HYBRID ACCESS CONTROL MECHANISM IN TWO-TIER FEMTOCELL NETWORKS

A Thesis

by

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ABSTRACT

The cellular industry is undergoing a major paradigm shift from voice-centric, structured homogeneous networks to a more data-driven, distributed and heterogeneous architecture. One of the more promising trends emerging from this cellular revolution are femtocells. Femtocells are primarily viewed as a cost-effective way to improve both capacity and indoor coverage, and they enable offloading data-traffic from macrocell network. However, efficient interference management in co-channel deployment of femtocells remains a challenge. Decentralized strategies such as femtocell access control have been identified as an effective means to mitigate cross-tier interference in two-tier networks. Femtocells can be configured to be either open access or closed access. Prior work on access control schemes show that, in the absence of any coordination between the two tiers in terms of power control and user scheduling, closed access is the preferred approach at high user densities. Present methods suggest that in the case of orthogonal multiple access schemes like TDMA/OFDMA, femtocell access control should be adaptive according to the estimated cellular user density.

The approach we follow, in this work, is to adopt an open access policy at the femtocell access points with a cap on the maximum number of users allowed on a femtocell. This ensures the femto owner retains a significant portion of the femtocell resources. We design an iterative algorithm for hybrid access control for femtocells that integrates the problems of uplink power control and base station assignment. This algorithm implicitly adapts the femtocell access method to the current user density. The distributed power control algorithm, which is based on Yates' work on standard interference functions, enables users to overcome the interference in the system and satisfy their minimum QoS requirements. The optimal allocation of femtocell resources is incorporated into the access control algorithm through a constrained sum-rate maximization to protect the femto owner from starvation at high user densities. The performance of a two-tier OFDMA femtocell network is then evaluated under the proposed access scheme from a home owner viewpoint, and network operator perspective. System-level simulations show that the proposed access control method can provide a rate gain of nearly 52% for cellular users, compared to closed access, at high user densities and under moderate-to-dense deployment of femtocells. At the same time, the femto owner is prevented from going into outage and only experiences a negligible rate loss. The results obtained establish the quantitative performance advantage of using hybrid access at femtocells with power control at high user densities. The convergence properties of the proposed iterative hybrid access control algorithm are also investigated by varying the user density and the mean number of femto access points in the network. It is shown that for a given system model, the algorithm converges quickly within thirty iterations, provided a feasible solution exists.

To My Family

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CHAPTER I

INTRODUCTION

Wireless communication networks have become a ubiquitous part of modern life, transforming the way we live, conduct business and interact. Since the inception of cellular concept in the 1960s, the communications industry has witnessed tremendous growth with new technologies being developed and brought to market on an almost daily basis. The history of mobile telephony can be traced back to the 1980's when the first-generation (1G) voice-only analog networks were introduced. They were replaced by the second-generation (2G) digital phones equipped with fax, data and messaging services. The third generation (3G) ushered in the era of multimedia computing and entertainment on mobile phones and today we are at the cusp of a wireless revolution with superior fourth-generation (4G) LTE-Advanced networks ready to roll out by 2013 [1]. At the same time technological breakthroughs in semiconductor fabrication and VLSI design have enabled highly advanced wireless mobile platforms integrating the functionality of different devices – cell phones, cameras, MP3 players etc – thereby, dramatically altering the wireless landscape.

In this rapidly evolving wireless ecosystem, one of the decisive constraining factors is the available radio spectrum, which is a limited and precious resource. In United States, the FCC is the governing body that regulates spectrum and divides it broadly into two bands – the licensed frequency band wherein cellular systems, television networks and military applications operate and the unlicensed spectrum that is utilized by the wireless local area networks (WLANs). Traditionally the cellular architecture and its wired backbone network are carefully planned, adhering to the standardized protocols provided by institutions such as ITU, IEEE and 3GPP, and deployed entirely under the central authority of network operators. The performance of macrocell systems is influenced heavily by the randomness in environment due to fading and user mobility, and so reliable connectivity with a minimum quality of service (QoS) is not always guaranteed. On the other hand, the WLANs are mostly user-deployed and operate according to the more robust, flexible, decentralized albeit rather inefficient protocols laid out by the IEEE 802.11 standards. Mobility of user is limited and vertical handovers are supported only by dual-mode devices. Clearly, the progression of wireless communication standards along this line of development presents a sort of dichotomy – the cellular networks that provide large coverage and mobility at relatively low data rates and the short-ranged WLANs with high data rates but low mobility [2].

A. Small Cells and Heterogeneous Networks

The conventional cellular technologies, optimized for homogeneous traffic, were designed as the next generation of the older cellular voice networks, long before any substantial mobile Internet really existed. As mobile data services and applications continue to increase with the rise in usage of a multitude of bandwidth intensive application-driven wireless multimedia devices such as smart-phones, tablets and netbooks, there is a staggering demand for high data rate services, better coverage and more spectrum resources for future wireless networks. Global mobile data traffic forecasts [3], as shown in Figure 1, predict a nearly exponential growth in user data traffic and network load which puts an intense pressure on the current wireless cellular infrastructure, slowly pushing it to a breaking point. In fact, according to some recent surveys [4] in the coming years, a majority of mobile data usage – nearly 50% of voice traffic and 70% of data traffic – will be indoor and nomadic, rather than truly mobile. This poses an additional challenge for the operators to increase indoor

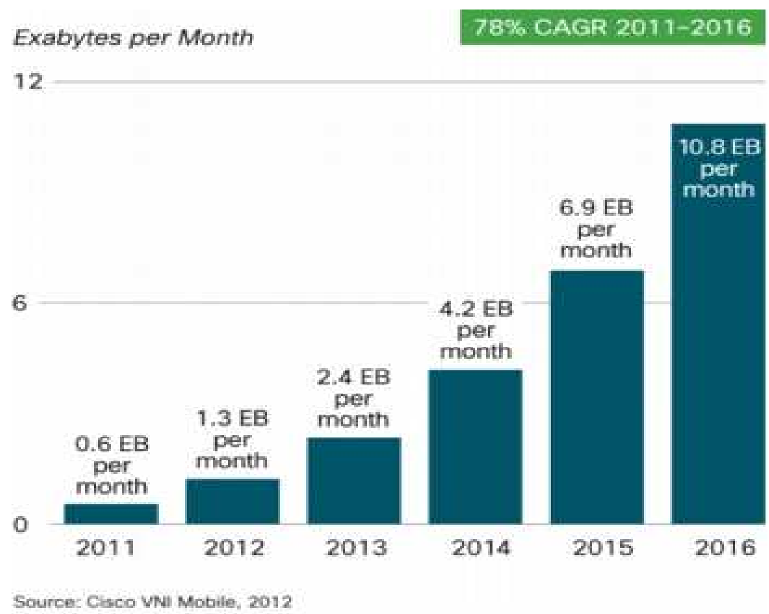

Fig. 1. Cisco forecast for growth of global mobile traffic by 2016.

coverage to deliver satisfactory user experience. Such a rapid growth in mobile data activity has called for the cellular industry to develop innovative new technologies and cellular topologies such as the WiMAX (802.16e), HSPA and LTE by 3GPP and EVDO by 3GPP2 that can meet these demands in an energy efficient manner. These data-centric standards employ techniques of frequency reuse to combat interference problems, but this requires centralized control and more importantly, results in poor spatial reuse of spectrum.

To address the next step of improved coverage and capacity, it has been widely recognized that the focus in future should be on increasing spatial reuse and link capacity by embracing the concept of small cells, that was first introduced nearly three decades ago [5]. The idea is to scale down the size of cell that leads to higher capacity gains as a result of more efficient frequency reuse with high spatial density [6]. As such, this discussion naturally leads to the notion of Heterogeneous Networks (HetNets) which basically refers to a tiered network architecture using a combina-

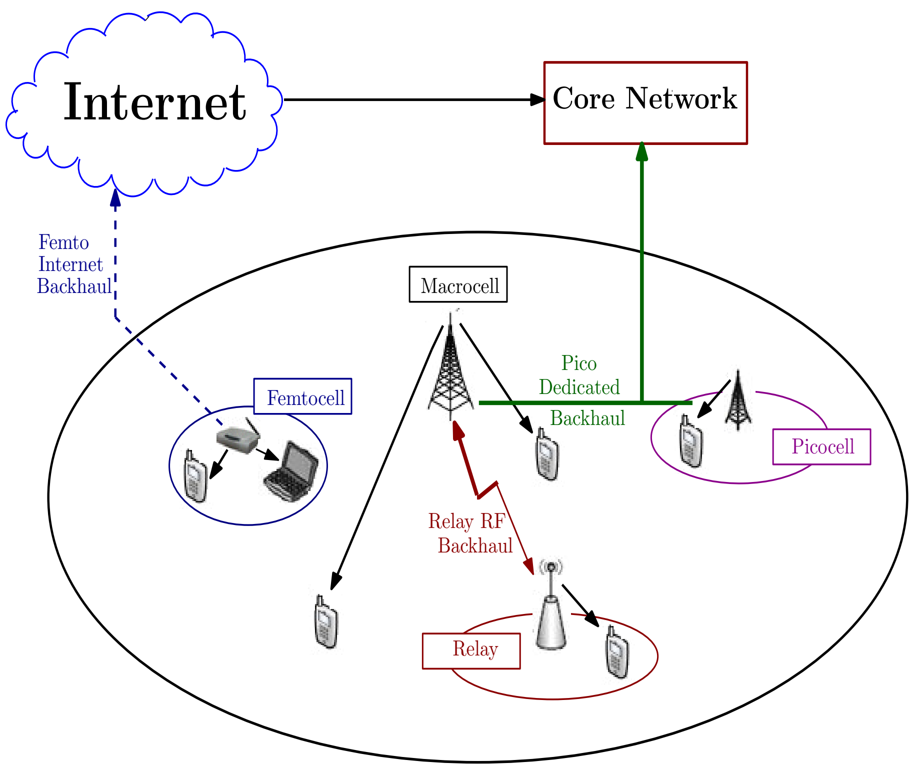

Fig. 2. Heterogeneous wireless network architecture.

tion of microcells [7], distributed antennas [8], relays [9], operator deployed picocells or consumer deployed femtocells [10] underlying the top layer macrocell network, all working together, in general, in the same system bandwidth to provide the best coverage and capacity possible. Figure 2 depicts an example of heterogeneous wireless network architecture. The positive attributes of heterogeneous networks have attracted much attention from both wireless industry and research community over the past few years. Organizations such as the Small Cell Forum are committed to the promotion and wide-scale adoption of small cells for provision of high-quality 2G/3G/4G coverage and services within residential, enterprise, public and rural access markets. However deploying and operating new infrastructure to enable further miniaturization of the cell is potentially expensive. Besides, in case of microcells and distributed antenna systems, there is no substantial improvement in indoor reception. For small cell architecture to deliver the capacity gain economically, it is imperative that we create new designs that perform all the required functions of radio access, power control and backhaul conditioning, are easy to deploy and most importantly are at least an order of magnitude cheaper than the equivalent macrocell.

1. Femtocell Concept

One of the more promising solutions that seems to be emerging from this paradigm shift in cellular network architecture is the femtocell concept. Femtocells are essentially short-range ($10-50$m), low-cost, low-power ($10-100$mW) home base stations that are generally deployed by the end user in a plug-and-play manner and are connected to the network through a DSL or RF backhaul channel [11]. In that, femtocells resemble Wi-Fi access points. However unlike Wi-Fi systems they operate in the licensed frequency bands and utilize one or more commercial cellular standards. With reduced transmit-receive distances, femtocells lower transmit power, prolong handset battery life, achieve a higher SINR and provide better QoS to indoor users that is otherwise not attainable via macrocell coverage operating at higher frequencies [11, 12]. Compared to the traditional small cells, femtocells are more autonomous and self-adaptive, that is they automatically integrate themselves into existing macrocellular networks which makes their large scale deployments possible. Thus, a femtocell deployed indoors ensures fixed-mobile convergence with the currently in use handset devices providing seamless interfacing with the cellular network, enabling handoffs, interference management, billing, and authentication. The service providers pay very little upfront cost in deploying and operating femtocells and this is a key advantage in comparison with other techniques for increasing node density, such as relays and microcells. Finally, femtocells support a transition from wired services to using only wireless smart-devices at home [13] and so, they are beneficial for both users and operators. By the start of 2011, an estimated 2.3 million femtocells were already deployed globally, and this is expected to reach nearly 50 million by 2014 [14]. Today the issue of offloading data traffic away from congested cellular networks has become one of the most discussed topics in the wireless industry. Femtocells and Wi-Fi can work together to create a converged network, providing better indoor solutions, high data rates and expanding existing mobile networks into previously remote areas. Femtocells, along with Wi-Fi offloading, are expected to carry over 60% of all global data traffic by 2015, thereby improving macrocell reliability [15] and thus, femtocell networks are under intense investigation and rapid deployment [16, 17, 18].

An important aspect of femtocell design is the access mechanism. Femtocells can be configured in three different types of access modes [19, 20] to either allow or block unsubscribed users as enumerated below.

i) Closed access: The femtocell allows only its own subscribed users to establish connection. Mostly femtocells deployed in residential areas employ this access mechanism for security reasons [21].

ii) Open access: All types of users, both subscribed femtocell user equipments as well as unregistered macrocell user equipments, are allowed to connect. Open access allows for network operators to deploy femtocells in public areas where macrocell coverage is weak such as airports and shopping complexes.

iii) Hybrid access: Nonsubscriber users are allowed onto the femtocell but with an upper limit on the amount of the femtocell resources. Hybrid access may be used in case of enterprise femtocells [20].

Different deployment configurations can be adopted to manage frequency allocation in two-tier networks. Orthogonal spectrum splitting is one approach wherein the licensed spectrum is divided into two distinct bands: one used by the macrocells and the other by femtocells [22]. Although this method eliminates interference across tiers, it is very inefficient in terms of frequency reuse. Co-channel assignment [23], in which both macrocells and femtocells share access to the entire spectrum, is desirable from the network operator's perspective [24]. The third deployment configuration called partial co-channel assignment [25] proposes division of spectrum into two parts, one that is dedicated to the macrocell and the other part that is shared by both macrocell and femtocells. This work assumes co-channel deployment of femtocells as it enables more efficient utilization of available spectrum. However, co-channel deployment of femtocells on a large scale impacts the capacity and performance of existing macrocell networks, and so several aspects such as the access methods [19, 26, 27, 28]; efficient spectrum allocation [22, 29]; timing and synchronization [30, 31]; handoffs and mobility management [28, 32]; self-configuration of femtocells [23, 33, 34]; and security [11, 35] need further investigation before their widespread implementation. Simple handoff mechanisms with low signaling overhead are required to ensure smooth transitions across different radio access modes. Synchronization is another issue for femtocells as delays lead to traffic congestion and achieving synchronization over the IP-based backhaul is difficult.

One of the major challenges is electromagnetic interference that endangers the successful co-existence of femtocells and macrocells [26, 28, 36]. Co-channel spectrum sharing between femtocells and macrocells, and the 'randomness' in femtocell locations differentiate the two-tier network interference problem from that in conventional cellular networks [37]. The interference profile in a two-tier femtocell network is classified into two categories

i) Co-tier Interference: The interference type between network elements of same tier – neighboring femtocells.

ii) Cross-tier Interference: The interference type between network elements of different tiers – macrocells and femtocells.

Possible interference scenarios in a two-tier femtocell network are described in Figure 3. Asymmetric transmission power levels at numerous points within the network due to dependency on location of users from base station, labeled *near-far effect*, may result in severe interference creating coverage holes called *deadzones* or the *loud neighbor problem* [27] where QoS degrades significantly. For example on the uplink, a macrocell user equipment located at cell-edge creates a deadzone at the neighboring femtocell. On the downlink, due to high path-loss and shadowing, a cell edge macrocell user equipment may experience high interference from the nearby femtocells. Thus there is a need for effective interference management techniques in order to reduce interference, co-tier as well as cross-tier, considerably and improve the overall network capacity. Different types of femtocells have been designed and deployed based on the air-interface technologies, standards used, services provided and access control mechanisms – 3G femtocells use the UMTS-based WCDMA air-interface while the more recent 4G WiMAX and LTE femtocells employ OFDMA. Both uplink and downlink interferences are observed only when the aggressor (source of interference) and the victim are operating on the same frequency. OFDMA femtocells are more favorable for resolving interference issues than their CDMA counterparts, primarily because OFDMA provides freedom in both frequency and time slot allocation, while CDMA can exploit channel variation only in time domain. In this thesis, we consider a two-tier network model with OFDMA femtocells sharing the entire spectrum with the macrocell base station. With intelligent resource management we can enhance frequency reuse in the OFDMA-femtocell tier and maximize cell throughput by reducing

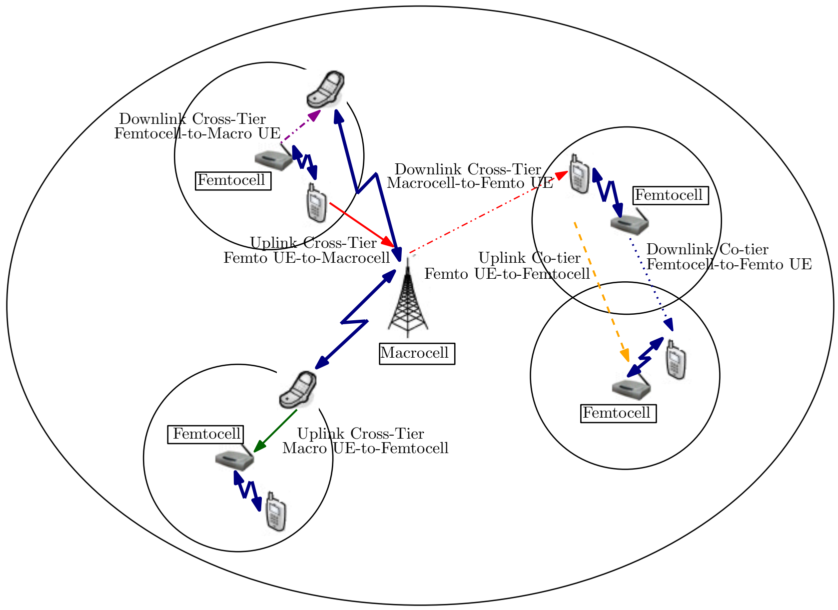

Fig. 3. Interference scenarios in femtocell networks.

both co-tier and cross-tier interference.

B. Interference Management in Femtocell Networks

Most of the previous literature in the area of interference management focus on the interaction between macrocells; results on co-existence of femtocells and macrocells is limited. The Small Cell Forum recently published a report [38] that evaluates extreme cases of cross-tier interference based on both co-channel and adjacent channel deployment. Claussen carried out system-wide simulations in [24] to investigate the impact of deploying femtocells on existing macrocell networks and the feasibility of their co-channel operation by varying femtocell coverage [39]. The ad hoc locations and dynamic nature of femtocells in the network and the fact that their backhaul connection is most likely run by a third party render centralized coordination between macrocell and femtocells nearly impossible, and so two-tier networks need to adopt decentralized strategies for interference mitigation [22, 40]. To overcome the issue of interference, several cancellation techniques are considered in [41], but soon disregarded due to the large number of cancellation errors. A scheme to avoid cross-tier interference using sectorial antennas at the femtocell base station with time-hopped CDMA to reduce the number of potential interferers is proposed in [26]. In [42] the idea is to select a set of predefined antenna patterns dynamically for optimizing femtocell coverage area based on mobility events of users to lessen femtocell power leakage. However installing more hardware on the antennas only increases the cost of femtocell base stations which is not agreeable with the customers. Therefore interference management schemes based on interference avoidance, such as power control and radio resource management, are preferred.

Co-channel uplink and downlink cross-tier interference can be reduced if a femtocell can avoid using the frequency resources that are being used by nearby macrocell user equipments through efficient spectrum sensing. In [43], Yi Wu et al. examine such a femto-aware spectrum arrangement scheme based on a partial co-channel deployment method under closed access mode, but their scheme turns out to be inefficient at high cellular user density. It is shown in [44] that using fractional frequency reuse, where different reuse factors are applied in cell center and edge regions, downlink cross-tier interference can be avoided by assigning portions of the entire spectrum to those femtocells that are not being used in the macrocell sub-area. But such fixed partitioning degrades the throughput performance due to inefficient usage of spectrum. A distributed channel assignment algorithm for mitigating interference among femtocells, disregarding femto-to-macro cross-tier interference, is given in [45]. Formation of groups of femtocell base stations and exchange of information (such as path-loss, geographical location, etc.) among neighboring femtocells for intelligent spectrum access is also considered [46]. Another interference avoidance framework based on inter-base-station cooperation and collaborative frequency scheduling is proposed in

[47]. However, implementing such co-operative schemes is quite complex and requires large amount of overhead signaling.

Performance analysis of a two-tiered network in terms of capacity and coverage statistics (outage) based on interference management through power control is presented in [48]. Power control algorithms discussed in literature have focused on reducing the power at the femtocell base station to control their impact on nearby macrocell users. For example, a distributed downlink adaptive power control method in heterogeneous wireless networks with macrocells and femtocells based on a Stackleberg game model is analyzed in [49]. A power control approach based on spectrum sensing is introduced in [50], where the femtocell chooses its transmit power based on its distance from macrocell and femtocell density. Uplink power control for femtocell users is considered in [40], where the authors focus on tackling the near-far problem by forcing femto users to reduce their SINR targets and correspondingly decrease their data rate. Such a utility-based non-cooperative femtocell SINR adaptation is related to existing game theory literature on non-cooperative power control [51]. Prior femtocell research on interference mitigation has also proposed hybrid frequency assignments [52] and adjusting the maximum transmit power of femtocell users [53]. In contrast, this thesis addresses a decentralized strategy for interference management, that is, access control with transmit power regulation in femtocell networks [19, 27, 37].

C. Access Control in Femtocell Networks

The context of interference in a macrocell-femtocell network is defined by the type of access control employed for femtocells, which decides who gets to access the femtocell. Access control mechanisms play a crucial role in mitigating cross-tier interference and avoiding additional handover attempts. The benefits and drawbacks of existing methods for access control in femtocell networks are described in [19]. Selection of an appropriate access mechanism, depending on the user profile and the scenario under consideration, can dramatically influence the capacity and performance of the overall network [19, 20]. So far, only closed access femtocells, referred to as closed subscriber group by 3GPP [54], have been deployed. Closed access ensures only subscribers monopolize their femtocell resources such as backhaul and capacity, guarantees both privacy and security and so, it is mostly preferred by home users. However, prohibiting access to other neighboring users implicitly introduces interference into the system further complicating the problem of interference mitigation. Typically, cell-edge macrocell user equipments transmitting near a closed access femtocell create an uplink deadzone problem. A worst case scenario is when an unsubscribed macrocell user equipment enters a house hosting a closed subscriber group femtocell resulting in powerful cross-tier interference on both uplink and downlink. In dense femtocell deployments, severe co-tier interference can also be experienced when a user installs a femtocell in the immediate vicinity of another closed access mode femtocell that is already in use. Open/hybrid access mechanisms are being considered in order to mitigate both cross-tier and co-tier interference caused by closed access in femtocell networks.

Open access guarantees that the user is always connected to the strongest server, and so cell-edge macrocell user equipments that cause strong macro-to-femto interference can be handed in to a neighboring femtocell. Chandrashekhar et al. [26] claim that tier based open access helps in mitigating uplink cross-tier interference and improves network-wide area spectral efficiency resulting in increase in overall network capacity. Similar results are suggested based on extensive simulation-centric studies conducted by the 3GPP RAN 4 group [55, 56, 57]. On the flip side, open access negatively impacts the performance of femto owners who now have to share their resources with other users. It may potentially deteriorate the QoS provided to remaining cellular users due to increased femto-to-macro interference from the handed over cellular users [37]. Open access also substantially increases the number of handovers between cells due to the movement of outdoor users which is unfavorable to network operators as it results in increase in signaling overhead as well as call drops due to handover failures. Moreover, pricing management becomes complicated for operators as femtocell subscribers may not be willing to support the unregistered users for free.

From the above discussion, it seems like femtocell subscribers prefer closed access in order to reserve all the femtocell resources to themselves, while open access is the preferred approach for the network operators as it enhances the overall network throughput and enables offloading traffic from the macrocell as well. A comparative analysis of femtocell open and closed access schemes under different scenarios is presented in [55]; Network performance and downlink capacities under both closed and open access modes are explored in [56]; Feasible combinations of femtocells and macrocells under the constraint of network interference are examined in [57]. The results derived in these papers suggest that, in reality, choosing an appropriate access mode is arguably more complicated. Rather than a fixed access control scheme like open or closed access, adaptive open access is more effective in interference mitigation in two-tier networks enabling co-channel deployment of femtocells. However, increased handover frequency and resulting overhead signaling is still a possible challenge to the implementation of an adaptive open access scheme. An open access method with an upper limit on the femtocell resources allocated to cellular users is examined in [19], while López-Pérez et al. [28] propose combining intracell handovers with power control to significantly reduce the number of handovers in open access and mitigate cross-tier interference in co-channel deployment of OFDMA femtocells.

Since femtocells are installed by users out of their own self-interest, it is important to ensure that the benefits of reduced interference with adaptive open access are not undermined by the loss of femtocell resources. Hence, optimization of femtocell resource allocation should be incorporated into the process of selecting femtocell access control. Based on simulations of open and closed access in HSDPA, taking into account both femtocell backhaul constraints and cross-tier interference, [27] concludes that open access with a restriction on the number of supported users at the femtocell base station is the preferred approach. Similar results are proved on the uplink by Andrews et al. in [37] and they also demonstrate that choice of access control mechanism is largely influenced by the underlying multiple access technology, CDMA or OFDMA. It is shown that in case of a non-orthogonal multiple access scheme like CDMA, open access is the unanimous choice of access control as it provides more than 300% rate gain to the home user and does not require femtocells to adopt adaptive resource allocation to realize these benefits. Conversely, in TDMA/OFDMA, the choice of femtocell access control is highly sensitive to the cellular user density [37, 58], and so while deploying TDMA/OFDMA femtocells, the access control as well as femtocell resource allocation should be adapted according to the current cellular user density. But as the authors clearly point out, these conclusions are contingent on absence of any inter-base-station coordination in terms of power control and user scheduling. Their conjecture is that open access with coordination between macrocell and femtocells will be the suitable approach in high cellular user density. In this thesis, we are interested in testing their hypothesis by combining the problem of uplink power control with a hybrid access control mechanism that involves optimizing resource allocation in femtocells. Our algorithm builds on prior research on power control and SINR feasibility in conventional cellular systems presented by Foschini et al. [59], Zander [60], Grandhi et al. [61], [62] and Bambos et al. [63]. Associated results on centralized/distributed/constrained power control, admission control and base station assignment are presented in [59, 60, 62], [64]–[71].

D. Thesis Contribution

To cope with the problem of interference in co-channel deployment of femtocells, this thesis defines a fully distributed algorithm for hybrid access control in the uplink in a two-tier OFDMA femtocell network. The objective is to evaluate the expected system performance of the proposed access scheme given a celluar user and femtocell density, from the perspective of both femtocell subscriber (femto owner's average rate) and the network operator (cellular users' sum throughput). We adopt an approach similar to that presented in [58] with an upper limit, K, on the number of cellular users allowed on a femtocell. Instead of using fixed transmit power on the uplink, we integrate the problem of base station assignment with distributed standard iterative uplink power control with a fixed target SINR requirement based on the work of Yates et al. [64, 65]. Using well known results on the decomposition of power control and resource allocation [72, 73, 74]; at each iteration our algorithm we formulate the problem of allocating femtocell resources, which in our system model correspond to time slots on the OFDM subcarrier, as a constrained maximization of a weighted sum-rate objective function. We also consider maximization of a proportionally fair log utility function, as a tradeoff between throughput efficiency and allocation fairness in femtocells. Finally, we discuss some important results on rate of convergence of distributed algorithms using fixed point iterations with standard interference functions [64, 75] and examine the number of iterations required for convergence of our proposed scheme, given a cellular user and base station density.

E. Organization of Thesis

The remainder of the thesis is organized as follows. In Chapter II, we review some basic theory on distributed iterative power control algorithms and standard interference functions as defined by Yates [64]. We describe both the fixed base station assignment algorithm used by the femto subscriber and the minimum power assignment algorithm in the context of a cellular user under a maximum transmit power constraint. Prior literature on resource allocation algorithms in OFDMA networks that solve the problem of user scheduling, with regard to assigning time slots, for fixed transmit power is presented in Chapter III. The problem of femtocell resource allocation as both a constrained sum-rate optimization and maximization of a proportionally fair utility function is discussed. In Chapter IV, we describe the system model and assumptions; the handover metrics and iterative procedure employed in our hybrid access algorithm are explained in detail. Numerical results, based on system-wide simulations, quantifying the improvement in network capacities by using hybrid access control in a macrocell-femtocell network in comparison with open and closed access are also summarized in Chapter IV. In Chapter V, we analyze the rate of convergence of our proposed distributed iterative algorithm for hybrid access control by varying the cellular user and femtocell base station density. Finally, we provide our conclusions and possible extensions in Chapter VI.

CHAPTER II

STANDARD ITERATIVE POWER CONTROL ALGORITHMS

An important component of resource management in a communication system is power control. Transmit power is a key degree of freedom in conserving energy, preserving network connectivity and reducing interference, typically in cellular networks. Co-channel interference is one of the major restraining factors in achieving high user density in wireless communication systems. The adaptive control of transmission power enables user devices to maintain an acceptable connection and satisfy their QoS requirements, while limiting the interference seen by other users. Power control has been shown to increase the call carrying capacity for channelized systems [66], as well as in CDMA systems [59, 62] through efficient spectral reuse. Prior work on both uplink and downlink power control, in [59, 61, 66], provide a wide and deep set of results in terms of modeling, analysis, and design of cellular systems and ad hoc networks. In this thesis, we consider the power control problem on the uplink, that is from the mobile user equipment to its base station. In cellular network engineering, power control on uplink is crucial since minimizing power consumption of mobile devices is more important than base station's transmit power. Moreover, base stations can ensure orthogonality of resources allocated to mobile devices within their coverage area and so, intra-cell interference on the downlink can be limited more easily than on the uplink.

The uplink power control problem is set up in a general multi-cell network framework with $\mathcal{M} = \{1, 2, ..., M\}$ base stations and $\mathcal{N} = \{1, 2, ..., N\}$ users, where, at any given time, each user is served by only one of the M base stations. Let $m_i \in \mathcal{M}$ be the receiving base station with which user $i \in \mathcal{N}$ is associated. Let S_i be the set of users in the system that cause interference on the uplink to user i. In an orthogonal multiple access scheme such as TDMA/OFDMA, users being served by the same base station as user i do not interfere with each other and so, $S_i := \{j \mid m_j \neq m_i\}$. The term $h_{i,j}$ denotes the channel gain between user j and base station m_i, and correspondingly we define the $N \times N$ normalized channel gain matrix $\mathbf{G}$ where

$$G_{i,j} = \begin{cases} \frac{h_{i,j}}{h_{i,i}}, & j \in S_i \\ 0, & \text{otherwise} \end{cases} \tag{2.1}$$

We designate user i's non-negative uplink transmit power level as p_i watts. Let σ_i be the noise power at base station m_i. The total interference and noise to user i at base station m_i is given by

$$q_i = \sum_{j \in S_i} p_j h_{i,j} + \sigma_i = \sum_{j \in S_i} p_j G_{i,j} h_{j,j} + \sigma_i \tag{2.2}$$

and so, the received SINR γ_i of user i at its serving base station m_i is

$$\gamma_i = \frac{p_i h_{i,i}}{q_i} \tag{2.3}$$

Suppose $\mathbf{D_h} = \text{diag}(h_{1,1}, h_{2,2}, ..., h_{N,N})$ and $\mathbf{D}(\boldsymbol{\gamma}) = \text{diag}(\gamma_1, \gamma_2, ..., \gamma_N)$, then combining (2.2) and (2.3) we get the following *basic equations* in matrix notation

$$\mathbf{q} = \mathbf{G}\mathbf{D}(\boldsymbol{\gamma})\mathbf{q} + \boldsymbol{\sigma} \tag{2.4}$$

$$\mathbf{D_h}\mathbf{p} = \mathbf{D}(\boldsymbol{\gamma})\mathbf{G}\mathbf{D_h}\mathbf{p} + \mathbf{D}(\boldsymbol{\gamma})\boldsymbol{\sigma} \tag{2.5}$$

A power control problem formulated over a period of time for a target equilibrium is often modeled as an optimization problem with transmit power $\mathbf{p}$ as a decision variable. The objective function chosen is of form $U(\boldsymbol{\tau})$, where $\boldsymbol{\tau}$ denotes a QoS metric, such as SINR which is in turn a function of the transmit powers. It is assumed that the objective function is additive across all users in the system and locally dependent: $U(\boldsymbol{\tau}) = \sum_i U_i(\boldsymbol{\tau_i})$. For technical reasons, a primary constraint is imposed on maximum transmit power $p_{\max,i}$ for every user i; in particular, we have $0 \leq p_i \leq p_{\max,i}$ for every user i. Another constraint enforced in the optimization problem is based on users' inelastic requirements, for example a minimum target SINR at the serving base station of a user.

A more complex class of constraints on QoS feasibility region may also be considered, related to the feasible SINR region. An SINR vector $\boldsymbol{\gamma}$ is said to be feasible if there exists an interference vector $\mathbf{q} \geq 0$ and a transmit power vector $\mathbf{p} \geq \mathbf{0}$ that satisfy (2.4) and (2.5), respectively. Further, it is assumed that $\mathbf{G}$ is primitive or that its directed graph is strongly connected [76]. Suppose $\rho(\cdot)$ denotes the spectral radius function of such a positive, primitive matrix, Zander shows in [66] that an SINR vector $\boldsymbol{\gamma}$ is feasible if and only if $\rho(\mathbf{GD}(\boldsymbol{\gamma})) < 1$, when $\boldsymbol{\sigma} \neq 0$ and $\rho(\mathbf{GD}(\boldsymbol{\gamma})) = 1$, when $\boldsymbol{\sigma} = 0$. But, when the network is heavily loaded, setting the target $\boldsymbol{\gamma}$ to be feasible becomes challenging. Besides, network operators may also want to give more preference to high tariff paying users by putting them in high QoS classes and so optimizing the SINR assignment according to the user density and channel conditions is important [69]. Nevertheless, in this thesis, we do not consider the problem of joint SINR assignment and power control. Instead, we work under the framework of fixed SINR based on the minimum QoS requirements of users.

Early work considered non-iterative, synchronous and centralized algorithms in which the power control problem is described as an eigenvalue problem for a non-negative matrix [61, 66]. The optimal power vector was found by matrix inversion performed by a central controller, which is fully aware of channel gains of all users. Due to the computational complexity of these centralized power control algorithms, distributed versions have been developed which rely only on local information [59, 60, 64, 77]. In two-tier femtocell networks, it is difficult to coordinate femtocell and macrocell base stations in a centralized manner to regulate transmit power. Accordingly, this thesis focuses on convergent, distributed and iterative power control algorithms. In the following sections, we review some main results related to distributed iterative power control for the deterministic channel in cellular systems [59] and then we formulate the power control problem in the context of our macrocell-femtocell network.

A. Distributed Power Control with Fixed SINR

Prior research on power control focuses on voice and data transmission where the required QoS objective is to attain a predetermined target SINR at the receiving base station [59, 63]. For a given SINR requirement $\mathbf{\Gamma}$, capacity can be maximized by SINR balancing, that is adjusting the transmission power such that all links operate at a common SINR [78]. The starting point for much of the research in distributed power control is an iterative algorithm proposed by Foschini and Miljanic [59], which describes a constant SINR approach. At its core, this approach is competitive – each link attempts to continuously maintain its target SINR by overcoming the interference presented by all the other signals. A simple system model is considered where each user is assumed to have a fixed gain to its assigned base station as well as to all other base stations in the network. The deterministic channel model is based on the assumption that the power adaptation interval is substantially longer than the fluctuation periods in the wireless channel between users. The power control problem is formulated as a minimum transmit power optimization:

$$\begin{aligned} \text{minimize} \quad & \sum_i p_i \\ \text{subject to} \quad & \text{SINR}_i(\mathbf{p}) = \frac{p_i h_{i,i}}{\sum_{j \in S_i} p_j h_{i,j} + \sigma_i} \geq \Gamma_i \quad \forall i \\ \text{and} \quad & p_i \geq 0 \quad \forall i \end{aligned} \tag{2.6}$$

where each user i attains its individual target SINR requirement, Γ_i, at its assigned base station m_i, while minimizing its own transmit power level and respecting the QoS constraints of other users. Setting the transmit power of user to a value no more than that required in meeting a minimum SINR constraint per user eliminates unnecessary interference which is important for maximizing frequency reuse in a multicell environment. The SINR constraint can be represented in matrix form with componentwise inequalities,

$$(\mathbf{I} - \mathbf{D}(\boldsymbol{\Gamma})\mathbf{G})\mathbf{p} \geq \boldsymbol{\eta} \text{ with } \mathbf{p} \geq 0 \tag{2.7}$$

where $\mathbf{I}$ is the identity matrix, $\mathbf{D}(\boldsymbol{\Gamma}) = \mathrm{diag}(\Gamma_1, \Gamma_2, ..., \Gamma_N)$ is the minimum SINR threshold, $\mathbf{G}$ is the normalized channel gain matrix (2.1) and

$$\boldsymbol{\eta} = \left(\frac{\Gamma_1 \sigma_1}{h_{1,1}}, \frac{\Gamma_2 \sigma_2}{h_{2,2}}, ..., \frac{\Gamma_N \sigma_N}{h_{N,N}} \right)$$

is the vector of noise power scaled by the SINR constraints and channel gains. Under the assumption that the the matrix $\mathbf{D}(\boldsymbol{\Gamma})$ is elementwise non-negative and irreducible, from the Perron-Frobenius theorem and standard matrix theory [79], we have the following equivalent statements for SINR feasibility:

(i) The Perron-Frobenius eigenvalue $\rho(\mathbf{D}(\boldsymbol{\Gamma})\mathbf{G}) < 1$;

(ii) There exists a transmit power vector $\mathbf{p} \geq 0$ such that $(\mathbf{I} - \mathbf{D}(\boldsymbol{\Gamma})\mathbf{G})\mathbf{p} \geq \boldsymbol{\eta}$;

(iii) The inverse $(\mathbf{I} - \mathbf{D}(\boldsymbol{\Gamma})\mathbf{G})^{-1} = \sum_{k=0}^{\infty} \mathbf{D}(\boldsymbol{\Gamma})\mathbf{G}^{\mathbf{k}}$ exists and is componentwise positive with $\lim_{k\to\infty} (\mathbf{D}(\boldsymbol{\Gamma})\mathbf{G}) = 0$.

Furthermore, if the fixed target SINR $\boldsymbol{\Gamma}$ is feasible then, we have that $\mathbf{p}^* = (\mathbf{I} - \mathbf{D}(\boldsymbol{\Gamma})\mathbf{G})^{-1}\boldsymbol{\eta}$ is a Pareto optimal solution to (2.7). That is, if $\mathbf{p}$ is any other feasible solution to (2.7), then $\mathbf{p} \geq \mathbf{p}^*$ componentwise and so, $\mathbf{p}^*$ minimizes the total power consumption of all users. We note that previous work on this power control algorithm refer to the above optimality criteria as Pareto optimal, hinting at a utility maximization formulation of the problem. In fact, the above listed conditions for SINR feasibility guarantee *global* power optimality for every user in the network under (2.6).

Foschini and Miljanic [59] describe a simple power control algorithm for the users in the network and as long as $\rho(\mathbf{D}(\mathbf{\Gamma})\mathbf{G}) < 1$, this iterative algorithm will always result in exponentially fast convergence to $\mathbf{p}^*$, otherwise it diverges to infinity.

$$\mathbf{p}[t+1] = \mathbf{D}(\mathbf{\Gamma})\mathbf{G}\mathbf{p}[t] + \boldsymbol{\eta}$$

for $t \in \{1, 2, ...\}$. The above algorithm can be simplified into the following distributed version where each user iteratively sets its power level to attain an acceptable connection assuming other users keep their power constant

$$p_i[t+1] = \frac{\Gamma_i}{\mathrm{SINR}_i[t]} p_i[t]$$

for each user $i \in \mathcal{N}$. In this sense, the algorithm is fully distributed as each user makes its power decision for the next step autonomously; the next power level chosen is simply a function of the users individual SIR target, its current power level, and its own observed SINR. The distributed power control algorithm and all the variants discussed later, are fairly practical in that the iteration step can be written as

$$p_i[t+1] = \frac{\Gamma_i[R_i[t] - h_{i,i}p_i[t]]}{h_{i,i}}$$

where $R_i[t] = \sum_j h_{i,j}p_j[t] + \sigma_i$ is the total received power at base station m_i using power vector $\mathbf{p}[t]$. If the uplink and downlink face the same attenuation, the user i can estimate its uplink channel gain $h_{i,i}$ from a downlink pilot tone from its base station m_i. Furthermore, the downlink channel can also provide user i with the total received power (signal plus noise) at m_i. The landmark result shown in [59] is that this decentralized power update algorithm also converges to the global optimum $\mathbf{p}^*$. Thus, in ad hoc network deployments such as heterogeneous networks, robust and reliable QoS can be provided to all users by utilizing distributed power control algorithms.

B. Standard Interference Function

A general framework for uplink power control is presented by Yates in [64]. This framework identifies a wide class of iterative algorithms and derives convergence results for both synchronous and asynchronous versions of the power control iteration. The target SINR constraint for users is described by a vector inequality of interference constraints of the form

$$\mathbf{p} \geq \mathbf{I}(\mathbf{p}) \tag{2.8}$$

where $I_i(\mathbf{p})$ represents the effective interference that user i must overcome. We define $m_i = k$ if user i is assigned to base station $k \in \mathcal{M}$. Let $\mu_{k,i}(\mathbf{p})$ be the normalized received SINR of user i at base station k under power allocation vector $\mathbf{p}$. Then, given that user i's fixed target SINR is Γ_i, we have

$$I_i(\mathbf{p}) = \frac{\Gamma_i}{\mu_{k,i}(\mathbf{p})} = \frac{\Gamma_i}{h_{k,i}} \left(\sum_{j \in S_i} h_{k,j} p_j + \sigma_k \right)$$

For a system with these interference constraints, the iterative power control algorithm is given by

$$\mathbf{p}[t+1] = \mathbf{I}(\mathbf{p}[t]) \tag{2.9}$$

A power vector $\mathbf{p} \geq 0$ is feasible if $\mathbf{p}$ satisfies (2.8), and an interference function $\mathbf{I}(\mathbf{p})$ is feasible if (2.8) is satisfied. The feasibility index $\boldsymbol{R_I}$ of a standard interference function $\mathbf{I}(\mathbf{p})$ is

$$\boldsymbol{R_I} = \max\{c \in \mathbb{R} \mid \mathbf{p} \geq c\mathbf{I}(\mathbf{p}) \text{ for some feasible } \mathbf{p}\}$$

A standard interference function $\mathbf{I}(\mathbf{p})$ is feasible if and only if $\boldsymbol{R_I} \geq 1$ [67]. In the case when $\mathbf{I}(\mathbf{p})$ is infeasible, [63, 77] address the admission control problem of finding a subset of users that can attain acceptable connections.

Yates analyzes the convergence results for a *standard interference function* $\mathbf{I}(\mathbf{p})$ that satisfies the following three properties:

i) *Positivity*: $\mathbf{I}(\mathbf{p}) > 0$.

ii) *Monotonicity*: If $\mathbf{p} \geq \mathbf{p'}$, then $\mathbf{I}(\mathbf{p}) \geq \mathbf{I}(\mathbf{p'})$.

iii) *Scalability*: For all $\alpha > 1$, $\alpha\mathbf{I}(\mathbf{p}) \geq \mathbf{I}(\alpha\mathbf{p})$.

The positivity property is implied by non-zero background receiver noise. The monotonicity property suggests that when user i reduces his transmit power, then all other users will benefit from this power reduction. Scalability implies that if user i is able to meet his SINR constraint under transmit power vector $\mathbf{p}$, then he will have a more than acceptable connection when all transmit powers are uniformly scaled up by a factor α. When $\mathbf{I}(\mathbf{p})$ is a standard interference function, then iteration (2.9) is referred to as the *standard power control algorithm*.

Starting from an initial power vector $\mathbf{p}$, n iterations of the standard power control algorithm result in the power vector $\mathbf{I}^n(\mathbf{p})$. The convergence properties for the sequence $\mathbf{I}^n(\mathbf{p})$ are presented in [64]. Yates proved that if the standard power control algorithm has a fixed point, then that fixed point is unique and if $\mathbf{p}$ is a feasible power vector, then $\mathbf{I}^n(\mathbf{p})$ is a monotone decreasing sequence of feasible power vectors that converges to a unique fixed point $\mathbf{p^*}$. This implies that $\mathbf{p} \geq \mathbf{p^*}$ for any feasible power vector $\mathbf{p}$, that is, the fixed point $\mathbf{p}^*$ is the solution of $\mathbf{p} \geq \mathbf{I}(\mathbf{p})$ corresponding to minimum transmit power vector. The feasibility of $\mathbf{I}(\mathbf{p})$ implies the existence of a unique fixed point $\mathbf{p}^*$. The generalized result derived in Yates' work on standard interference functions is summarized below.

Theorem 2.1. *(Yates [64]). Starting from any initial power vector* $\mathbf{p}$*, the standard power control algorithm converges to a unique fixed point, provided a feasible solution exists.*

It is shown in [64], that the above result holds true in both synchronous and asynchronous version of the standard power control algorithm. The asynchronous algorithm, based on the model developed by Bertsekas and Tsitsiklis in [80], allows users to update their transmit power using outdated measurements of the interference caused by other users. When the target SINR is feasible, as defined by the interference function of the system, then both the synchronous and asynchronous standard power control algorithms will find the minimum power solution.

Under fixed assignment, we denote B_i as the base station assigned to user i in the system, which is assumed to be fixed. The interference function is denoted by $\mathbf{I}^{\mathrm{FA}}$ and the SINR requirement of user i is written as

$$p_i \geq I_i^{\mathrm{FA}}(\mathbf{p})$$

In [59, 61, 66, 78], analytical approaches to attaining a common SINR or maximizing the minimum SINR are considered. For fixed SINR, the constraint set of the max-min SINR problem is a cone of feasible power vectors. Figure 4 shows the feasible region for a system of two users assigned to their respective base stations, where $p_i = [\mathbf{D}(\mathbf{\Gamma})\mathbf{G}]_i^{(k)}\mathbf{p} + \eta_i^{(k)}$ is the minimum power user i needs to communicate with base station k. The distributed power control algorithm described by Foschini and

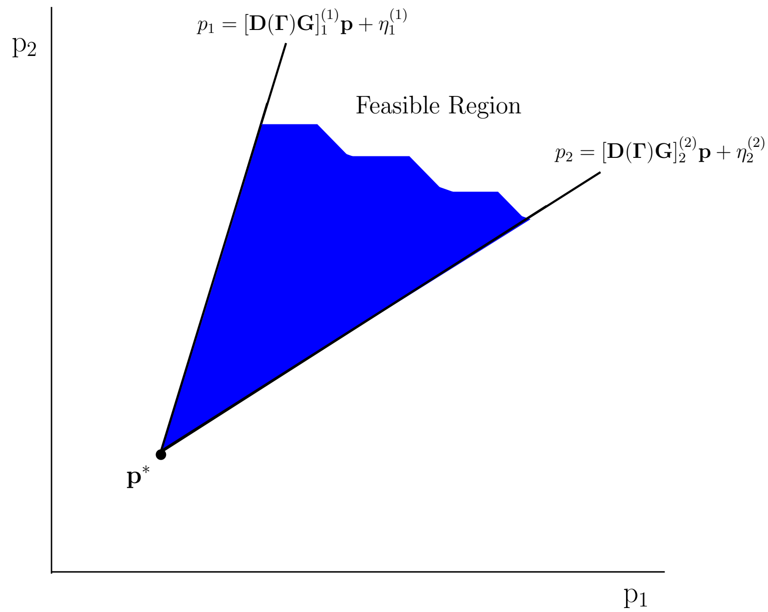

Fig. 4. Feasible region for an instance of fixed base station assignment.

Miljanic [59] and Zander [60] solves the subproblem of finding a feasible transmit power vector $\mathbf{p}$ for a fixed common SINR target and a fixed base station assignment with the standard power control iteration: $\mathbf{p}[t+1] = \mathbf{I}^{\text{FA}}(\mathbf{p})[t]$. These methods find the power vector $\mathbf{p} = \mathbf{p^*}$, the vertex of the cone of feasible powers. It can be readily verified that $\mathbf{I}^{\text{FA}}(\mathbf{p})$ is a standard interference function with

$$I_i^{\text{FA}}(\mathbf{p}) = \frac{\Gamma_i}{h_{B_i,i}} \left(\sum_{j \in S_i} h_{B_i,j} p_j + \sigma_{B_i} \right) \quad \forall i$$

and thus, the algorithm defined in [59] converges for both synchronous and asynchronous versions, provided that there exists a feasible solution.

The assumption of fixed base station made in previous work [59]–[61] is not truly realistic as channels and base stations can be reassigned to users at any time, even when a call is in progress. Yates and Huang [65], consider the combined problem of regulating transmit powers and assigning base stations to devices using a minimum power assignment algorithm. The received SINR of user i at its serving base station thus becomes, a function of both transmit power allocation $\mathbf{p}$ and base station assignment $\mathbf{b}$. The optimization framework for distributed power control with fixed SINR target $\mathbf{\Gamma}$ considered earlier (2.6) is modified in order to include base station assignment $\mathbf{b}$ as another optimization variable:

$$\begin{aligned} \text{minimize} \quad & \sum_i p_i \\ \text{subject to} \quad & \text{SINR}_i(\mathbf{p}, \mathbf{b}) = \frac{p_i h_{b,i}}{\sum_{j \in S_i(\mathbf{b})} p_j h_{b,j} + \sigma_b} \geq \Gamma_i, \quad \forall i \\ & p_i \geq 0 \quad \forall i \\ & b \in \Omega_i, \quad \forall i \end{aligned}$$

where $S_i(\mathbf{b})$ is set of users interfering with user i under base station assignment $\mathbf{b}$ and Ω_i is a set of feasible base station assignments for user i. The minimum transmit power in this context can be viewed as minimization over the set of feasible power vectors and base station assignments. The feasible region is typically not a convex set and so standard approached for convex optimization are not directly applicable. Figure 5 describes the feasible region under minimum power assignment for a system of two users and two base stations. Four base station assignments are possible, corresponding to the four cones with vertices labeled $p^{(i)}$, $i \in \{1, 2, 3, 4\}$ and the union of shaded region depicts the non-convex feasible region. The SINR constraint of user i is $\max_b \, p_i \mu_{b,i}(\mathbf{p}) \geq \Gamma_i$, which can be written as

$$p_i \geq I_i^{\text{MPA}}(\mathbf{p}) = \min_b \; M_i^b(\mathbf{p})$$

where

$$M_i^b(\mathbf{p}) = \frac{\Gamma_i}{h_{b,i}} \left(\sum_{j \in S_i(\mathbf{b})} h_{b,j} p_j + \sigma_b \right)$$

Each user updates its transmit power and base station assignment under the assump-

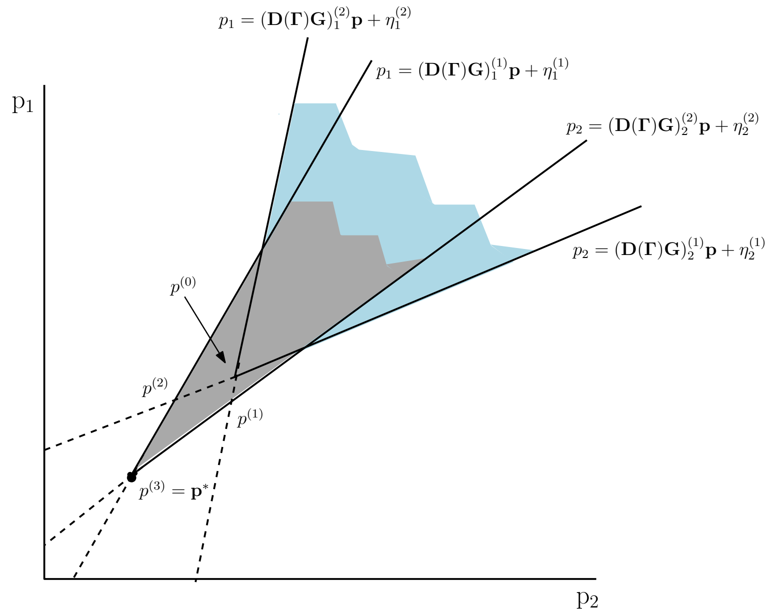

Fig. 5. Feasible region for an instance of minimum power assignment.

tion that the remaining users keep their powers fixed. At each iteration, a cellular user is assigned to the base station at which minimum transmit power is required to maintain its target SINR.

$$\mathbf{p}[t+1] = \mathbf{I}^{\text{MPA}}(\mathbf{p}[t]) \quad \text{and} \quad \mathbf{b}[t+1] = \mathbf{B}^{\text{MPA}}(\mathbf{p}[t]) \tag{2.10}$$

where $B_i^{\text{MPA}} = \text{argmin}_b \; M_i^b(\mathbf{p})$. The minimum power assignment can also be considered as a generalization of soft handoff. Huang and Yates [65] show that the joint power control and base station assignment update algorithm in (2.10) is a standard interference function. Provided a feasible solution exists and starting from any initial power vector $\mathbf{p}$, convergence to a unique fixed point $(\mathbf{p^*, b^*})$ that solves the minimum power assignment problem is guaranteed.

Yates also examines convergence results for extensions to the existing framework of standard interference functions discussed above. An important generalization is in terms of maximum and minimum power constraints on users in the system. Given a standard interference function $\mathbf{I}(\mathbf{p})$ and a maximum transmit power constraint $p_{\max,i}$ on user i, the constrained interference function $\mathbf{I}^{p_{\max}}(\mathbf{p}) = (I_1^{p_{\max}}(\mathbf{p}), ..., I_N^{p_{\max}}(\mathbf{p}))$ is defined as

$$I_i^{p_{\max}}(\mathbf{p}) = \min\{p_{\max,i}, I_i(\mathbf{p})\} \tag{2.11}$$

and the standard constrained power control iteration is given by $\mathbf{p}[t+1] = \mathbf{I}^{p_{\max}}(\mathbf{p}[t])$. Yates shows that if $\mathbf{I}(\mathbf{p})$ is standard, then $\mathbf{I}^{p_{\max}}(\mathbf{p})$ is also standard. However, in this case, satisfying the SINR constraint $\mathbf{p} \geq \mathbf{I}^{p_{\max}}(\mathbf{p})$ does not guarantee an acceptable connection. When $\mathbf{I}(\mathbf{p})$ is infeasible, then the constrained power control iteration is guaranteed to converge, allowing for detecting infeasibility in the system. The convergence results for standard constrained interference functions are derived for fixed base station assignment [62] and minimum power assignment [65].

Another useful extension is interference averaging, which is done to reduce the fluctuations in transmitter powers possibly due to inaccurate measurements. Given a standard $\mathbf{I}(\mathbf{p})$ and a constant $\theta \in (0, 1]$, the standard interference averaging power control iteration is defined as

$$\mathbf{p}[t+1] = \mathbf{I}^{\mathrm{av}}(\mathbf{p}[t]) = \theta\mathbf{I}(\mathbf{p}[t]) + (1-\theta)\mathbf{p}[t] \tag{2.12}$$

Yates verifies that if $\mathbf{I}(\mathbf{p})$ is standard, then $\mathbf{I}^{\mathrm{av}}(\mathbf{p})$ is also a standard interference function that converges to a fixed point $\mathbf{p}^*$ that satisfies $\mathbf{p}^* = \mathbf{I}^{\mathrm{av}}(\mathbf{p}^*)$. Other extensions to standard iterative power control are also considered, such as active link protection [63] and hybrid interference functions, but we shall use (2.11) and (2.12) in our algorithm defined in Chapter IV. The standard power control iteration in a two-tier macro/femto network is described in the next section.

C. Iterative Power Control in a Two-Tier Femtocell Network

In a two-tier network, cross-tier interference can significantly deteriorate the performance and capacity of the system. Efficient decentralized radio resource management schemes in femtocell networks are critical in order to guarantee a certain target QoS, maintain the planned coverage area, and at the same time offer high network capacity. Controlling cross-tier interference in co-channel macro/femto networks through power control is suggested in [40, 48, 53]. Andrews et al. [40] propose a distributed utility based SINR adaptation at femtocells in order to mitigate femto-to-macro interference. Our objective is not to reduce the received SINR of any user, but rather we are interested in guaranteeing all users a fixed SINR target at their serving base station. Therefore, in our algorithm we employ a distributed iterative power control for regulating the transmit powers of all users, both femto owners and cellular users, such that total transmit power is minimized and each user attains a fixed target SINR at its serving base station. Such schemes fall within the general framework for uplink power control provided by Yates [64].

Suppose that the N cellular users are indexed $\mathcal{U}_{\mathrm{c}} = \{1, 2, ..., N\}$ and the M femtocells distributed through the cell site are denoted by set $\mathcal{B}_{\mathrm{FAP}} = \{2, 3, ..., M+1\}$. The set of all base stations, the central macrocell base station and the M femtocells, is labeled $\mathcal{B} = \{1, 2, ..., M+1\}$. Correspondingly the M femto owners are indexed $\mathcal{U}_{\mathrm{f}} = \{N+1, ..., N+M\}$. In our setup, we consider co-channel deployment of OFDMA femtocells and so, users being served by the same base station are mutually orthogonal. For a given cellular user density, the common target SINR for all cellular users is Γ_{c} and femto owners have a fixed SINR target of Γ_{f}. The power control iterations used for both femto owners and cellular users is explained in detail below.

1. Fixed Base Station Assignment

As femtocells are deployed by consumers in their own interest, it is rational to assume that the femto owner is always connected to its own femtocell. At any iteration of the power control algorithm, let $\mathcal{U}_{\text{macro}}$ be the set of cellular users associated with the macrocell base station. Each cellular user $j \in \mathcal{U}_{\text{macro}}$ causes interference to the femto owner on the uplink during its time slot, $1/N_{\text{macro}}$, where $N_{\text{macro}} = |\mathcal{U}_{\text{macro}}|$. Ignoring co-tier interference between femtocells for analytical tractability, the received SINR of femto owner i at its own femtocell base station $\mathcal{B}^i_{\text{FAP}} = k$ is

$$\text{SINR}_{k,i} = \frac{h_{k,i}p_i}{\sum_{j \in \mathcal{U}_{\text{macro}}} \frac{1}{N_{\text{macro}}} h_{k,j}p_j + \sigma_k} \tag{2.13}$$

and the standard distributed constrained power control iteration, with a maximum transmit power constraint $p_{\max,i}$, for femto owner i connected to femtocell k, which is fixed, is given by

$$p_i[t+1] = I_i^{\text{CFA}}[t] = \min\left\{\frac{\Gamma_{\text{f}}}{\text{SINR}_{k,i}[t]}p_i[t],\ p_{\max,i}\right\} \tag{2.14}$$

2. Minimum Power Assignment

In our hybrid access control algorithm, the cellular user employs minimum power assignment algorithm with a maximum transmit power constraint of $p_{\max,i}$ in order to select the base station at which minimum power is required to satisfy its QoS requirements. Let the set of users connected to a femtocell $k \in \mathcal{B}_{\text{FAP}}$ be $\mathcal{U}^k_{\text{FAP}}$. We denote the time fraction on OFDM subcarrier occupied by each user $j \in \mathcal{U}^k_{\text{FAP}}$ with $x_{k,j}$. The received SINR of a macrocell user $i \in \mathcal{U}_c$ at the macrocell base station is given by

$$\text{SINR}_{1,i} = \frac{h_{1,i}p_i}{\sum_{k=2}^{M+1} \sum_{j \in \mathcal{U}^k_{\text{FAP}}} x_{k,j}h_{1,j}p_j + \sigma_1} \tag{2.15}$$

At any other femtocell base station $k \in \mathcal{B}_{\text{FAP}}$, the received SINR is given by the (2.13). Then the standard distributed constrained power control iteration for the minimum power assignment algorithm is

$$p_i[t+1] = I_i^{\text{CMPA}}[t] = \min\left\{\min_{b\in\mathcal{B}}\left\{\frac{\Gamma_{\text{c}}}{\text{SINR}_{b,i}[t]}p_i[t]\right\},\ p_{\max,i}\right\} \tag{2.16}$$

and the corresponding base station assignment at each iteration is

$$b_i[t+1] = \arg\min_{b\in\mathcal{B}}\left\{\frac{\Gamma_{\text{c}}}{\text{SINR}_{b,i}[t]}p_i[t]\right\} \tag{2.17}$$

It is important to note that the cellular user is not physically assigned to a base station at the end of each iteration of our constrained minimum power assignment algorithm, but instead the optimal transmit power and base station assignment of the user is determined from the value to which the algorithm converges. Combining base station assignment with distributed uplink transmit power regulation for cellular users provides for hybrid/open access control of femtocells with coordination among the two tiers in terms of power control. The power control iteration for both femto subscribers as well as the cellular users is interlinked with the problem of femtocell resource allocation described in Chapter III, which decides the optimal fraction of time resources to be allotted to users connected to a femtocell at each iteration.

CHAPTER III

FEMTOCELL RESOURCE ALLOCATION

In this thesis, we want to evaluate the capacity performance of a two-tier femtocell network under a hybrid access control scheme. The inter-cell interference in a hybrid macro/femto network depends on the underlying access mechanism for femtocells. The importance of incorporating the problem of optimal femtocell resource allocation with the choice of access method, so as to protect the femtocell owner from starvation under hybrid/open access mode, has already been discussed in Chapter I. In a wireless system, there are usually two resources that we need to manage within a femtocell: power and channels. Power is a physical resource that affects both coverage and throughput. In the case of OFDMA, channels are defined as combinations of two physical measures: sub-carriers or time-slots. Most of the initial work on resource allocation and power control in OFDM systems focuses on the downlink case [73, 81]. However, the optimality results derived for the downlink cannot be directly carried over to the uplink because of per-user transmit power constraints on uplink and other network constraints described in [72]. Previous work in the area of resource management on uplink OFDM has considered the joint problem of power control and allocation of sub-carriers [72, 82] using dual decomposition methods. In [83], the authors work on related models by considering utility maximization, where utility is a function of the instantaneous rate achieved by a user. In our work, we divide this combined problem into two sequential optimizations – the uplink transmit power control optimization achieved using distributed iterative algorithms for power control in two-tier networks, presented in Chapter II, and the resource allocation optimization with fixed transmit power for each femtocell in the network model.

The discrete nature of sub-carrier assignments in OFDM systems usually lead to hard integer programming problems and, as such, we relax the integer constraint and instead consider a mathematical abstraction where multiple users can occupy one subcarrier or tone via orthogonal time-sharing. We consider a simplified network model with $\mathcal{M} = \{1, 2, ..., M\}$ base stations and $\mathcal{N} = \{1, 2, ..., N\}$ users on a common OFDM sub-channel, with a maximum power constraint $p_{\max,i}$ on user i. At any given time, a user is associated with only one of the M base stations in the network and each base station $m \in \mathcal{M}$ serves a set $\mathcal{C}_m$ of users, where $\mathcal{C}_m \subseteq \mathcal{N}$. Each user $i \in \mathcal{C}_m$ transmits over the subcarrier in its time slot to its serving base station m with transmit power p_i. The time-slot assignment to users associated with base station m is modeled by a positive vector $\mathbf{x}_m \in \mathbb{R}^{L_m}$, where $L_m = |\mathcal{C}_m|$. Here, $x_{m,i}$ is the fraction of the OFDM sub-channel allocated by base station m to user i, where the total allocation across all users should be no larger than 1, i.e., $\sum_{i\in\mathcal{C}_m} x_{m,i} \leq 1$. We recall from Chapter II that our objective for power control is to achieve a fixed target SINR for all users while minimizing the power consumption and it should be noted that the optimal weight vector in terms of power minimization will be achieved with equality, $\sum_{i\in\mathcal{C}_m} x_{m,i} = 1$ [73]. Let $\phi_{m,i}$ be the total power budget of user $i \in \mathcal{C}_m$ over the set of OFDM subcarriers on the uplink; that is, $\phi_{m,i} = p_{m,i}x_{m,i}$. Suppose that the deterministic channel gain from a user i to a base station k (not necessarily its serving base station) is $h_{k,i}$ and the total noise power received at base station k is σ_k, then the received SINR γ_i of user i at its serving base station m is

$$\gamma_i = \frac{h_{m,i}p_i}{\sum\limits_{\substack{j\in \mathrm{C}_k \\ k\in\mathcal{M},\, k\neq m}} x_{k,j}h_{m,j}p_j + \sigma_m}$$

Let us denote the normalized received SINR of user i at base station m to be $\mu_{m,i}$, so that

$$\gamma_i = p_i\mu_{m,i} = \frac{\phi_{m,i}\mu_{m,i}}{x_{m,i}}$$

Then the feasible rate region $\mathbf{R}_m$ for the users connected to base station m is determined by the Shannon formula

$$\mathbf{R}_m = \left\{ \mathbf{r}_m \in \mathbb{R}^{L_m} \ : \ r_{m,i} = x_{m,i} \log_2 \left(1 + \frac{\phi_{m,i}\mu_{m,i}}{x_{m,i}} \right), \quad \forall i \in \mathcal{C}_m \right\}$$

subject to

$$\sum_{i \in \mathcal{C}_m} x_{m,i} \leq 1 \quad \forall m \in \mathcal{M}$$

and the constraint set is $\mathcal{X}_m = \{(\mathbf{x_m}, \mathbf{p_m}) \,|\, 0 \leq x_{m,i} \leq 1, \; 0 \leq p_i \leq p_{\max,i} \, \forall i \in \mathcal{C}_m\}$. Here, $r_{m,i}$ is the achieved rate of user i connected to base station m and, by continuity, we assume that if $x_{m,i} = 0$ then

$$r_{m,i} = x_{m,i} \log_2 \left(1 + \frac{\phi_{m,i}\mu_{m,i}}{x_{m,i}} \right) = 0$$

In our algorithm for hybrid access, to be discussed in detail in Chapter IV, we dynamically allocate the femtocell resources at each iteration of the distributed power control algorithm. That is, at every step of the iterative standard power control algorithm, introduced in Chapter II, we evaluate the optimal fraction of resources allocated to the users associated with each femtocell in the system model, fixing the uplink transmit power of the users to the value obtained from the power control iteration. In our two-tier network model, we consider M femtocells distributed across the cell site, labeled as $\mathcal{B}_{\text{FAP}} = \{1, 2, ..., M\}$. We assume that all users have saturated queues with infinite amount of data to be transmitted. Let $\mathcal{U}^k_{\text{FAP}}$ be the set of users, both the femto owner and handed over cellular users, being served by femtocell $k \in \mathcal{B}_{\text{FAP}}$. At the beginning of each allocation cycle, or epoch, our objective is to maximize a utility function of the form $\mathbf{U}_k(\mathbf{r}_k) = \sum_{i \in \mathcal{U}^k_{\text{FAP}}} U_{k,i}(r_{k,i})$ for each femtocell base station $k \in \mathcal{B}_{\text{FAP}}$, where $r_{k,i}$ is the achieved throughput of user i in that epoch. The function $U_{k,i}(r_{k,i})$ is taken to be an increasing concave function of user i's rate.

It characterizes the elasticity of user traffic. The utility function can also be modeled to capture the intuitive notion of *fairness*. For example, consider a class of utility function characterized by a fairness parameter $\alpha \geq 0$ defined as

$$U_{k,i}(r_{k,i}) = \begin{cases} \log(r_{k,i}) & \text{if } \alpha = 1, \\ (1-\alpha)^{-1} r_{k,i}^{(1-\alpha)} & \text{if } \alpha \neq 1 \end{cases}$$

The optimal solution obtained by maximizing such an α-fair utility function satisfies the definition of α-fairness as described in [84]. Setting $\alpha = 0$ yields a *maximum throughput* resource allocation rule that maximizes the sum throughput during each epoch. For $\alpha = 1$, we get a *proportionally fair* rule that implements time-based fairness and provides a good tradeoff between throughput efficiency and fairness.

The maximum transmit power constraint enforced on each user $i \in \mathcal{U}_{\text{FAP}}^k$; $p_i \leq p_{\max,i}$ for all $k \in \mathcal{B}_{\text{FAP}}$, is satisfied by the transmit power vector obtained from the power control iteration. Therefore, in the case of $\alpha = 0$ with a weighted sum-rate objective function, the constrained optimization problem of allocating the resources for each femtocell $k \in \mathcal{B}_{\text{FAP}}$ reduces to

$$\begin{aligned} \max_{\mathbf{x}_k \in \mathcal{X}_k} & \sum_{i \in \mathcal{U}_{\text{FAP}}^k} w_i r_{k,i} \\ \text{subject to} & \sum_{i \in \mathcal{U}_{\text{FAP}}^k} x_{k,i} = 1 \end{aligned} \tag{3.1}$$

where the constraint set $\mathcal{X}_k = \left\{ \mathbf{x} \mid \epsilon \leq x_{k,i} \leq 1,\ \epsilon > 0\, \forall i \in \mathcal{U}_{\text{FAP}}^k \right\}$. Here, w_i is a static weight associated with user i, which represents the preference given to that user. While the macrocell allocates its resources equally to all its users, the femtocell is obligated to give higher preference to its owner and so the static weights in our optimization formulation are chosen such that this condition is fulfilled. A positive lower bound on $x_{k,i}$ ensures that under a constrained sum-rate maximization, a cellular user always receives a non-zero portion of the femtocell resources and that the fraction of femtocell resources allotted to the handed-in cellular user remains significant even at very high user densities. It is reasonable to expect that the minimum throughput and corresponding target SINR requirements for femto owners and cellular users will be potentially different, typically a higher data rate requirement for femto owners, because femtocells are deployed by end users in their own self-interest. Utilizing a weighted sum-rate objective function in our femtocell resource allocation framework, though most efficient in terms of capacity, is not fair to the cellular users. Thus, we also consider a weighted proportionally-fair allocation rule at each femtocell modeled as

$$\begin{aligned} \max_{\mathbf{x}_k \in \mathcal{X}_k} \sum_{i \in \mathcal{U}^k_{\text{FAP}}} & w_i \log(r_{k,i}) \\ \text{subject to} \sum_{i \in \mathcal{U}^k_{\text{FAP}}} & x_{k,i} = 1 \end{aligned} \tag{3.2}$$

where the constraint set $\mathcal{X}_k = \{\mathbf{x} \mid x_{k,i} \leq 1 \quad \forall i \in \mathcal{U}^k_{\text{FAP}}\}$.

This completes our discussion on the theory behind the working of our hybrid access algorithm in two-tier macro/femto networks. In the subsequent sections, we examine the key steps in our algorithm in more detail and study the capacity performance of our two-tier network model under hybrid access.

CHAPTER IV

AN ALGORITHM FOR HYBRID ACCESS CONTROL

In Chapter I, we discussed the two types of access control mechanisms – closed and open – that are implemented in two-tier femtocell networks. Prior work in access methods [19, 27, 37] conclude that, under co-channel deployment of femtocells, open access with a constraint on the maximum number of users supported by the femtocell base station, referred to as a hybrid access method in our work, is the preferred approach. Moreover, the choice of femtocell access control mechanism depends on whether the underlying multiple access scheme is orthogonal (TDMA/OFDMA) or non-orthogonal (CDMA) [58]. In the case of TDMA/OFDMA on the uplink, the access method preferred by the femto owner and the cellular user is a function of the cellular user density. According to the results derived in [37, 58], at medium user densities, both femto owner and cellular users prefer open/hybrid access while at a high user density closed access is preferred by both parties. However, it should be noted that this analysis was done under the assumption of no coordination between base stations in terms of power control or user scheduling. The authors in [58] conjecture that at high cellular densities, hybrid access with coordination between the two tiers will be the appropriate access control mechanism of choice for both femto and cellular users.

As we discussed in Chapter II, power control is employed in wireless systems in order to assist users with bad channels and limit overall interference as seen by users. In two tier femtocell networks, where interference management between the two tiers is further exacerbated by decentralization, distributed power control schemes are necessary to guarantee a minimum QoS to all users. In addition, resource allocation should also be incorporated into the problem of choosing an appropriate access control mechanism. This will ensure that the femto subscriber is not deprived of femtocell resources, when the femtocell allows unregistered cellular users under open/hybrid access mechanism. In our hybrid access scheme, the combined power control and base station assignment algorithm implicitly adapts the access control method employed with the cellular user density. In the following sections, we first describe our communication model adopted in this thesis. Following that, the handover metrics and resource allocation method used in our algorithm are explained in detail. We evaluate the system performance under our proposed hybrid access algorithm from both the femto subscribers' perspective (average throughput of femto owner) as well as from the point of view of a network operator (cellular users' sum throughput) through simulation results.

A. System Model

In our system, we consider a single macrocell base station, with index set $\mathcal{B}_1 = \{1\}$. This base station is located at the center of a circular region $\mathcal{C}$ of radius R, providing a coverage area $|\mathcal{C}| = \pi R^2$. We employ a stochastic geometry framework for modeling the random spatial distribution of femtocells. The macrocellular network is overlaid with femtocell hotspots of radius R_f, which are randomly distributed on $\mathbb{R}^2$ according to a homogeneous spatial Poisson point process Ω_f with intensity λ_f. The mean number of femtocells per cell site is readily obtained as $N_{\mathrm{f}} = \lambda_f |\mathcal{C}|$. The N macrocell users, labeled $\mathcal{U}_C = \{1, 2, ..., N\}$, are assumed to be uniformly distributed within the macrocell area. Suppose that an instance of the spatial Poisson point process generates M femtocells indexed $\mathcal{B}_{\mathrm{FAP}} = \{2, 3, ..., M+1\}$. Let $\mathcal{B} = \mathcal{B}_1 \cup \mathcal{B}_{\mathrm{FAP}}$ denotes the set of all $M+1$ base stations in our system model. A snapshot of our communication model is shown in Figure 6. We assume that there is only

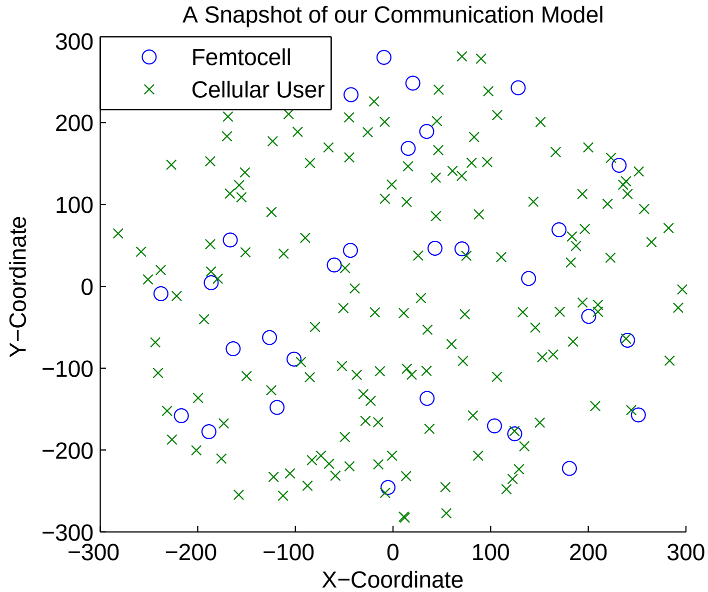

Fig. 6. An snapshot of our system model with $N = 150$ and $N_{\mathrm{f}} = 30$.

one femto owner active on each femtocell and that the M femto subscribers are labeled $\mathcal{U}_{\mathrm{FAP}} = \{N+1, N+2, ..., N+M\}$. Since a femto owner is communicating with its femtocell within a small indoor area, it is reasonable to assume that it is located at a deterministic distance d from its femtocell access point. The femto user is always associated with its own femtocell, while the cellular users can be served by the macrocell base station, or the femtocell hotspots under our hybrid access scheme.

Orthogonal signaling is considered and we assume that the $N + M$ users, represented by set $\mathcal{U} = \mathcal{U}_C \cup \mathcal{U}_F$, and the $M + 1$ base stations in $\mathcal{B}$ share a common OFDM subcarrier of bandwidth W KHz on the uplink. The set of users that cause interference on the uplink to user $i \in \mathcal{U}$ is given by $S_i = \{j \in \mathcal{U} | B_j \neq B_i\}$, where B_i is the base station serving user i. In our setup, we neglect femtocell-to-femtocell interference for analytical tractability. Ignoring co-tier interference between femtocells is justifiable because, typically, propagation between femtocells suffers at least a double wall partition loss and, consequently, the contribution of femtocell transmissions to

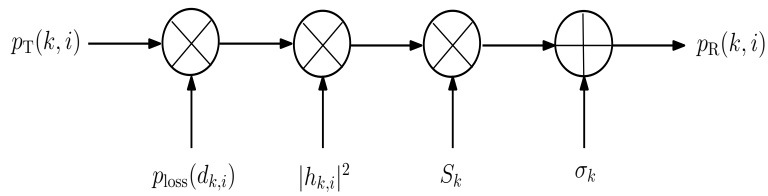

Fig. 7. Block diagram of wireless channel model.

overall interference is negligible compared to the cross-tier interference from neighboring macrocell users. Backhaul capacity available at each femtocell is assumed to be sufficient for supporting up to K users and, hence, it is not considered a bottleneck for the users being served by a femtocell.

1. Channel Model and Interference

The uplink channel gain for each base station is composed of a fixed distance dependent path loss, a slowly varying component modeled by lognormal shadowing, short-term Rayleigh flat fading and additive white noise, as illustrated in Figure 7. In this figure, $p_{\mathrm{T}}(k,i)$ is the transmit power with which user i communicates with base station k, and $p_{\mathrm{R}}(k,i)$ is the received power of user i at base station k. The path loss exponents are denoted by α for outdoor environments and by β for indoor transmissions. In particular, the uplink channel gain between user $i \in \mathcal{U}$ and base station $k \in \mathcal{B}$ is given by

$$H_{k,i} = p_{\mathrm{loss}}(d_{k,i}) \cdot |h_{k,i}|^2 \cdot S_k$$

Here, $p_{\mathrm{loss}}(d_{k,i})$ denotes the path loss attenuation effect for a user i at a distance of $d_{k,i}$ from base station k such that

$$p_{\mathrm{loss}}(d_{k,i}) = \begin{cases} (d_{k,i})^{-\alpha}, & \text{outdoor transmission} \\ (d_{k,i})^{-\beta}, & \text{indoor transmission} \end{cases}$$

We also incorporate wall penetration loss into our channel model by assuming a power loss of W_l dB for cross-wall transmission. The term $|h_{k,i}|^2$ denotes the uplink path gain due to Rayleigh channel fading. The shadow fading component is given by $10\log(S_k) = S'_k$ where S'_k is taken to be a normal random variable with mean 0, standard deviation σ_{MBS} at the macrocell base station and σ_{FAP} at femtocell base stations respectively. An important assumption that we make in our algorithm is that the channel conditions remain constant, or that the channel model is deterministic.

In Chapter II, we derived the standard interference functions for both a femto owner and a cellular user sharing a common spectrum. The interference at the femtocell base station is the aggregation of interference from uplink mobile users, and it is typically dominated by a small number of mobile users transmitting at relatively high power to the main base station [26]. Thus, it is appropriate to modify the function for total interference and noise at a femtocell base station from (2.13) in Chapter II by considering only the cellular users present in its immediate vicinity. Let $\mathcal{U}^k_{\mathrm{macro}}$ be the set of macrocell users within a coverage radius of R_f of femtocell $k \in \mathcal{B}_{\mathrm{FAP}}$ with $N^k_{\mathrm{macro}} = |\mathcal{U}^k_{\mathrm{macro}}|$, and let $\mathcal{U}^k_{\mathrm{FAP}}$ be the set of users, both the femto owner and handed in cellular users, associated with femtocell k. For any user $i \in \mathcal{U}^k_{\mathrm{FAP}}$, the uplink interference and noise at femtocell access point k is

$$I^k_{\mathrm{femto}} = \sum_{j \in \mathcal{U}^k_{\mathrm{macro}}} \frac{1}{N^k_{\mathrm{macro}}} h_{k,j} p_j + \sigma_k \tag{4.1}$$

The total interference and noise at the macrocell base station is obtained from (2.15) in Chapter II

$$I_{\mathrm{macro}} = \sum_{k=2}^{M+1} \sum_{j \in \mathcal{U}^k_{\mathrm{FAP}}} x_{k,j} h_{1,j} p_j + \sigma_1 \tag{4.2}$$

We assume that the users in both tiers regulate their uplink transmit power through a distributed standard iterative power control scheme, as described in Chapter II. The base station assignment is integrated with power control. This enables cellular users to be assigned to their nearest femtocells, it solves the problem of uplink deadzone at the femtocell due to severe cross-tier interference, and it also facilitates macrocell offloading. By restricting the maximum number of users allowed on a femtocell to K and optimizing resource allocation for every femtocell at each step of our iterative hybrid access algorithm, we ensure that the femto subscriber does not incur a major drop in allocated resources due to the handed in cellular users. Thus, we expect our hybrid access control algorithm to improve the capacity performance of macrocell users considerably and, at the same time, reduce the outage probability of femto owner significantly at high user densities. Next, we describe the key steps in our iterative hybrid access algorithm and present our analysis based on the system-wide simulations.

B. Hybrid Access Procedure

Under our proposed hybrid access mechanism, cellular users are assigned to a nearby femtocell as a result of the combined power control and base station assignment algorithm. When a femtocell base station deploys open/hybrid access control, it can choose to serve cellular users based on certain hand over metrics. Let the target rate for a cellular user be T_{c}. Furthermore, assume that each femto owner has a rate requirement of T_{f}. According to this constraint, each user has a target SINR that represents its QoS requirement in our setting. A user is assumed to satisfy its minimum QoS criteria if its received SINR is at or above its target SINR, otherwise it is in outage and its effective rate is zero. In addition, a maximum power constraint of $p_{\max}$ is imposed on all user equipments in the system; if a user i requires transmit power $p_i > p_{\max}$ to achieve his target SINR, then it is considered to be in outage.

1. Power Control and Handover Metrics

The algorithm initializes all users in the system with zero power, $\mathbf{p}(0) = \mathbf{0}$. At each iteration of our hybrid access algorithm, a cellular user chooses the base station where its minimum QoS requirement is satisfied and its power consumption is minimized. The cellular users have a common target SINR $\Gamma_{\mathrm{c}} = 2^{NT_{\mathrm{c}}} - 1$. A macrocell user is handed over to a nearby femtocell if it requires minimum transmit power to achieve its target SINR at the femtocell base station. From Chapter II, the constrained power control iteration for a cellular user $i \in \mathcal{U}_c$ expressed in (2.16) is given by

$$p_i[t+1] = \min\left\{\frac{\gamma_c I_{\mathrm{macro}}[t]}{H_{1,i}},\ \min_{k\in\mathcal{B}_{\mathrm{FAP}}}\left\{\frac{\gamma_c I^k_{\mathrm{femto}}[t]}{H_{k,i}}\right\},\ p_{\max}\right\} \tag{4.3}$$

During an iteration, if a cellular user i is in outage, that is it requires $p_i > p_{\max}$ to satisfy its SINR requirement at any access point in the system, then we set its transmit power to $p_{\max}$ and assign it to the macrocell base station for the next iteration. Therefore, the base station assignment update (2.17) for a cellular user is

$$b_i[t+1] = \begin{cases} 1, & \text{if } p_i[t+1] > p_{\max} \\ \arg\min\limits_{b\in\mathcal{B}}\left\{\frac{\gamma_c}{\mathrm{SINR}_{b,i}[t]}p_i[t]\right\}, & \text{else} \end{cases} \tag{4.4}$$

Eventually, at the end of completion of this iterative procedure, if the user is still unable to attain its target SINR Γ_{c}, then we drop the call and set its rate to zero. Moreover, since the maximum number of users allowed on a femtocell is restricted to K, the algorithm must also ensure that this condition is not violated during the base station assignment update. In the event that a cellular user is assigned to a femtocell operating at its full capacity of K users, the corresponding minimum power assignment iteration is modified as follows: the user is reassigned to another feasible base station where second-least transmit power is required. At high cellular user densities, the number of handovers to femtocells increases and these cellular users, when handed over to a femtocell, cause interference to the macrocell. In absence of coordination in terms of power control or user scheduling, this increased femto-to-macro interference becomes significant and adversely affects the performance of open/hybrid access by reducing the sum throughput of the remaining cellular users on the macrocell. The iterative power control on the uplink utilized in our algorithm enables cellular users being served by the macrocell to adjust their transmit power to satisfy their target SINR and, thus, the sum throughput of cellular users does not deteriorate with the addition of femtocells in the macrocell tier.

A femtocell provides service to cellular users within its range when the femto subscriber fails to achieve its target SINR requirement $\Gamma_{\mathrm{f}} = 2^{T_{\mathrm{f}}} - 1$ due to significant cross-tier interference. The constrained power control update under fixed base station assignment for a femto owner i_k associated with femtocell k at each iteration of our algorithm is described in (2.14) in Chapter II

$$\begin{aligned} p_{i_k}[t+1] &= \min\left\{\frac{\gamma_f I_{\text{femto}}^k[t]}{H_{k,i}},\, p_{\max}\right\} \\ b_{i_k}[t+1] &= k \end{aligned} \tag{4.5}$$

In closed access with $K = 1$ and at high cellular user density, the probability of outage for femto owner is quite large due to excessive macro-to-femto interference. At any intermediate iteration of our algorithm, if a femto owner goes into outage, or $p_{i_k} > p_{\max}$, we fix its transmit power to $p_{\max}$. A typical handover metric used in this scenario is that, the femtocell picks the most noisy interferer from its set of neighboring cellular users for service, provided the total number of users being served by that femtocell does not exceed K. In the final iteration, if the femto owner remains in outage, then we set its effective rate to zero. This handover metric reduces the macro-to-femto interference and, correspondingly, the transmit power required by the femto owner to achieve its target SINR decreases. In closed access, a femto owner consumes all the available femtocell resources. Yet this type of metric allows the femto owner to share the femtocell resources with unregistered cellular users to avoid going into outage at high user densities. Thus, our proposed hybrid access procedure with power control is preferable for both parties.

2. Time Resource Allocation in OFDMA per Subband

We assume that all the users possess saturated queues and generate elastic traffic. In the macrocell network, since all users have the same rate requirement and are i.i.d. located within the macrocell coverage area, time resources on the OFDM subcarrier are allotted fairly and symmetrically among them. That is, at any given time, if there are $\bar{N}$ cellular users being served by the macrocell base station, then each user is served with a time fraction of $1/\bar{N}$. In contrast, a femtocell gives higher priority to its own subscriber and the femtocell can distribute its resources unevenly among its users. At each iteration of our algorithm, the optimal fraction of resources to be allocated to each user connected to the femtocell is formulated as a constrained maximization of a weighted sum-rate objective function. It is an important fact that the target SINR of a cellular user in the macrocell (both under closed and open/hybrid access) increases with the cellular density. Intuitively, as the number of cellular users within the cell site increases, each of them has a smaller time fraction and must therefore boost their target SINR to achieve their rate requirement. At high cellular user densities, the target SINR Γ_{c} can be quite high. Under a max sum-rate scheme, the handed in cellular users competing for resources with the femto owner end up dominating the femtocell time resources, thereby pushing the femto owner to starvation. The static weights w_i assigned to femto subscriber and the handed over cellular users on femtocell k are chosen appropriately to avoid such behavior. Moreover, a minimum rate constraint is imposed on the cellular users handed in to the femtocell to guarantee a minimum QoS. The constrained sum-rate throughput maximization as shown in (3.1) from Chapter III is:

$$\begin{aligned} \max_{\mathbf{x}_k} \quad & \sum_{i \in \mathcal{U}_{\text{FAP}}^k} w_i x_{k,i} \log\left(1 + \frac{\gamma_{k,i}}{G}\right) \\ \text{subject to} \quad & \sum_{i \in \mathcal{U}_{\text{FAP}}^k} x_{k,i} = 1 \\ & r_{k,i} \geq T_{\text{c}}, \quad \text{if } i \text{ is a cellular user} \\ & \epsilon \leq x_{k,i} \leq 1, \quad \forall i \in \mathcal{U}_{\text{FAP}}^k \end{aligned} \tag{4.6}$$

where $\gamma_{k,i}$ is the received SINR of user i at femtocell k. As mentioned before, the throughput constraint allows cellular users to satisfy their rate requirement at low-to-medium cellular user densities, while a lower bound $\epsilon > 0$ on the fraction of resources allotted $x_{k,i}$ guarantees substantial rate gain at high densities at a negligible rate loss for femto owner. Further, we compare the capacity contours of the users under the constrained sum rate maximization scheme with the rates achieved by utilizing a proportional fairness resource allocation method at the femtocell. The resource allocation optimization framework is modified as shown in (3.2),

$$\begin{aligned} \max_{\mathbf{x}_k} \quad & \sum_{i \in \mathcal{U}_{\text{FAP}}^k} w_i \log\left(x_{k,i} \log\left(1 + \frac{\gamma_{k,i}}{G}\right)\right) \\ \text{subject to} \quad & \sum_{i \in \mathcal{U}_{\text{FAP}}^k} x_{k,i} = 1 \\ & r_{k,i} \geq T_{\text{c}}, \quad \text{if } i \text{ is a cellular user} \\ & 0 \leq x_{k,i} \leq 1, \quad \forall i \in \mathcal{U}_{\text{FAP}}^k \end{aligned} \tag{4.7}$$

The MATLAB function '*fmincon*' based on the interior point method is used to solve this constrained convex optimization problem. As in Chapter III, the proportional fairness method is not throughput efficient, but it provides for a more equitable distribution of resources among the users.

The power control update and femtocell resource allocation together give the transmit power vector $\mathbf{p}$, the base station assignment vector $\mathbf{k}$, and the optimal fraction of resources allotted to femtocell users $\mathbf{x}$. The hybrid access procedure discussed above is summarized in the pseudo-code presented in Algorithm 1.

Algorithm 1 Key Steps in Hybrid Access Algorithm

```
repeat
  Initialize t ← 1, p(0) = [0, 0, .., 0]_{1×(N+M)}, k(0) = [1, 1, .., 1, 2, 3, .., M + 1]_{1×(N+M)}.
  Set x_{(k,1)}(0) = 1 for subscriber of femtocell k, for all k ∈ B_{mathrmFAP}
  while t ≤ MAXITER do
    Calculate the total interference plus noise at both macrocell base station, I_macro(t),
    and at each femtocell base station k, I^k_femto.
    Cellular user adapts its power and base station assignment using constrained minimum power assignment algorithm
    p_i(t+1) = min{ γ_c I_macro(t) / H_{1,i}, min_{k∈B_FAP} { γ_c I^k_femto(t) / H_{k,i} }, p_max } and
    b_i(t+1) = arg min_{b∈B} { γ_c / SINR_{b,i}(t) · p_i(t) }
    If cellular user is assigned to a fully occupied femtocell, then that user is assigned
    the next most feasible base station.
    if p_i(t+1) > p_max and t < MAXITER then
      p_i(t+1) ← p_max and b_i(t+1) ← 1.
      At t = MAXITER, user is dropped.
    end if
    Femto subscriber i_k on femtocell k adapts its power using fixed base station assignment algorithm
    p_{i_k}(t+1) = min{ γ_f I^k_femto(t) / H_{k,i}, p_max } and
    b_{i_k}(t+1) = k
    if p_i(t+1) > p_max and |U^k_FAP| < K then
      Hand over the most interfering cellular user within R_f = 30m to femtocell k
    end if
    Substitute p(t+1) and b(t+1) in femto resource allocation optimization.
    For each femtocell k, x_k(t+1) = argmax_x Σ_i w_i x_{(k,i)} log(1 + γ_i(t+1)/G)
    subject to Σ_i x_{(k,i)} = 1, ε ≤ x_{(k,i)} ≤ 1, and rate r_{k,i} ≥ T_c if i is a cellular user
  end while
until 1000 iterations
```

Although we use the hybrid model for access control, the overhead signaling from handovers could still affect the data rates achieved by femto and cellular users. As the exact implementation of the overhead channels varies considerably across protocols, it is difficult to quantify their impact. For these reasons, we do not include the analysis of overhead communication in this algorithm. In the following section, we study the capacity performance of the users in the network from the viewpoints of both the femtocell owner and the network operator. Specifically, we examine the overall improvement observed by using our hybrid access scheme over a closed access control mechanism.

C. Performance Analysis and Numerical Results

The LTE and WiMAX standards promote a similar form of OFDMA, in which the end user is assigned a portion of the spectrum for a time subframe. Each subband in OFDMA is orthogonal and allocated in a TDMA fashion, along the time axis. From an analysis perspective, we consider OFDMA on a per subband basis where the users access the spectrum through orthogonal time sharing. Our objective is to analyze the overall performance of a two-tier network model under our proposed hybrid access control scheme. We compare the sum throughput of cellular users in the case of closed access ($K = 1$) with the improved data rate achieved using our algorithm. We also study the impact of adding more femtocells to the existing macrocell tier, under both a closed access scheme and our hybrid access mechanism. Notations and system parameters are summarized in Table I.

We evaluate the performance of the system when our hybrid access control algorithm is implemented, averaged over 1000 instances of our system model. First, we analyze the capacity contours obtained under both closed access and hybrid access with different K values, when the mean number of femtocells per cell site is $N_{\mathrm{f}} = 3$. Figures 8 and 9 show the achieved sum throughput of cellular users and the number of users dropped, respectively, as functions of the number of cellular users

Table I. Notations and Simulation Parameters

Symbol	Description	Value
W	Bandwidth of OFDM subcarrier	15 MHz
R	Macrocell radius	300 m
R_f	Femtocell radius	30 m
d	Distance between home owner and femto base station	5 m
N	Number of cellular users	0–160
N_{f}	Average number of femtocells per cell site	3,10
α, β	Path loss exponents	4,2
T_{c}	Cellular user rate requirement	0.1 bps/Hz
T_{f}	Femto owner rate requirement	2 bps/Hz
G	Shannon gap	3 dB
S_{macro}	Shadow fading at macro base station	8 dB
S_{femto}	Shadow fading at femto base station	5 dB
N_0	Noise power spectral density	-174 dBm/Hz

in the network. Under closed access, $K = 1$, the received SINR of a cellular user at the macrocell base station remains constant. We observe that beyond a certain cut-off load, the number of users dropped increases sharply as seen in Figure 9. This is because, as the number of cellular users increases, the target SINR Γ_{c} becomes infeasible for users with bad channels, who are unable to access a nearby femtocell and thus, fail to satisfy their QoS requirements. Correspondingly, we see a decline in the sum capacity curve of cellular users at high user densities in Figure 8. In hybrid access, the received SINR of each cellular user in the macrocell is not constant, due to the fluctuating level of interference created by cellular users transitioning to and

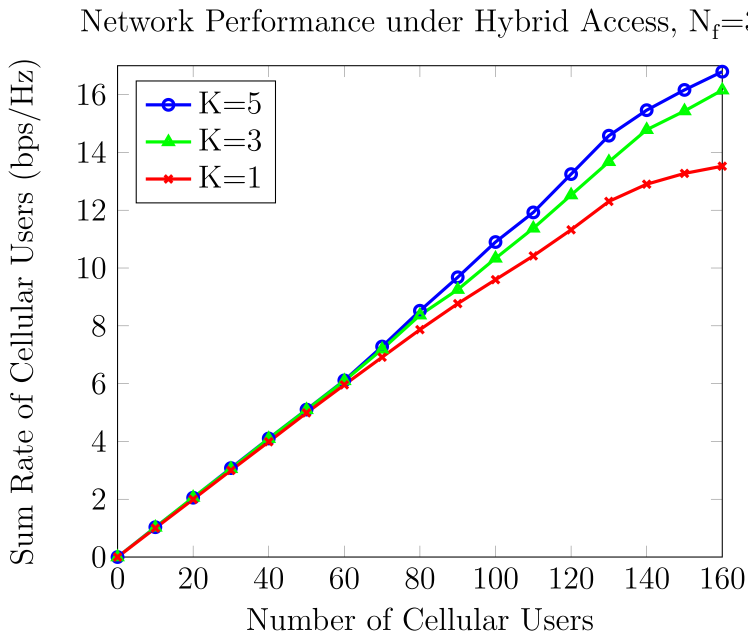

Fig. 8. Achieved sum throughput of cellular users, $N_{\mathrm{f}} = 3$.

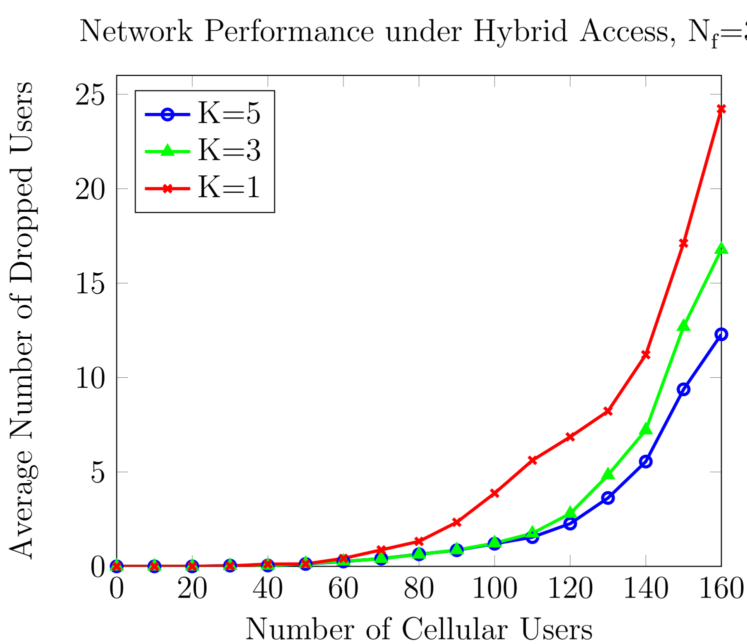

Fig. 9. Number of macrocell users dropped, $N_{\mathrm{f}} = 3$.

from femtocell access points. Still, these cellular users served by a femtocell must be within the immediate vicinity of that femtocell access point according to our handover criteria, which greatly reduces the randomness in their locations. Moreover, the femtocell allocates a large portion of its time resources to the femto owner and, as such, the femto-to-macro interference remains constant for most of the time. By means of power control, we ensure that the remaining cellular users on the macrocell do not suffer from this increased femto-to-macro interference and are able to adapt their transmit power to achieve their target SINR at the macrocell base station. Figure 8 shows that when an open/hybrid access control mechanism is adopted and the maximum number of cellular users allowed to access a femtocell is raised to $K = 3$, at low-to-medium user density, the achieved sum throughput of cellular users is nearly the same as that in closed access. However, at high cellular user densities, we notice a considerable increment in the sum capacity of macrocell users compared to that under closed access. This gain in capacity can be attributed to two factors: (a) by offloading macrocell users with bad channel conditions to nearby femtocells, the fraction of time resources available per user for the remaining cellular users increases and hence the rate per user also increases, (b) the cellular users that are handed over to a femtocell are allotted a fraction of time resources which, at high user densities, is still higher than the time fraction $1/N$ assigned under the macrocell base station. The number of dropped users reduces substantially due to macrocell offloading. Nevertheless, at high cellular densities, we have nearly $N_{\text{drop}} = 16$ since the femtocell density, at $N_{\text{f}} = 3$, is quite low. Keeping the mean number of femtocells fixed, we wish to assess the potential advantage/disadvantage of increasing the value of K to five. We find that, with the addition of cellular users to the system, the sum capacity further increases due to the increased macrocell offloading. Although the maximum number of allowable cellular users on a femtocell is greater compared to the case of $K = 3$, the

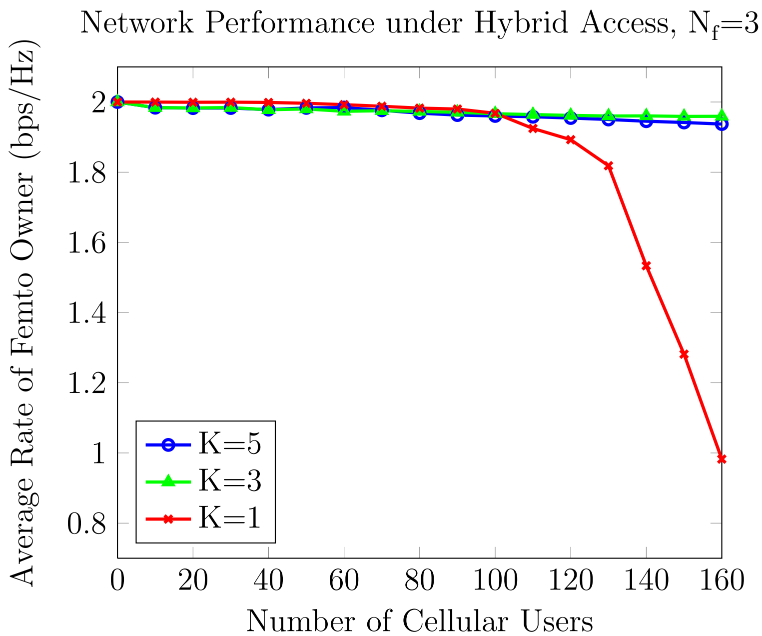

Fig. 10. Average throughput of femto owner, $N_{\mathrm{f}} = 3$.

gain is not proportionally higher. The reason is that cellular users that are handed over to the femtocells must be located within their small coverage radius and, even when the macrocell is heavily loaded, it is not statistically probable to have a large number of celluar users within this admissible region.

The average throughput of a femto owner in the network is shown in Figure 10. In closed access, at high user densities, there is a significant drop in the average rate of femto subscriber. Indeed, the outage probability of a femto owner increases with the number of cellular users in the neighborhood due to excessive macro-to-femto interference. A worst case scenario is when a cellular user is located within the indoor environment of a closed access femtocell, causing an uplink deadzone problem at the femtocell access point and hence, driving the femto owner into outage. However, in our scheme, the metric applied lets the most interfering cellular users be handed over to a nearby femtocell, thereby protecting the femto subscriber from going into outage. In

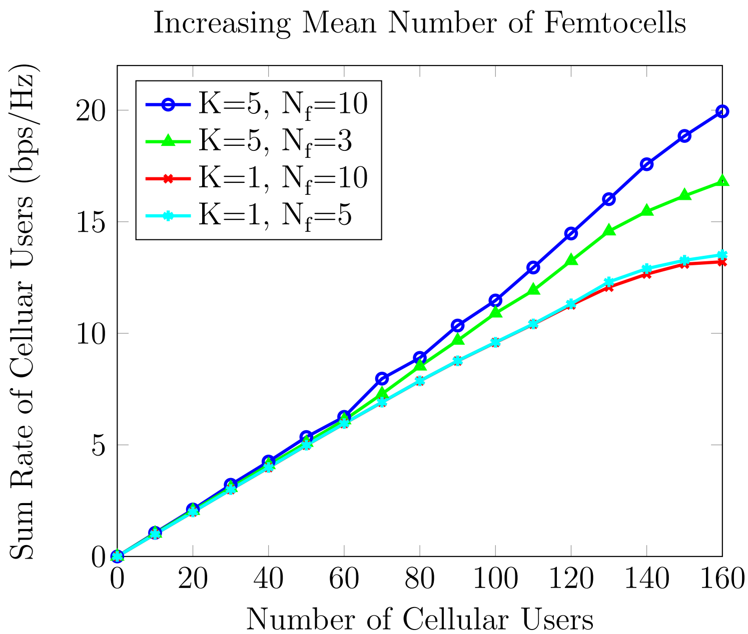

Fig. 11. Achieved sum throughput of cellular users, $N_{\mathrm{f}} = 3$ versus $N_{\mathrm{f}} = 10$.

our hybrid access scheme, the femto owner shares its resources with the unregistered cellular users. The optimization of femtocell resource allocation guarantees that the average rate of the femto owner is not heavily compromised due to incoming cellular users. Even at high cellular densities, the femto owner suffers only a minimal rate loss while his outage probability is negligible.

From the above analysis, we note that only increasing the value of K does not considerably increase macrocell offloading. We want to study the performance of the system upon adding more femtocell access points to the cell site. From Figures 11 and 12, we observe that the addition of femtocell access points under the closed access scheme deteriorates the throughput performance of both cellular users and femto owners, due to increased cross-tier interference. However, we do realize a tangible gain of nearly 52% in the achieved sum rate of cellular users by increasing the number of femtocells per cell site under our proposed hybrid access algorithm. In

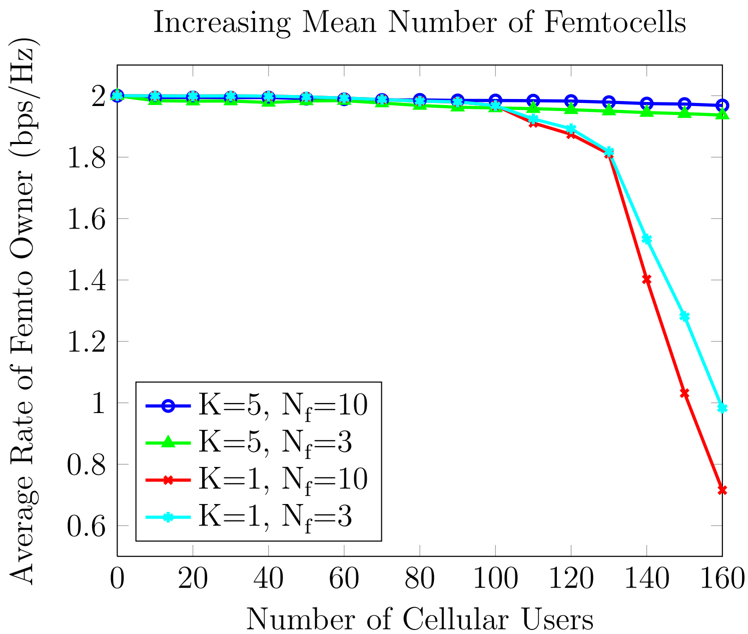

Fig. 12. Average throughput of femto owner, $N_{\mathrm{f}} = 3$ versus $N_{\mathrm{f}} = 10$.

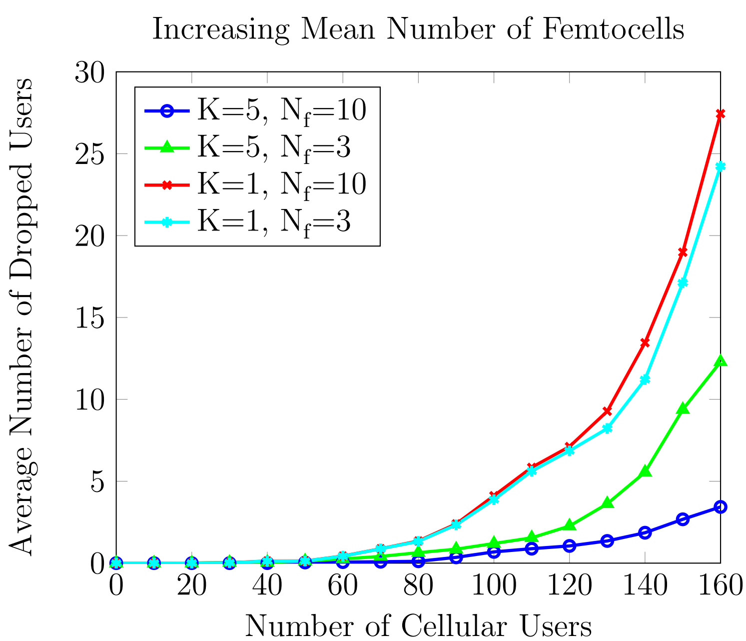

Fig. 13. Number of macrocell users dropped, $N_{\mathrm{f}} = 3$ versus $N_{\mathrm{f}} = 10$.

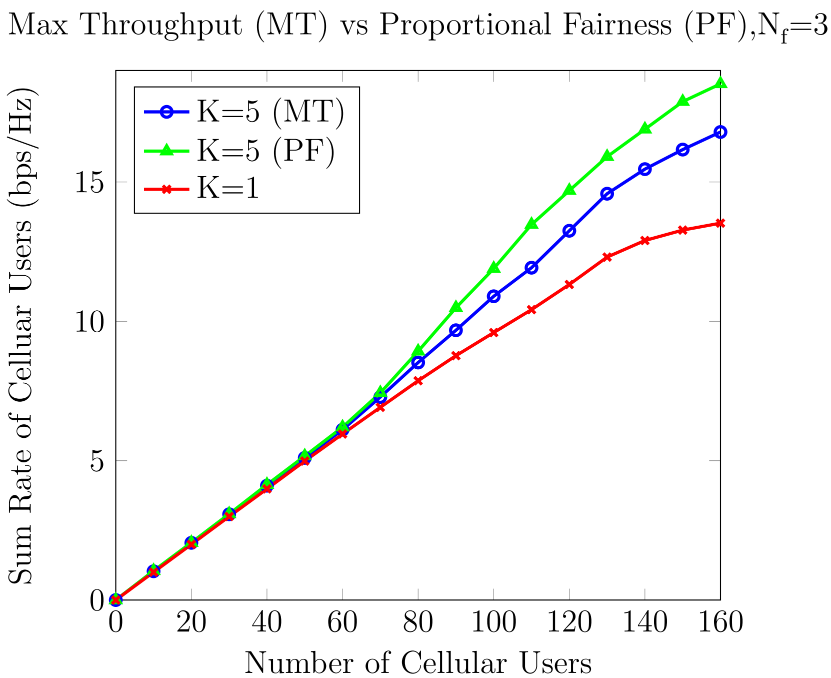

Fig. 14. Achieved sum throughput of cellular users, proportional fairness versus constrained sum-rate maximization, $N_{\mathrm{f}} = 3$.

addition to the two aforementioned factors, which are responsible for this rate gain, the extent of macrocell user offloading also increases when the underlying macrocell tier is augmented with more femtocell hotspots. This further improves the overall achieved sum throughput of cellular users. The average throughput of the femto owner remains almost equal to the rate achieved when the mean number of femtocells is $N_{\mathrm{f}} = 3$. Figure 13 shows that at high user densities, when the mean number of femtocells is raised from three to ten under closed access, the average number of cellular users dropped from the system marginally increases. When hybrid access is used at femtocells, as the number of femto base stations per cell site increases, for users far away from the macrocell base station or with bad channel, accessibility to a nearest femtocell is higher. Hence, the number of cellular users dropped decreases substantially compared to the number of dropped calls at a low femtocell density of

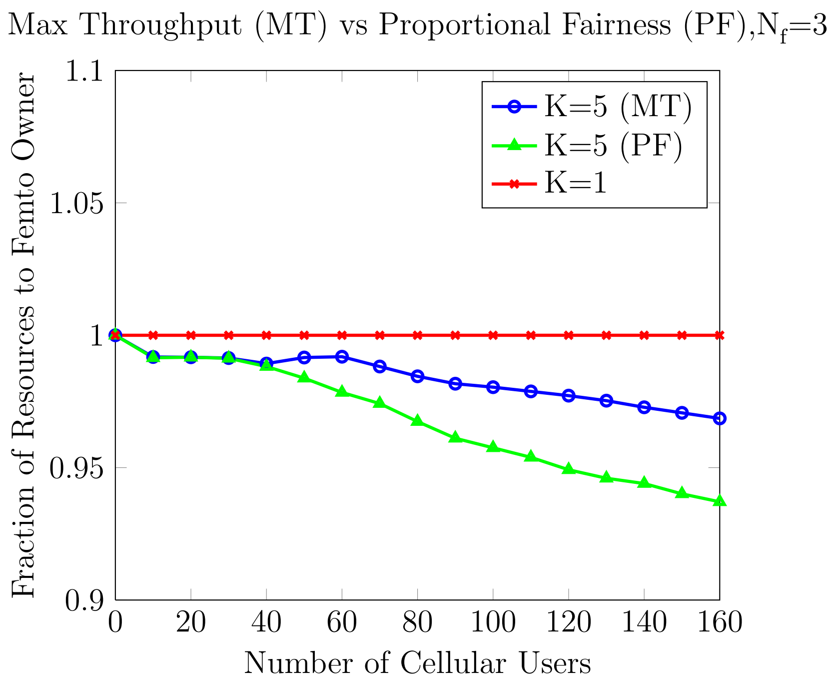

Fig. 15. Optimal fraction of time resource allotted to home user, proportional fairness versus constrained sum-rate maximization, $N_\mathrm{f} = 3$.

$N_\mathrm{f} = 3$.

In Chapter III, we discussed the tradeoff between throughput efficiency and fairness in resource allocation methods. We estimate the improvement in capacity for cellular users by implementing proportional fairness scheme at the femtocells for optimizing resource allocation. With $K = 5$ and $N_\mathrm{f} = 3$, we see from Figure 14 that the sum capacity of macrocell users, at high cellular densities, further increases compared to the case of sum-rate maximization subject to rate constraints. Under proportional fairness, the fraction of time resources allocated by a femtocell to the handed over cellular users is comparatively larger than the time resources assigned under constrained sum-rate maximization. Thus, macrocell offloading with a proportionally fair resource allocation method enables improving the sum rate gain by a factor of 12.5% over the constrained sum-rate maximization scheme. Certainly,

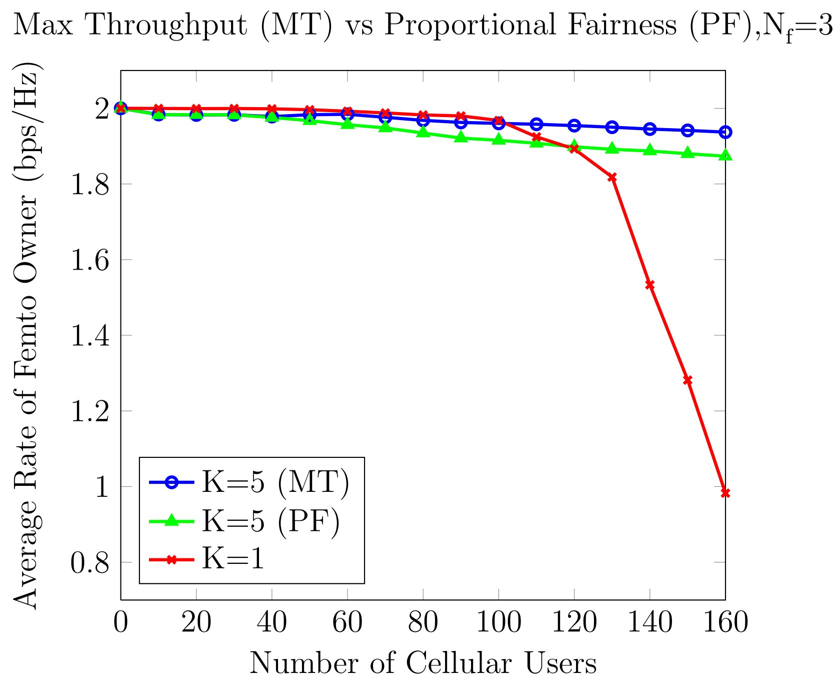

Fig. 16. Average throughput of femto owner, proportional fairness versus constrained sum-rate maximization, $N_{\mathrm{f}} = 3$.

adjusting the static weights allotted to users in the resource allocation optimization framework influences both the time fraction allocation to users and the sum capacity achieved by users. This rate gain for cellular users comes at a small price for the femto owners. As cellular users are added and the time resources allotted to these users also marginally increases under proportional fairness, correspondingly, the fraction of resources available for the home owner decreases as shown in Figure 15. Regardless, the femtocell still allocates a major portion of the over-the-air resources to the femtocell and Figure 16 shows that with proportional fairness at the femto sites, there is no appreciable drop in the average capacity for the femto owners. At high user densities, this average throughput remains significantly higher than that produced by the closed access scheme.

Based on system-wide simulations, we have evaluated the expected capacity performance of our two-tier femtocell network, given a cellular user density and a mean number of femtocell base stations per cell site, from both the home owner and network operator perspectives. Another important metric for the success of our algorithm is convergence, and more importantly, rate of convergence which is discussed in the next chapter.

CHAPTER V

CONVERGENCE OF HYBRID ACCESS ALGORITHM

In general, power control algorithms in wireless systems can be both iterative and non-iterative. Non-iterative algorithms are computationally expensive and require a centralized controller with complete information of all nodes and users. Clearly, iterative algorithms are preferred in decentralized networks. The hybrid access control mechanism employed in this thesis is a fully distributed iterative algorithm that integrates uplink power control and base station assignment with the optimal allocation of femtocell resources. From the numerical results in Chapter IV, we observe that through power control, even the users with bad channels are able to satisfy their minimum QoS requirements and achieve their target rates. Due to the distributed nature of iterative algorithms, an important criteria that should be satisfied is convergence. Otherwise, the transmission powers of users tend to diverge or cycle, leading to excessive energy dissipation and shorter battery life. Under fixed base station assignment, the convergence problem with maximum transmit power constraints is examined in [62]. The convergence criteria for the problem of integrated power control and base station assignment with a constraint on maximum power is addressed in [65].

Convergence properties of iterative algorithms rely on the Perron-Frobenius theory for irreducible, non-negative matrices. For a non-negative matrix $\mathbf{A}$, the Perron-Frobenius eigenvalue is its spectral radius $\rho(\mathbf{A})$. Convergence of iterative power control algorithms is determined by the spectral radius of the non-negative matrix formed by the product of the diagonal matrix of SINR targets and the normalized channel gain matrix, i.e., $\mathbf{D}(\mathbf{\Gamma})\mathbf{G}$. From Chapter II, we recall that the fixed point iteration in the distributed power control algorithm given by

$$\mathbf{p} = \mathbf{D}(\boldsymbol{\Gamma})\mathbf{G}\mathbf{p} + \boldsymbol{\eta}$$

has a non-negative solution $\mathbf{p}$ for any non-negative, non-zero $\boldsymbol{\eta}$ if and only if the spectral radius $\rho(\mathbf{D}(\boldsymbol{\Gamma})\mathbf{G}) < 1$. As calculation of the spectral radius can be cumbersome, sufficient conditions for convergence of iterative power control algorithms using bounds on spectral radius given by Perron, Mink and Ostrowski are derived in [85].

A generalized framework for uplink iterative power control algorithms was given by Yates [64]. This framework yields sufficient conditions for convergence to a fixed point, as discussed in Chapter II. In particular, for a *standard interference function* $\mathbf{I}(\mathbf{p})$, if there exists power assignment $\mathbf{p}$ such that $\mathbf{p} \geq \mathbf{I}(\mathbf{p})$, then for any initial $\mathbf{p}(0)$, the sequence $\mathbf{p}[t+1] = \mathbf{I}(\mathbf{p}[t])$ converges to a unique fixed point $\mathbf{p}^*$. Moreover, $\mathbf{p}^* \leq \mathbf{p}$ for any assignment $\mathbf{p}$ such that $\mathbf{p} \geq \mathbf{I}(\mathbf{p})$. Any transmit power vector that satisfies the interference constraint $\mathbf{p} \geq \mathbf{I}(\mathbf{p})$ is feasible. However, under a maximum power constraint of $\mathbf{p}_{\max}$, though $\mathbf{p}_{\max} \geq \mathbf{I}(\mathbf{p}_{\max})$ implies that the constrained power control iteration (2.16) always converges to the unique fixed point $\mathbf{p}^*$, when $p_i^* = p_{\max}$, the fixed point is infeasible in that user i will be transmitting at maximum power with an unacceptable SINR. This permits the system to detect the infeasibility.

While the convergence results for standard iterative power control problems are well established, understanding the rate of convergence of these algorithms is equally important. When working under constant channel model, we would want these power control algorithms to converge quickly so that when the SINR feasibility criterion is satisfied, the algorithm can track variations in the radio propagation. Alternatively, in the case of SINR infeasibility, fast convergence to the fixed point allows fast detection of an infeasible situation. A contraction mapping argument with respect to weighted maximum norm is used in [75] to show that for a general form of iterative power control algorithms, existence of a fixed point implies convergence at a geometric rate to the fixed point. That is, if $\mathbf{I}(\mathbf{p})$ is a contraction of rate $\alpha < 1$ with respect to any norm, then the sequence $\mathbf{p}[t]$ generated by the iteration $\mathbf{p}[t+1] = \mathbf{I}(\mathbf{p}[t])$ will converge to a fixed point $\mathbf{p^*}$ geometrically at rate α such that

$$||\mathbf{p}[t] - \mathbf{p}^*|| \leq \alpha^t ||\mathbf{p}(0) - \mathbf{p}^*|| \tag{5.1}$$

Mitra proves that the fixed assignment power control algorithm (2.14) is a contraction mapping if and only if the assignment is feasible [86]. Estimating the rate of convergence for the general minimum power assignment with a maximum power constraint (2.16) is difficult because, for many intermediate iterations, an infeasible base station assignment may be used though the system eventually converges to a feasible solution. Nevertheless, assuming the existence of a unique fixed point $\mathbf{p^*} = \mathbf{I}(\mathbf{p^*})$ associated with a unique base station assignment $\mathbf{b^*}$, Huang and Yates [75] prove that starting for any initial power vector $\mathbf{p}$, the sequence $\mathbf{p}[t]$ converges geometrically to the fixed point $\mathbf{p^*}$. The rate constant, α, depends on the number of users in the system, the uplink channel gains $h_{k,i}$ and any other constraints on transmit power.

In our hybrid access algorithm, the femto subscriber employs a fixed base station assignment power control with a maximum power constraint, while the constrained minimum power assignment is used for cellular users. If there exists a unique fixed point to the power control iteration, then the algorithm should converge geometrically to that fixed point. However, as we saw in Chapter IV, as the maximum number of users allowed on a femtocell is restricted to K, we modify the power control and base station assignment iteration to honor this constraint. Moreover, at each iteration we also execute the femtocell resource allocation optimization that decides the fraction of time resources to be allotted to each user on a femtocell for the next iteration. In the context of our algorithm, it is important to analyze the rate of convergence as

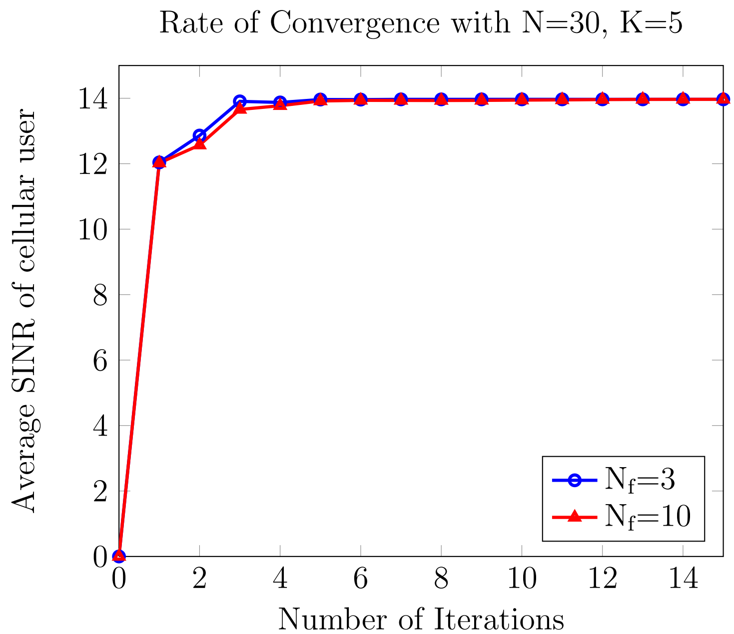

Fig. 17. Number of iterations required for convergence by cellular users starting from zero power, $N = 30$.

the results discussed above may not be directly applicable.

We study the convergence properties for a given channel model, under both low and high cellular user densities. Also, we examine the effect of adding more base stations to the network. In the case of low cellular user density with $N = 30$, Figures 17 and 18 show the number of iterations required for convergence; that is, for the average received SINR of users to equal the target SINR, for both cellular users and the femto subscriber. Starting from the zero power vector, at fairly low femtocell base station density, $N_{\mathrm{f}} = 3$, convergence is attained very quickly within 2-4 iterations for both cellular and femto users. When the mean number of femto hotspots per cell site is increased to $N_{\mathrm{f}} = 10$, the required number of iterations increases marginally.

When the number of users is increased to $N = 100$, Figures 19 and 20 show the rate of convergence for the cellular user and the femto owner respectively. Clearly, the number of iterations required by the cellular users for convergence to the target SINR

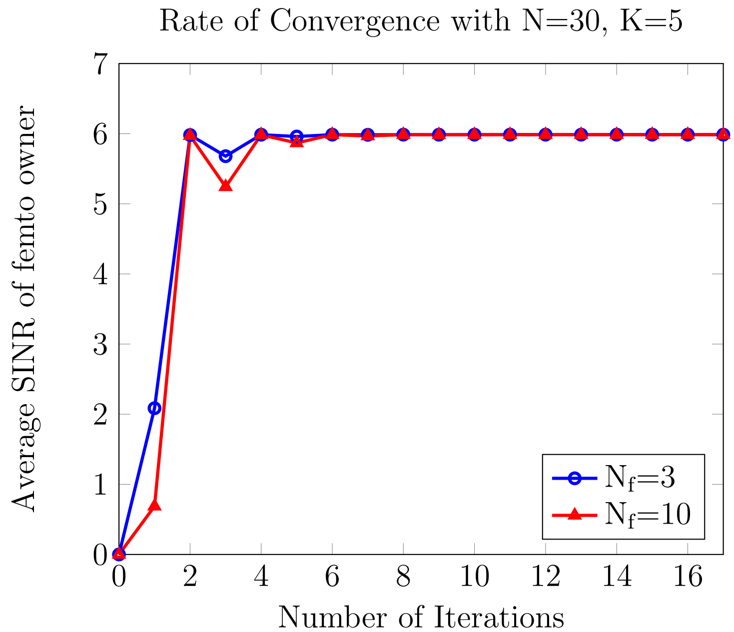

Fig. 18. Number of iterations required for convergence by femto owners starting from zero power, $N = 30$.

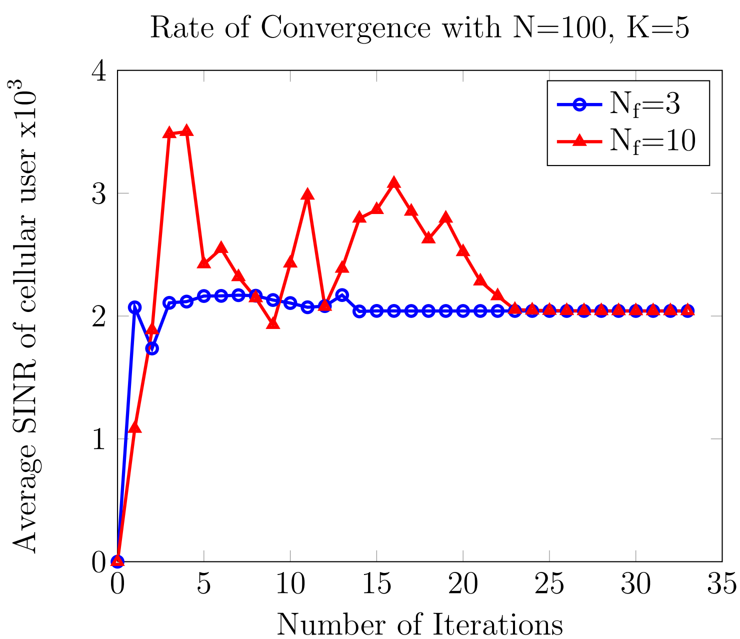

Fig. 19. Number of iterations required for convergence by cellular users starting from zero power, $N = 100$.

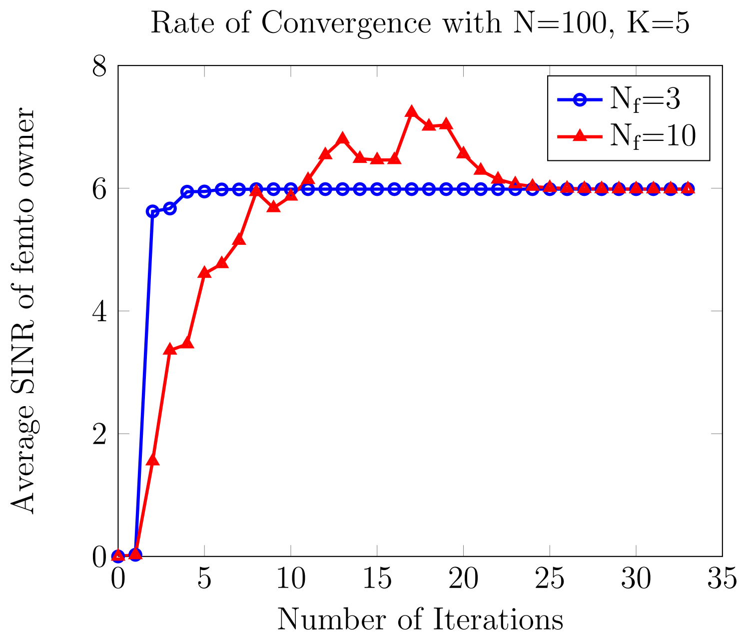

Fig. 20. Number of iterations required for convergence by femto owners starting from zero power, $N = 100$.

increases by a tangible margin to nearly fifteen iterations. Here, it is important to note that as the number of cellular users increases, the target SINR Γ_c also increases and convergence slows down. The SINR target of femto owner Γ_f is invariant to changes in cellular user density. We also observe that, at low femtocell density, increasing the number of users does not significantly affect the rate of convergence. When the mean number of femtocell base stations is increased to $N_f = 10$, the rate of convergence further drops and the fluctuations in received SINR of users for the intermediate assignments increases, as shown in Figures 19 and 20. As the number of base stations in the system model increases, the set of possible base station assignments over which the minimization occurs becomes much larger, which alters the rate of convergence. Thus, with the addition of cellular users and femtocell access points to the system, the number of iterations required for convergence also increases.

Next, we study the number of iterations required for convergence when the initial

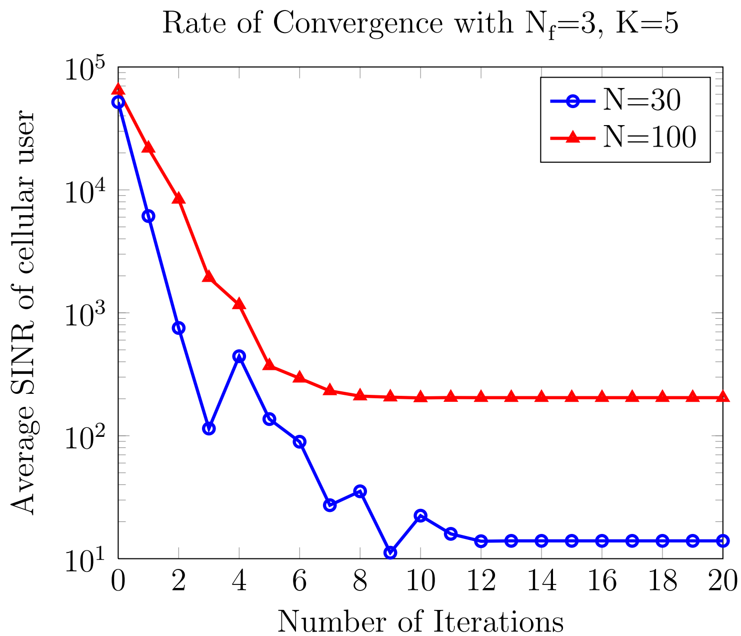

Fig. 21. Number of iterations required for convergence by cellular users starting from maximum power, $N_{\mathrm{f}} = 3$.

power assignment is changed from the zero vector to $\mathbf{p}(0) = \mathbf{p}_{\max}$. Figure 21 shows the number of iterations required for convergence starting from maximum transmit power vector, where the Y-axis represents the average received SINR of cellular users. Under a low cellular user density of $N = 30$, the SINR target Γ_{c} is small and the fixed point $\mathbf{p}^*$ tends to be close to the zero power vector. In such circumstances, convergence is faster when starting from zero power then when the initial power assignment is $\mathbf{p}_{\max}$. On the other hand, when the system is more heavily loaded at $N = 100$, the number of iterations required for convergence starting from $\mathbf{p}_{\max}$ is less compared to the case with $\mathbf{p}(0) = \mathbf{0}$, since when the offered load is increased, Γ_{c} increases and the fixed point moves away from the zero vector and closer to $\mathbf{p}_{\max}$.

Thus, we observe that even under conditions of heavy user load and high base station density, our algorithm converges within thirty iterations, provided a feasible solution exists.

CHAPTER VI

CONCLUSIONS

In this work, we evaluate the capacity performance of a two-tier femtocell network under a decentralized hybrid access control mechanism. Our algorithm essentially combines a standard iterative power control and base station assignment algorithm with the optimal allocation of femtocell resources. We assume that all user devices in the system regulate their uplink transmit power to satisfy their minimum QoS requirement, a target SINR, such that their total power consumption is minimized. Uplink power control problem in a deterministic channel for a fixed target SINR lies within the framework provided by Yates [64]. The femto subscriber is assumed to be always associated with its femtocell access point and, for that reason, we use a fixed base station assignment power control for the femto owners. On the other hand, the cellular users employ a constrained minimum power assignment algorithm and they can be assigned to the macrocell base station or handed off to nearby femtocells. Optimal allocation of femtocell resources is incorporated into the power control iteration to guarantee that the femto owner retains access to a large portion of time resources, despite the growing number of unregistered macrocell users handed in to the femtocell.

The numerical results help in analyzing the expected performance of the system, given a user density and mean number of femto access points per cell site. At low-to-medium user densities, the sum capacity achieved by the users under either closed access or our hybrid scheme is nearly equal. Under closed access, as the number of users increases beyond a cut-off load, the SINR target becomes infeasible for users with bad channels. Closed access does not permit hand off to nearby femtocells and, thus, the number of users dropped increases sharply at high user densities resulting in a decline in achieved sum throughput. Moreover, closed access leads to severe cross-tier interference on the uplink to the femto owner. The outage probability of the femto owner is large when the network is heavily loaded and, accordingly, its average throughput is substantially reduced. When hybrid access is adopted at the femtocells, the time fraction of resources allotted to the cellular users remaining on the macrocell increases due to macrocell offloading. Thus, hybrid access improves overall capacity and our simulation studies show a substantial rate gain of nearly 23.5% at high user densities when $N_{\mathrm{f}} = 3$ under our access scheme. The femto owner is also benefited by our access method because, at high user densities, the most noisy interferers in close vicinity of the femtocell are handed in. This solves the uplink deadzone problem at the femto access point, thereby preventing outage. The resource allocation optimization ensures that the femto owner suffers only a negligible rate loss even when it has to share its resources with the cellular users. Addition of new femto access points to the existing macrocell tier under closed access is detrimental to capacity performance of both cellular user and femto owner at high user densities. However, under our hybrid access algorithm, as the mean number of femtocell base stations is increased to ten, the rate gain of cellular users is further improved to almost 52% compared to closed access scheme. With more femto access points available, the macrocell offloading increases and the number of users dropped greatly decreases. By implementing a proportionally fair resource allocation scheme at the femto base stations, the sum capacity of the cellular users can be further increased by 12.5% compared to the case of constrained sum-rate maximization.

Though the femto-to-macro interference increases when open/hybrid access is deployed at the femtocells, distributed power control ensures the users attain their target SINR and rate constraint. Hybrid access also enables offloading user traffic from the macrocell network; this improves the overall capacity of mobile users and also enhances macrocell reliability. The hybrid access control algorithm mitigates the macro-to-femto interference by letting strong interferers simply use femtocells to avoid outage at high user densities. As the interference reduces, the power control algorithm employed in our scheme allows the femto owner to reduce his power further to satisfy its SINR constraint. This helps femto devices to become more energy efficient. By integrating power control with base station assignment, our hybrid access algorithm inherently adapts the femtocell access mechanism to the current cellular user density because the handoff metric in our scheme depends on the cross-tier interference caused by the users in the system. This thesis provides supporting evidence to the fact that hybrid access mechanism using power control and femtocell resource allocation optimization uniformly provides better capacity and reliability for the two-tier network and is beneficial for both parties at high user densities.

Convergence of the proposed algorithm in terms of the number of iterations required to achieve the target SINR is studied as a function of the number of cellular users and the femtocell base station density. The results obtained suggest that, as long as a feasible solution exists for the system, the algorithm converges quickly within thirty iterations to a unique optimal power and base station allocation.

It should be noted that the limiting factor in the effectiveness of our algorithm is the ability of the mobile devices to collect accurate information about the channel conditions since we are working under the assumption that all users possess perfect knowledge of the channel. In future work, a time varying channel model should be considered with feedback of channel estimates in the power control algorithm to make the algorithm more robust to channel uncertainties. In this framework, we assume the existence of a feasible solution to the system which is predicated on the feasibility of target SINR. However, SINR feasibility cannot be guaranteed apriori. Thus, further work should also consider the problem of joint power control and SINR assignment.

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