performance of our approach that is contrasted with other model using the same BS selection procedure, weighted water filling resource allocation algorithm and a different cluster formation technique.

5.2 Introduction

Femtocells have been incorporated to traditional wireless networks as a promising solution to increase their current capacity and to improve indoor coverage without any additional costs. Femtocell (FC) is a end-user base station (BS) with short-range and low-cost connected to the cellular network through a fixed broadband backhaul. FC deployment brings several benefits such as offloaded traffic from macrocell, enhanced spectral efficiency and prolonged battery life of mobile equipment. Despite all these advantages, there are still some challenges that need to be addressed such as resource management, interference mitigation, mobility management, access control and time synchronization (Zhang and De la Roche, 2010).

Since femtocells operate in the same licensed spectrum as the overlaid macrocell, spectrum allocation as well as interference mitigation have attracted the attention of many researchers. The spectrum allocation can be classified into two categories: spectrum partitioning or spectrum sharing. In spectrum partitioning, dedicated portion of subcarriers is assigned to each tier (Chun-Han and Hung-Yu, 2011) while in spectrum sharing approach, subcarriers are shared among the two tiers (Cheng *et al.*, 2012). The former has been used for non-dense FC deployment whereas the latter is recommended for dense deployment but requires interference management schemes to uphold Quality of Service (QoS) transmission and to enhance network throughput. There are different research work focused on spectrum sharing such as: power control (Torregoza *et al.*, 2010), fractional frequency reuse (Dalal *et al.*, 2011), soft frequency reuse (Jeong *et al.*, 2010), full frequency reuse in femto tier (Abdelnasser *et al.*, 2014) and the use of cognitive radios (Bennis and Perlaza, 2011).

The coexistence of FCs and MCs can introduce interference between the femtocell and macrocell DL transmissions, which depends on the FC access control mechanism. The access control mechanism determines whether a public user can have access to a nearby FC or not. There are three access control mechanisms: closed access, open access and hybrid access (Zhang and De la Roche, 2010). In closed access, FC subscribers get full benefit from their own FC but it limits the network capacity and increases the interference to nearby macro users, which is known as a dead-zone problem. Open access mechanism allows any users to make use of FCs. However, open access mechanism requires high coordination between FCs and macrocell which may result in traffic congestion over the backhaul connection among FC and the network core. Hence, a new hybrid access control mechanism is proposed to combine the benefits and to overcome the limitations of the two previous access control mechanisms.

In the literature, some hybrid access mechanisms have been proposed such as the work in (Valcarce *et al.*, 2009), where femtocells reserve part of the allocated resources for their own subscribers. Previous research works have demonstrated that hybrid access outperforms closed and open access by reducing the interference while guaranteeing the performance of their own subscribers (Valcarce *et al.*, 2009; Choi *et al.*, 2008; Li *et al.*, 2010). Due to these benefits, we focus on hybrid access FCs. According to (3GPP-TR-36.921, 2011), the optimal power setting should be different from closed access FCs because it should be a compromise between the overall system performance versus resources used by public users in FCs instead of a trade-off between performance at the FC/femtousers and interference caused to the MC/macrousers. Moreover, we assume that the network operator is willing to allocate some extra resources (i.e. subcarriers or subchannels) to femtocell which adopts hybrid access and grants access to public users like the utility refunding mechanism proposed in (Chen *et al.*, 2012).

To reduce the complexity of resource allocation models in dense femtocell networks, few cluster formation schemes have been proposed. The majority are oriented to closed access femtocell network. These approaches aim different objectives such as: the maximization of FC subscribers data rate while minimize the co-tier interference among the clusters (Hatoum *et al.*, 2011), upholding the QoS for subscribers transmission (Hatoum *et al.*, 2012b, 2014), and minimization of the co-tier interference among the clusters (Lin and Tian, 2013) or interference alignment within the cluster (Pantisano *et al.*, 2013). Few cluster based resource allocation models focus on granting access to public users (Chun-Han and Hung-Yu, 2011) or universal subcarrier reuse in femto tier (Abdelnasser *et al.*, 2014). Nevertheless, they do not provide incentives for FC owners to grant the access to public users, determine the optimal cluster size and/or adapt the allocated bandwidth per tier taking into account the satisfied demand of public users by FCs. In the scenario where hybrid access FC are considered, a large size cluster will require more resources from the macrocell depending on the public user density within the FC cluster vicinity.

Hence, the introduction of hybrid access femtocells imposes new technical challenges for the resource allocation and clustering techniques due to the contrasting factors that affect the overall system performance, such as: (i) access to public users, satisfaction of own FC subscribers and mechanisms to motivate FC owners to grant access to public users, (ii) level of offloaded traffic from the macrocell and dedicated bandwidth allocated to femto tier, (iii) Bandwidth reuse at femto tier, power adaptation and interference, and (iv) handover and users mobility.

Accordingly, the following limitations of previous works can be noticed:

- excess of unused resources in macrocell regardless of the level of the traffic offloaded to femtocells;
- QoS subscriber transmissions are not guaranteed by granting access to public users through FCs;
- mechanisms to motivate FC owners to grant access to nearby public users; and
- lack of adaptive power control that finds a trade-off between overall system performance and resources used by public users in FC.

To overcome above limitations, we propose a model to perform cluster formation, BS selection and resource allocation for OFDMA macro-femtocell network aiming at the maximization of the network throughput. Since the targeted problem has to be solved in short time due to the time duration of resource block in OFDMA technology (3GPP-TR-36.921, 2011), our resource allocation algorithm is based on Particle Swarm Optimization (PSO). PSO is a good candidate to speed up the optimization process and obtain a satisfying near-optimal solution (Bratton and Kennedy, 2007). PSO has been investigated to solve the subcarrier allocation for OFDMA macrocell systems in (Gheitanchi *et al.*, 2007) and for LTE systems in (Su *et al.*, 2012). These prior works show that PSO has reduced complexity compared to linear search and sorted list approaches. In our previous work (Estrada *et al.*, 2013b), we have shown that for given BS selection, PSO can indeed enhance the network throughput in comparison with Weighted Water Filling algorithm.

Thus, the proposed approach consists of three components: (1) a BS selection algorithm to balance the traffic load among the clusters, (2) a cluster formation algorithm using a new merging metric, and (3) a centralized resource allocation algorithm based on PSO taking into account all FC clusters and determines the required number of subcarriers in femto tier. In particular, our contribution is a model that performs:

- bandwidth adaptation per tier based on average satisfied demand of public users through FCs;
- BS selection based on user demands and locations, FC proximity and cluster load;
- enhanced power distribution over active bandwidth in each BS;
- universal subcarrier reuse at femto tier; and
- reduction of inter-cluster interference and running time.

To evaluate the performance of the proposed clustering scheme alone, we propose to use the Weighted Water Filling (WWF) algorithm for resource allocation without FC power control. Then, to evaluate the performance of the clustering together with PSO based resource allocation approach, we propose to use a benchmark model that employs (Chun-Han and Hung-Yu, 2011) WWF based resource allocation and a cluster formation scheme based on the perceived interference levels and FC bandwidth reduction (Abdelnasser *et al.*, 2014). The benchmark model has been modified to select first the best serving BS per user in order to balance the traffic load per cluster, to allocate bandwidth and transmitted power to achieve the signal to noise ratio (SNR) target using a modified version of WWF.

The remainder of the paper is organized as follows: Section 5.3 describes the targeted problem and presents the problem formulation. Section 5.4 presents the cluster based resource allocation model and the benchmark model and its modifications to cope with the same constrains as the proposed model. Section 5.5 presents the performance measurements. Section 5.6 shows the results obtained for our model in comparison with a heuristic model. Finally, Section 5.7 concludes the paper.

5.3 Problem Statement

We consider a macrocell with a set of underlaid femtocells as shown in Fig. 5.1. Both MC and FCs are assumed to operate using OFDMA technology. We consider downlink (DL) transmission. According to (3GPP-TR-36.921, 2011), each mobile device can identify FCs and macrocell that could potentially provide service within a coverage area and notify this list to the serving macro BS. Thus, the macrocell is able to determine which public users might be connected to FCs as well as which FCs can be grouped into clusters such they can serve more public users and increase the network throughput.

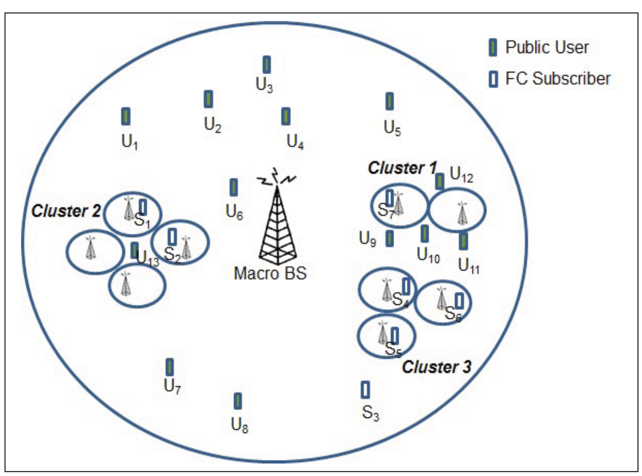


Figure 5.1 Network Example with three FC clusters.
S_i and U_i are FC subscribers and public user respectively

Let's assume that 10 channels are available in the overlaid MC with a bandwidth of B_c. These 10 channels should be allocated among FCs and MC in such way that maximizes the network throughput and minimizes the blocking ratio. The mobile users $(U_1, ...U_13, S_1, ..S_7)$ can be allocated to macrocell or femtocell depending on the access mechanism applied in FC. For simplicity, the spectrum efficiency in macrocell is assumed to be equal to 2 bps/Hz and in each femtocell is equal to 6 bps/Hz. There are many possible solutions to perform the resource allocation which will depend on spectrum usage, access mechanism and the clustering technique applied. For further consideration, we selected and analyzed the following four approaches that combine FC access mechanism, spectrum usage in femto tier and cluster formation technique.

a. For spectrum partitioning and FC deployed with closed access policy, more users allocated to femtocells is the best solution to maximize the network throughput. According to Fig. 5.1, only 6 FC subscribers can be served by FCs because they are located under their own FC coverage area and 4 users by macrocell. Therefore, the throughput can be estimated as 44 B_c and blocking ratio is be equal to 0.5. It can be noticed that this approach tends to prioritize the subscriber transmissions leading to the bandwidth starvation in macrocell.

b. For spectrum sharing and FC deployed with closed access policy, the channel reuse is allowed inside each FC. Since each femtocell has at most one subscriber under its coverage, only one channel needs be allocated to femto tier but the co-tier interference will be present among neighboring FCs. For this type of scenario, FC power control has been proposed to prioritize the macro user transmission, which leads to a spectrum efficiency reduction in femtocells. In our example, let's say that the spectrum efficiency is reduced to 4 bps/Hz, then, the throughput can be estimated as 42 B_c and the blocking ratio of 0.25.

c. For spectrum sharing, FCs deployed in closed access mode and cluster formation that is used to avoid the co-tier interference within each cluster, the maximum number of channels required is given by cluster with more subscribers on its coverage, which is the cluster $Cluster_3$ in Fig. 5.1. Thus, 3 and 7 channels can be orthogonally allocated to femto tier and macro tier respectively, leading to a blocking ratio of 0.35 and a throughput value of 50 B_c. The latter shows that clustering indeed reduces the co-tier interference and increases the network throughput at expenses of increasing the blocking ratio.

d. For spectrum sharing, FCs deployed in hybrid access mode and cluster formation to avoid the co-tier interference within each cluster, the cluster that can potentially serve more users will be used to determine the maximum number of channels required at femto tier. In the Fig. 5.1, $Cluster_1$ has 5 potential users, which means that 5 channels should be allocated to each tier. The whole network increases the sum of user data rates by means of using FCs to serve public users (approximately to 76 B_c) and the blocking ratio is reduced to 0.2.

Last resource allocation approach seems to be the best solution from the operatorś perspective. However, from FC owner's point of view, FCs belonging to the cluster that serves more public users have no incentive to grant access to public users while FCs belonging to the other clusters have extra resources that can be allocated to their own subscribers.

Cluster formation is intended to avoid the interference among its members through the orthogonal subcarrier assignment and to enhance the network throughput by means of enabling the subcarrier reuse in different clusters. However, there is still a presence of the inter-cluster interference that affects FC on the cluster edge (FC close to other clusters in the network, such as some FCs in $Cluster_1$ and $Cluster_3$ in Fig. 5.1).

In summary, a compromise between maximizing network throughput, clustering technique, power control and FCs owner incentives should be determined.

Problem Formulation

Our proposed cluster based resource allocation model is presented in this section. This model aims at the maximization of the two-tier network throughput by means of optimizing the sum of achievable user data rates in a overlaid macrocell with several FCs being grouped into disjoint clusters. According to Shannon's Law, the sum of the achievable data rates can be formulated as:

$$\max_{\mathbf{X},\mathbf{A},\mathbf{b},\mathbf{P}} \sum_{i\in\{MS\}} \sum_{s\in\{SC\}} A_i^m b_i^s log_2(1+SINR_i^{m,s})+$$
$$\sum_{c\in\{C\}} \sum_{i\in\{MS\}} \sum_{j\in\{m,FC^c\}} \sum_{s\in\{SC\}} X_j^c A_i^j b_i^s log_2(1+SINR_i^{j,s}), \tag{5.1}$$

where vectors **X**, **A**, **b** and **P** correspond to femtocell-cluster membership, user-base station association, bandwidth and power assignment for each user. First term of (5.1) corresponds to the MC throughput and the second term is the sum of data rate in femto tier. C is the set of disjoint FC clusters and X_j^c is a binary variable that indicated the FC j is a member of cluster c. A_i^j is a binary variable that determines if the BS j is selected for user i. The vector **b** consists of real variables, b_i^s, indicating that subcarrier s is allocated to user i. $SINR_i^{j,s}$ is the signal to interference plus noise ratio perceived by the mobile user over the subcarrier s and is given by:

$$SINR_i^j = \frac{P_i^j}{PL_i^j \times (N_0 + I_i^{s,FC})}, \qquad j \in FC, i \in MS. \tag{5.2}$$

It is worth to notice that as we are considering orthogonal subcarrier assignment among the two-tier and among the members of a cluster, therefore, the co-tier interference comes from other clusters sharing the same set of subcarriers. Thus, the co-tier interference can be expressed by:

$$I_i^{s,FC} = \sum_{k\in C\setminus c} \sum_{f\in FC} \sum_{h\in\{MS\setminus i\}} X_f^k A_h^f \frac{P_h^{s,f}}{PL_i^f} \tag{5.3}$$

Our objective function is subject to the following constraints:

$$\sum_{s\in\{SC\}} b_i^s \le A_i^m \frac{\min(D_i, D^{max})}{l_f^{mod}} + \sum_{j\in\{FC\}} A_i^j \frac{D_i}{l_f^{mod}} \qquad ; i \in MS, \tag{5.4}$$

$$\sum_{i\in\{MS\}} A_i^m \sum_{s\in\{SC\}} b_i^s < B_m, \tag{5.5}$$

$$\sum_{i\in\{MS\}} \sum_{j\in\{FC^c\}} A_i^j \sum_{s\in\{SC\}} b_i^s \le B - B_m \qquad ; c \in \{C\}, \tag{5.6}$$

$$\sum_{i\in\{N\}} P_i^j \leq A_i^j P_j^{Total} \qquad ; j \in \{m, FC\}, \tag{5.7}$$

$$log_2\left(1+\frac{P_i^j}{PL_i^j \times (N_0 + I_i^{s,FC})}\right) \geq l_j^{mod} A_i^j \qquad ; i \in MS, j \in \{m, FC\}, \tag{5.8}$$

$$\sum_{j\in\{FC\}} X_j^c \leq N_{bs}^c \qquad ; c \in C \tag{5.9}$$

$$\sum_{c\in\{C\}} X_j^c \leq 1 \qquad j \in FC \tag{5.10}$$

We briefly explain the model constraints as follows: The upper bound for the allocated bandwidth per user to satisfy his demand is presented by constraint (5.4). The upper bound for allocated bandwidth to macro and femto tiers are given by constraints (5.5) and (5.6) respectively. B_m is a variable that determines the bandwidth allocated to macro tier. The upper bound of transmitted power per BS is determined by constraint (5.7). Constraint (5.8) represents the lower bound of the spectrum efficiency per BS. Constraint (5.9) corresponds to the upper bound of the cluster size and constraint (5.10) indicates that one FC can only be assigned to one cluster c.

Our problem is NP-hard as it was proven in (Hong and Garcia, 2012). This means that there is no polynomial-time algorithm that can obtain the optimal solution for bandwidth and power allocation together with BS selection. Moreover, since equations (5.1) and (5.8) are non-linear functions, we propose to replace (5.1) by

$$\max_{\mathbf{b},\mathbf{P}} \sum_{i\in\{MS\}} \sum_{s\in\{SC\}} A_i^m b_i^s l_m^{mod} + \sum_{c\in C} \sum_{i\in\{MS\}} \sum_{f\in FC} \sum_{s\in\{SC\}} X_j^c A_i^j b_i^s l_j^{mod} \tag{5.11}$$

assuming that the log term should be at least equal to the spectral efficiency required in the MC, l_m^{mod}, or FC, l_f^{mod}. Our MIP model attempts to solve the clustering and resource allocation in a two-tier network taking into account user locations, demands and FC locations. In addition, a piece wise segment linear approximation can be used to replace the log term in 5.8 as we did in our previous work in (Estrada *et al.*, 2014) to solve the resource allocation problem using

Linear Programming. However, this model is more time consuming than our previous work due to the new variables representing FC cluster membership.

One way to find the optimal cluster configuration can be done by exhaustive search. This means to perform the joint BS selection and resource allocation over all possible given cluster configuration. Thus, if a cluster configuration yields to the highest throughput, then, this configuration is selected as the new best cluster configuration. This procedure is repeated until there is no further throughput improvement. The total number of possible ways of grouping a set of FCs into disjoint clusters can be derived using the Stirling Partition number (Bogart *et al.*, 2011, ,Chapter 5) and given by

$$C_{conf}^{Total} = \sum_{j=1}^{|FC|} \frac{1}{j!} \sum_{i=0}^{j} (-1)^{j-i} \binom{j}{i} i^{|FC|} \tag{5.12}$$

Nevertheless, the maximum cluster size should be known before running the algorithm. Moreover, exhaustive search requires high running time since the number of possible cluster configuration increases exponentially with the number of FCs. For example, with only 5 FCs, there are 15 or 25 possible cluster configurations with a maximum cluster size of 2 or 3 respectively.

Therefore, alternative cluster formation techniques need to be investigated in order to reduce the complexity of a centralized resource allocation for a macro-femtocell network in order to balance the traffic load among the clusters and to reduce the inter-cluster interference.

5.4 Cluster based Resource allocation model

Since exhaustive search requires high complexity and running time, we propose a spectrum partitioning approach that performs: (1) BS selection procedure to balance the public users traffic load among the existing clusters, (2) resource allocation for the macro-femtocell network that mitigates the inter-cluster interference, maximizes the network throughput while guaranteeing QoS subscribers connections and adaptively determines the allocated bandwidth for both tiers, and (3) cluster formation based on the cluster size and cluster availability in terms of connected users and allocated resources.

5.4.1 BS selection per user

Here, the BS selection procedure is described. Our objective is to balance the traffic load of public users among the current clusters while guaranteeing the QoS of FC subscriber transmissions. First, the mobile users are sorted according to their type (i.e. FC subscriber transmission should have priority inside their own FC) and weighted demand. Second, the algorithm chooses FCs with better link rate conditions than the macrocell for each user. Then, FC are sorted according to the cluster size of the cluster where they belong to and their available capacity (in terms of number of users and resources). If the FC set is empty, the public user is associated to the MC. This procedure is repeated until all users are allocated either to one FC or macrocell. The algorithm 5.1 presents the BS selection procedure.

Our BS selection procedure allocates users to FC with higher available capacity and member of cluster with lower number of FC. Doing so, we avoid having FC cluster with higher load than any other cluster in the network.

5.4.2 Cluster formation mechanism

In this paper, a heuristic cluster algorithm is proposed to balance traffic load among the FC clusters such they would have almost the same size, allocated resources and associated public users if it is possible. Initially, each FC is considered as a cluster. Thus, the cluster number, $|C|$, is equal to the femtocell number in the network, $|FC|$. Once BS selection is performed, the resources are allocated to each cluster taking into account the average bandwidth required by FCs. Then, the resource allocation is carried out by means of orthogonal subcarrier allocation within a cluster and FC power control is performed to mitigate interference and to achieve target SINR.

Algorithm 5.1 BS Selection Algorithm

Data: MS Set of users,
FC, m Set of Femtocell and m represents Macrocell,
User Locations (X_i, Y_i),
FC Locations (X_f, Y_f),
Demands(D_i)
Result: (Y_i^j) BS selection
begin
  Sort set MS in decreasing order by their type of user (T_u) and weighted demand (D_u);
  for *each* $u \in MS$ **do**
    Determine the FC_{user} with higher link rate than the MC and available capacity in terms of users.
    if $FC_{user}! = 0$ **then**
      Sort this FC set in decreasing order by: link rate, available capacity, available resource in its cluster, available number of FC to be connected to the cluster.
      Assign user to the first FC in the ordered list.;
      $Y_u^j \leftarrow 1$;
      Increase the number of femto or macrousers on FCs depending on its type.;
      if $T_u = 2$ **then**
        $N_{SU}^j \leftarrow N_{SU}^j + 1$;
      end
      else
        $N_{PU}^j \leftarrow N_{PU}^j + 1$;
      end
      Reduce the available capacity of femtocell j.;
    end
    else
      Assign user to the macrocell. ;
      $Y_u^m \leftarrow 1$;
    end
  end
end

The resource manager entity can identify the interfering FC set by means of the measurement reports delivered by mobile users. The proposed clustering scheme pursues to merge stand alone (SA) FCs that causes interference to clusters with available capacity in terms of available subcarriers without exceeding the maximum cluster size allowed in a given period of time. The cluster formation procedure is presented in Algorithm 5.2.

Algorithm 5.2 Clustering Algorithm

Data: FC Set of Femtocell
Result: (X_j^c) Cluster Configuration
begin
  Initialization
  Each FC j is a cluster initially, so there are totally $|FC|$ clusters
  for *each FC i without cluster* **do**
    Determine the set of interfering Clusters, $Cluster_{Int}^i$ of Cluster i
    for *each element* j *of* $Cluster_{Int}^i$ **do**
      Calculate the merging metrics for the interfering clusters
    end
    Sort the cluster j in descending order of the metric
    Select the first cluster (j)
    for *each element* j *of* $Cluster_{Int}^i$ **do**
      if $|FC^j|+1 \leq N_C^{MAX}$ **then**
        Add FC i to the femtocells set belonging to cluster j, FC^j;
        break;
      end
      else
        Select the next cluster in $Cluster_{Int}^i$
      end
    end
  end
end

Our merging metric is defined as

$$METRIC_{cl}^j = \max\left(0, 1-\frac{|FC_j|}{N_c^{FC}}\right) * \max\left(0, 1-\frac{|SC^{SU,j}|}{SC^j}\right) * \max\left(0, 1-\frac{SC^j}{SC^{FT}}\right) \quad (5.13)$$

where $SC^{SU,j}$ represents the number of subcarriers required by the subscribers in the cluster j and SC^j is the number of subcarriers allocated to cluster j, which should be less or equal to the number of subcarriers allocated to femto tier in a given period of time, SC^{FT}. N_c^{FC} is the maximum cluster size. Our metrics consists of three components: (1) FC number that can be added to a cluster j without trespassing the maximum cluster size, (2) the available capacity (i.e. number of users that can be connected to the cluster j), and (3) the available resources (subcarriers or subchannels). For this reason, we named our clustering scheme as Load Balanced Clustering scheme (LBC). In the case that two or more clusters have the same metric value, the algorithm selects the highest interfering cluster to merge to the stand alone FC.

5.4.3 PSO based Resource allocation per cluster

Particle Swarm Optimization (PSO) is a population-based search approach and depends on information sharing among the population members to enhance the search process using a combination of deterministic and probabilistic rules. PSO has been proven to yield the same effectiveness of the evolutionary algorithms but it requires less number of function evaluations (Bratton and Kennedy, 2007). PSO algorithm uses two vectors that determine the position and velocity of each particle n at each iteration k. These two vectors are updated based on the memory gained by each particle. The position x_n^{k+1} and velocity v_n^{k+1} of a particle n at each iteration k are updated as follows:

$$x_n^{k+1} = x_n^k + \delta_t v_n^k, \tag{5.14}$$

$$v_n^{k+1} = \omega v_n^k + c_1 r_1 (p_k^{local} - x_n^k) + c_2 r_2 (p_k^{global} - x_n^k), \tag{5.15}$$

where δ_t is the time step value typically considered as unity (Perez and Behdinan, 2007), p_k^{local} and p_k^{global} are the best ever position of particle n and the best global position of the entire swarm so far (current iteration k), r_1 and r_2 represent random numbers in the interval [0,1]. Parameters ω, c_1 and c_2 are the configuration parameters that determines the PSO convergence behavior. First term corresponds to the inertia of particle i which is used to control the exploration abilities of the swarm. Large inertia produces higher velocity updates allowing the algorithm to explore the search space globally. Conversely, small inertia values force the velocity to concentrate in a local region of the search space. Second and third term are associated with cognitive knowledge that each particle has experienced and the social interactions among particles respectively. Parameters c_1 and c_2 are known as the cognitive scaling and social scaling factors (Bratton and Kennedy, 2007).

According to (Perez and Behdinan, 2007), the convergence of PSO is guaranteed if the following two conditions are met:

$$0 \leq (c_1 + c_2) \leq 4, \tag{5.16}$$

and

$$\frac{c_1 + c_2}{2} - 1 \leq \omega \leq 1. \tag{5.17}$$

For our resource allocation algorithm, two vectors (b, P) are used to define the location of each particle n in the search space, where b and P represents allocated bandwidth per user and transmitted power per user respectively. We also keep two different velocity vectors (v_b, v_P) to update the particle location in each iteration using (5.15). We define a bandwidth step increase as δ_b, which can be the bandwidth used per subcarrier. In addition, we propose to use a discrete number of power levels to reduce the search space.

One classic way to accommodate constraints is to add penalties proportional to the degree of constraint infeasibility. The main concern with this method is that the quality of the solution depends directly on the value of the specified scaling parameters. For that reason, we use a parameter-less scheme, where penalties are based on the average of the objective function and the level of violation of each constraint during each iteration (Perez and Behdinan, 2007). Thus, the penalty coefficients are determined by

$$cp_l = |\overline{f}(x)| \frac{\overline{g_l}(x)}{\sum_{j=1}^{C} [\overline{g}(x)]^2}, \tag{5.18}$$

where $\overline{f}(x)$ is the average objective function, $\overline{g}(x)$ is the average level of l_{th} constraint violation over the current population and C is the number of constraints (Perez and Behdinan, 2007).

Thus, our fitness function is defined by

$$f'(x) = \begin{cases} f(x_n^k), & \text{if } x_n^k \text{ is feasible} \\ f(x_n^k) + \sum_{l=1}^{C} cp_l \widehat{g}(x_n^k), & \text{otherwise} \end{cases}. \tag{5.19}$$

and $\widehat{g}(x_n^k)$ is determined as follows:

$$\widehat{g}(x_n^k) = \max\Big(0, [g_j(x_n^k)]\Big). \tag{5.20}$$

Accordingly, the average of the fitness function for any population is approximately equal to $\overline{f}(x) + |\overline{f}(x)|$.

Our objective function is to maximize the network throughput. As PSO is defined to solve a minimization problem, we change our objective function in (5.1) to

$$f(\mathbf{b{,}P}) = Q - \sum_{i \in \{MS\}} \sum_{j \in \{m,FC\}} A_i^j b_i log_2(1 + SNR_i^j) \tag{5.21}$$

where Q is a largest number at least twice the value of the maximum throughput than can be achieved. In such way, we convert our maximization problem into a minimization problem. The parameter A_i^j is equal to 1 if $bs_n(i)$ is equal to j and 0 otherwise, which is determined as described in Section 5.4.1. Our fitness function is given by

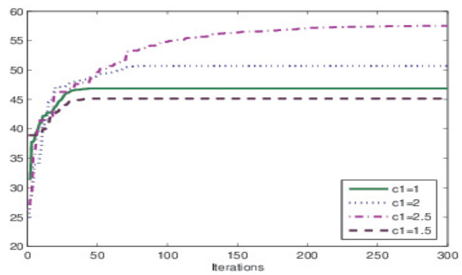
$$f'(x) = \begin{cases} f(\mathbf{b{,}P}), & \text{for feasible solutions} \\ f(\mathbf{b{,}P}) + \sum_{l=1}^{C} k_l \widehat{g}\mathbf{(b{,}P)}, & \text{otherwise} \end{cases}. \tag{5.22}$$

where constraints (5.4 - 5.8) defined in Section 5.3 are included in $\sum_{l=1}^{C} k_l \widehat{g}\mathbf{(b{,}P)}$ to penalize unfeasible solutions. The algorithm 5.3 presents our joint power and bandwidth allocation for a given user-BS association. Vectors $\mathbf{r_1}, \mathbf{r_2}, \mathbf{r_3}, \mathbf{r_4}$ are composed of random numbers between 0 and 1 with the same cardinality as vector $\mathbf{b}$ and $\mathbf{P}$, which is equal to the cardinality of the user set.

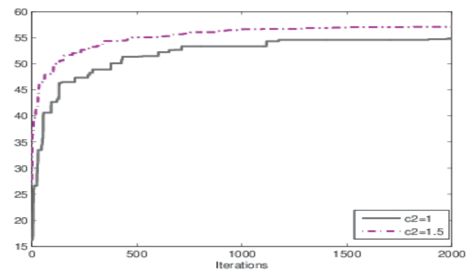
Algorithm 5.3 PSO based Resource Allocation algorithm

Data: MS User Locations (x_i, y_i),
FC Locations (x_f, y_f),
Demands (D_i)
and BS selection per user (bs_i).
Result: Bandwidth and power allocation per user (b_i, P_i).
begin
  for *each* $i \in MS$ **do**
    if $bs_i = m$ **then**
      $b_i^{max} \leftarrow \frac{D_i}{l_{mod}^{m}}$;
      $P_i^{max} \leftarrow \min(P_z^{max}, SNR_k^{max} \times N_O \times PL_i^m)$;
    end
    else
      $b_i^{max} \leftarrow \frac{D_i}{l_{mod}^{f}}$;
      $P_i^{max} \leftarrow \min(P_f^{max}, SINR_k^{max} \times (N_O + I_{th}) \times PL_i^f)$;
    end
  end
  Generate initial swarm with the particle positions and velocities as follows;
  $\mathbf{b} \leftarrow \mathbf{r_1}.\mathbf{b^{max}}$;
  $\mathbf{P} \leftarrow \mathbf{P^{min}} + \mathbf{r_2}.(\mathbf{P^{max}} - \mathbf{P^{min}})$;
  $\mathbf{v_b} \leftarrow \mathbf{r_3}.\mathbf{b^{max}}$;
  $\mathbf{v_P} \leftarrow \mathbf{P^{min}} + \mathbf{r_4}.(\mathbf{P^{max}} - \mathbf{P^{min}})$;
  Evaluate Fitness Function;
  Determine first global best of the swarm;
  while $k \leq MaxIteration$ **do**
    Update Position;
    Evaluate Fitness Function;
    Determine best local for each particle;
    Determine best global in the swarm and update the best global;
    Update velocity;
  end
end

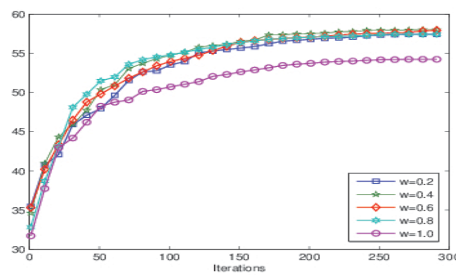
We also analyze the effectiveness for the proposed PSO model using different values of cognition and social behavior factors (c_1, c_2). Figure 5.2 shows the convergence of throughput using different setting of parameters c_1, c_2 and ω.



a) Cognitive Factors (c_2 =1, ω=0.7)



b) Social Behavior Factors (c_1 =2.5, ω=0.7)



c) Inertia Weights (c_1 =2.5, c_2=1)

Figure 5.2 Analysis of Particle Swarm Optimization model for BS selection and resource allocation problem

PSO-RAM algorithm requires between 100 to 1000 iterations to converge to a solution as shown in Figure 5.2. It can be notice that the maximum throughput value for the proposed model is reached with c_1=2.5, c_2=1 and ω in the interval of [0.2, 0.9]. An adaptive PSO approach that adaptively changes the inertia factor from a minimum value to a maximum value as follows:

$$\omega_k = \omega_{max} - (\omega_{max} - \omega_{min}) \times \frac{k}{k_{max}} \tag{5.23}$$

has been proven to reduce the convergence time in other optimization problems (Shi and Eberhart, 1998). Therefore, we propose to use this variation of PSO with $\omega_{min} = 0.2$ and $\omega_{max} = 0.9$. In the Appendix IV, we demonstrate that the PSO based resource allocation algorithm indeed provides a near-to-optimal solution for a non-dense macro femtocell network.

5.4.4 Benchmark Model

The resource allocation model was selected taking into account that they pursue the same objective function as in our model, which is maximize the network throughput while guaranteeing the user satisfaction in both tiers. In (Chun-Han and Hung-Yu, 2011), bandwidth allocation is performed using Weighted Water Filling (WWF) algorithm taking into account pre-fixed user selection per BS and no power limitation. The latter means that the bandwidth is assigned assuming that user data rates can be provided without limitation of maximum transmitted power per BS. According to (Yang, 2010), the total power assigned to users should be less than or equal to the maximum transmitted power per BS. Thus, we modified their algorithm and changed it in order to assign the required transmitted power to satisfy the SINR target as long as the sum of the allocated power do not trespass the maximum transmitted power per BS. Algorithms 5.4 and 5.5 presents the modified version of Weigthed Water Filling for macrocell and femtocells respectively.

In (Abdelnasser *et al.*, 2014), an approach that reduces the complexity of exhaustive search of the joint clustering and resource allocation is proposed, allowing the universal subcarrier reuse in femto tier. In their work, two severely interfering femtocells are motivated to form a cluster by increasing their data rates through the co-tier interference avoidance. Since orthogonal subchannel allocation is performed within each cluster to avoid co-tier interference, then, as cluster size increases, the available subchannels per FC decreases. Therefore, femtocells are also penalized because of the bandwidth reduction per FC when a new femtocell is incorporate to a cluster. Thus, we define their merging metric as follows:

$$METRIC_{cl}^{j} = \frac{I_f^j}{\sum\limits_{k\in C} I_f^k} \times \max\left(0, \frac{\max(SC_{req}^{j}, SC^{FT}) - SC_{req}^{f}}{\max(SC_{req}^{j}, SC^{FT}) + SC_{req}^{f}}\right) \tag{5.24}$$

where the first term corresponds to the motivation to avoid co-tier interference among a cluster and a stand alone FC and the second term is penalty due to the reduction of the cluster bandwidth if the new femtocell f is incorporated. SC_{req}^{j} and SC_{req}^{f} are the number of subcarriers

Algorithm 5.4 MC Weighted Water Filling Algorithm

Data: Available bandwidth **B**,
Available power **P**,
Demand D_i,
BS selection **BS** per user
Result: Bandwidth and power allocation per user and FC

begin
  $U \leftarrow \{F, MS^m\}$;
  Compute w_i^m, $b_i^{required}$ as follows;
  for *each* $f \in FC$ **do**
    for $i \in MS^f$ **do**
      $w_i^f \leftarrow \sqrt{\frac{1}{r_i^f}}; b_{i,f}^{req} \leftarrow \frac{D_i}{l_{mod}^f}$;
    end
  end
  if *User i is FC* **then**
    $w_i^m \leftarrow \sum_{j \in MS^f} w_j^f; b_{i,f}^{req} \leftarrow \sum_{j \in \{MS^f\}} b_{j,f}^{req}$;
  end
  else
    $w_i^m \leftarrow \sqrt{\frac{1}{r_i^m}}; b_{i,m}^{req} \leftarrow \frac{D_i}{l_{mod}^m}$;
  end
  Sort U according to the bandwidth required divided by the weight;
  while $i \in U$ **do**
    $b_i^{wwf} \leftarrow \min\left(\frac{b_i^{required} - b_i^{k-1}}{w_i^m}, \frac{B - \sum_{k=1}^{i-1} \sum_{j=k}^{MS^m+FC} b_j}{\sum_{j=i}^{MS^m+FC} w_j^m}\right)$;
    for $j = i \rightarrow |U|$ **do**
      while *b_i is not satisfied and B and P_m^{Total} are not exhausted* **do**
        $b_j^k \leftarrow b_j^{k-1} + w_j^m b_i^{wwf}$;
      end
    end
    if *user i is MS* **then**
      $p_i^m \leftarrow \min\left(SNR_{th}^m N_0 PL_i^m, \min(P_m^{max}, P_m^{res})\right)$;
    end
  end
end

required by the cluster j and the femtocell f respectively. We named this clustering scheme as interference mitigation and bandwidth reduction based clustering scheme (IMBR).

Algorithm 5.5 FC Weighted Water Filling Algorithm

Data: Bandwidth assigned to FC (B_f^m),
Set of weights (w_i^f),
Set of users assigned to femtocell f (MS_f)
Result: Resources allocation per user (B_{MS}^f, P_{MS}^f).
begin
  Sort MS^f according to the bandwidth required divided by the weight;
  while $i \in MS^f$ **do**
    $b_i^{wwf} \leftarrow \min\left(\frac{b_i^{required} - b_i^{k-1}}{w_i^f}, \frac{B_f^m - \sum_{k=1}^{i-1}\sum_{j=k}^{MS^f} b_j}{\sum_{j=i}^{MS^f} w_j^f}\right)$;
    for $j = i \rightarrow |MS^f|$ **do**
      while *b_i is not satisfied and B_f and P^f are not exhausted* **do**
        $b_j^k \leftarrow b_j^{k-1} + w_j^f b_i^{wwf}$;
      end
    end
    $p_i^f \leftarrow \min\left(SNR_{th}^f N_0 PL_i^f, \min(P_f^{max}, P_f^{res})\right)$;
  end
end

For convenience, the benchmark model uses the same BS selection procedure as our model but the resource allocation algorithm is based on Weighted Water Filling algorithm.

5.5 Performance Metrics

To evaluate the performance of the models, we use the following metrics:

Throughput: The achievable throughput is calculated based on Shannon's Law Capacity. Accordingly, the network throughput can be expressed as:

$$T = \sum_{i \in \{MS\}} \sum_{j \in \{m,FC\}} Y_i^j b_i log_2(1 + SNR_i^j). \tag{5.25}$$

Subscriber Satisfaction: Subscriber satisfaction is defined as the ratio between the sum of assigned subscriber data rates and the sum of subscriber demands and is given by:

$$S = \frac{\sum\limits_{i \in \{SU\}} \sum\limits_{j \in \{m,FC\}} Y_i^j b_i l_j^{mod}}{\sum\limits_{i \in \{SU\}} D_i}. \tag{5.26}$$

Power Consumption: The total power consumed in the network is the total transmitted power by macro BS and femto BSs and is determined as follows:

$$P^{Total} = \sum_{i \in \{MS\}} \sum_{j \in \{m,FC\}} Y_i^j P_i. \tag{5.27}$$

Bandwidth Usage: The bandwidth usage is the sum of bandwidth assigned in both tiers and is given by:

$$BW^{Total} = \sum_{i \in \{MS\}} Y_i^m b_i + \max_c \left(\sum_{i \in \{MS\}} \sum_{j \in \{FC^C\}} Y_i^k b_i \right), \tag{5.28}$$

where FC^c is the FC set of the cluster C.

5.6 Simulation Results

The main assumptions and the system configuration are described in this section. Table 5.1 shows the chosen network and environment parameters, which are similar to the scenario used in our previous work (Estrada *et al.*, 2014).

OFDMA physical layer assumptions for each zone are shown in Table 2.1 given in Section 2.3 which are similar to the work in (Tarhini and Chanjed, 2007). In particular, the number of bits used for modulating the signal is 6, 4, 2 or 1 for users is in Z_1, Z_2, Z_3 or Z_4, respectively.

The proposed model is compared with the benchmark model described in Section 5.4.4 under two scenarios as follows:

Table 5.1 System Parameters

Name	Description
B	50 MHz
P_m^{Total}, P_f^{Total}	(50 dBm, 10 dBm)
R_m, R_f	500 m, 20 m
α_f, α_m	3, 3.7
C_z^{max}	(10, 7, 3, 1)
l_z^{mod}, l_f^{mod}	(2, 6)
W_l	-3 dB
N_0	-174 dBm/Hz
f_c	2.3 MHz
N^f	4

Incremental PU Number: Simulation runs for different set of public users increasing from 10 to 60 with 5 user increment and 10 FCs are deployed within an area of 240x80 meters as illustrated in Fig. 5.1. Public users are randomly located within FC vicinity.

Incremental FC number: FC number is increased from 10 to 50 and high density of public users close to FCs is considered.

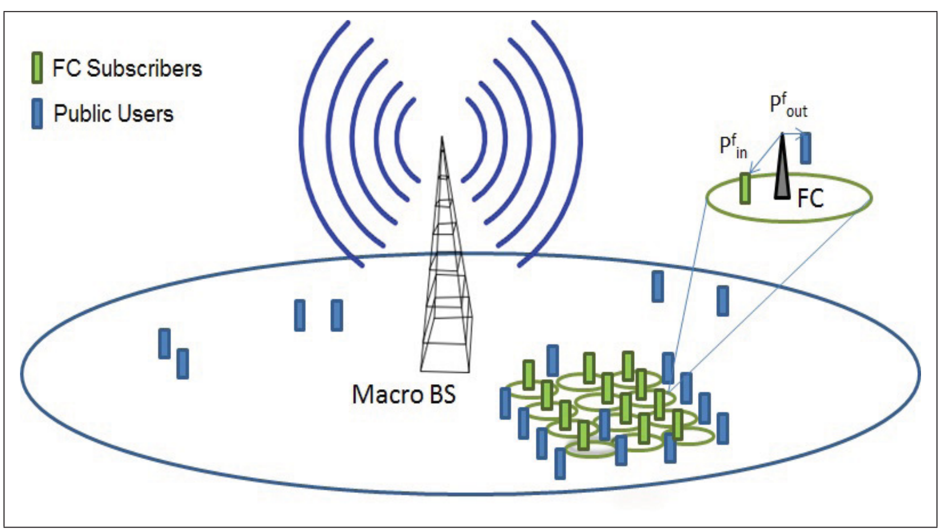


Figure 5.3 Network Example: Nine femtocell are deployed within an area of 240x80 meters, and the majority of the mobile users are close to the FC neighbor

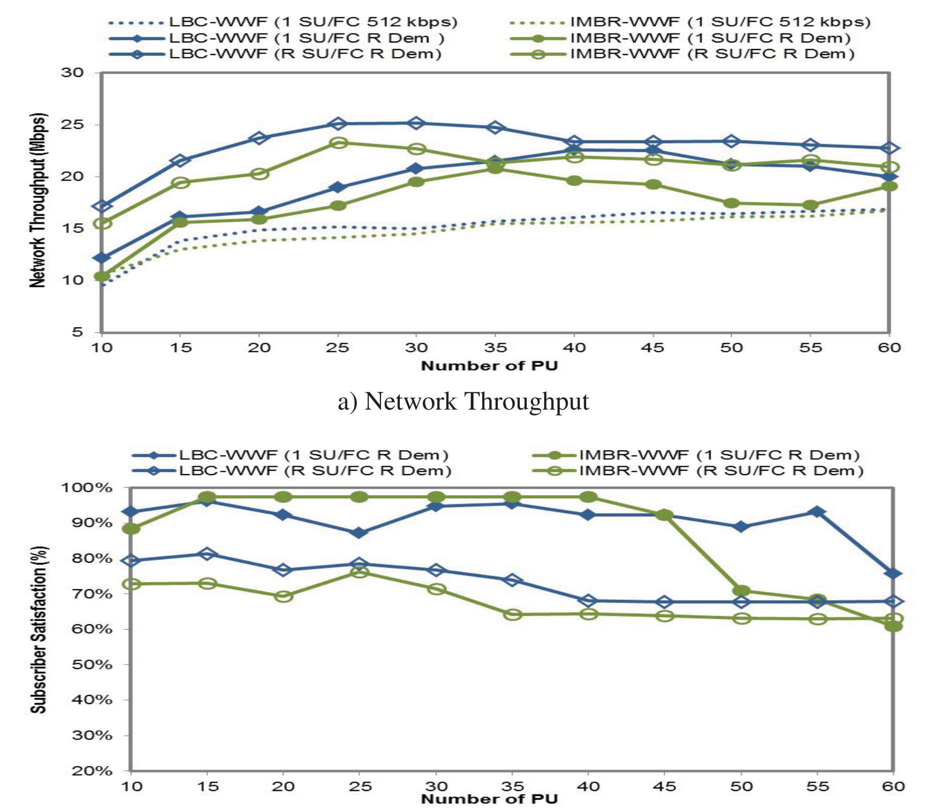
Owing to the fact that the proposed solution incentivizes FC to grant access to public users through the extra subcarrier allocation to FC clusters, we consider the following cases:

- one subscriber per FC with fixed demand (512 bps) or variable demand (128 bps - 1 Mbps);
- variable subscriber number per FC with variable demand (128 bps - 1 Mbps).

In the following, we present: (1) the performance of the Load Balance Clustering scheme (LBC) in comparison with Interference Mitigation and Bandwidth Reduction based Clustering scheme (IMBR) using the WWF based resource allocation algorithm, and (2) the performance comparison between our complete model that consists of the LBC clustering scheme together with PSO based resource allocation (LBC-PSO) and LBC clustering scheme together with WWF based resource allocation (LBC-WWF). Finally, the performance of LBC-PSO model is presented under the incremental FC number scenario in comparison with IMBR-PSO.

5.6.1 Clustering scheme comparison

In this section, the performance of both clustering schemes is analyzed using the WWF based resource allocation under incremental PU number. Figure 5.4a shows the network throughput as a function of the public user number for several cases with one subscriber or variable number of subscribers per FC. Subscriber demands are fixed or randomly generated (shown as F. Dem and R. Dem in the figures). As expected, both clustering approaches present similar network throughput values when the requested demand per subscriber is the same (512 kbps per subscriber), which is shown as dotted lines. In particular, our clustering technique reaches the highest throughput for the cases when one subscriber asks for variable demand or each FC has variable number of subscribers with random demand. In addition, it can be observed that the throughput curves reach a maximum for the different scenarios. This means that it is not possible to assign more public users to the current cluster configuration that allows the femtocell to obtain extra resources or enhanced SINR for their own subscribers. In particular case of 1 subscriber per FC, we can see that this maximum is reached at 30 public users close to the FCs.



a) Network Throughput

b) Subscribers Satisfaction

Figure 5.4   Performance Metrics under the Incremental PU Number Scenario

From Fig. 5.4b, it can be appreciated that our clustering scheme enhances subscriber satisfaction in the case with random number of subscribers per FC asking for variable demand. In particular in this case, our proposed clustering scheme also presents interference values close to the ones obtained using IMBR scheme in this case as shown in Fig. 5.5. It can be observed that our proposed clustering technique is less affected by the interference level changes while IMBR presents instability in the interference curve (specially in the case with random number of subscriber per FC). The IMBR model takes into account two factors that affect the cluster formation, which are bandwidth reduction of the cluster and the interference levels. Thus, one of these factors may have higher influence than the other in a given period of time leading to this oscillating behavior. Nevertheless, the LBC-WWF model fails to reduce the interference level in comparison with IMBR scheme in the case with one subscriber per FC, which is due to the lack of power control in the modified WWF algorithm to reduce the inter-cluster interference since the algorithm runs in a distributed fashion inside each cluster.

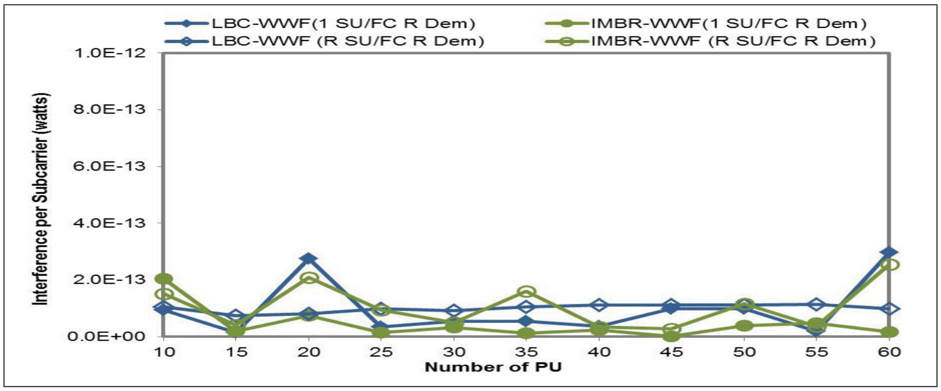


Figure 5.5 Interference Level for the incremental PU number scenario

Table 5.2 shows the distribution of public users among the two tiers for the cases with one subscriber per FC with random demand and random FC subscribers with random demand. As our model attempts to balance the traffic load of public users among the existing clusters taking into account their availability, we can see that our clustering solution increases the number of connected users compared with the IMBR clustering technique and accommodates more public users to be served by FCs. Therefore, our clustering scheme reduces the blocking ratio in the two-tier network. In the particular case with one subscriber per FC and 60 public users within the FC vicinity, it can be observed that the number of connected users is equal to 59, which corresponds to a blocking ratio around 2% for LBC while using IMBR clustering, only 53 users can be connected which corresponds to a blocking ratio around 9%.

Moreover, we can see that the number of public users connected to FC does not reach the maximum FC network capacity (which is 30 public users in the case of 1 subscriber per FC). This is owing to the fact that the clusters are formed in order to have some resources to be added to the FC subscribers transmission in our model. In the case of IMBR clustering technique, this is due to the penalization of the cluster bandwidth reduction.

Table 5.2 Public Users Distribution per Tier

1 SU per FC with Random Demand				
PU	**LBC WWF**		**IMBR WWF**	
	FT	**MT**	**FT**	**MT**
10	7	3	9	1
20	11	9	16	4
30	20	10	21	9
40	24	16	22	18
50	25	25	23	24
60	26	33	21	32
Random SUs per FC with Random Demand				
PU	**LBC WWF**		**IMBR WWF**	
	FT	**MT**	**FT**	**MT**
10	5	5	8	2
20	10	10	11	9
30	13	17	15	15
40	15	25	11	29
50	13	37	11	38
60	13	47	12	46

To demonstrate the efficiency of the proposed clustering technique, table 5.3 presents spectral efficiency (γ_{SU}) per subscribers in cluster member FCs and stand alone (SA) femtocells, the average gain in terms of subcarriers obtained for subscribers transmissions if FCs belong to cluster, and the average number of subcarriers allocated per user in each tier. Both schemes achieve the target SINR for subscribers in FC member of a cluster. It can be observed that the number of additional subcarriers for subscribers transmissions in our model is greater than the one obtained using IMBR clustering scheme (shown in the columns of Extra SC). Finally, LBC clustering scheme presents a higher number of allocated subcarriers per user at femto tier in comparison with IMBR scheme.

In summary, the proposed cluster technique achieves better throughput in comparison with the interference mitigation and bandwidth reduction based clustering scheme. This is owing to the fact that our main objective is to balance the traffic load from public users in order to get a cluster configuration that allows FC to get extra resources for their own subscribers by granting access to public users while guaranteeing QoS transmission of the two user types.

Table 5.3 QoS Guarantee and Extra Resources for subscribers in Femto tier

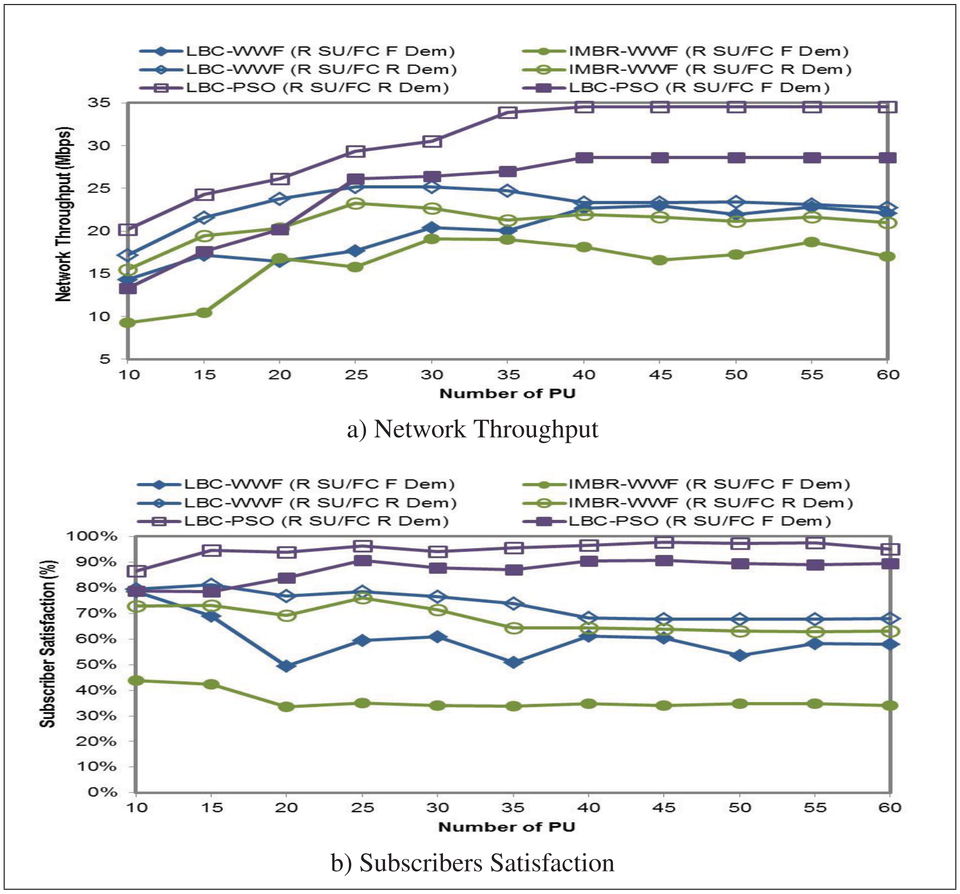
PU	**γ_{SU} in cluster**		**γ_{SU} in SA FC**		**Extra SC**		**Avg SC MT**		**Avg SC FT**	
	LBC WWF	**IMBR WWF**	**LBC WWF**	**IMBR WWF**	**LBC WWF**	**IMBR WWF**	**LBC WWF**	**IMBR WWF**	**LBC WWF**	**IMBR WWF**
10	7.31	7.26	6.73	6.04	4	2	17	17	4	3
20	7.30	7.05	5.11	4.41	1	1	15	14	3	2
30	7.30	7.12	4.47	0	1	1	11	10	3	2
40	7.27	7.09	4.97	0	2	1	9	10	2	1
50	7.06	7.12	5.08	0	1	1	7	7	2	1
60	7.06	7.17	5.08	0	1	1	6	6	2	1

5.6.2 Resource Allocation algorithm comparison

In this section, we compare the proposed clustering technique using two different resource allocation algorithms, namely WWF and PSO. By doing so, we want to show the advantages of using PSO instead of WWF. Figure 5.6 shows the network throughput and the subscribers satisfaction for the scenarios with random number of subscribers SU per FC with a fixed demand of 512 Kbps and variable demand between 128 kbps and 1 Mbps. In the case of fixed demand, LBC-PSO presents a throughput gain around 28% compared to LBC-WWF, which is due to the power distribution enhancement over the active bandwidth to tackle the perceived interference in femto tier.

In Fig. 5.6b, we can observe that using WWF model with any of the clustering schemes (i.e. LBC-WWF and IMBR-WWF), there is a drop on the subscriber satisfaction curve. This is mainly due to the lack of power control in WWF algorithm to mitigate the inter-cluster interference since resources are independently allocated in each cluster. Unlike WWF, PSO algorithm is centralized and includes a constraint to reduce the inter-cluster interference level. Thus, the subscriber satisfaction is enhanced with a gain between 30% and 40%.

Figure 5.7 shows the average interference per subcarrier obtained using the LBC-PSO, LBC-WWF and IMBR-WWF models. Our proposed clustering technique with WWF algorithm does not reduce the average interference level but together with Particle Swarm optimization reduces indeed the interference level below the value obtained by the IMBR-WWF model. From Fig.



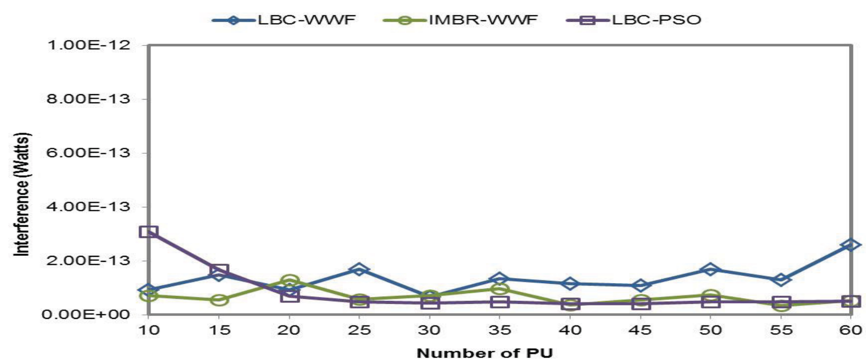
a) Network Throughput

b) Subscribers Satisfaction

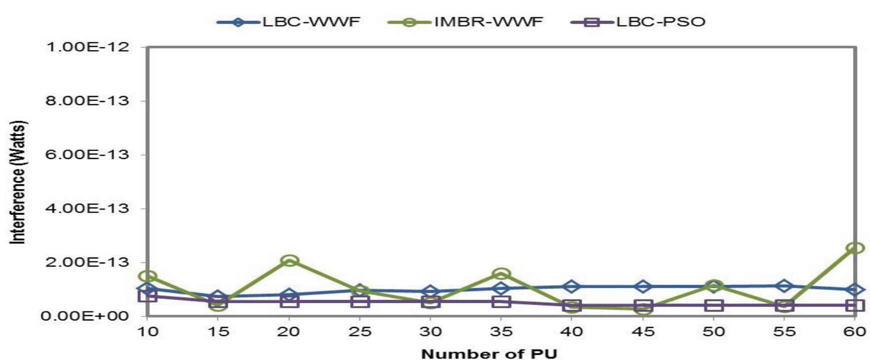
Figure 5.6   Performance Metrics for the incremental PU number scenario

5.7a, it can be observed that the interference is higher for the proposed model for the initial cluster configurations in comparison to the LBC-WWF and IMBR-WWF models. However, as the number of public user increases our solution can effectively reduce the interference levels below the values obtained for the IMBR-WWF.

Table 5.4 presents the power consumption and bandwidth usage per tier for different number of public users for the case with random subscriber number per FC and variable demand. It is also included the number of blocked users. One can observe that the LBC-PSO model increases the power consumption by about 6 dBm at femto tier while MC power consumption is reduced by 3 dB compared to LBC-WWF model. For the scenario with more than 40 public users, both models start blocking some public users. The main difference is that LBC-WWF model rejects



a) Scenario with Fixed Demand/SU



b) Scenario with Random Demand/SU

Figure 5.7 Average interference per Subcarrier for scenarios with random number of subscribers per FC

public users due to the power starvation at the macro tier without using the total bandwidth while the proposed model starts blocking public users because the bandwidth is exhausted.

Table 5.4 Power Consumption and Bandwidth Usage
(Scenario with Random number of SU per FC with variable Demand)

PU Number	Power Consumption (dBm)				Bandwidth(%)				Blocking Ratio(%)	
	LBC-PSO		LBC-WWF		LBC-PSO		LBC-WWF		LBC-PSO	LBC-WWF
	FT	MT	FT	MT	FT	MT	FT	MT		
10	13.80	51.43	13.06	51.35	20	32	19	14	0	0
20	16.27	55.70	13.13	56.38	26	59	15	48	0	0
30	17.49	56.71	13.68	57.83	27	73	14	64	0	0
40	18.82	56.81	12.02	59.03	29	71	11	75	0	2
50	18.82	56.81	12.48	59.03	29	71	11	77	8	12
60	18.82	56.81	12.28	59.03	29	71	11	80	17	15

Table 5.5 presents the QoS guarantee and extra resources allocated to FC subscribers. In comparison with LBC-WWF, LBC-PSO is able to achieve higher spectral efficiency (γ_{SU}) and high number of additional subcarriers for own FC subscribers having similar values of average number of subcarrier per users in both tiers.

Table 5.5 QoS Guarantee and Extra Subcarriers for subscribers at Femto tier

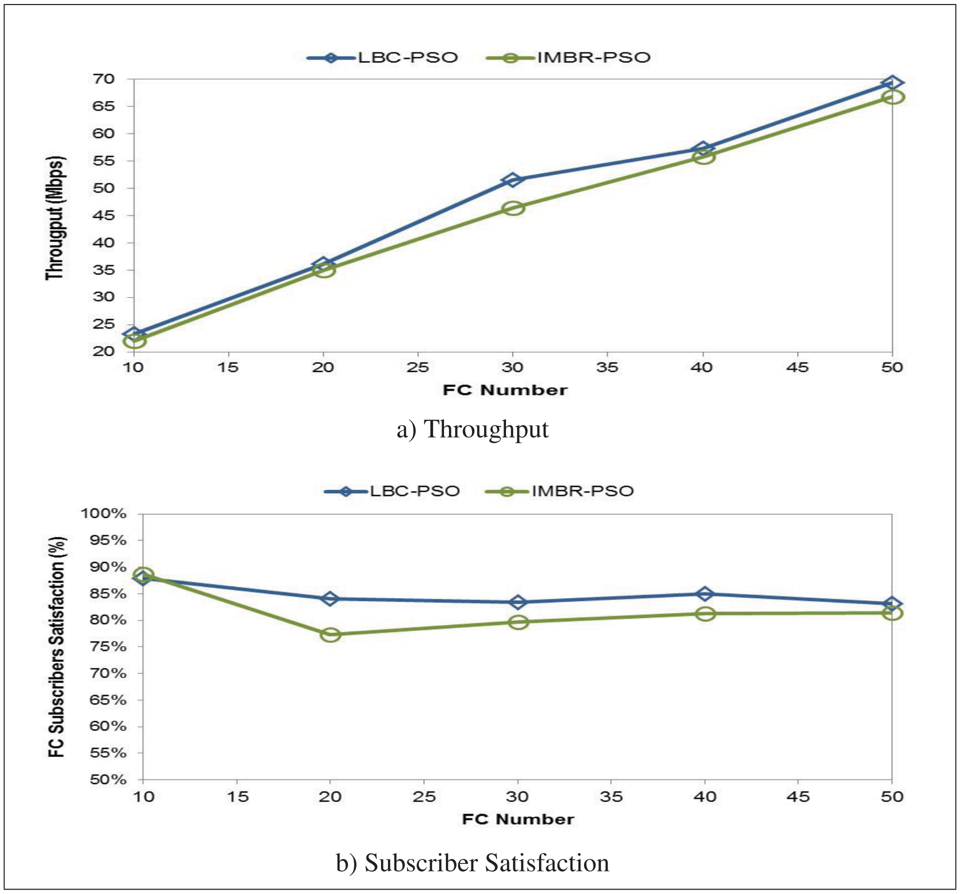
PU Number	**γ_{SU} in cluster**		**Extra SC**		**Avg. SC MT**		**Avg. SC FT**	
	LBC-PSO	LBC-WWF	LBC-PSO	LBC-WWF	LBC-PSO	LBC-WWF	LBC-PSO	LBC-WWF
10	7.80	6.62	1.67	1.00	16	16	5	5
20	8.05	7.05	3.67	3.25	12	14	5	5
30	8.16	7.23	4.17	3.50	10	11	5	5
40	8.21	6.70	3.33	1.00	7	7	5	4
50	8.21	6.93	3.33	1.25	7	7	5	4
60	8.21	6.68	3.33	1.00	7	5	5	4

In summary, the proposed PSO based RA approach together with the proposed clustering scheme presents several advantages such as: improved throughput, enhanced power distribution, lower interference levels and improved subscribers satisfaction, number of additional subcarriers allocated for subscriber transmissions.

5.6.3 FC Density and Cluster Size

In this section, we present the performance of the proposed model under variable density of FC in a specific coverage area. Figure 5.8 shows the network throughput and subscriber satisfaction as a function the number of FCs for high density of public users that are close FCs (i.e. the total of user number that FCs might potentially serve).

Figure 5.8a demonstrates that both models enhance the throughput as the number of FC increases, however, LBC-PSO model obtains a throughput gain between 4 and 11% in comparison with IMBR-PSO model. The subscriber satisfaction is also improved by LBC-PSO model with values between 85% and 90% as shown in Fig. 5.8b, while IMBR-PSO model gives subscriber satisfaction values between 75% and 90%. This is owing to the fact that our model aims



a) Throughput

b) Subscriber Satisfaction

Figure 5.8 Performance Metrics for incremental FC number scenario

at guaranteeing the target SINR of subscribers transmission as well as the compensation with extra subcarriers allocated for own FC subscribers transmissions.

Table 5.6 presents the subscriber QoS guarantees in terms of spectral efficiency (γ_{SU}), the average of extra resources allocated to FC members of a cluster and the mean and the standard deviation of cluster size (CS) for both clustering schemes and PSO based resource allocation algorithm. Both models are able to achieve the target spectral efficiency (i.e. $\gamma_{SU} = 6$ bit/symbol) but LBC-PSO model allocates higher number of extra subcarriers for FC subscribers when it is possible.

It can be observed that both models reduce the average number of allocated subcarriers per user in macro tier as the number of public users that are close to FC increases. This is owing to the fact that some users being denied service at lower tier need to be served by macrocell. Since our

Table 5.6 QoS Guarantee and Extra Resources for subscribers at Femto tier

FC	γ_{SU} in cluster		Extra SC	
Number	LBC-PSO	IMBR-PSO	LBC-PSO	IMBR-PSO
10	6.84	7.03	0.5	0.4
20	7.39	7.05	0.8	0.4
30	7.13	7.15	1.0	0.0
40	6.98	7.11	0.4	0.24
FC	Avg. SC per User MT		Avg. SC per User FT	
Number	LBC-PSO	IMBR-PSO	LBC-PSO	IMBR-PSO
10	10	9	5	5
20	4	5	5	5
30	3	4	5	4
40	3	3	4	4
FC	Cluster Size Mean		Cluster Size Std. Dev.	
Number	LBC-PSO	IMBR-PSO	LBC-PSO	IMBR-PSO
10	1.42	1.42	0.53	0.53
20	1.33	1.17	0.48	0.39
30	1.76	1.30	0.83	0.47
40	1.73	1.37	0.75	0.49

PSO based macrocell resource allocation model aims at the fair subcarriers distribution among the allocated users, the average number of allocated subcarrier per user is indeed reduced as the number of macro users increases. In order to avoid the reduction of average number of subcarrier allocated per user in macrocell, PSO based RA algorithm should be changed to consider that the average number of allocated subcarriers per user in macro tier should be at least equal to the average number of subcarriers allocated per user in femto tier. In such a case, the blocking ratio of macro users will increase. However, this is out of the scope of the paper.

It is also worth noticing that LBC-PSO model has higher cluster size mean than IMBR-PSO model, which means that the femto tier will obtain more resources from the macrocell because more public users can be connected to the FC clusters. For the LBC-PSO model, the standard deviations values indicate that there are clusters with size between 1 and 3 while for the IBMR-PSO model, the clusters might have a maximum of 2 femtocells.

5.6.4 Complexity and Running Time

The complexity of the PSO based resource allocation model depends on the number of subcarriers, the number of users, FC number and the number of cluster in the network. However, the running time is limited by the maximum number of iterations, k_{max}, which can be assumed to be increasing function of the number of users in the network or a fixed value. In our case, PSO algorithm requires between 5 and 10 sec to converge to a solution for the resource allocation problem with given cluster configuration and BS selection per users as we determine after the convergence analysis presented in Section 5.4.3.

However, it is the clustering scheme that requires high running time as FC number increases under worst case scenario, which is high density of public users (i.e. FC fulfilled capacity). This running time is given in Table 5.7 for different FC number and public user number. It can be noticed that our model requires higher running time in comparison with LBC-WWF model, which can be reduced using other PSO variants. This can be addressed in a future research work.

Table 5.7 Running time

FC Number	PU Number	Time (sec)	
		LBC-PSO	LBC-WWF
10	30	8	1
20	60	42	3
30	90	103	8
40	120	189	43
50	150	305	89

Once the clusters are established, this procedure is performed taking into account the stand alone FC that can be merged with current clusters if the resources are exhausted for every cluster or it is not possible to allocate public users to the any cluster without depriving FC subscriber transmissions. Therefore, the two-tier network should keep low number of stand alone FCs so the running time of the clustering mechanism can be reduced since there will be less probability to form new cluster configurations.

5.7 Conclusion

A novel resource allocation model is introduced. The model consists of a Particle Swarm Optimization based resource allocation algorithm and a load balance clustering scheme. The proposed model is able to determine the best serving BS and the bandwidth and power allocation for each user taking into account its demand, location, FC proximity and current cluster configuration. Our solution was tested under the incremental public user number scenario and compared with a benchmark model that employs WWF for resource allocation and an interference mitigation and bandwidth reduction based clustering scheme. We have demonstrated that the proposed approach indeed improves the overall network throughput without depriving subscribers satisfaction by means of rewarding FCs with extra resources for their own transmission. Moreover, in the tested scenarios, MC power consumption is reduced by 3 dB since FCs grant access to public users. By means of FC power control, the proposed solution reduces the inter-cluster interference and allows the efficient bandwidth usage. The main disadvantage of the benchmark model is the lack of FC power control which increases the inter-cluster interference level and therefore degrades the QoS of FC subscribers transmissions. The main disadvantage of the LBC-PSO model is the high complexity and therefore the large running time. In a future work, we will investigate the PSO variants that allows to improve the required time to find a near-to-optimal solution and the cluster formation mechanism and its stability to convert our LBC-PSO model into a distributed model, which can reduce even more the running time.

GENERAL CONCLUSION

Femtocells are effective solutions to quickly improve the indoor coverage and the capacity of the current cellular networks. Nevertheless, to become a viable solution, the resource manager entity should take into account several parameters such as user locations, femtocell proximity, access control policy, channel allocation mechanism and clustering technique in order to enhance the network throughput. Due to the limited wireless resources and other limiting-capacity factors, current access control policies are not powerful enough to guarantee the QoS of subscribers transmissions. This has lead to the introduction of the hybrid access policy, which imposes new technical challenges for macro-femtocell networks due to the contrasting factors that affect the overall system performance. Consequently, the objective of this thesis was the resource optimization of the macro-femtocell network while guaranteeing the QoS of subscribers. To achieve this, several resource allocation algorithms were presented:

- base station selection together with bandwidth and power assignment using orthogonal channel allocation for non-dense deployment;
- joint BS selection, subcarrier, power allocation enabling full subcarrier reuse for non-dense deployment;
- low-complexity resource allocation model that jointly determines serving BS, subcarrier and power allocation and enables full subcarrier reuse per OFDMA zone, and subcarrier reuse among inner MC zones and femtocell located in outer zones;
- heuristic resource allocation model that consists of: BS selection procedure, a cluster based resource allocation model, and a cluster formation technique.

The resource allocation model presented in Chapter 2 overcomes the limitations of the prior work that assumes fixed transmitted power in both tiers and those performing FC power control giving priority to macro users. The BSS-RAM model is able to determine optimal serving base station together with the optimal amount of bandwidth and power for each user taking into account the user demands and locations. Linear Programming theory was applied to formulate the optimization problem and several mathematical approximations were used to convert the real convex-problem to a LP model. A performance comparison with a modified version of Weighted Water Filling algorithm was presented. Simulation results showed that WWF model requires between 5% and 16% more power than BSS-RAM model to achieve the same user satisfaction and is less tolerant to the noise changes than BSS-RAM model. Thus, it is demonstrated that the BSS-RAM model can effectively enhance the network throughput and the power distribution among active DL transmissions in each BS, and makes the macro-femtocell network more tolerant to environmental noise changes. In addition, the mean square error caused due to the mathematical approximations and the formula for required MC transmitted power were derived. It was shown that the theoretical transmitted power values are close to the results obtained in the simulations and the mean square error is around 0.13% of the throughput gain. Therefore, one can conclude that bandwidth allocation together with adaptive power per user and BS selection enable the BSS-RAM model to enhance the network throughput, to enhance power distribution over the active DL communications and to reduce the impact of noise.

In Chapter 3, the resource allocation model takes into account subcarrier granularity and enables full subcarrier reuse among the two tiers and neighboring femtocells. The subcarrier reuse is allowed if the received interference is less than a given threshold, which was calculated under the consideration of fixed transmitted power in macrocell and femtocells to guarantee the target SINR in their respective downlink transmissions. Linear Programming theory was applied to formulate the optimization problem which should determine the BS selection, subcarrier allocation and transmitted power per mobile user. For comparison purposes, three benchmark models were used. The first model is the underlay spectrum sharing, which assumes the same value of transmitted power per subcarrier in each BS (including the macro BS). The second one is the controlled-underlay spectrum sharing that performs adaptive power control per subcarrier at femto tier. The third benchmark model is the BSS-RAM model presented in Chapter 2. Simulations results showed that the Controlled-SC model outperforms BSS-RAM model having lower blocking ratio, higher throughput and higher user satisfaction. The Controlled-SC model allows to use a 100% of bandwidth at the macro tier and 48% of bandwidth is reused at the femto tier whereas BSS-RAM model only allows to use 50% of the bandwidth in each tier. In addition, the Controlled-SC model presented the best results in comparison with the other two benchmark models. Therefore, it is demonstrated that the power adaptation per subcarrier in all BSs allows to increase the number of connected users to FCs while improving the overall user satisfaction under scenarios with incremental traffic load and variable FC user density. However, this improvement is limited by FC capacity and the interference threshold.

It was shown that the computational complexity of the previous models increases exponentially with the FC number, subcarrier number and the FC user density. To reduce this complexity, the following techniques were applied: the division of the problem into subproblems related to each OFDMA macrocell zone and the cluster configuration. The first technique was applied to the low complexity resource allocation model presented in Chapter 4 for a given cluster configuration. First, the MC resource are allocated to the OFDMA zones taking into account the user distribution. Then, the set of users and femtocells is divided into disjoint subsets per zone. Thus, each zone runs the resource allocation algorithm that determines the BS selection, subcarrier allocation and transmitted power per user while enabling the subcarrier reuse among MC inner zone and FC located in MC outer zones and also between macro users and femtocell within the same MC zone. The proposed solution was compared to other two schemes which are spectrum partitioning among macro users and femtocell in each zone (i.e. BSS-RAM is applied in each zone), and spectrum partitioning with partial subcarrier reuse inside femtocells. A performance analysis was included when Random walk is incorporated as the mobility model. Low mobility users were located within the FC neighborhood. Simulation results showed that the proposed SS-FSR model reaches 75% of throughput gain, serves around 32% more users and reduces the handover ratio and call dropping ratio by up to 3% and 2%, respectively, when compared to spectrum partitioning approach. In fact, one can conclude that the spectrum sharing with full subcarrier reuse model provides better throughput for different arrival rates and variable FC user densities and requires less number of handovers compared to the benchmark models.

Finally, a heuristic cluster based resource allocation model is presented in Chapter 5 with the integration of a novel cluster formation technique for hybrid access femtocells and the bandwidth adaptation per tier. The main objective of the clustering technique is to balance the traffic load from public users and femtocells among established clusters and to motivate FC to become a cluster member through the allocation of extra resources for own subscribers transmissions. Particle Swarm Optimization was used as an alternative optimization tool to solve the resource optimization problem. For performance comparison purpose, a decentralized benchmark model was used. The benchmark model is based on Weighted Water Filling Algorithm and a clustering technique that takes into account the interference level and bandwidth reduction per cluster member. Both models were tested under the incremental public user number scenario and variable FC density. Simulation results showed that the proposed model presents several advantages when compared to the benchmark model. This advantages are: MC power consumption is reduced by 3 dB, the subscriber satisfaction is increased by around 35% and an efficient bandwidth usage is achieved having similar values of inter-cluster interference as the benchmark model. Therefore, one can conclude that this approach indeed improves the overall network throughput while guaranteeing the QoS of subscribers transmissions by means of the proposed clustering technique for hybrid access femtocells.

Future Work

This research work addressed the resource allocation problem in OFDMA macro-femtocell network taking into account the hybrid access policy for different scenarios. Some perspectives for the continuation of this thesis are listed below:

- set of weights related to the service plan that mobile users are paying for should be investigated. This might provide preferential treatment to user paying more over other users;
- dynamic changes on MC zones can be analyzed and the impact of cluster formation techniques on the performance of the resource allocation model;

- new pricing mechanism for hybrid access femtocells that encourage the FC owner to open their access to public users;
- performance comparison among several alternative optimization tools applied to the resource optimization problem for dense deployment;
- performance evaluation of the intra-handover among OFDMA zones for the resource allocation proposed in Chapter 4;
- for the cluster formation technique, an analysis of its stability and the fair distribution of the extra subcarriers among the FC members as well as the appropriate cluster head selection for the distributed cluster formation regarding hybrid access femtocells;
- alternative mechanisms to mitigate inter-cluster interference should be investigated for distributed cluster formation scheme;
- performance evaluation of the model presented in Chapter 4 using different clustering techniques.

APPENDIX I

MILP BS SELECTION AND RESOURCE ALLOCATION MODEL

For the spectrum partitioning scenario, the set of Equations from (5.11) to (2.22) are replaced by (A I-1) to (A I-13), including the constraints of the upper and lower bound of SNR in both tiers.

$$\max_{\mathbf{x},\mathbf{b},\mathbf{P}} \sum_{i\in\{N\}} w_i^m x_i^m l_z^{mod} \sum_{j=0}^{j=T} \beta_j^i 2^j \sum_{i\in\{N\}} \sum_{f\in\{F\}} w_i^f x_i^f l_f^{mod} \sum_{j=0}^{j=T} \beta_j^i 2^j, \tag{A I-1}$$

subject to

$$B_C \sum_{i\in\{N\}} \sum_{j=0}^{j=T} \beta_j^i 2^j \leq B, \tag{A I-2}$$

$$x_i^m + \sum_{f\in\{F\}} x_i^f \leq 1 \qquad ; i \in N, \tag{A I-3}$$

$$\sum_{i\in\{N\}} x_i^f \leq N^f \qquad ; f \in F, \tag{A I-4}$$

$$\sum_{i\in\{N\}} P_i^m \leq P_m^{Total}, \tag{A I-5}$$

$$m_k \left(\frac{P_i^m}{PL_i^m N_0} \right) + a_k \geq l_z^{mod} x_i^m \qquad ; i \in N, k \in K, \tag{A I-6}$$

$$x_i^m SNR_{min}^k \leq \left(\frac{P_i^m}{PL_i^m N_0} \right) \leq SNR_{max}^k x_i^m \qquad ; i \in N, k \in K, \tag{A I-7}$$

$$m_k \left(\frac{P_i^f}{PL_i^f N_0} \right) + a_k \geq l_f^{mod} x_i^f \qquad ; i \in N, f \in F, \tag{A I-8}$$

$$x_i^f SNR_{min}^k \leq \left(\frac{P_i^f}{PL_i^f N_0} \right) \leq SNR_{max}^k x_i^f \qquad ; i \in N, f \in F, \tag{A I-9}$$

$$B_C \sum_{j=0}^{j=T} \beta_j^i 2^j \leq x_i^m \frac{S_i}{l_z^{mod}} + \sum_{f\in\{F\}} x_i^f \frac{S_i}{l_f^{mod}} \qquad ; i \in N, f \in F, \tag{A I-10}$$

$$B_C \sum_{j=0}^{j=T} \beta_j^i 2^j \leq B \left(\sum_{f\in\{F\}} x_i^f + x_i^m \right) \qquad ; i \in N, \tag{A I-11}$$

$$P_i^m \leq P_z^{max} x_i^m \qquad ; i \in N, \tag{A I-12}$$

$$P_i^f \leq P_f^{max} x_i^f \qquad ; i \in N, f \in F. \tag{A I-13}$$

APPENDIX II

PWS LINEAR APPROXIMATION

The log_2 term function in (3.28) can be approximated to a sum of linear segments using the algorithm in (Imamoto and Tang, 2008). To do so, we first evaluate the received power levels plus noise and interference in zone Z_3 using typical values of transmitted power for commercial macro BS (i.e. 25dBm W or 35dBm (Dufková *et al.*, 2011)). We verified that their values vary from 6.11x10^{-14} to 1.63x10^{-13}. For femtocells, we perform a similar analysis for these values using the transmitted power in femto BS between -10 dBm and 10dBm (3GPP-TR-36.921, 2011). These values are in the range of: (1) 5.63x10^{-14} to 1.47x10^{-13} for QPSK modulation, (2) 3.75x10^{-13} to 1.23x10^{-12} for 16-QAM and (3) 6.3x10^{-12} to 1x10^{-10} for 64-QAM.

Table-A II-1 shows two different PWS linear approximations using the minimum value equal to the noise, N_0, and the maximum value equal to the maximum received power level of 64-QAM, i.e. 1x10^{-10}.

Table-A II-1   PWS Linear Approximation

3-PWS Linear Approximation					
Segment	m_l	a_l	LS_l^{min}	LS_l^{max}	ε_l
1	2.15x10^{13}	-46.41	3.11^{-14}	2.2x10^{-13}	0.8251
2	9.96x10^{11}	-41.87	2.2 10^{-13}	3.66x10^{-12}	0.9037
3	4.6x10^{10}	-37.76	3.66x10^{-12}	10^{-10}	0.6799
4-PWS Linear Approximation					
1	1.43x10^{13}	-45.31	3.11^{-14}	2.3x10^{-13}	0.5212
2	1.89x10^{12}	-42.4	2.3 10^{-13}	1.77x10^{-12}	0.6134
3	2.52x10^{11}	-39.49	1.77x10^{-12}	1.33^{-11}	0.5097
4	3.4x10^{10}	-36.57	1.33x10^{-11}	10^{-10}	0.4790

From Table-A II-1, we can see that the 3-PWS linear approximation simplifies the representation of the log term for these values obtained by means of the use of one segment per modulation technique. Thus, the received power plus noise and interference values can be evaluated in segment 1 for QPSK, segment 2 for 16-QAM and segment 3 for 64-QAM.

Using the 4-PWS linear approximation, the received power for 64-QAM can be evaluated in two segments. Therefore, it can be represented by the sum of two power variables: one for the third segment and one for the fourth segment, but only one can be greater than zero for a given solution.

In general, the received power can be represented as the sum of several power variables corresponding to each segment of a PWS linear approximation, which increases the complexity of the proposed model. This can be addressed as future research work, but we only consider the 3-PWS linear approximation since the proposed solution is complex enough due to amount of variables related to bandwidth, power and BS selection.

APPENDIX III

MSE THROUGHPUT ERROR DUE TO THE PWS LINEAR APPROXIMATION

An error is introduced in the network throughput as we are using a linear approximation. Then, the mean square error (MSE) of the throughput can be estimated as follows:

$$\mathrm{E}[\varepsilon_T] = \frac{\sum\limits_{j \in \{m,FC\}} \sum\limits_{i \in \{MS\}} \sum\limits_{s \in \{S\}} \mathrm{E}\left[b_i^{s,j}\left(\varepsilon_l - \varepsilon_1\right)\right]^2}{N_s}, \tag{A III-1}$$

where ε_l and ε_1 are the difference between log_2 function and the evaluation of PWS linear segment, g_l given in section II. ε_l at any given instant t are given by

$$\varepsilon_l = log_2\left(\frac{P_i^{s,k}}{PL_i^k} + Noise + I_i^s\right) - g_l\left(\frac{P_i^{s,k}}{PL_i^k} + Noise + I_i^s\right), \tag{A III-2}$$

$$\varepsilon_1 = log_2\left(Noise + I_i^s\right) - g_1\left(Noise + I_i^s\right), \tag{A III-3}$$

respectively. Since $b_i^{s,j}$ are constant, (A III-1) is reduced to:

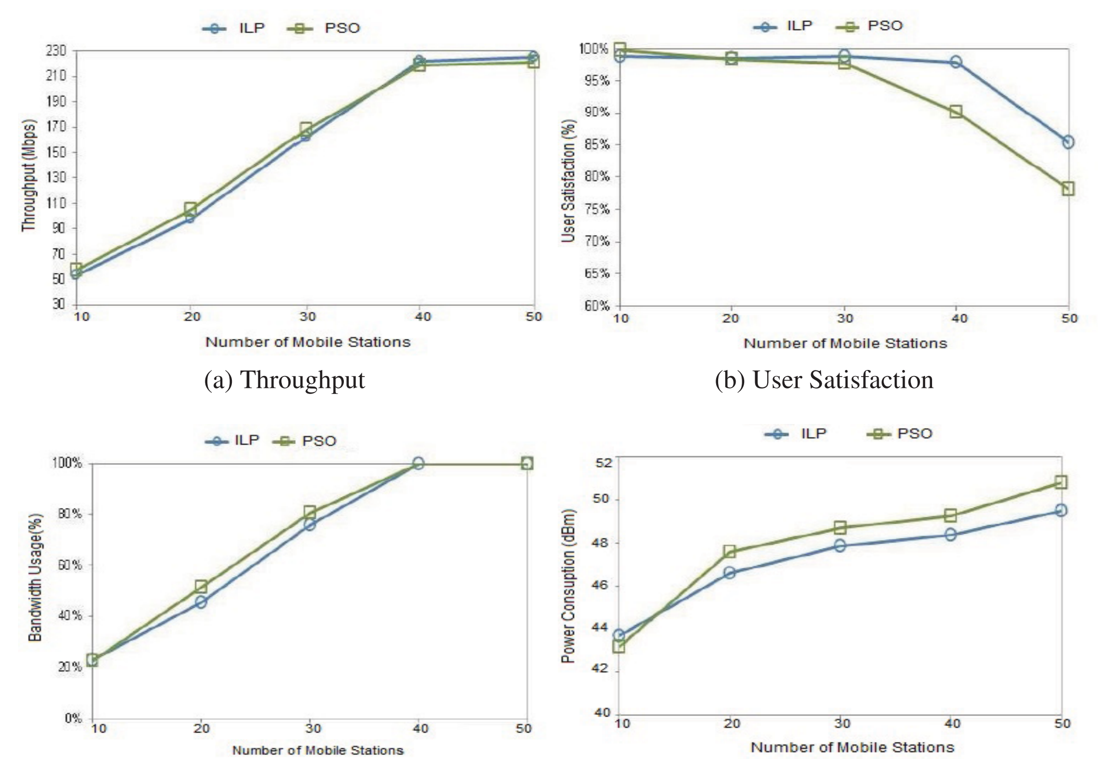
$$\mathrm{E}[\varepsilon_T] = \frac{\sum\limits_{j \in \{m,FC\}} \sum\limits_{i \in \{MS\}} \sum\limits_{s \in \{S\}} b_i^{s,j}\left(\mathrm{E}[\varepsilon_l]^2 - 2\mathrm{E}[\varepsilon_l]\mathrm{E}[\varepsilon_1] + \mathrm{E}[\varepsilon_1]^2\right)}{N_s}, \tag{A III-4}$$

The average error for each segment is presented in Table-A II-1. Obviously, MSE throughput error depends on the number of subcarrier assigned to each BS and modulation technique (i.e. MSE error due to linear approximation).

APPENDIX IV

COMPARISON BETWEEN PSO AND ILP BASED RESOURCE ALLOCATION MODELS

In this appendix, the performance comparison among the PSO based resource allocation model and the optimal ILP model described in Chapter 3 is presented. Fig.-A IV-1 shows the network throughput, user satisfaction, bandwidth usage and power consumption for both models under the incremental traffic scenario with a cluster of 5 femtocell with low FC user density. Both models present similar throughput values however the power consumption in PSO model is 1 dB higher than the ILP model. This can be attributed to the discrete steps of power increase assumed in the PSO based approach. From Fig.-A IV-1b, it can be seen that ILP model presents higher user satisfaction compared to PSO model. This means that excess of a particular user data rate in PSO model increases the overall throughput while reduces the satisfaction of the remaining users.



(a) Throughput
(b) User Satisfaction
(c) Bandwidth Usage
(d) Power Consumption

Figure-A IV-1 Performance Analysis of PSO and ILP models

The complexity of the ILP model depends on the number of subcarriers that comprise the licensed spectrum, mobile user density within FC coverage area, the number of femtocells in the cluster and the total transmitted power in MC (Estrada *et al.*, 2013a). The complexity of the PSO based model depends on the number of iterations used to find a near-to-optimal solution. We define the maximum iterations value equal to 500 since we observed that the number of iterations required for the convergence varies from 100 to 500 depending on the number of users in the network. Table-A IV-1 presents the required time to find an optimal or near-to-optimal solution for both models.

Table-A IV-1 Running Time

MS	ILP	PSO
10	0.08	0.05
20	0.2	0.12
30	2.17	1.12
40	79.95	14.15
50	302.54	26.13

As we expected, the running time of PSO model is indeed lower than the ILP model but it still increases exponentially. This is owing to the fact that the number of iterations required to converge depends on the number of the users in the network and number of femtocell in the cluster. In this particular scenario, only 5 femtocells were deployed within a cluster. One can expect that if the number of FC in the cluster increases, the required time to find a near-to-optimal solution also increases.

In summary, we have demonstrated that PSO based resource allocation approach finds a near-to-optimal solution.

BIBLIOGRAPHY

3GPP-TR-136.913. April 2011. *Requirements for further advancements for evolved universal terrestrial radio access (E-UTRA) (LTE-advanced)*. Technical Report TR 136.913 v 10.0.0.

3GPP-TR-36.921. May 2011. *Evolved universal terrestrial radio access (E-UTRA) TDD home enode b (HeNB) radio frequency (RF) requirements analysis*. Technical Report TR 36.921 version 10.0.0 R.10.

Abdelnasser, Amr, Ekram Hossain, and Dong In Kim. March 2014. "Clustering and Resource Allocation for Dense Femtocells in a Two-Tier Cellular OFDMA Network". *Wireless Communications, IEEE Transactions on*, vol. 13, n° 3, p. 1628-1641.

ABI-Research. 2012. "A weekly technology research update from ABI Research, July 2012".

Agrawal, Avneesh. 2009. *Heterogeneous networks:a new paradigm for increasing cellular capacity*. Presentation.

Akoum, Salam, Marious Kountouris, and Robert Heath. 2011. "On Imperfect CSI for the Downlink of a Two-Tier Network". In *Information Theory Proceeding (ISIT)*. p. 553-557. IEEE.

Alden, John. 2012. *Exploring the value and economic valuation of spectrum*. Technical presentation.

Alsawah, A and I Fijalkow. Sept. 2008. "Resource allocation in OFDMA downlink with reduced feedback overhead". In *Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium on*. p. 1-5.

Amiri, Babak, Mohammad Fathian, and Ali Maroosi. 2009. "Application of shuffled frog-leaping algorithm on clustering". *The International Journal of Advanced Manufacturing Technology*, vol. 45, n° 1-2, p. 199-209.

Androne, C., T. Palade, E. Puschita, A. Moldovan, I. Vermesan, and R. Colda. 2011. "Study of co-channel cross-layer interference for the downlink communication in femtocell networks". *Signals, Circuits and Systems (ISSCS), 10th International Symposium*, vol. 10, p. 1-4.

Assaad, M. Sept 2008. "Optimal Fractional Frequency Reuse (FFR) in Multicellular OFDMA System". In *Vehicular Technology Conference, 2008. VTC 2008-Fall. IEEE 68th*. p. 1-5.

Auer, G., V. Giannini, C. Desset, I. Godor, P. Skillermark, M. Olsson, M.A. Imran, D. Sabella, M.J. Gonzalez, O. Blume, and A. Fehske. October 2011. "How much energy is needed to run a wireless network?". *Wireless Communications, IEEE*, vol. 18, n° 5, p. 40 -49.

Bai, Yong, Juejia Zhou, and Lan Chen. 2009. "Hybrid Spectrum Usage for Overlaying LTE Macrocell and Femtocell". In *Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE*. p. 1-6.

Bennis, M. and S.M. Perlaza. June 2011. "Decentralized Cross-Tier Interference Mitigation in Cognitive Femtocell Networks". In *Communications (ICC), 2011 IEEE International Conference on*. p. 1 -5.

Bharucha, Z., G. Auer, and H. Hass. 2010. "Dynamic Resource partitioning for Downlink femto-to-macro-cell interference avoidance". *EURASIP Journal on Wireless Communications and Networking*, vol. 2010, p. 77-88.

Blum, Christian, 2013. *GECCO '13 Companion: Proceedings of the 15th Annual Conference Companion on Genetic and Evolutionary Computation*, New York, NY, USA. ACM. ISBN 978-1-4503-1964-5.

Boccuzzi, Joseph and Michael Ruggiero, 2011. *Femtocells Design and Application*. New York, NY, USA : McGraw Hill, 257 p.

Bogart, K., Clifford Stein, and Robert Drysdale, 2011. *Discrete Mathematics for Computer Scientists*.

Bohge, M., J. Gross, A Wolisz, and M. Meyer. Jan 2007. "Dynamic resource allocation in OFDM systems: an overview of cross-layer optimization principles and techniques". *Network, IEEE*, vol. 21, n° 1, p. 53-59.

Bratton, D. and J. Kennedy. 2007. "Defining a Standard for Particle Swarm Optimization". In *SIS*. p. 120-127.

Chan, Felix T. S.and Kumar Manoj Tiwari, 2007. *Swarm Focus on Ant and Particle Swarm Optimization*.

Chandrasekhar, V. and J.G. Andrews. Oct 2008. "Spectrum allocation in two-tier networks". In *Signals, Systems and Computers, 2008 42nd Asilomar Conference on*. p. 1583-1587.

Chandrasekhar, V. and J.G. Andrews. July 2009. "Uplink capacity and interference avoidance for two-tier femtocell networks". *Wireless Communications, IEEE Transactions on*, vol. 8, n° 7, p. 3498-3509.

Chandrasekhar, V., J.G. Andrews, T. Muharemovic, Zukang Shen, and A. Gatherer. August 2009. "Power control in two-tier femtocell networks". *Wireless Communications, IEEE Transactions on*, vol. 8, n° 8, p. 4316 -4328.

Chen, Chun-Wei, Chih-Yu Wang, Shih-Lung Chao, and Hung-Yu Wei. 2010. "DANCE: a game-theoretical femtocell channel exchange mechanism". *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 14, n° 1, p. 13–15.

Chen, Yanjiao, Jin Zhang, and Qian Zhang. May 2012. "Utility-Aware Refunding Framework for Hybrid Access Femtocell Network". *Wireless Communications, IEEE Transactions on*, vol. 11, n° 5, p. 1688-1697.

Cheng, Shin-Ming, Weng-Chon Ao, and Kwang-Cheng Chen. June 2011. "Efficiency of a Cognitive Radio Link with Opportunistic Interference Mitigation". *Wireless Communications, IEEE Transactions on*.

Cheng, Shin-Ming, Weng-Chon Ao, Fan-Min Tseng, and Kwang-Cheng Chen. 2012. "Design and Analysis of Downlink Spectrum Sharing in Two-Tier Cognitive Femto Networks". *Vehicular Technology, IEEE Transactions on*, vol. 61, n° 5, p. 2194-2207.

Chinneck, J.W. 2001. "Practical Optimization: a Gentle Introduction". Carleton University, Ottawa, ON, Canada, http://www.sce.carleton.ca/faculty/chinneck/po.html.

Choi, D., P. Monajemi, Shinjae Kang, and J. Villasenor. Nov 2008. "Dealing with Loud Neighbors: The Benefits and Tradeoffs of Adaptive Femtocell Access". In *IEEE GLOBECOM*. p. 1-5.

Chu, Xiaoli, Yuhua Wu, L. Benmesbah, and Wing-Kuen Ling. April. "Resource Allocation in Hybrid Macro/Femto Networks". In *Wireless Communications and Networking Conference Workshops (WCNCW), 2010 IEEE*. p. 1-5.

Chun-Han, K. and W. Hung-Yu. 2011. "On-Demand Resource Sharing Mechanism Design in two-tier OFDMA femtocell networks". *Transaction Vehicular Technology*, vol. 60-3, p. 1059-1071.

Coletti, Claudio, Liang Hu, Nguyen Huan, István Z. Kovács, Benny Vejlgaard, Ralf Irmer, and Neil Scully. Sept. 2012. "Heterogeneous Deployment to Meet Traffic Demand in a Realistic LTE Urban Scenario". In *Vehicular Technology Conference (VTC Fall), 2012 IEEE*. p. 1 -5.

Dalal, A., Hailong Li, and D.P. Agrawal. Oct. 2011. "Fractional Frequency Reuse to Mitigate Interference in Self-Configuring LTE-Femtocells Network". In *Mobile Adhoc and Sensor Systems (MASS), 2011 IEEE 8th International Conference on*. p. 49 -54.

Dow, A. 2008. *Evolution to femtocells for radio access: Challenges for existing cellular networks*. Presentation 27-AD.

Dufková, Kateřina, Jean-Yves Le Boudec, Miroslav Popović, Milan Bjelica, Ramin Khalili, and Lukáš Kencl. 2011. "Energy consumption comparison between macro-micro and public femto deployment in a plausible LTE network". In *Proceedings of the 2nd International Conference on Energy-Efficient Computing and Networking*. (New York, NY, USA 2011), p. 67–76. ACM.

Elbeltagi, Emad, Tarek Hegazy, and Donald Grierson. 2005. "Comparison Among Five Evolutionary-based Optimization Algorithms". *Adv. Eng. Inform.*, vol. 19, n° 1, p. 43–53.

Estrada, R., A Jarray, H. Otrok, Z. Dziong, and H. Barada. Sept 2013a. "Energy-Efficient Resource-Allocation Model for OFDMA Macrocell/Femtocell Networks". *Vehicular Technology, IEEE Transactions on*, vol. 62, n° 7, p. 3429-3437.

Estrada, R., H. Otrok, and Zbigniew Dziong. Dec 2013b. "Resource allocation model based on Particle Swarm Optimization for OFDMA macro-femtocell networks". In *Advanced Networks and Telecommuncations Systems (ANTS), 2013 IEEE International Conference on*. p. 1-6.

Estrada, Rebeca, Hadi Otrok, Zbigniew Dziong, and Hassan Barada. 2013c. "Joint BS selection and resource allocation model for OFDMA macro-femtocell networks incorporating mobility". In *Mobile and Wireless Networking (MoWNeT), 2013 International Conference on Selected Topics in*. p. 42-47.

Estrada, Rebeca, Abdallah Jarray, Hadi Otrok, and Zbigniew Dziong. 2014. "Base station selection and resource allocation in macro–femtocell networks under noisy scenario". *Wireless Networks*, vol. 20, n° 1, p. 115-131.

Fantacci, R., D. Marabissi, D. Tarchi, and I Habib. September 2009. "Adaptive modulation and coding techniques for OFDMA systems". *Wireless Communications, IEEE Transactions on*, vol. 8, n° 9, p. 4876-4883.

Fehske, A.J., F. Richter, and G.P. Fettweis. 2009. "Energy Efficiency Improvements through Micro Sites in Cellular Mobile Radio Networks". In *GLOBECOM Workshops, 2009 IEEE*. p. 1 -5.

FemtoForum. 2010. "Femtocells: Natural Solution for Offload". Femto Forum brief, www.4gamericas.org/documents/016+Femtocells+Natural+Solution+for+Offload.pdf.

G. He,M. Debbah, E. Altman. 2010. "A bayesian game-theoretic approach for Distributed Resource Allocation in Fading Multiple Access Channels". *EURASIP Journal on Wireless Communications and Networking*, vol. 2010, p. 67-76.

Geetha, T. August 2013. "A diverse versions and variations of Particle Swarm Optimization (PSO) algorithm for real world complex optimization problems". *International Journal of Emerging Technology and Advanced Engineering*, vol. 3, n° 8, p. 454-459.

Gheitanchi, S., F. Ali, and E. Stipidis. 2007. "Particle Swarm Optimization for Resource Allocation in OFDMA". In *Digital Signal Processing, 2007 15th International Conference on*. p. 383-386.

Gheitanchi, Shahin, Falah Ali, and Elias Stipidis. Feb 2010. "Particle Swarm Optimization for Adaptive Resource Allocation in Communication Networks". *EURASIP Journal Wireless Communication Networks*, vol. 2010, p. 1-13.

Group, Mobile Wimax. 2009. *Coverage and performance evaluation of mobile cellular structured WIMAX*. Technical report.

Guvenc, I., Moo-Ryong Jeong, F. Watanabe, and H. Inamura. 2008. "A hybrid frequency assignment for femtocells and coverage area analysis for co-channel operation". *Communications Letters, IEEE*, vol. 12, n° 12, p. 880-882.

Han, K. 2009. "Optimization of femtocell network configuration under interference constraints". In *Proceedings of the 7th international conference on Modeling and Optimization in Mobile Ad Hoc, and Wireless Network*. p. 90-96. IEEE Press: Seoul, Korea.

Han, Kwanghun, Youngkyu Choi, Dongmyoung Kim, Minsoo Na, Sunghyun Choi, and Kiyoung Han. June 2009. "Optimization of femtocell network configuration under interference constraints". In *Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks, 2009. WiOPT 2009. 7th International Symposium on*. p. 1 -7.

Hanm, Kwanghun, Youngkyu Choi, and Dongmyoung Kim. 2009. "Optimization of Femtocell Network Configuration under Interference Constraints". *International Symposium on Modeling and Optimization in Mobile Ad Hoc and Wireless Networks*, vol. 7, p. 1-7.

Hans-Florian, Geerdes, 2008. *UMTS Radio Network Planning: Mastering Cell Coupling for Capacity Optimization*. Berlin, Germany : Mobile Research Center Publications, 181 p.

Hatoum, A., N. Aitsaadi, R. Langar, R. Boutaba, and G. Pujolle. June 2011. "FCRA: Femtocell Cluster-Based Resource Allocation Scheme for OFDMA Networks". In *Communications (ICC), 2011 IEEE International Conference on*. p. 1 -6.

Hatoum, A, R. Langar, N. Aitsaadi, R. Boutaba, and G. Pujolle. Dec 2012a. "QoS-based power control and resource allocation in OFDMA femtocell networks". In *Global Communications Conference (GLOBECOM), 2012 IEEE*. p. 5116-5122.

Hatoum, A., R. Langar, N. Aitsaadi, and G. Pujolle. June 2012b. "Q-FCRA: QoS-based OFDMA femtocell resource allocation algorithm". In *IEEE ICC*. p. 5151-5156.

Hatoum, A, R. Langar, N. Aitsaadi, R. Boutaba, and G. Pujolle. Jun 2014. "Cluster-Based Resource Management in OFDMA Femtocell Networks With QoS Guarantees". *Vehicular Technology, IEEE Transactions on*, vol. 63, n° 5, p. 2378-2391.

Hong, Mingyi and A. Garcia. December 2012. "Mechanism Design for Base Station Association and Resource Allocation in Downlink OFDMA Network". *Selected Areas in Communications, IEEE Journal on*, vol. 30, n° 11, p. 2238-2250.

Hoteit, S., S. Secci, R. Langar, G. Pujolle, and R. Boutaba. Dec 2012. "A bankruptcy game approach for resource allocation in cooperative femtocell networks". In *IEEE GLOBECOM*. p. 1800-1805.

Hu, Fanglong, Kan Zheng, Lei Lei, and Wenbo Wang. 2011. "A Distributed Inter-Cell Interference Coordination Scheme between Femtocells in LTE-Advanced Networks". In *IEEE Vehicular Technology Conference*. p. 1-5. IEEE.

Huang, Liang, Yiqing Zhou, Jinlong Hu, Xue Han, and Jinlin Shi. June 2012. "Coverage optimization for femtocell clusters using modified particle swarm optimization". In *Communications (ICC), 2012 IEEE International Conference on*. p. 611-615.

IBM. 2011. "IBM ILOG CPLEX Optimizer". http://www.ibm.com/software/integration/optimization/cplex-optimizer.

IEEE-802.16. 2004. *Standard for local and metropolitan area networks: Air interface for fixed broadband wireless access system*. Standard 802.16-2004.

IEEE-802.16m. "IEEE standard for local and metropolitan area networks - part 16: Air interface for broadband wireless access systems - advanced air interface".

Imamoto, A. and B. Tang. 2008. "Optimal Piecewise Linear Approximation of convex functions". In *Proceedings of the World Congress on Engineering and Computer Science*. p. 1191-1194. WCECS.

Infonetics. 2012. "Market Outlook: Femtocells, Small Cells & WiFi". Small Cells Asia, Taipei www.ateshow.com/agile_assets/398/Infonetics_1545.pdf.

ITU-TR-36.921. 1997. *Guidelines for evaluation of ratio transmission technologies for IMT-2000*. Recommendations RM.1225.

Jeong, Yeonjune, Ju Yong Lee, Min Young Chung, Tae-Jin Lee, and Hyunseung Choo. Oct 2010. "Femtocell Frequency Planning Scheme in Cellular Networks Based on Soft Frequency Reuse". In *Cyber-Enabled Distributed Computing and Knowledge Discovery (CyberC), 2010 International Conference on*. p. 176 -180.

Jianmin Zhang, Kedi Wu and Aiping Huang;. 2010. "Optimal Distributed Subchannel, Rate and Power Allocation Algorithm in OFDM-Based Two-Tier Femtocell Networks". In *IEEE Vehicular Technology Conference*. p. 1-5. IEEE.

K., Garg Vijay, 2007. *Wireless Communications and Networking*. San Francisco, CA,USA : Elsevier Morgan Kaufmann, 840 p.

Kachitvichyanukul, Voratas. Sep 2012. "Comparison of Three Evolutionary Algorithms: GA, PSO, and DE". *Industrial Engineering & Management Systems*, vol. 11, n° 3, p. 215-223.

Kang, Xin, Rui Zhang, and M. Motani. April 2012. "Price-Based Resource Allocation for Spectrum-Sharing Femtocell Networks: A Stackelberg Game Approach". *Selected Areas in Communications, IEEE Journal on*, vol. 30, n° 3, p. 538 -549.

Karloff, Howard, 2009. *Linear Programming*. New York, NY,USA : Birkhauser, 142 p.

Kelif, Jean Marc and Marceau Coupechoux. 2010. "Joint Impact of Pathloss Shadowing and Fast Fading - An Outage Formula for Wireless Networks". *CoRR*, vol. abs/1001.1110.

Kennedy, J. and R. Eberhart. Nov 1995. "Particle swarm optimization". In *Neural Networks, 1995. Proceedings., IEEE International Conference on*. p. 1942-1948 vol.4.

Khan, T.A., T.A. Taj, M.K. Asif, and I. Ijaz. 2012. "Modeling of a standard Particle Swarm Optimization algorithm in MATLAB by different benchmarks". In *INTECH*. p. 271-274.

Kim, Juhee and Wha Sook Jeon. Jan 2012. "Fractional frequency reuse-based resource sharing strategy in two-tier femtocell networks". In *Consumer Communications and Networking Conference (CCNC), 2012 IEEE*. p. 696-698.

Le, Long Bao, Dinh Thai Hoang, D. Niyato, E. Hossain, and Dong In Kim. June 2012. "Joint load balancing and admission control in OFDMA-based femtocell networks". In *Communications (ICC), 2012 IEEE International Conference on*. p. 5135-5139.

Lee, Taeyoung, Hyuntai Kim, Jinhyun Park, and Jitae Shin. Sept. 2010a. "An Efficient Resource Allocation in OFDMA Femtocells Networks". In *Vehicular Technology Conference Fall (VTC 2010-Fall), 2010 IEEE 72nd*. p. 1 -5.

Lee, Taeyoung, Jisun Yoon, Sangtae Lee, and Jitae Shin. July 2010b. "Interference management in OFDMA Femtocell systems using Fractional Frequency Reuse". In *Communications, Circuits and Systems (ICCCAS), 2010 International Conference on*. p. 176-180.

Lee, Y.L., T.C. Chuah, J. Loo, and A Vinel. 2014. "Recent Advances in Radio Resource Management for Heterogeneous LTE/LTE-A Networks". *Communications Surveys Tutorials, IEEE*, vol. PP, n° 99, p. 1-39.

Li, Wei, Wei Zheng, Haijun Zhang, Tao Su, and Xiangming Wen. Sept 2012a. "Energy-efficient resource allocation with interference mitigation for two-tier OFDMA femtocell networks". In *Personal Indoor and Mobile Radio Communications (PIMRC), 2012 IEEE 23rd International Symposium on*. p. 507-511.

Li, Yang-Yang, Leon Yen, and E.S. Sousa. Dec 2010. "Hybrid user access control in HSDPA femtocells". In *GLOBECOM Workshops (GC Wkshps), 2010 IEEE*. p. 679 -683.

Li, Zhuo, Song Guo, Wenzhong Li, Sanglu Lu, Daoxu Chen, and V. C M Leung. April 2012b. "A particle swarm optimization algorithm for resource allocation in femtocell networks". In *Wireless Communications and Networking Conference (WCNC), 2012 IEEE*. p. 1212-1217.

Lin, Shangjing and Hui Tian. April 2013. "Clustering based interference management for QoS guarantees in OFDMA femtocell". In *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*. p. 649-654.

Ling, J., D. Chizhik, , and R. Valenzuela. 2009. "On resource allocation in dense femto-deployments". In *International Conference on Microwaves, Communications, Antennas and Electronics Systems COMCAS*. p. 1-6. IEEE.

Liu, Weiqiang, Xiaohui Chen, and Weidong Wang. April 2012. "Price-based uplink resource allocation for hybrid-spectrum femtocell networks". In *Wireless Communications and Networking Conference (WCNC), 2012 IEEE*. p. 2665 -2670.

Lopez-Perez, D., A Valcarce, G. de la Roche, and Jie Zhang. September 2009. "OFDMA femtocells: A roadmap on interference avoidance". *Communications Magazine, IEEE*, vol. 47, n° 9, p. 41-48.

Lucent-Alcatel. 2007. *The LTE network architecture: A comprehensive tutorial*. Strategic white paper.

Marshoud, H., H. Otrok, H. Barada, R. Estrada, A Jarray, and Z. Dziong. Oct 2012. "Resource allocation in macrocell-femtocell network using genetic algorithm". In *Wireless and Mobile Computing, Networking and Communications (WiMob), 2012 IEEE 8th International Conference on*. p. 474-479.

Marshoud, H., H. Otrok, H. Barada, R. Estrada, and Z. Dziong. April 2013. "Genetic algorithm based resource allocation and interference mitigation for OFDMA macrocell-femtocells networks". In *Wireless and Mobile Networking Conference (WMNC), 2013 6th Joint IFIP*. p. 1-7.

Mathworks. 2012. "MATLAB (R2012a)". https://www.mathworks.com.

Meerja, Khalim Amjad, Pin-Han Ho, and Bin Wu. 2011. "A Novel Approach for Co-channel Interference Mitigation in Femtocells Networks". In *Global Telecommunications Conference*. p. 1-6. IEEE.

Mhiri, Fadoua, Kaouthar Sethom, and Ridha Bouallegue. 2013. "A survey on interference management techniques in femtocell self-organizing networks". *Journal of Network and Computer Applications*, vol. 36, n° 1, p. 58 - 65.

Microsoft. 2010. "Visual Studio". http://www.microsoftstore.com/Visual-Studio.

Moon, Jung-Min and Dong-Ho Cho. Jan 2013. "Formation of cooperative cluster for coordinated transmission in multi-cell wireless networks". In *Consumer Communications and Networking Conference (CCNC), 2013 IEEE*. p. 528-533.

Nain, P., D. Towsley, Benyuan Liu, and Zhen Liu. March 2005. "Properties of random direction models". In *INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE*. p. 1897 - 1907 vol. 3.

Pantisano, F., M. Bennis, W. Saad, and M. Debbah. Dec 2011. "Cooperative Interference Alignment in Femtocell Networks". In *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*. p. 1-6.

Pantisano, F., M. Bennis, W. Saad, M. Debbah, and M. Latva-aho. Nov 2013. "Interference Alignment for Cooperative Femtocell Networks: A Game-Theoretic Approach". *Mobile Computing, IEEE Transactions on*, vol. 12, n° 11, p. 2233-2246.

Pateromichelakis, Emmanouil, Mehrdad Shariat, Atta Ul Quddus, and Rahim Tafazolli. 2011a. "A femtocell power control scheme to mitigate interference using listening TDD frame". In *Information Networking International Conference*. p. 241-244. IEEE.

Pateromichelakis, Emmanouil, Mehrdad Shariat, Atta Ul Quddus, and Rahim Tafazolli. 2011b. "On the analysis of co-tier interference in femtocells". *Personal Indoor and Mobile Radio Communications*, vol. 22, p. 122-126.

Perez, Ruben and Kamran Behdinan. 2007. "Particle Swarm Optimization in Structural Design". In *Swarm Intelligence: Focus on Ant and Particle Swarm Optimization*. p. 532-555.

Pyun, S. and D. Cho. 2010. "Resource Allocation Scheme for Minimizing Uplink Interference in Hierarchical Cellular Networks". In *IEEE Vehicular Technology Conference*. p. 1-5. IEEE.

Reddy, Y.B. and V.V. Phoha. Jan 2007. "Genetic Algorithm Approach for Resource Allocation in Multi-User OFDM Systems". In *Communication Systems Software and Middleware, 2007. COMSWARE 2007. 2nd International Conference on*. p. 1-6.

Sadr, S. and R. Adve. June 2012. "Hierarchical resource allocation in femtocell networks using graph algorithms". In *Communications (ICC), 2012 IEEE International Conference on*. p. 4416-4420.

Santos, Saulo M., Mêuser J.S. Valença, and Carmelo J.A. Bastos-Filho. 2012. "Comparing Particle Swarm Optimization Approaches for Training Multi-Layer Perceptron Neural Networks for Forecasting". In *Intelligent Data Engineering and Automated Learning - IDEAL 2012*.

Saquib, N., E. Hossain, Long Bao Le, and Dong In Kim. June 2012. "Interference management in OFDMA femtocell networks: issues and approaches". *Wireless Communications, IEEE*, vol. 19, n° 3, p. 86 -95.

Shahid, Adnan, Saleem Aslam, and Kyung-Geun Lee. 2013. "A Decentralized Heuristic Approach towards Resource Allocation in Femtocell Networks". *Entropy*, vol. 15, n° 7, p. 2524-2547.

Shaohong, Wu, Zhang Xin, Zheng Ruiming, Yin Zhiwei, Fang Yinglong, and Yang Dacheng. 2009. "Handover Study Concerning Mobility in the Two-Hierarchy Network". In *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*. p. 1-5.

Shi, Yuhui and R. Eberhart. 1998. "A modified particle swarm optimizer". In *Evolutionary Computation Proceedings, 1998. IEEE World Congress on Computational Intelligence.* p. 69-73.

Strinati, E.C., A. De Domenico, and A. Duda. March 2011. "Ghost femtocells: A novel radio resource management scheme for OFDMA based networks". In *Wireless Communications and Networking Conference (WCNC), 2011 IEEE*. p. 108 -113.

Su, Lin, Ping Wang, and Fuqiang Liu. 2012. "Particle swarm optimization based resource block allocation algorithm for downlink LTE systems". In *APCC*. p. 970-974.

Sundaresan, K. and S. Rangarajan. 2009. "Efficient resource management in OFDMA Femto Cells". In *Proceedings of the 10th ACM international symposium on Mobile ad hoc networking and computing*. p. 33-42. Mobihoc 2009.

Tarhini, Ch. and T. Chanjed. 2007. "On capacity of OFDMA-based IEEE802.16 WIMAX including Adaptive Modulation and Coding (AMC) and inter-cell interference". *IEEE Workshop Local & Metropolitan Area Networks*, vol. 2007, p. 139-144.

Tariq, F., L.S. Dooley, AS. Poulton, and Yusheng Ji. July 2011. "Dynamic fractional frequency reuse based hybrid resource management for femtocell networks". In *Wireless Communications and Mobile Computing Conference (IWCMC), 2011 7th International*. p. 272-277.

Torregoza, J., R. Enkhbat, and W. Hwang. 2010. "Joint Power control, base station assignment, and channel assignment in cognitive femtocell networks". *EURASIP Journal on Wireless Communications and Networking*, vol. 2010, p. 53-66.

Valcarce, A., D. Lopez-Perez, G. De La Roche, and Jie Zhang. Sept 2009. "Limited access to OFDMA femtocells". In *Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium on*. p. 1 -5.

Xiaoli, Chu, Wu Yuhua, D. Lopez-Perez, and Xiaofeng Tao. 2011. "On Providing Downlink Services in Collocated Spectrum-Sharing Macro and Femto Networks". *IEEE Wireless Communications Transactions*, vol. 10-12, p. 4306-4315.

Yang, Lin, Lu Zhang, Tao Yang, and Wei Fang. 2011. "Location-Based Hybrid Spectrum Allocation and Reuse for Tiered LTE-A Networks". In *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*. p. 1-5.

Yang, Samuel, 2010. *OFDMA Systems Design and Analysis*. Norwood, MA,USA : Artech House, 295 p.

Yi, Youwen, Jin Zhang, Qian Zhang, and Tao Jiang. March 2012. "Spectrum leasing to femto service provider with hybrid access". In *INFOCOM, 2012 Proceedings IEEE*. p. 1215 -1223.

Zalzala, A. M. S. and P. J. Flemming, 1997. *Genetic Algorithm in Engineering Systems*. Stevenage, Herts, United Kingdom : Institution of Electrical Engineering in London, 267 p.

Zhang, Jianmin, Zhaoyang Zhang, Kedi Wu, and Aiping Huang. 2010a. "Optimal Distributed Subchannel, Rate and Power Allocation Algorithm in OFDM-based Two-Tier Femtocell Networks". In *Vehicular Technology Conference*. p. 1-5. IEEE.

Zhang, Jianmin, Zhaoyang Zhang, Kedi Wu, and Aiping Huang. May 2010b. "Optimal Distributed Subchannel, Rate and Power Allocation Algorithm in OFDM-Based Two-Tier Femtocell Networks". In *Vehicular Technology Conference (VTC 2010-Spring), 2010 IEEE 71st*. p. 1 -5.

Zhang, Jie and Guillaume De la Roche, 2010. *Femtocells: Technologies and Deployment*. West Sussex,United Kingdom : Wiley Publishing, 328 p.

Zhang, Y. 2010. "Resource Sharing of Completely Closed Access in Femtocell Networks". In *Wireless Communications and Networking Conference*. p. 1-5. IEEE.

Zhang, Yan. April. "Resource Sharing of Completely Closed Access in Femtocell Networks". In *Wireless Communications and Networking Conference (WCNC), 2010 IEEE*. p. 1-5.

Zhang, Yonghong and C. Leung. Nov 2009. "Subchannel Power-Loading Schemes in Multiuser OFDM Systems". *Vehicular Technology, IEEE Transactions on*, vol. 58, n° 9, p. 5341-5347.

Zhong, Yi and Wenyi Zhang. June 2012. "Downlink analysis of multi-channel hybrid access two-tier networks". In *Communications (ICC), 2012 IEEE International Conference on*. p. 2479 -2484.

Zhou, Juejia, Xiaoming She, Lan Chen, and H. Otsuka. Aug 2011. "QoS guaranteed radio resource allocation scheme using Genetic Algorithm for OFDMA". In *Communications and Networking in China (CHINACOM), 2011 6th International ICST Conference on*. p. 594-599.