POWER CONTROL AND DEPLOYMENT ALGORITHMS FOR
DENSE FEMTOCELL NETWORKS

A Dissertation in
Computer Science
by
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Abstract

Femtocells are low-cost, user-deployed wireless base stations that have been introduced by wireless service providers as a way to improve service at specific locations without costly base station buildouts or upgrades. Dense femtocell networks are networks consisting of a large number of femtocells deployed within a short distance of each other, such as might be used to provide coverage inside a large building or subway station. Due to the proximity of numerous femtocells, interference from neighboring femtocells is a significant problem in dense femtocell networks. This dissertation introduces algorithms for power management and deployment of dense femtocell networks that seek to reduce downlink interference and femtocell power consumption. A number of approaches to interference management are taken by the algorithms in this dissertation, including pilot power reduction, selective activation, and transmission radius reduction. Using simulations and experiments, we show that our algorithms reduce both interference and total network power consumption.
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Chapter 1  
Introduction

Wireless networks have emerged as one of the most important technologies of the 21st century. Mobile telephony and data have become an integral part of modern society, but providing ubiquitous, high-speed wireless coverage in a wide variety of radio environments is challenging. Femtocells were developed as a way for individuals or organizations to improve their wireless service of their own volition. They are small, user-deployed, self-configuring wireless base stations with coverage ranges of 10-30 meters that connect to the cellular core network through users’ local networks. This dissertation introduces power management and deployment algorithms for dense femtocell networks.

Wireless service providers have developed a number of ways to extend the reach of their networks. Basic long-range coverage is provided by macrocells, which have the strongest transmission power and typically cover a range of 1-10 kilometers. Microcells provide medium-range or directional outdoor coverage, with typical ranges of 100-500 meters. Finally, picocells provide short-range coverage, often indoors. Femtocells and picocells are functionally similar, but picocells are managed and deployed by service providers, while femtocells are purchased and deployed by end-users or organizations. Since femtocells are user-deployed, they include self-configuration algorithms that tune their transmission parameters for the local radio environment, to reduce interference.

Femtocells can be configured to allow all users to connect, known as open access, or only a specific subset of users, known as closed access. Under closed access, users that are not allowed to connect to the femtocell network remain connected to the macrocell. This creates the possibility of femtocell-macrocell interference—interference from femtocells to macrocell users as femtocell downlink transmissions
interfere with macrocell downlink transmissions. Since they are closer, femtocell
transmissions are likely to be much stronger than macrocell transmissions, which
can reduce performance for macrocell users. Open access femtocells are easier
to manage from an interference standpoint, since all users can join the femtocell
network. If the femtocell network reaches capacity, the users who are excluded
from the network will suffer high interference.

Dense femtocell networks are networks of multiple femtocells placed in close
proximity to one another, for example, to provide full coverage in subway stations,
airports, academic buildings, or other public spaces. Due to the large number of base
stations within transmission range of each other, femtocell-femtocell interference—
interference from femtocells to other femtocells’ users—begins to affect performance,
and can lead to severe service degradation. This dissertation presents algorithms
reduce interference in dense CDMA and OFDMA femtocell networks.

Femtocells can reduce wireless network power consumption, by reducing the
need for larger, more powerful macrocells or microcells. However, the cumulative
power consumption of dense femtocell networks can be high, leading to situations
where adding femtocells causes a net increase in power consumption. Since reducing
interference in a network can often reduce power consumption, these two goals are
complementary, and the algorithms in this dissertation reflect this. The algorithms
in Chapters 3 and 4 are designed to reduce power consumption as well as interference.

The algorithms described in this dissertation take multiple approaches to man-
aging femtocell interference and power consumption. Broadly, they are dynamic
and distributed algorithms that use local information to make decisions that shape
global network performance. They avoid centralization to reduce decision-making
latency and network traffic. The algorithms differ in types of decisions that they
make, and the information and models that they use to make those decisions.

Chapter 2 describes a game theoretic algorithm for managing femtocell pilot
powers in CDMA networks. The approach is two-fold: initially, pilot adjustment
algorithms designed for dense deployments are used to cooperatively adjust femtocell
pilots. Additionally, a dynamic femtocell pilot adjustment algorithm reduces
femtocell pilots in response to detected user activity. Both methods leverage a
local interference management server that enables cooperation between femtocells
without communicating over the core network. The chapter describes a utility-
based algorithm that sets femtocell pilot levels by finding the Nash equilibrium of
an $N$-player strategic game. Using simulations, we find that the game-theoretic interference management algorithm reduces outage probabilities relative to a naive interference management scheme by up to 43%. This chapter is derived from previously published work [1,2].

Chapter 3 describes a greedy algorithm that uses two different network quality metrics to deploy femtocells in a way that reduces inter-femtocell interference. It approaches femtocell deployment as a combinatorial optimization problem. First, accelerated greedy algorithms using one of two metrics—femtocell coverage and area spectral efficiency—are introduced. Then, motivated by an analysis of the strengths and weaknesses of each metric, an algorithm that takes the weighted sum of both metrics is described. We evaluate our algorithms using extensive simulations, and find that our weighted sum algorithm decreases outage probability by up to 30% relative to existing greedy approaches. Furthermore, our algorithm can lead to a reduction in total network energy usage by up to 14%. This chapter was previously published as [3].

Chapter 4 describes a distributed, selective activation algorithm that disables unused femtocells and enables them dynamically as users join the network. Provisioning the capacity of wireless networks is difficult in scenarios where peak load is significantly higher than average load, for example in airports or train stations. Deploying enough femtocells to serve peak loads requires a large number of femtocells that will remain idle most of the time, which wastes a significant amount of power. To reduce the energy consumption of over-provisioned femtocell networks, this chapter considers a femtocell selective activation problem. We define an integer non-linear optimization problem and prove that it is NP-Hard. Then we introduce GreenFemto, a distributed femtocell selective activation scheme that powers down idle femtocells and activates them when users are in range. We prove that GreenFemto converges to a locally Pareto-optimal solution and study its performance using extensive simulations of an LTE wireless system. Overall, we find that GreenFemto requires up to 55% fewer femtocells to serve a given user load, relative to an existing femtocell power-saving procedure, and comes within 10% of a globally optimal solution. This chapter is based on a paper published as [4].

Finally, Chapter 5 introduces a distributed algorithm for network configuration, called Radius Reduction and Scheduling (RRS), to improve the performance and
fairness of dense femtocell networks. RRS determines cell sizes using a Voronoi-Laguerre framework, then schedules users using a scheduling algorithm that includes vacancy requests to increase fairness in dense femtocell networks. We prove that our algorithm always terminate in a finite time, producing a configuration that guarantees user or area coverage. Simulation results show a decrease in outage probability of up to 50%, as well as an increase in Jain’s fairness index of almost 200%.
Chapter 2  Dynamic, Utility-based Femtocell Interference Management

2.1 Introduction

Femtocells are user-deployed cellular base stations that rely on external packet networks, such as home Internet connections, for backhaul. They provide a means for users to improve cellular coverage and signal quality in their own homes, while allowing network operators to extend the reach of their network without costly network upgrades. Femtocells transmit at low powers and have a typical coverage radius in the tens of meters, ideally transmitting at powers high enough to provide full interior coverage, yet low enough not to cause interference to exterior macrocell users.

Femtocells are typically configured to use the same frequencies as the macrocells with which they coexist. This is spectrally efficient, but can cause interference problems depending on the access policy of the femtocell. There are three types of access policies for femtocells: closed access, open access, and hybrid. Closed access femtocells use a whitelist to determine which cellular users can use the femtocell. Open access femtocells are open to the public, with no restrictions on which users can use the femtocell. Hybrid access femtocells reserve connection slots for users on a whitelist, while allowing open access if resources allow it.

Although femtocells using all types of access policy improve network coverage for femtocell users, closed access femtocells can increase interference due to femtocell pilot and data transmissions. While interference due to user transmissions is only
an issue when the femtocell is in use, interference from femtocell pilot and control channels signals is continuous and can be significant. Additionally, open and hybrid access femtocells can cause an increase in core network signaling due to unwanted user handovers [5,6]. In this chapter we consider femtocells with both open and closed access policies.

The standard femtocell deployment model assumes household users deploy femtocells as a second-tier network to improve reception in their homes, while an overlay network of macrocells deployed by service providers maintains primary coverage. This architecture is known as a hierarchical cell structure. Hierarchical cell structures allow wireless providers to improve coverage and spectral efficiency with a finer level of control than traditional macrocells.

In addition to the traditional deployment model, femtocells can be used in high-density deployments [7], similar to 802.11 wireless, and as primary coverage in areas with poor overlay network coverage, such as underground. These deployment models suffer from more difficult interference challenges relative to the standard two-tier network model. In particular, cumulative interference from closed-access femtocells in high-density, public deployments can increase outage rates.

When femtocells are deployed indoors in standalone homes, femtocell interference to public users is limited due to the low density of femtocells and the isolation of femtocells from public users. Only a small number of public users are affected by closed access femtocell interference. By contrast, when femtocells are deployed in mixed-use public and private locations, such as a university campus or a commercial office building, a large number of public users may be affected by femtocell interference. For example, consider a scenario in which a university installs femtocells to increase cellular coverage for its students, but chooses to exclude the general public for security purposes. While students will see better performance, interference levels for visitors will be high, leading to service degradation and outages. In this scenario, naive femtocell interference management can lead to an overall decrease in connectivity versus the macrocell-only case.

This chapter is an extension of previous work on dynamic femtocell interference management [1], with the addition of a game theory-based pilot adjustment algorithm.

Game theory has been applied as a tool for distributed decision-making in many networking problems [8], notably in distributed power control [9,10]. We apply a
game-theoretic framework to the problem of femtocell interference management in enterprise deployments, through the development of a utility-based cooperative femtocell pilot adjustment algorithm.

First, we describe an intuitive measurement-based pilot adjustment algorithm. Then, we introduce our utility-based pilot adjustment algorithm. Finally, we introduce a dynamic algorithm that employs user activity detection [5] to reduce femtocell powers when macrocell users are nearby. All three algorithms leverage a local interference manager that allows inter-femtocell communication without using the core network. Our results show that the game-theoretic algorithm reduces outage probabilities by up to 43% in the open access femtocell case, and 17% in the closed access femtocell case.

The remainder of the chapter is organized as follows: we provide common background and motivation for our algorithms, and introduce the interference manager, in Section 2.2. We introduce the measurement-based pilot adjustment algorithm in Section 2.3 and the game theoretic algorithm in Section 2.4. We describe the dynamic algorithm in Section 2.5. Our system model is detailed in Section 2.6 and simulation results are presented in Section 2.7. We conclude in Section 2.9.

2.2 Algorithm Overview

In this section, we motivate our pilot adjustment algorithms and describe an interference management server that allows inter-femtocell cooperation, which is necessary for the algorithms described in the next three sections.

2.2.1 Algorithm Motivation

In this chapter, we take two approaches to improving femtocell connectivity by adjusting femtocell pilots. First, we introduce novel pilot estimation algorithms that use either femtocell-femtocell measurements or game theory to improve initial pilot estimates. Then we introduce a dynamic algorithm that uses user activity detection [5] to temporarily reduce femtocell pilots when macrocell users are nearby. The dynamic algorithm is used in combination with the initial pilot estimation algorithms.
Traditionally, femtocell pilots are estimated during the femtocell setup procedure to provide coverage with a radius of $R_f$ meters \cite{6}, based on macrocell measurements at the femtocell. However, radio environments are difficult to predict, and simple estimates can lead to poor coverage from underpowered pilots or excess pilot interference from overpowered pilots. In these conditions, new pilot estimation techniques can improve coverage or reduce interference by providing better pilot estimates. Furthermore, pilot interference is primarily a \textit{temporal} issue—ideally pilots are strong when no users are present to interfere with, to increase coverage, and weak when macrocell users are active, to reduce downlink interference. This suggests that a \textit{dynamic} pilot adjustment algorithm can increase connectivity, especially for macrocell users near closed femtocells.

To illustrate the balance between connectivity and pilot strength, we used 100 simulation runs in the environment described in Section 2.6 to generate Figure 2.1. In this example, 50\% of users can connect to the femtocells. The solid line indicates
Figure 2.2: Femtocell network architecture including a local interference management server.

As femtocell pilots increase, the number of users connected to macrocells decreases due to two factors: substitution, and interference. Substitution occurs when macrocell users switch to femtocells; but not all macrocell users can access the femtocells. Those that cannot switch to femtocells will suffer from increased interference from femtocells. Overall the connected rate peaks at low power, then decreases as the femtocell connected rate peaks, and cannot counteract the decreasing macrocell connected rate. The goal of the pilot adjustment algorithms is to find the femtocell pilot powers that maximize connectivity.

The spatial distributions of femtocells, femtocell users, and macrocell users play a large role in determining both the total number of connected users, and the impact of femtocell control channels on macrocell users. The algorithms in this chapter exploit both spatial and temporal locality to provide a balance between coverage and interference.

2.2.2 Interference Management Server

Traditionally, intra-tier cooperation amongst femtocells and inter-tier cooperation between femtocells and macrocells are both impossible due to the high level of core network signaling required. This limits the amount of information that femtocells can use to tune transmission powers. While inter-tier cooperation
requires a prohibitive amount of communication across the core network, \textit{intra}-tier cooperation at a single deployment site is possible with a local interference manager.

With the addition of a local interference manager, cooperative femtocell interference management algorithms can take advantage of local information exchange amongst femtocells to gain more information about the local radio environment. We introduce a locally-deployed femtocell interference management server. This server is installed at the site of large femtocell deployments, and acts as both a femtocell gateway aggregator and interference management server, as illustrated in Figure 2.2. The femtocell gateway aggregation function reduces the number of individual connections at the core network femtocell gateway, while the interference management function manages interference information exchange between femtocells located at a single site without impacting the core. Since the interference management information does not need to traverse the core, the impact of femtocell cooperation is limited to the local network. We characterize the traffic load incurred by using an interference manager in Section 2.5.

2.3 Measurement-based Pilot Adjustment

\begin{algorithm}
\caption{Measurement-based Initial Pilot Adjustment}
\begin{algorithmic}
  \For{femtocells $i$}
    \State $C_i :=$ neighboring femtocells
    \State $m_i :=$ strongest received macrocell pilot
    \State $\tau_i := f(m_i)$ \Comment{ measured interference and noise level}
    \If{$\tau_i > \tau_i$}
      \While{$\tau_i > \tau_i$}
        \State $c_i :=$ strongest interfering femtocell
        \State $p_c := \frac{1}{2}p_c$ \Comment{measured interference power}
      \EndWhile
    \Else
      \State $\tau_i < \tau_i$
      \While{$\tau_i > \tau_i$}
        \State $c_i :=$ weakest interfering femtocell
        \State $p_c := 2p_c$ \Comment{measured interference power}
      \EndWhile
    \EndIf
  \EndFor
\end{algorithmic}
\end{algorithm}

The measurement-based algorithm is a pilot adjustment algorithm that is run once over all femtocells, during femtocell setup. It is an intuitively simple algorithm that we use to provide a comparison for the game-theoretic algorithm, and to
illustrate the use of the interference manager. The algorithm is used in conjunction
with the cooperative dynamic algorithm and is presented in Figure 1.

The measurement-based algorithm is run over all femtocells at a site. Each
femtocell measures its neighbors’ pilot signals to determine whether their pilot levels
are too high or too low. Femtocell $i$ signals to its neighboring femtocells $c \in C_i$
to adjust their pilots upwards or downwards until overall measured interference at
femtocell $i$, $\tau_i$, reaches a target, $\tau_i$, based on the strongest received macrocell pilot
(lines 3-5).

The algorithm incorporates information about the local radio environment by
relying on measured interference levels. If measured interference exceeds the target
level, the femtocell of interest requests that the strongest interfering femtocell
reduces its pilots by 3 dB, repeating until interference is below the target (lines
6-11). Conversely, if interference is below the target level, the femtocell of interest
signals a 3 dB pilot increase to the weakest interfering femtocell (lines 12-17).
Femtocells only adjust their pilots in response to other femtocells’ requests—they
do not adjust their pilots based on their own measurements.

2.4 Game Theoretic Pilot Adjustment

In this section, we introduce a game theoretic framework to model femtocell pilot
power adjustment as an $N$-player strategic game, for which we find the Nash
equilibrium via a distributed algorithm. The definitions in this section are from [8].

2.4.1 Femtocell Pilot Game

We begin by defining the femtocell pilot game as a non-cooperative strategic game,
with femtocells as the players of the game:

Definition 1. Non-cooperative strategic game A non-cooperative strategic
game is a formal description of a game, $G = (N, S_i, u_i), i \in N$, where $N$ is the set of
players, $\{1, \ldots, N\}$, $S_i$ is the set of available strategies for player $i$, and $u_i : S \rightarrow \mathbb{R}$
is the utility function for player $i$, where $S = S_1 \times \cdots \times S_N$, is the set of feasible
strategies for the entire game.

The game proceeds in turns, with player $i$ choosing a strategy $s_i \in S_i$ that
maximizes his utility.
Each player’s strategy set defines the set of all possible actions a player can take during their turn of the game. A strategy, \( s_i \), for player \( i \) is simply a femtocell pilot power level. The vector of strategies for each player, \( s = [s_0, \ldots, s_N] \), is known as a strategy profile and indicates the current state of the game. The vector \( s_{-i} \) denotes the strategies of all players except player \( i \). Players choose their individual strategies \( s_i \) in response to \( s_{-i} \).

In this model, we assume that players have complete information, in other words, they know the strategy sets and utility functions for all players. With complete information, equilibrium is reached in one “round” of the game. The assumption of complete information does not carry over to the algorithm for finding the Nash equilibrium in Section 2.4.5 but it is easily worked around, as we discuss later.

In the femtocell pilot game, femtocells are the players \( i \in N \). Femtocell \( i \)'s set of feasible strategies, \( S_i \), is the set of possible pilot power values it can choose:

\[
S_i = \{p_i \in \mathbb{R} : 0 < p_i \leq p^{MAX}\}
\]

\( S_i \) is a compact set, and the strategy set, \( S = S_1 \times \cdots \times S_N \) is a convex, compact set. Strategy profiles are the vector of all femtocell pilot powers. Strategy profiles are evaluated and compared using utility functions, which we describe next.

### 2.4.2 Femtocell Utility Function

The utility function for each player, \( u_i(s_i, s_{-i}) \), is a function that quantifies the desirability of a given strategy profile to that player. Recall that the goal of femtocell pilot adjustment is to increase overall network connectivity. Then the utility function should be chosen such that strategy profiles (pilot powers) that increase connectivity have high utility. If we assume that more users can connect to femtocells with larger coverage radiiuses, then a femtocell’s coverage radius, \( R_i \), is a reasonable measurement of connectivity. We can define \( R_i \) by solving the feasible SINR equation for \( R_i \):

\[
\frac{s_i g_i R_i}{I_i(s_{-i})} \geq \tau_i
\]

\[
R_i(s_i, s_{-i}) = \sqrt{\frac{s_i}{\kappa_i I_i(s_{-i})}}
\]
where $\tau_i$ is the target SINR level for user $i$, $g_i R_i[\text{dB}] = 37.5 + 20 \log(r) + 10$ [11] is the estimated path loss in dB at $R_i$ meters from femtocell $i$, $I_i(s_{-i})$ is the interference from other base stations at femtocell $i$ and $\kappa_i$ is a constant dependent on $\tau_i$ and the path loss function $l_i$.

$I_i(s_{-i})$ is the interference and noise contribution from both femtocells and macrocells, is analogous to the measured interference level at a femtocell, and is defined as:

$$I_i(s_{-i}) = \sum_{s_j \in s_{-i}} s_j g_{ij} + \omega \sum_{m \in M} p_m g_{im} + \sigma_i$$

where $\omega$ is the orthogonality factor between macrocells and femtocells, $p_m$ is the transmission power of macrocell $m$, and $\sigma_i$ is the background noise level. We assume all femtocells use the same channel.

Coverage radius is a natural choice for a utility function, but it is inappropriate for direct use as a utility function because $R_i$ is a monotonically increasing function over the set of feasible strategies for a single femtocell, $S_i$. Therefore, each femtocell will set its pilot to $p^{\text{MAX}}$ to maximize its utility, which trivializes the femtocell pilot game, and leads to high levels of pilot interference. Pilot interference is an externality: it decreases the utility of other femtocells, but has no effect on the utility of the femtocell that increases its pilot.

To account for the cost of this externality, we add a price to the utility function. The price factors the external cost of pilot interference into each femtocell’s utility function by reducing a femtocell’s utility in proportion to the external cost it inflicts upon others. In this case, the price is chosen to scale linearly with the normalized pilot transmission power ($\frac{s_i}{p^{\text{MAX}}}$) and exponentially with interference ($e^{I_i(s_{-i})}$) in Watts. The utility function with price is defined for $0 < I_i(s_{-i}) < 1$:

$$u_i(s_i, s_{-i}) = R_i(s_i, s_{-i}) - e^{I_i(s_{-i})} \frac{s_i}{p^{\text{MAX}}} R_i(s_i, s_{-i})$$

Recall that $0 < s_i \leq p^{\text{MAX}}$. Over this interval, $u_i$ is a strictly concave function:

$$\frac{\partial^2 u_i}{\partial s_i^2} = - \frac{3e^{I_i(s_{-i})}}{4\kappa_i \sqrt{I_i(s_{-i})} p^{\text{MAX}} x^{3/2}} < 0, 0 < s_i \leq p^{\text{MAX}}$$

The graph of $u_i$ over the domain of allowable pilot powers is a curve that approaches 0 at $s_i = 0$ and again at $s_i = \frac{p^{\text{MAX}}}{e^{I_i(s_{-i})}}$, and is negative from $s_i = \frac{p^{\text{MAX}}}{e^{I_i(s_{-i})}}$ to $s_i = p^{\text{MAX}}$. 

13
If \( I_i(s_{-i}) \) is held constant, utility reaches a maximum at \( s_i = \frac{p_{MAX}}{3e_i(s_{-i})} \). The exact shape of the graph is determined by the interference at the femtocell, with higher interference leading to lower overall utility, and a correspondingly lower maximum.

In the design of this utility function, we have made a choice to strongly discourage femtocells from increasing their pilots to \( p_{MAX} \). This could reduce coverage when the macrocell is weak, femtocell density is low, or if path loss is high at the femtocell. Our simulation results in Section 2.7 show that on average, limiting femtocell pilot powers helps more than it hurts, but this may not always be the case. Alternative utility functions can include more information about the local radio environment, the details of which are left for future work.

With utility functions in place, we have a numerical metric of the quality of any strategy profile. Next, we discuss properties of optimal strategy profiles, and properties of Nash equilibria.

### 2.4.3 Pareto Optimality

Strategy profiles are defined over all players in the game, but utility functions are necessarily local. Since utility functions are different for each player, optimality is difficult to define. We rely on Pareto optimality, defined as follows:

**Definition 2. Pareto Optimal** A strategy profile \( s^* \in S \) is Pareto-optimal if for every strategy profile \( s \in S \), for every player \( i \in N \), the following is true:

\[
u_i(s^*_i, s^*_{-i}) \geq u_i(s_i, s_{-i})
\]

And for at least one player \( j \in N \), the following is true:

\[
u_i(s^*_i, s^*_{-i}) > u_i(s_i, s_{-i})
\]

A strategy profile is Pareto optimal if there are no strategies that increase utility for at least one player without decreasing utility for at least one other player. In other words, a Pareto optimal strategy profile cannot be improved upon without hurting at least one player. Multiple points can be Pareto optimal, and the curve connecting the Pareto optimal points is known as the Pareto frontier.

Pareto optimality gives a notion of optimality that applies to all players in a game, but the definition gives no way to efficiently find Pareto optimal points.
2.4.4 Nash Equilibrium

A Nash equilibrium is defined as follows:

Definition 3. **Nash Equilibrium** A Nash equilibrium of a non-cooperative game \( G = (N, S_i, u_i), i \in N \) is a strategy profile \( s^* \in S \) such that the following is true for all players \( i \in N \) and all strategies \( s_i \in S_i \):

\[
u_i(s^*_i, s^*_{-i}) \geq u_i(s_i, s^*_{-i})\]

A strategy profile is a Nash equilibrium if no player can *unilaterally* increase his utility. A game can have 0, 1, or multiple Nash equilibria, but the femtocell pilot game with utilities as described in the last section has exactly one Nash equilibrium.

**Theorem 1.** The femtocell pilot game, \( G = (N, S_i, u_i), i \in N \), with utility function \( u_i(s_i, s_{-i}) = R_i(s_i, s_{-i}) - e^{l_i(s_{-i})} \frac{p_i}{p_{MAX}} R_i(s_i, s_{-i}) \) and strategy space \( S = S_0 \times \cdots \times S_N \), \( S_i = \{0, p_{MAX}\}, i = 0, 1, \ldots \), has exactly one Nash equilibrium.

**Proof.** Rosen [12] proved the existence and uniqueness of the Nash equilibrium in \( n \)-person games with concave utility functions over convex strategy sets. The strategy set as defined in Section 2.4.1 is convex. The utility functions \( u_i \) are concave, as shown in Section 2.4.2. \( \square \)

Nash equilibria can be Pareto optimal, but in many cases, they are not, and it is difficult to say, in general, if the Nash equilibria for a game will be Pareto optimal. For a thorough discussion of the Pareto optimality of Nash equilibria, see [8]. In the femtocell pilot game, the Nash equilibrium is not always Pareto optimal, but some scenarios lead to Pareto optimal Nash equilibria.

The Nash equilibrium is the strategy profile that is selected if each player independently maximizes his utility. This independence reduces the complexity of finding the Nash equilibrium, especially with a large number of players, and distributed algorithms.

2.4.5 Distributed Nash Equilibrium Algorithm

The femtocell utility function described above relies on a complete strategy profile, \( s \), to calculate femtocell \( i \)'s utility. Although mathematically elegant, relying on
Algorithm 2: Distributed Nash Equilibrium

```
while not converged do
    for femtocells $i \in N$ do
        $\tau_i :=$ measured interference level at femtocell $i$
        $s_i := \arg \max_{s \in S_i} u_i(s_i, \tau_i)$
    end for
```

A complete strategy profile in a distributed algorithm requires that all femtocells exchange pilot power information in every round of the game, which is inefficient. Alternatively, each femtocell can replace the calculated interference, $I(s_{-i})$, with local measurements of its interference and noise level, $\tau_i$:

$$R_i(s_i, \tau_i) = \sqrt{\frac{s_i}{\kappa_i \tau_i}}$$

$$u_i(s_i, \tau_i) = R_i(s_i, \tau_i) - \frac{s_i}{p_{MAX}} R_i(s_i, \tau_i)$$

Using local utility functions, we can find the Nash equilibrium of a femtocell pilot game using the distributed algorithm in Figure 2. Each femtocell locally, independently, and simultaneously maximizes its utility function. This maximization is repeated with updated measurements of $\tau_i$ until convergence is achieved. In our experiments, this has always occurred in under ten rounds.

### 2.5 Dynamic Interference Management

In this section we introduce an interference management algorithm that dynamically reduces femtocell pilots in response to user activity, that we use in conjunction with the pilot adjustment algorithms described in Sections 2.3 and 2.4.

#### 2.5.1 Dynamic Interference Management Algorithm

The cooperative dynamic interference management algorithm dynamically adjusts femtocell pilot powers in response to detected user activity. User activity is detected by monitoring the radio channel for increases in the received power level over previously calibrated background noise levels. The full algorithm is described in Figure 3.
Algorithm 3: Cooperative Dynamic Pilot Adjustment

1 for femtocells i do
2 \( c_i := \) number of neighboring femtocells \( v_{own} := 0 \) \( v_{other} := 0 \) while True do
3 if no users connected to i then
4 \( d_i := \) detected noise level if \( u(d_i) > v_{own} \) then
5 \( \alpha_{v_{own}} := \frac{1}{2^{1/(v_{other} + 1)}} \) \( p_i := \alpha_{v_{own}} p_i \) \( v_{own} := v_{own} + 1 \) transmit \( d_i \) to interference manager else if \( u(d_i) < v_{own} \) then
6 \( p_i := p_i/\alpha_{v_{own}} \) \( v_{own} := v_{own} - 1 \) notify interference manager of end of user activity
7 else if users connected to i then
8 if interference manager sends \( d_i \) then
9 if \( u(d) > v_{other} \) then
10 \( \alpha_{v_{other}} := \frac{1}{2^{1/(v_{other} + 1)}} \) \( p_i := \alpha_{v_{other}} p_i \) \( v_{other} := v_{other} + 1 \)
11 else if interference manager signals end of activity then
12 \( p_i := p_i/\alpha_{v_{other}} \) \( v_{other} := v_{other} - 1 \)

When a user is detected at femtocell \( i \), it temporarily adjusts its pilot signal downward by a pilot reduction factor, \( \alpha_i \), for the duration of the detected user activity (lines 5-11). When the detected noise level returns to baseline, the femtocell resets its pilot to its original level, thereby restoring coverage (lines 13-16). Temporary pilot adjustments allow femtocells to reduce interference when needed, while continuing to maintain a high level of coverage.

During its setup period, each femtocell identifies the number of femtocells in its neighborhood by identifying received pilot signals (line 2). When no users are connected, femtocells periodically measure \( d_i \) (line 6), the detected power rise above the noise floor. The power rise above the noise floor is determined by comparing the instantaneous receive power measurement with the noise floor as measured during femtocell setup. The function \( u(\cdot) \) estimates the number of nearby users based on the detected power rise; we use \( u(d_{[dB]}) = \lceil d/10 \rceil \).

The appropriate value for \( \alpha_i \) is dependent on the distributions of femtocells, femtocell users, and macrocell users. If few femtocell users are expected, or other femtocells are nearby, then femtocell coverage is less important, and \( \alpha_i \) can be smaller. If a high interference level is detected at the femtocell, \( \alpha_i \) should be larger,
as high levels of interference can indicate nearby macrocell users transmitting at high power to communicate with the macrocell, or multiple nearby users.

We define $\alpha_i$ using a function, $f(c_i, d_i) = (c_i + u(d_i))/2$, of the number of other femtocells detected, $c_i$, and the estimated number of nearby users, $u(d_i)$:

$$\alpha = \frac{1}{2(1+f(c_i,d_i))}$$

Setting $\alpha_i$ using $c_i$ and $d_i$ accounts for both femtocell and user density around the femtocell of interest.

A femtocell that is in use is unable to detect user activity directly, but the cooperative dynamic algorithm uses the interference manager to notify in-use femtocells of nearby user activity (lines 17-30). When an unused femtocell detects user activity, it announces that it has detected user activity by sending the interference manager its measured interference level, $d$. The interference manager forwards $d$ to any neighboring in-use femtocells, which then reduce their pilot signals. To eliminate repeated notifications for the same user activity, only one notification per call is sent to each in-use femtocell.

### 2.5.2 Local Signaling Load

Although the interference manager eliminates the need for core network signaling, local network signaling load may still be a concern.

The dynamic cooperative algorithm triggers at least two messages every time a femtocell detects user activity: one for the notification of the start of user activity, and one for the notification of the end of user activity. If one of the femtocell’s neighbors is in use, this triggers an additional message from the interference manager to the in-use neighbor. The number of femtocells that will detect user activity at a randomly chosen location depends on the femtocell distribution. If we assume that femtocells are distributed according to a spatial Poisson point process [13] with intensity $\lambda$, we can bound the expected number of notification messages as follows.

Assuming a fixed detection radius, $R_d$, the expected number of femtocells that will detect a randomly placed user’s activity is $\lambda\pi R_d^2$. The expected number of neighbors for a randomly chosen femtocell is $\lambda\pi R_d^2$. Notification messages are only sent from femtocells that are not in use to femtocells that are in use. If we assume that all $\lambda\pi R_d^2$ neighbors are in use, and 1 femtocell detects the activity,
then the expected number of messages that are sent for the detection of that user is $\lambda \pi R_d^2 + 1$—1 from the femtocell that detects the activity to the interference manager, and $\lambda \pi R_d^2$ to the neighbors that are in use. When the user activity ends, another $\lambda \pi R_d^2 + 1$ messages will be sent, making the total $2\lambda \pi R_d^2 + 2$. With $m$ users, the upper bound becomes $2m\lambda \pi R_d^2 + 2m$. Therefore, the load scales linearly with the number of users, which is well within the capabilities of a local network capable of supporting many femtocells. As an example, in the model described in Section 2.6, the total number of messages sent in a simulation with 20 users and 50 femtocells was 1977.

2.6 System Model

We simulated a WCDMA system with 19 sectorized macrocells arranged in a standard hexagon pattern. We modeled both a suburban campus environment and a dense urban environment. The 2 km$^2$ suburban environment, shown in Figure 2.3, is based on the PSU campus, and consists of large, widely-spaced mixed-use glass, brick, and concrete buildings with public and private spaces, totaling 31% indoor area. Building interiors are modeled on real interior layouts, and include a mixture of small offices, medium-sized classrooms, and large open areas. The 1.7 km$^2$ urban environment, shown in Figure 2.4, is based on the financial district in New York City, with mixed-use glass and concrete buildings. Building interiors are modeled using a standard design with offices, hallways, and conference rooms.
Table 2.1: Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_t$</td>
<td>-174 dBm/Hz</td>
<td>Thermal noise</td>
</tr>
<tr>
<td>$N_{ms}$</td>
<td>-7 dB</td>
<td>MS noise figure</td>
</tr>
<tr>
<td>$f$</td>
<td>1900 Mhz</td>
<td>Carrier Frequency</td>
</tr>
<tr>
<td>$R_M$</td>
<td>750 m</td>
<td>Target macrocell radius</td>
</tr>
<tr>
<td>$R_f$</td>
<td>15 m</td>
<td>Target femtocell radius</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>4.5 dB</td>
<td>Downlink $E_b/N_0$ target</td>
</tr>
<tr>
<td>$W$</td>
<td>3.84 Mcps</td>
<td>Chiprate</td>
</tr>
<tr>
<td>$S$</td>
<td>384, 144, 64 kbps</td>
<td>User data rates</td>
</tr>
<tr>
<td>$P_{max,m}$</td>
<td>43 dBm</td>
<td>Max transmit power, macrocell</td>
</tr>
<tr>
<td>$P_{max,f}$</td>
<td>23 dBm</td>
<td>Max transmit power, femtocell</td>
</tr>
<tr>
<td>$P_{pilot,m}$</td>
<td>33 dBm</td>
<td>Pilot power, macrocell</td>
</tr>
<tr>
<td>$P_{pilot,f}$</td>
<td>20 dBm</td>
<td>Max pilot power, femtocell</td>
</tr>
</tbody>
</table>

Femtocells are placed on building interiors only. Two types of femtocell deployments are considered: a uniformly random distribution, and a planned, hexagonal distribution, where femtocells are placed in a hexagonal grid, with distance $2R_f$ between femtocells.

Macrocell pilot signals are set at 10% of the maximum transmit power, and other common channels are assumed to use the same power as the pilot [14]. Static femtocell pilots are initially tuned to achieve coverage at $R_f$ meters, based on received macrocell power, and estimated path loss corresponds to the Motley-Keenan indoor wall model [11], $l_{[dB]} = 37.5 + 20 \times \log R_f + 10$, including a 7 dB margin for fading and a 3 dB wall loss. The use of macrocell measurements to set initial femtocell powers is discussed in more detail in [6]. Femtocell common
Table 2.2: Closed Access Outage Probabilities

<table>
<thead>
<tr>
<th>Environment</th>
<th>Suburban</th>
<th>Urban</th>
<th>Suburban</th>
<th>Urban</th>
<th>Suburban</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Rate</td>
<td>64</td>
<td>144</td>
<td>384</td>
<td>64</td>
<td>144</td>
<td>384</td>
</tr>
<tr>
<td>Baseline</td>
<td>0.082</td>
<td>0.335</td>
<td>0.702</td>
<td>0.028</td>
<td>0.202</td>
<td>0.608</td>
</tr>
<tr>
<td>Static</td>
<td>0.070</td>
<td>0.222</td>
<td>0.511</td>
<td>0.024</td>
<td>0.174</td>
<td>0.559</td>
</tr>
<tr>
<td>Measurement</td>
<td>0.072</td>
<td>0.202</td>
<td>0.481</td>
<td>0.027</td>
<td>0.169</td>
<td>0.553</td>
</tr>
<tr>
<td>Utility</td>
<td><strong>0.068</strong></td>
<td><strong>0.185</strong></td>
<td><strong>0.459</strong></td>
<td>0.026</td>
<td><strong>0.153</strong></td>
<td><strong>0.537</strong></td>
</tr>
</tbody>
</table>

Table 2.3: Open Access Outage Probabilities

<table>
<thead>
<tr>
<th>Environment</th>
<th>Suburban</th>
<th>Urban</th>
<th>Suburban</th>
<th>Urban</th>
<th>Suburban</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Rate</td>
<td>64</td>
<td>144</td>
<td>384</td>
<td>64</td>
<td>144</td>
<td>384</td>
</tr>
<tr>
<td>Baseline</td>
<td>0.112</td>
<td>0.330</td>
<td>0.692</td>
<td>0.062</td>
<td>0.138</td>
<td>0.637</td>
</tr>
<tr>
<td>Static</td>
<td>0.010</td>
<td>0.038</td>
<td>0.306</td>
<td>0.038</td>
<td>0.093</td>
<td>0.522</td>
</tr>
<tr>
<td>Measurement</td>
<td>0.009</td>
<td>0.024</td>
<td>0.210</td>
<td>0.037</td>
<td>0.096</td>
<td>0.507</td>
</tr>
<tr>
<td>Utility</td>
<td><strong>0.007</strong></td>
<td><strong>0.014</strong></td>
<td><strong>0.175</strong></td>
<td>0.036</td>
<td><strong>0.071</strong></td>
<td><strong>0.485</strong></td>
</tr>
</tbody>
</table>

Channels are assumed to use the same power as the pilot.

Users are modeled as data-only users with an activity factor of 1, at three fixed data rates: 64, 144, and 384 kbps. Data rates and activity factors are fixed for simplicity and illustrative purposes. Macrocell-only users connect to the macrocell with the strongest received pilot signal. Femtocell whitelisted users connect to the base station with the strongest received pilot. Femtocell users will only connect to a femtocell if its pilot signal is the strongest; there is no priority given to femtocells.

Additional parameters are noted in Table 2.1. All parameter values, except femtocell transmit power, are from [14]. Femtocell transmit power is from [5].

Path loss is modeled using the Motley-Keenan wall model [11]:

\[
l_f^{[dB]}(r) = 37.5 + 20 \log(r/1000) + \sum l^w + x
\]

\(\sum l^w\) is the additional loss due to interior and exterior walls, with each interior wall contributing 2-4 dB, depending on the type of wall, and exterior walls contributing 15 dB.
2.7 Simulation Results

We evaluated the measurement-based and game-theoretic algorithms in a simulation environment with 50 femtocells, with open and closed access femtocells. In the closed access scenario, 50% of users are randomly chosen to be on the femtocell whitelist, which is shared between all femtocells. This scenario models the mixed public-private usage described in Section 2.1. Each result is the average of 100 runs of the simulation.

In addition to the measurement and game-theoretic algorithms, we consider two baseline scenarios: no femtocells and static femtocell pilot powers. In the static case, femtocell pilot strengths are estimated as described in Section 2.2 and do not change. We evaluated the dynamic algorithm from Section 2.5 with initial femtocell pilots as described in Section 2.2, but performance was uniformly worse than the measurement-based and game-theoretic algorithms; we omit those results for clarity’s sake. In the graphs, the static case is labeled “Static,” the measurement algorithm is labeled “MeasureCoop,” and the game-theoretic algorithm is labeled “UtilityCoop.”

Figure 2.5 illustrates the effect of the measurement algorithm on user SINRs with closed access femtocells. Red circles indicate users connected to the macrocell, red circles with ×s indicate femtocell-whitelisted users, and green squares indicate users in outage. In the static case, three users in the center, circled in white in Figure 2.5a, cannot connect due to excessive downlink interference from femtocells. With the measurement-based algorithm, one of the users in the center that was in outage is now able to connect to a femtocell, and one is able to connect to the macrocell; both are circled in white. Furthermore, switching some femtocell-whitelisted users to femtocells allowed more macrocell-only users to connect.

The full results for the closed access suburban and urban scenarios are in Table 2.3. For clarity, we focus on the suburban scenario. Figure 2.6 shows outage probability as a function of the total number of users in the system at 384 kbps. The baseline scenario with no femtocells reaches extremely high outage rates, demonstrating the limited capacity of the macrocell network for high data rate users. The baseline femtocell case, indicated by the dotted line with cross markers, increases total network capacity, and reduces outage rates by 27% relative to the case with no femtocells. The measurement and utility algorithms reduce outage
rates even further, with the utility algorithm reducing outages by 10% relative to the static femtocell case.

Figures 2.7 and 2.8 show the average femtocell pilot level and the number of users connected to femtocells, respectively. These graphs demonstrate that the utility algorithm finds more efficient femtocell pilot levels than the measurement algorithm. More users are able to connect to femtocells when pilots are set using the utility algorithm than when pilots are set using the measurement algorithm, despite the fact that average femtocell pilots are higher when using the measurement algorithm.

At 144 kbps, the utility and measurement algorithms again perform the best, with the utility-based algorithm reducing outages by 17% relative to the static case. At 64 kbps, scenarios with femtocells often perform worse than the baseline, illustrating one of the problems with femtocell deployment—femtocell interference can hurt connectivity when not all users have access to the femtocells. The utility-based algorithm performs the best again, while the measurement-based algorithm actually increases outage rates, albeit only by 3%.

In the urban scenario, with a large number of smaller buildings, the gain from femtocells is limited by the physical environment. Femtocell signals are almost impossible to detect through exterior walls, reducing their effective range. The utility-based algorithm makes the best use of femtocells in a difficult environment, with decreases in outage rates relative to the static pilot case of 12% at 144 kbps, and 4% at 384 kbps. At 64 kbps, the static case actually performs best. This is because at low bitrates, the downlink interference from femtocells to macrocell users hurts connectivity more than the presence of femtocells helps. At higher bitrates, the downlink interference is still a problem, but on average, the benefit provided by users connecting to femtocells is greater than the harm caused by interference.

With open access femtocells, outage rates are much lower overall, as expected, and the utility algorithm performs the best overall. Figure 2.11 shows outage rates at 344 kbps with open access femtocells. The utility algorithm reduces outage rates by 43% relative to the static femtocell case, and outperforms the measurement based algorithm by 17%. With closed access femtocells, the gains from the utility-based algorithm are limited by the number of users on the femtocell whitelist. With open access femtocells, the performance gain from the utility-based algorithm is more apparent.
Overall, the utility-based algorithm performs the best under almost all environments and data rates. This gain is from opportunistically increasing femtocell pilots in appropriate environments, and detecting user activity to dynamically adjust pilots downward when macrocell users are nearby. The measurement-based algorithm relies on the same methods as the utility-based algorithm, but the utility algorithm finds better results.

2.8 Related Work

A number of authors have studied femtocells from both a simulation-oriented perspective and an analytical perspective. Andrews, Claussen, et al. provide a thorough overview of research methods and problems in femtocells [15]. Claussen, et al. published a number of introductory simulation-based papers on femtocells [6, 7, 16, 18]. Papers [17, 18] were initial studies of the interference impact of femtocells, while other papers examined specific topics such as spatial diversity [16], femtocell pilot signal self-optimization [6], and dynamic femtocell power saving [5]. This work is most similar to [6] and [5], in that we also consider femtocell pilot optimization and user activity detection, but we introduce cooperation amongst femtocells and consider high-density femtocell deployments.

Chandrasekhar, Andrews, et al. published a series of analytical papers that covered topics such as uplink capacity [19], power control [20], and spatial diversity [21]. [19] examines the tradeoff between increasing the number of femtocells and the number of supportable macrocell users, and analyzes the use of time-hopping CDMA and sectorized femtocell antennas to reduce interference between tiers. [21] considers femtocells and mobiles with multiple antennas for interference management, and introduces a carrier-sensing mechanism for femtocells to reduce femtocell interference.

Game theory has been applied to problems in wireless networks by many authors [9, 10, 20, 22–28]. Han, et al. [8] provide a thorough introduction to game theory and a survey of the current state-of-the-art.

Guruacharya, et al. [27] apply game theory to the interactions between femtocells and macrocells by formulating the OFDMA power allocation problem as a Stackelberg game. Stackelberg games are games in which there are two groups of players: leaders and followers. Leaders are allowed to choose their strategies first.
In the paper, the macrocells choose their power allocation first, then the femtocells choose theirs. Although the Stackelberg game formulation is novel, the analytical complexity of solving the Stackelberg game precisely causes the approximation algorithm presented in the paper to underperform the Nash equilibrium. Kang, et al. [28] also use a Stackelberg game formulation for resource allocation; their results indicate that the Stackelberg game formulation leads to efficient power allocations in both sparse and dense femtocell networks.

In [20], Chandrasekhar, et al. analytically derive feasible SINR targets for combinations of macrocell and femtocell users, and use game-theoretic concepts to adaptively equalize femtocell SINR targets and reduce femtocell SINR targets when a macrocell user cannot reach its SINR target. They find the Nash equilibrium of a strategic game between femtocell and macrocell users, which they use to adjust femtocell user SINR targets, to balance quality of service between macrocell users and femtocell users. Due to the complexity of their analysis, their model is restricted to scenarios with one user per base station.

To the best of our knowledge, no papers consider femtocell pilot adjustment problems using game theory, though Felegyhazi, et. al. [23] consider setting macrocell pilot powers to increase profitability at wireless operator borders.

2.9 Summary

This chapter introduced three dynamic femtocell interference management algorithms: a dynamic algorithm that lowers femtocell pilots in response to detected user activity, and two pilot adjustment algorithms that cooperatively set femtocell pilots. One of the pilot adjustment algorithms relies on measurements between femtocells to set pilots, while the other finds the Nash equilibrium of a strategic femtocell pilot game. In a traditional femtocell network architecture, information exchange between femtocells is not possible due to bandwidth restrictions in the core network. We introduce a local interference manager that exploits locality to allow information exchange between femtocells located at a single site, which improves interference management, as measured by outage probability. The game theory-based cooperative interference management decreases outage probabilities by up to 35% relative to the baseline case, and up to 17% relative to static femtocell pilots.
Acknowledgments

This work was supported by NSF Grant CNS-0905447 and ARO Award W911NF-07-1-0318.
Figure 2.5: SINR at users, 144 kbps, randomly deployed femtocells, suburban environment. Red indicates high SINRs, while blue indicates low SINRs.
Figure 2.6: Outage probability v. number of users at 384 kbps, closed access femtocells, suburban environment.
Figure 2.7: Femtocell pilot strength at 384 kbps, closed access femtocells, suburban environment.
Figure 2.8: Number of users connected to femtocells v. number of users at 384 kbps, closed access femtocells, suburban environment.
Figure 2.9: Outage probability v. number of users at 144 kbps, closed access femtocells, suburban environment.
Figure 2.10: Outage probability v. number of users at 64 kbps, closed access femtocells, suburban environment.
Figure 2.11: Outage probability v. number of users at 384 kbps, open access femtocells, suburban environment.
Chapter 3  
Energy-Aware Enterprise Femtocell Deployment

3.1 Introduction

Femtocells are small, low-power, user-deployed wireless base stations that rely on external backhaul for connections to the cellular core network. In enterprises, multiple femtocells can be deployed in large buildings to serve a large population of public users. These deployments are much higher density than typical home deployments, and have the potential to create significant interference problems for users.

We consider the problem of dense femtocell deployment, while minimizing downlink outage probability and energy consumption. We first define a submodular set function maximization problem maximizing one of two set functions, femtocell coverage or area spectral efficiency (ASE), that we use as heuristics for reducing outage probability and energy consumption, which are dependent on user distribution. We introduce an accelerated greedy algorithm to maximize one of the two set functions. Given reasonable problem sizes, the running time of the naive greedy algorithm is several days, compared to a few hours for the accelerated version. Then, motivated by a desire to balance the strengths and weaknesses of deployments relying solely on femtocell coverage or ASE, we combine the two metrics in a weighted sum, giving us the Greedyα-ASECOVER algorithm. We show that this combined approach is better at reducing outage probability and energy consumption than the naive greedy approach.
Our results show that Greedy-ASECover can reduce downlink outage probabilities by up to 30% relative to existing greedy approaches, and 57% over randomly deployed femtocells. We also find that Greedy-ASECover can reduce network power consumption by up to 14% relative to the macrocell-only baseline.

This chapter is organized as follows: Section 3.2 discusses related work. Section 3.3 lays the mathematical foundations for the rest of the chapter. Section 3.4 introduces our greedy algorithms. Section 3.5 introduces our simulation model, while Section 3.6 describes our evaluation and discusses our final results. We conclude in Section 3.7.

3.2 Related Work

The difficulty of finding good cellular network deployments and configurations, combined with the potential cost and performance benefits of good network design make numerical and combinatorial optimization powerful and popular tools for designing and configuring networks. Whitaker and Hurley [29] provide an overview of the development of radio network planning and the application of optimization techniques to cellular networks. Son, et al. [30] considered the placement of microcell base stations in pre-existing deployments of macrocells to minimize energy consumption subject to ASE requirements. Femtocell deployment is most similar to microcell deployment with pre-existing macrocells, though femtocells are limited to indoor deployments. Recently, optimizing femtocell configuration has become a topic of research interest. Ashraf, et al. [31] consider coverage optimization by tuning femtocell pilot strengths in large enterprise deployments of femtocells, but they do not consider deployment optimization. Liu, et al [32] consider a joint deployment-power control problem for enterprise femtocells.

3.3 Problem Description

We define two set functions, femtocell coverage and area spectral efficiency, and a deployment optimization problem. Throughout this section, let \( \mathcal{L} \) denote the set of locations in the area of interest, and \( \mathcal{L}_I \subseteq \mathcal{L} \), the set of indoor locations, chosen from a grid dividing the area of interest into squares of area 1 m\(^2\). For a deployment of macrocells and femtocells, \( \mathcal{B} \), let \( \mathcal{B}_M \) denote the set of macrocell
locations, $\mathcal{B}_F$ denote the set of femtocell locations, and $\mathcal{B} = \mathcal{B}_M \cup \mathcal{B}_F$ denote the set of all base station locations.

### 3.3.1 Serving Base Station

The serving base station of a location $l \in \mathcal{L}$ is the unique base station $B \in \mathcal{B}$ such that the received pilot signal strength of base station $B$ at location $l$ is greater than the received pilot signal strength of all other base stations, $D \in \mathcal{B}\backslash\{B\}$.

$$B_l := \{B \in \mathcal{B} : P_{pilot}^B G_{B,l} \geq P_{pilot}^D G_{D,l}, \forall D \in \mathcal{B}\backslash\{B\}\}$$

(3.1)

$P_{pilot}^B$ is the pilot transmission power of base station $B$, and $G_{B,l}$ is the gain between base station $B$ and location $l$. In the case that multiple base stations satisfy this condition, we choose a unique base station using an arbitrary but deterministic method.

### 3.3.2 Femtocell Coverage

We define the coverage of a base station $B \in \mathcal{B}$ as the subset of locations $C \subseteq \mathcal{L}$ such that base station $B$ is the serving base station, $B_l$ for all locations $l \in C$:

$$C_L(\mathcal{B}_M \cup \mathcal{B}_F) := \{l \in \mathcal{L} : B_l = B\} \cup \{B\}$$

(3.2)

A location is covered by a base station if the received strength of that base station’s pilot signal is greater than the received strength of any other base station’s pilot signal. Coverage is based only on received pilot signal strength and does not consider interference from other base stations.

Using this definition of coverage, we define a femtocell coverage set function:

$$C(\mathcal{B}) := \left| \bigcup_{B \in \mathcal{B}_F} C_L(B) \right|$$

(3.3)

Intuitively, $C(\mathcal{B})$ counts the number of locations that are covered by femtocell deployment $\mathcal{B}_F \subset \mathcal{B}$ with underlying macrocell deployment $\mathcal{B}_M$. Femtocell coverage is directly related to the probability that a location will be covered by a femtocell,
but not the probability that a user at that location will be able to connect to a femtocell. It is possible for a location to be covered by a base station, but for a user at that location to be unable to achieve a high enough SINR to connect to the base station. It can be shown that femtocell coverage is a nondecreasing submodular set function; we do not show the proof due to space considerations.

3.3.3 Spectral Efficiency

The maximum signal-to-interference-and-noise ratio (SINR) at a location, \( l \), given base station deployment \( \mathcal{B} \), is:

\[
SINR_B(l) := \frac{P_{B_l}^{tx,max} G_{B_l,l}}{\sum_{D \in \mathcal{B} \setminus \{B\}} \alpha_D P_D^{tx,max} G_{D,l} + \sigma} \quad (3.4)
\]

\( P_{B_l}^{tx,max} \) is the maximum link transmission power of base station \( B_l \), and \( G_{B_l,l} \) is the gain between base station \( B_l \) and location \( l \). \( \alpha_D \) is the orthogonality factor between base station \( D \) and users on base station \( B \). \( \sigma \) is the background noise level. The numerator gives the maximum received signal strength at location \( l \) from the serving base station \( B_l \), while the denominator is the interference from other base stations—both macrocells and femtocells—and noise.

The spectral efficiency of a communications link is a measure of the link’s maximum achievable efficiency, in units of \((\text{bits/s})/\text{Hz}\), and is defined at a location \( l \) as:

\[
SE_B(l) := \log(1 + SINR_B(l)) \quad (3.5)
\]

The spectral efficiency of a link with a fixed bandwidth gives an upper bound on the throughput of the link.

3.3.4 Area Spectral Efficiency

Area spectral efficiency, first defined in [33], is a general metric for quantifying the performance of cellular systems. It is defined as the sum of the maximum average data rates per unit bandwidth per unit area. We define it as a set function computed over the set of all locations, \( \mathcal{L} \), with base station deployment \( \mathcal{B} \).

\[
ASE_{\mathcal{L}}(\mathcal{B}) := \frac{\sum_{l \in \mathcal{L}} SE_B(l)}{\sum_{l \in \mathcal{L}} A(l)} \quad (3.6)
\]
$A(l)$ is the area of each location. Under certain reasonable assumptions, ASE is a nondecreasing submodular set function \cite{30}.

Area spectral efficiency, when measured over a fixed area, is directly proportional to the achievable SINRs in that area with a given base station deployment. Since ASE is an average, it does not measure the distribution of SINRs over an area. Scenarios with uniformly high SINRs and scenarios with a combination of very high SINRs and very low SINRs can appear almost identical as measured by ASE.

### 3.3.5 Optimization Problem

Given the coverage and ASE set functions, we consider femtocell deployment as the following optimization problem:

$$\max_{B_F \subseteq \mathcal{L}_I} F_C(B_M \cup B_F)$$

where $F_C = C(B)$ or $ASE_C(B)$

subject to $B_F \subseteq \mathcal{L}_I$

$$|B_F| \leq k$$

The constraints restrict femtocells to indoor locations, and limit the total number of femtocells to the number specified in the deployment.

Note that this optimization problem maximizes either coverage or ASE. We do not directly minimize either outage probability or power consumption, which both depend heavily on scenario-specific user distribution information. In Section 3.6 we show that this problem is a good heuristic for reducing outage probability and power consumption.

### 3.4 Greedy Femtocell Deployment Algorithms

In this section we present three greedy femtocell deployment algorithms that approximately maximize femtocell coverage and ASE over the set of possible femtocell locations. All of the algorithms in this section deploy a fixed number of femtocells, $k$, at indoor locations $l \in \mathcal{L}_I \subseteq \mathcal{L}$. 

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Algorithm 4: Accelerated greedy femtocell deployment algorithm.

\textbf{Input}: $k$, number of femtocells to deploy
\textbf{Result}: $B_F$, a deployment of femtocells

\begin{algorithm}
\begin{algorithmic}[1]
\STATE $B_F := \emptyset$
\FOR{$l \in L_I$}
\STATE $\delta_l := F(l) - F(\emptyset)$
\ENDFOR
\WHILE{$|B_F| \leq k$}
\STATE $\delta' := 0$
\WHILE{$\delta' < \max_{l \in L_I \setminus (B_F \cup \{l'\})} \delta_l$}
\STATE $l' := \arg\max_{l \in L_I \setminus (B_F \cup \{l'\})} \delta_l$
\STATE $\delta' := F(B_F \cup \{l'\}) - F(B_F)$
\ENDWHILE
\STATE $B_F := B_F \cup \{l'\}$
\ENDWHILE
\RETURN $B_F$
\end{algorithmic}
\end{algorithm}

3.4.1 Accelerated Greedy Approximation Algorithms

We begin with two greedy algorithms based on the two submodular set functions introduced in Section 3.3. Son, et al. \cite{30} introduced the \textsc{GreedyASE} algorithm; here we introduce an \textit{accelerated} version, extend it with a femtocell coverage greedy algorithm, and introduce a weighted sum approach.

The greedy algorithm in Figure 4 takes as input the set of indoor locations $L_I$, a fixed set of macrocells, $B_M$, a set function $F$, and a deployment size $k$, and returns a deployment of femtocells, $B_F$. Recall that the set of locations is defined as the points on a grid dividing the area of interest into $1 \, m^2$ squares. At each step of the procedure, the greedy algorithm deploys a femtocell at the location that increases the set function the most. While this selection is generally suboptimal, it is bounded within $1 - \frac{1}{e}$ of the optimal solution by Theorem 4.1 in \cite{34}.

Since the calculation of the ASE set function is $O(|L|)$, the running time of a naive greedy algorithm is on the order of $O(|L|^2)$, which is unreasonably large when the number of locations is large. To maintain a manageable running time, we use an accelerated version of the greedy algorithm for submodular set functions, which we describe briefly.

The accelerated greedy algorithm first calculates the set function difference, $\delta_l = F(L) - F(\emptyset)$, for all potential femtocell locations, $l \in L_I$. The first femtocell is deployed at the location that gives the maximal increase, $l^* = \arg\max_{l \in L_I} \delta_l$, and added to $B_F$. The remaining $k - 1$ femtocells are deployed as follows. First, a femtocell candidate location is found at $l' = \arg\max_{l \in L_I} \delta_l$. Then, the set function difference at $l'$, $\delta' = F(B_F \cup \{l'\}) - F(B_F)$, is recalculated. If the new value of $\delta'$
is greater than the maximum existing set function difference, \( \max_{l \in L \setminus (B_F \cup \mathcal{P})} \delta_l \), a femtocell is deployed at \( l' \), and added to \( B_F \). Otherwise, the process of finding a candidate location and recalculating the set function difference is repeated, until a femtocell is deployed at the candidate location. This entire process is repeated until \( k \) femtocells have been deployed.

In our experience, with a set of 10,000 locations, the accelerated greedy algorithm evaluates the set function under 100 times per iteration, far fewer than the 10,000 evaluations of the naive greedy algorithm. In our test environment, this reduced the running time for a 30-femtocell deployment from 6 days to 8 hours. For submodular functions, the accelerated greedy algorithm has been shown to produce the same solution as the naive greedy algorithm [35].

Using the set functions defined in Section 3.3, we obtain two greedy algorithms: GreedyCover and GreedyASE. Each algorithm approximately solves the optimization problem in Equation 3.7 with its respective set function, either the femtocell coverage function in Equation 3.3, or the ASE function in Equation 3.6. Since these functions are submodular, the Nemhauser [34] bound for greedy algorithms applies, and the approximation bound is \( 1 - \frac{1}{e} \).

GreedyCover deploys femtocells to maximize coverage, leading to deployments that spread femtocells over a large area. This increases the probability that a user is in range of a femtocell, but since coverage does not measure SINR, not all covered users will have high enough femtocell SINRs to be able to connect to the covering femtocell. This problem is exacerbated at high data rates, which require higher SINRs. Area spectral efficiency measures SINR, making it a better predictor of connectivity than coverage. However, since ASE is an average, GreedyASE may deploy femtocells such that there are large increases in spectral efficiency at a small number of locations. While femtocell users at those locations will have very high data rates, the overall probability of connecting to a femtocell may be low. The strengths and weaknesses of femtocell coverage and ASE are complementary, suggesting that a combination of the two could outperform either alone. Next, we introduce Greedy\( \alpha \)-ASECover, which is based on a weighted sum combination of femtocell coverage and ASE.
3.4.2 Weighted Sum Greedy Approximation Algorithm

The greedy algorithms of the previous subsection maximize either ASE or cover, but not both. We introduce a third algorithm that maximizes a linear combination of cover and ASE, based on the set function below, $\alpha$-ASECover:

$$\alpha$-ASECover_{\mathcal{L}}(\mathcal{B}_F) = \alpha ASE_{\mathcal{L}}(\mathcal{B}_F) + (1 - \alpha) C_{\mathcal{L}}(\mathcal{B}_F) \tag{3.8}$$

$\alpha$-ASECover is a weighted sum of femtocell coverage and ASE, with the parameter $\alpha$ determining the balance between the two. By using $\alpha$-ASECover as the set function in the accelerated greedy algorithm in Figure 4, we obtain a third greedy algorithm, Greedy$\alpha$-ASECOVER. Greedy$\alpha$-ASECOVER maintains the $1 - \frac{1}{e}$ approximation bound since linear combinations of submodular functions are also submodular functions.

3.5 Simulation Details

This section describes the simulation environment and path loss models.

3.5.1 Simulation Environment

The simulation environment consists of a WCDMA cellular system with 19 3-sector macrocells arranged in a hexagonal pattern. The 2km$^2$ area of interest is in the center, with two layers of neighboring cells. We modeled a suburban campus environment, with a small number of large brick, glass, and concrete buildings. Buildings are modeled with realistic interiors, including small offices, medium-sized conference rooms, and large common areas.

Macrocell and femtocell pilot signals are set at 10% of the maximum transmit power, while common channels are assumed to consume the same amount of power as the pilot [14]. All femtocells are open access. A complete listing of model parameters is in Table 3.1, all of which were referenced from [14], except femtocell transmit power, which is from [5].
Table 3.1: Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_t$</td>
<td>-174 dBm/Hz</td>
<td>Thermal noise</td>
</tr>
<tr>
<td>$N_{ms}$</td>
<td>-7 dB</td>
<td>MS noise figure</td>
</tr>
<tr>
<td>$f$</td>
<td>1900 Mhz</td>
<td>Carrier Frequency</td>
</tr>
<tr>
<td>$R_M$</td>
<td>750 m</td>
<td>Target macrocell radius</td>
</tr>
<tr>
<td>$R_f$</td>
<td>15 m</td>
<td>Target femtocell radius</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>4.5 dB</td>
<td>Downlink $E_b/N_0$ target</td>
</tr>
<tr>
<td>$W$</td>
<td>3.84 Mcps</td>
<td>Chiprate</td>
</tr>
<tr>
<td>$S$</td>
<td>384, 144 kbps</td>
<td>User data rates</td>
</tr>
<tr>
<td>$P_{max,m}$</td>
<td>43 dBm</td>
<td>Max transmit power, macrocell</td>
</tr>
<tr>
<td>$P_{max,f}$</td>
<td>23 dBm</td>
<td>Max transmit power, femtocell</td>
</tr>
<tr>
<td>$P_{pilot,m}$</td>
<td>33 dBm</td>
<td>Pilot power, macrocell</td>
</tr>
<tr>
<td>$P_{pilot,f}$</td>
<td>20 dBm</td>
<td>Max pilot power, femtocell</td>
</tr>
</tbody>
</table>

3.5.2 Path Loss Models

The downlink macrocell path loss model is the COST 231 Walfisch-Ikagami two-slope model [36]:

$$l_M^{dB}(r) = 42.6 + 26 \log(r) + 20 \log(f) + x$$

$r$ is the distance in kilometers, and $f$ is the carrier frequency in Mhz. Indoor users are subject to an additional exterior wall loss of 15 dB. $x$ models shadow fading as a log-normal random variable with $\mu = 0$ and $\sigma = 7$ dB [14].

The femtocell path loss model is the Motley-Keenan indoor wall model [11]:

$$l_f^{dB}(r) = 37.5 + 20 \log(r/1000) + \sum l_w + x$$

$\sum l_w$ is the additional loss due to interior and exterior walls, with each interior wall adding 2-4 dB, dependent on wall material, and exterior walls adding 15 dB.

3.6 Results

In this section, we define outage probability and power consumption, our metrics for evaluating our algorithms.

3.6.1 Outage Probability

The optimization problem in Equation 3.7 maximizes coverage and ASE, which are useful metrics for describing the performance of a wireless network, but outage
probability remains the most comprehensive evaluation metric for wireless networks.

We first define users as a set of locations $\mathcal{U} \subseteq \mathcal{L}$, and connected users, $\mathcal{U}_C \in \mathcal{U}$ as the set of users, $U$ such that $\text{SINR}_{B,U}(U) \geq \tau$. $\text{SINR}_{B,U}$ denotes the power-controlled SINR at $U$ with interfering users in $\mathcal{U}$. $\tau$ is the current SINR target. Then outage probability for a set of users, $\mathcal{U}$, and base stations, $\mathcal{B}$ is defined as $O(\mathcal{U}, \mathcal{B}) = 1 - \frac{|\mathcal{U}_C|}{|\mathcal{U}|}$.

### 3.6.2 Power Consumption

The macrocell power model in this section is from Richter, et al.\cite{richter2012}. The total power consumption of a macrocell, $P_{\text{macro}}$, is divided into a static power level, $P_{\text{static}}$ and a dynamic power coefficient, $P_{\text{dynamic}}$, where $P_{\text{static}}$ models the energy consumed by a base station at idle, and $P_{\text{dynamic}}$ models the additional energy consumed per watt of transmit power. The total power consumption of a
Figure 3.2: Femtocell Users, 144kbps, 20 femtocells

macrocell, in watts, given distributions of users and base stations, is defined as

\[ P_{\text{macro}}[W](U, B) = \sum_{s=1}^{N_{\text{sectors}}} N_{\text{antennas}}^s \left( P_{\text{dynamic}} \times P_{\text{tx}}^s(U, B) + P_{\text{static}} \right) \]  \hspace{1cm} (3.9)

With \( N_{\text{sectors}} = 3 \), \( N_{\text{antennas}} = 2 \), \( P_{\text{dynamic}} = 3.77 \), and \( P_{\text{static}} = 68.73 \) W \[37\]. \( P_{\text{tx}}^s(U, B) \) is the total radio transmit power of the macrocell sector under the given user and base station distributions.

We also consider the net power consumption of the network:

\[ P_{\text{net}}[W](U, B) = P_{\text{macro}}[W](U, B) + \sum_{i \in B_F} P_{\text{femto}}[W] \]  \hspace{1cm} (3.10)

Using measurements of commercially available femtocells, we find that femtocell power consumption, \( P_{\text{femto}}[W] \), is a uniform 12 W under all load conditions, due to
the low maximum transmit power of femtocells (0.2 W). Ashraf, et al. [5] find the same value for femtocell energy consumption.

### 3.6.3 Simulation Results

We evaluated our deployments with 100 runs of simulations with 10, 20, and 30 femtocells. Users are uniformly distributed 384 and 144 kbps downlink circuit-switched indoor data users with an activity factor of 1. This load level was chosen to test femtocell deployments under high load, therefore outage probabilities for the baseline without femtocells are extremely high, and are included for reference only. We compare our results to the existing **GreedyASE** algorithm from Son, et al. [30], which is equivalent to $\alpha = 1.0$.

For clarity, the figures in this subsection show only selected $\alpha$ values. The baseline case, the solid line in all figures, is macrocell-only, with no femtocells
deployed. The random case, the + marker in all figures, is a uniformly distributed random deployment of femtocells at indoor locations. $\alpha = 1.0$ is the existing GreedyASE algorithm, and $\alpha = 0.0$ is the GreedyCover algorithm. Full outage probability and net power consumption results are listed in Table 3.2. The lowest values in each column are highlighted.

Figure 3.1 shows outage probability at 144 kbps, with a deployment of 20 femtocells. With 20 femtocells, femtocell coverage probability, $|C_L(B)|/|L|$, is below 50% for all $\alpha$ values. Despite the low femtocell coverage, outage probability is reduced significantly. $\alpha = 0.1$, with the circle marker, overlapping with $\alpha = 0$, shows a 67% decrease in outage probability compared to a random deployment, and a 30% decrease in outage probability compared to the GreedyASE algorithm, with the square marker. Figure 3.2 shows that the reduction in outage probability comes from an increase in the number of users connected to femtocells, relative to a random deployment and the $\alpha = 1.0$ deployment.

Our results show that deployments with $\alpha$ values between 0 and 1.0 decrease outage probabilities and network power consumption relative to naive greedy algorithms. The value of $\alpha$ that provides the most benefit depends on the data rate and the number of femtocells. Note that $\alpha$ values that reduce outage probability may not necessarily reduce power consumption, since low outage probabilities may be due to a higher number of users connected to femtocells. Overall, lower $\alpha$ values lead to higher femtocell usage, due to increased femtocell coverage, but this does not minimize outage probabilities. When deploying femtocells, a trade-off must be made between reducing outage probabilities and reducing energy consumption.

The total network power consumption graph in Figure 3.3 shows that certain $\alpha$ values decrease total network power consumption, including the power used by the femtocells. Table 3.2 shows that $\alpha = 0.5$ reduces power consumption by 14%. By contrast, random femtocell deployments increase total power consumption, due the power used by femtocells.

### 3.7 Summary

Large femtocell deployments can greatly impact co-channel macrocell networks. We showed that greedy approximation algorithms that maximize femtocell coverage and ASE are effective heuristics for reducing outage rates and energy usage. Then,
motivated by an analysis of the complementary strengths and weaknesses of each, we introduced Greedy$\alpha$-ASECover, a weighted sum algorithm that combines the femtocell coverage and ASE metrics. Simulation results show that femtocell deployments using a combination of coverage and ASE achieve lower outage probabilities relative to the deployments using the straightforward greedy approach. We find that using Greedy$\alpha$-ASECover to deploy femtocells can reduce outage probability by up to 30%, and reduce total network power consumption by up to 14%.
Table 3.2: Results

<table>
<thead>
<tr>
<th>Femtos/Users</th>
<th>144 kbps</th>
<th>384 kbps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outage Probability (%)</td>
<td>Net Power Consumption (W)</td>
</tr>
<tr>
<td></td>
<td>10/40</td>
<td>20/60</td>
</tr>
<tr>
<td>Baseline</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Random</td>
<td>38.7</td>
<td>51.3</td>
</tr>
<tr>
<td>α = 1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>α = 0.9</td>
<td>26.1</td>
<td>30.3</td>
</tr>
<tr>
<td>α = 0.8</td>
<td>26.1</td>
<td>29.0</td>
</tr>
<tr>
<td>α = 0.7</td>
<td>27.2</td>
<td>29.9</td>
</tr>
<tr>
<td>α = 0.6</td>
<td>26.0</td>
<td>26.1</td>
</tr>
<tr>
<td>α = 0.5</td>
<td>25.5</td>
<td>26.1</td>
</tr>
<tr>
<td>α = 0.4</td>
<td>24.9</td>
<td>26.1</td>
</tr>
<tr>
<td>α = 0.3</td>
<td>22.1</td>
<td>24.2</td>
</tr>
<tr>
<td>α = 0.2</td>
<td>20.0</td>
<td>22.7</td>
</tr>
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<td>α = 0.1</td>
<td>20.9</td>
<td>22.0</td>
</tr>
<tr>
<td>α = 0.0</td>
<td>23.0</td>
<td>22.2</td>
</tr>
</tbody>
</table>
Chapter 4  
Selective Activation in Dense Femtocell Networks

4.1 Introduction

The use of mobile broadband wireless devices is experiencing explosive growth. According to recent studies [38], global mobile broadband subscriptions will reach 4.4 billion by 2016, and global mobile data traffic has been growing at a rate of 150% yearly.

This increased use is characterized by a much higher reliance on these devices for indoor and outdoor high speed wireless data access. This has resulted in an increase in the occurrence of temporary, high-density concentrations of mobile users with high traffic demands [39], often indoors. Density increases can occur intermittently, such as during sporting events or concerts, or more regularly, as when trains arrive at high-traffic stations or at an airport gate. These increases temporarily place a very high, localized load on wireless networks, reducing service quality and leading to outages.

Provisioning wireless networks to manage the peak number of users in a congested area may reduce such a problem, but is expensive and wasteful during normal loads. Temporary, mobile wireless base stations [40] are not suitable for areas which may have regularly occurring congestion, such as subway stations or airports. For these reasons, there has been significant from the industry [39,41] and the research community [42–51] to design solutions based on the new technology of femtocell networks.
Femtocells are small, short-range wireless base stations that rely on user-provided Internet for backhaul. Provisioning a short-range small cell network for peak hotspot load is easier and cheaper than provisioning a long-range macrocell network for the same load. This makes small cells well-suited for managing indoor hotspots in locations that see periodic traffic, such as public transportation hubs, meeting halls, and classrooms.

In order to be able to successfully handle the high load generated by user hotspots, the femtocell network needs to be deployed at high density. Such dense deployment may result in a non-negligible network energy consumption. For example, assuming femtocells consume 6 W of power, a network of 1000 cells covering a university campus would consume more than 50 MWh/year. Solutions for designing high-density wireless networks mainly focus on user quality of service, and only marginally consider power consumption [39,42–44]. However, the temporal nature of user hotspots can be exploited to reduce the network energy expenditure. As an example, consider a small cell network that is provisioned to serve a peak load that is three times the average load. If the peak load is encountered 30% of the time, nearly 50% of the power used by the network is unnecessary.

In this paper, we study the problem of minimizing the energy consumption of dense small cell networks. Use cases include university campuses, sports arenas, or public transportation hubs. In these scenarios, user traffic exhibits time- and space-localized peaks. To reduce network energy consumption, we model the problem as a selective activation problem. Using selective activation, only a reduced set of femtocells are activated at a given time. The remaining cells are put to sleep to conserve power and are activated only when needed as traffic increases. We motivate the use of selective activation, rather than power-management, through measurements of real femtocell energy usage, which show that femtocell energy use is not dependent on load. Therefore, reducing femtocell energy usage is directly translated to reducing the number of active femtocells.

We formalize the selective activation problem as a non-linear optimization problem, which takes into account detailed aspects of LTE networks such as interference and resource block allocation. We show that the problem is NP-Hard and introduce GREENFEMTO, a distributed algorithm for femtocell selective activation. The algorithm does not assume cell synchronization and dynamically adapts the active set of cells on the basis of the user location and movement. We
prove that GreenFemto converges to a stable solution and that the solution is Pareto optimal.

We evaluate the performance of GreenFemto against a previously proposed femtocell power-saving algorithm using a realistic LTE simulator. Results show that GreenFemto outperforms the previous approach and reduces the energy consumption of the network by up to 55%, and comes within 15% of a globally optimal solution.

In summary, our contributions are the following:

- We perform real measurements of the energy consumption of femtocells to motivate the use of selective activation;
- We study the problem of reducing the energy consumption of densely deployed femtocell networks. We formulate this as a non-linear optimization problem and show that it is NP-Hard;
- We introduce GreenFemto, a distributed algorithm for femtocell selective activation. We prove that GreenFemto converges to a Pareto optimal solution;
- We compare the performance of GreenFemto through simulations, showing that it successfully reduces energy consumption and outperforms previous solutions.

4.2 Femtocell Power Measurements

In this section we analyze the power usage of commercially available femtocells to motivate the use of selective activation. We find that femtocells consume a fixed amount of power, independent of the number of and position of the users they are serving, which corroborates results presented in [5]. Although femtocell radio transmission power varies with the number and location of users being served, femtocell radios have a maximum transmit power in the range of 100-250 mW [52], leading to low variation in power consumption that is dominated by fixed-power components such as the processor, amplifier, and memory. Since femtocell power use remains constant relative to load and user position, the best way to control power consumption is to limit the number of active femtocells, regardless of the
load on the network. Therefore, we conclude that selective activation is the most effective way of reducing a femtocell network’s energy consumption.

We record the femtocell’s power usage with zero to five active users at two locations: location A, 0.5 meters away in the same room, with an average received signal strength indicator of -59 dBm, and location B, at the edge of the femtocell’s coverage radius, with an average received signal strength indicator of -91 dBm, approximately 15 meters away, through multiple interior walls. Each value in Table 4.1 is the average of five measurements. As femtocell load increases, the femtocell’s power usage remains stable. Based on the lack of correlation between the femtocell’s transmit power and its overall power consumption, and taking power supply inefficiency into account, we conclude that femtocells consume a fixed amount of power when activated, regardless of the number of users being served.

Since a femtocell’s power consumption arises largely from being powered on, we focus our design at the broad level of minimizing the number of femtocells that are active, rather than managing the power consumption of individual femtocells or users.

### 4.3 Network Model and Problem Formulation

In this section we define our network model and problem. We consider an LTE data network with femtocells. The channel bandwidth is divided into subchannels, each of which are further time-divided. Each time division on a subchannel is known as a resource block (RB). User transmissions are scheduled across RBs on the base station to which the user is associated. Base stations regularly transmit reference signals (RS) that are used to measure signal quality.

Consider an area of interest \( \mathcal{L} \), defined as a set of points \( p \in \mathcal{L} \). We define a set \( F = \{f_1, \ldots, f_K\} \) of \( K \) femtocells deployed over \( \mathcal{L} \). We consider two types of coverage: area coverage and user coverage. Area coverage is defined as coverage...
of a set of points regardless of users, and is used to detect users. User coverage is
defined as the ability to serve a user at a minimum transmission rate, and is used
for user service. We define two distinct thresholds for area and user coverage: \( t^a \)
and \( t^u \). A location or user is covered if the SINR of the RS at that point is above
\( t^a \) or \( t^u \), respectively.

A femtocell \( f_i \)’s coverage range, \( R^a_i \) or \( R^u_i \), is defined as the largest contiguous set
of locations at which \( f_i \)’s RS can be received with SINR above \( t^a \) or \( t^u \), respectively.
\( t^u > t^a \), therefore, \( ||R^a_i|| > ||R^u_i|| \). We assume each femtocell is aware of its location
and coverage range\(^1\). A location is redundantly covered if it is covered by at least
two femtocells. Femtocells communicate locally using the network that they use
for backhaul.

Users are defined as a set \( U = \{u_1, \ldots, u_M\} \). Users are served by femtocells
that have enough free RBs to schedule the user for transmission. Users are rejected
if no femtocell can schedule the user. To emphasize the effect of user rejections,
we formalize our algorithms in a network model without macrocells, however, this
is not a requirement for our algorithms. Nevertheless, since femtocell networks
are often deployed to improve signal quality in areas with poor-or-no macrocell
coverage, such as subways, this is a reasonable assumption.

The selective activation problem is to find a minimal set of active femtocells,
\( F^* \subseteq F \), that provides full area and user coverage. This implies that all locations
in \( L \) have an SINR above \( t^a \), and all users have an SINR above \( t^u \). The assignment
of users in \( U \) to femtocells in \( F^* \) must be feasible in terms of femtocell capacity
and must satisfy user requirements in terms of minimum acceptable rate. If not all
users can be served at their rate targets, users are rejected one by one.

## 4.4 Interference-Aware Femtocell Activation Optimization

In this section we give a theoretical formulation of the problem, described in Section
4.3, to determine a subset of the available femtocells, so as to serve a given set
of users at a minimum transmission and provide area coverage while minimizing
energy consumption.

\(^1\)In a centrally managed and deployed network, femtocell coverage ranges can be estimated at
deployment.
An activation policy determines which femtocells should be activated to serve the given set of users and can be expressed by means of an activation vector $\bar{X} \triangleq \{x_1, x_2, \ldots, x_M\}$, where the value of the variable $x_i$ is 1 if the femtocell $f_i$ is activated, while it is 0 if $f_i$ is disabled.

The objective of our problem is to find an activation policy that serves all users in $U$ with the minimum number of active femtocells; that is, an activation vector $\bar{X}$ that minimizes:

$$\sum_{i=1}^{N} x_i \quad (4.1)$$

If a cell $f_i \in F$ serves the user $u_j \in U$, it provides the user with a given number of resource blocks, which is represented in the problem by integer variable $y_{ij}$. Femtocells have a capacity limitation, as the amount of resource blocks available for each cell is limited to $b_{\text{MAX}}$. Since the energy consumption of a femtocell is not dependent on the number of resource blocks it allocates, it is beneficial to users for femtocells to allocate as many resource blocks as possible, which improves quality of service. Therefore, we assume that every active cell allocates all its available resource blocks, as expressed in the following constraint:

$$\sum_{j=1}^{M} y_{ij} = x_i \cdot b_{\text{MAX}}, \quad \forall i \text{ s.t. } f_i \in F \quad (4.2)$$

Given a user $u_j$, being served by the cell $f_i$, and given the activation vector of the network $\bar{X}$, the rate requirement $r$ for the user $u_j$ can be defined as a function $b_{ij}(\cdot)$, that returns the minimum number of resource blocks $b_{ij}(\bar{X})$ that user $u_j$ needs from cell $f_i$ to operate with rate higher than or equal to $r$, given that user $j$’s SINR is above $t^u$. The function $b_{ij}$ depends on system-wide SINR calculations, therefore it is non-linear and there is no known closed form expression in terms of the elements of $\bar{X}$. Therefore, the user quality requirement implies that $y_{ij} \geq b_{ij}(\bar{X})$ when the cell $f_i$ is selected to serve user $u_j$.

Before translating this into a constraint of our optimization problem, further note that every user $u_j$ must be served by one and only one cell, and it must receive all resource blocks from the same cell. In order to express this property, we introduce a binary assignment variable $z_{ij}$. The variable $z_{ij}$ is one if user $u_j$ is served by cell $f_i$ and zero otherwise. The variable $z_{ij}$ expresses the mutually exclusive constraint that a user is either served by cell $f_i$ with at least $b_{ij}(\bar{X})$ resource blocks
(the case when \( z_{ij} = 1 \)), or it is served by one of the other cells \( f_k \), with \( k \neq i \) (the case when \( z_{ij} = 0 \)). This property can be expressed by the following set of constraints:

\[
\begin{align*}
y_{ij} & \geq z_{ij} \cdot b_{ij}(\bar{X}) & f_i \in F, u_j \in U \quad (4.3) \\
\sum_{k=1, k \neq i}^{N} y_{kj} & \leq (1 - z_{ij}) \cdot |F| \cdot b_{\text{MAX}} & f_i \in F, u_j \in U \quad (4.4) \\
y_{ij} & \leq b_{\text{MAX}} \cdot z_{ij} & f_i \in F, u_j \in U \quad (4.5) \\
\sum_{k=1, k \neq i}^{N} y_{kj} & \geq 1 - z_{ij} & f_i \in F, u_j \in U \quad (4.6)
\end{align*}
\]

Finally, in order to let cells detect users in their coverage range and enable activation decisions, we impose an additional constraint on area coverage. Each cell \( f_i \) is able to detect the presence of users in their area coverage range, \( R^a_i \). Note that the area coverage range is larger than the user coverage range, \( R^u_i \), and cell \( f_i \) may be unable to serve a user at distance \( R^a_i \). Nevertheless, if every point of the area of interest is within the coverage range of an active cell, the network is able to sense any incoming users and activate additional femtocells as needed.

We model coverage ranges as open intervals, that is, femtocell \( f_i \) does not cover the border of its area \( R^a_i \). We define an intersection point as a point at which the borders of two coverage ranges intersect, or a point at which a coverage range intersects with the border of the area \( \mathcal{L} \). We denote by \( \mathcal{I} \) the set of all intersection points in \( \mathcal{L} \). In the following theorem, we extend a result from [54] that shows that the coverage of the points in \( \mathcal{I} \) implies complete coverage of \( \mathcal{L} \) to the case of general non-convex shaped coverage areas.

**Theorem 2.** Given a set of femtocells \( F \), deployed over an area \( \mathcal{L} \) and generating a set of intersection points \( \mathcal{I} \subset \mathcal{L}, \mathcal{I} \neq \emptyset \), if a subset \( \hat{F} \subseteq F \) covers all points in \( \mathcal{I} \), then \( \hat{F} \) completely covers \( \mathcal{L} \).

**Proof.** The set of coverage ranges partitions the area \( \mathcal{L} \) into coverage patches \( H_1, \ldots, H_m \), where patches are bounded by the borders of coverage ranges or by the borders of \( \mathcal{L} \).
The border of a coverage patch $H_i$ contains intersection points everywhere the border of two coverage ranges, or the border of a coverage range and the border of $\mathcal{L}$, intersect.

We proceed by contradiction. Let $p \in \mathcal{L}$ be a point not covered by the femtocells in $\hat{F}$ and let $H_p$ be the coverage patch to which it belongs. $H_p$ always exists since the coverage patches partition $\mathcal{L}$.

All points in $H_p$ have the same coverage degree, by definition of coverage patch, thus $H_p$ is also not covered. Since we define coverage ranges to be open intervals, an intersection point on the border of $H_p$, generated by the intersection of the borders of two coverage ranges $R_i$ and $R_j$, is not covered by the femtocell $f_i$ and $f_j$. As a result, the intersection points on the border of $H_p$ are also uncovered.

This is a contradiction of the assumption that all intersection points are covered by the cells in $\hat{F}$, therefore the uncovered point $p$ does not exist.

$\mathcal{I}$ includes all the intersection points generated by the coverage regions of all the femtocells in $F$. According to Theorem 4.4, if all points of $\mathcal{I}$ are within the coverage range of an active cell, all of $\mathcal{L}$ is covered, and the active cells are able to detect the presence of a user in any point of the area.

Therefore, we include area coverage as follows. Let $l \in \mathcal{I}$ be a point in the region of interest. Let $p_{il}$ be a binary constant coefficient which is equal to 1 if the point $l$ is in the coverage range of femtocell $f_i$. Then, in order to have complete area coverage, the activation set $\bar{X}$ must satisfy the following constraint.

$$\sum_{i=1}^{N} x_i p_{il} \geq 1, \quad \forall l \in \mathcal{L} \quad (4.7)$$

Summarizing the previous discussion, we obtain the following integer non-linear optimization problem, hereby referred to as MinActivation:

$$\min \sum_{i=1}^{N} x_i \quad (4.8)$$

$$\sum_{j=1}^{N} y_{ij} = x_i \cdot b_{\text{MAX}} \quad \forall i: f_i \in F \quad (4.9)$$

$$y_{ij} \geq z_{ij} \cdot b_{ij}(\bar{X}) \quad f_i \in F, u_j \in U \quad (4.10)$$
\[
\sum_{k=1}^{N} \sum_{k \neq i} y_{kj} \leq (1 - z_{ij}) \cdot |F| \cdot b_{\text{MAX}} \quad f_i \in F, u_j \in U \\
y_{ij} \leq b_{\text{MAX}} \cdot z_{ij} \quad f_i \in F, u_j \in U \\
\sum_{k=1}^{N} y_{kj} \geq 1 - z_{ij} \quad f_i \in F, u_j \in U \\
\sum_{i=1}^{N} x_i p_i \geq 1 \quad \forall l \in \mathcal{L}
\] (4.11) (4.12) (4.13) (4.14)

The following theorem proves that the \textbf{MinActivation} is NP-Hard by showing that Set Cover is a special case of \textbf{MinActivation}.

\textbf{Theorem 3}. \textbf{MinActivation} is NP-Hard.

\textit{Proof}. We show that Set Cover is a sub-problem of our problem. Let us consider a general instance of Set Cover. We define \( \Omega \) as the set of all elements, and \( S = \{S_1, \ldots, S_n\} \) subsets such that \( S_i \subseteq \Omega \) for \( i = 1, \ldots, n \) and \( \cup_{S_i \in S} S = \Omega \). According to Set Cover we should find the smallest subset of \( S \) such that all elements in \( \Omega \) are covered.

We can create an instance of \textbf{MinActivation} from a general instance of Set Cover by the following procedure:

1. Add a point in \( \mathcal{L} \) for each element of the universe \( \Omega \).
2. Add a femtocell \( f_i \) in \( F \) for each set \( S_i \) in \( S \). \( f_i \) can cover the points in \( \mathcal{L} \) corresponding to the elements in \( S_i \).

No users are needed in the reduction, so \( U = \emptyset \).

A solution to \textbf{MinActivation} finds an activation vector \( \vec{X} \) that identifies a minimum set of active femtocells needed to cover all points in \( \mathcal{L} \). This corresponds to the smallest subset of \( S \) that covers all elements in \( \Omega \). Therefore, Set Cover is a special case of \textbf{MinActivation} and thus our problem is NP-Hard. \( \square \)

\subsection*{4.5 The GreenFemto Algorithm}

In this section we introduce \textbf{GREENFEMTO}, a distributed algorithm that finds a locally Pareto optimal solution to \textbf{MinActivation}. The algorithm consists of two
parts that address two different aspects of user management: user detection and user reassignment.

4.5.1 Overview

A femtocell can be active or inactive. Active femtocells provide area coverage and can serve users, but consume energy. Inactive femtocells do not provide coverage or serve users, but do not consume energy. We assume that femtocells can be turned on remotely using Wake-on-LAN \[55\].

For each femtocell \( f_i \in F \) we define \( U_i \subseteq U \), the set of users \( f_i \) can serve. We say that a femtocell \( f_j \) is a neighbor of a femtocell \( f_i \), if their coverage ranges overlap, that is \( R_i^u \cap R_j^u \neq \emptyset \). We refer to the set of all neighbors, awake or sleeping, of \( f_i \) as \( B_i \). The set of active neighbors is denoted by \( B_i^* \), and inactive neighbors by \( B_i^o \).

\( c_i \) is the residual capacity of the femtocell \( f_i \), that is, the number of free RBs it can schedule. We assume that each femtocell \( f_i \) knows the coverage ranges, \( R_i^u \) and \( R_j^u \), of each of its neighbors.

**GREENFEMTO** keeps a minimal set of sentinel femtocells active for area coverage. This set is found by disabling redundant femtocells, as identified using the procedure in Section 4.5.4. Users are detected by sentinel femtocells, and either served directly by the sentinel femtocell or served by a newly awoken femtocell. After femtocells are awoken, user reassignment and a redundancy test are performed to minimize the number of active femtocells. These procedures are described in detail in the following sections.

The overall flow of the algorithm can be seen in the femtocell state diagrams in Figures 4.1 and 4.2. Figure 4.1 shows the actions taken by femtocells when users join or leave the network, or when timeouts occur. Figure 4.2 shows the actions taken when femtocells receive messages.

4.5.2 User Detection and Femtocell Activation

When a new user \( u_j \) joins the network, at least one femtocell detects the user, since femtocells provide area coverage. This femtocell is referred to as the sentinel femtocell, \( f_s \). Furthermore, we assume that \( u_j \) notifies \( f_s \) of the active set of cells \( F_{u_j}^u = \{ f_1^{u_j}, \ldots, f_k^{u_j} \} \) that can serve it. Based on our model assumptions, the cells in \( F_{u_j}^u \) are neighbors of each other.
Figure 4.1: Femtocell state diagram for user events

If $f_s$ is able to serve the user, that is, $c_s \geq b_{s_j}(\bar{X})$, it decreases its residual capacity $c_s$ and broadcasts an Info message with its new capacity. If $u_j$ cannot be served, $f_s$ checks whether $u_j$ can be served by another cell in $F_{u_j}$, i.e. whether $\exists f_i \in F_{u_j}$ s.t. $c_i \geq b_{s_j}(\bar{X})$. In this case, $f_s$ does not serve the user and the user selects a femtocell to attach to from $F_{u_j}$. Otherwise, if all the cells in $F_{u_j}$ have insufficient residual capacity, $f_s$ broadcasts a WakeUp message to its sleeping neighbors in $B_{o_s}$.

Inactive neighbors that receive a WakeUp message become active, set their capacities to $c^{max}$, and broadcast an Awake message. Neighboring cells that receive the Awake message reply with an Info message with their capacity to inform the newly awakened cells of the current state of the network.

Cells receiving Awake messages schedule a timeout, $t_i$, in the interval $(0, \tau_{max}]$, that triggers user reassignment. We assume that timeouts are non-overlapping. As the newly awakened cells receive Info messages, they also schedule timeouts. If a new user is detected by an awakened femtocell $f_a$ during its timeout interval, the user detection algorithm runs as normal, but the timeout for $f_a$ is not reset. When the timeout occurs, the scheduled user reassignment takes place.

A pseudocode description of the algorithm, as executed in the sentinel femtocell, is in Algorithm 5.
4.5.3 User Reassignment

When a timeout occurs for a femtocell $f_i$, it determines whether it can become inactive by performing a redundancy test, described in detail in the next section. A femtocell $f_i$ is redundant if its currently active neighbors $B_i^*$ can both cover $f_i$’s area coverage range, $R_a$, and serve all of $f_i$’s users, $U_i$. The test begins with each user $u_i \in U_i$ sending $f_i$ the active set of femtocells to which it can connect. If every user responds with at least two femtocells, $f_i$ can determine whether there is enough residual capacity in its neighbors to support a reassignment.

A user reassignment is a function $\mathcal{R} : U_i \rightarrow B_i^*$ such that for each user $u \in U_i$, $\mathcal{R}(u)$ is the neighboring cell of $f_i$ to which $u_j$ is reassigned. In Section 4.5.4 we present a method for performing a redundancy test and determine a reassignment. If $f_i$ is redundant, it sends a Sleep message, which notifies its neighbors of the reassignment and reserves space on the new cell for incoming users, transfers its users to its neighbors according to the reassignment, and finally turns itself off.

When a femtocell $f_j$ receives a Sleep message and reassignment $\mathcal{R}(\cdot)$, it updates its stored state of $f_i$ and reserves resources for incoming users according to $\mathcal{R}(\cdot)$. Furthermore, to prevent race conditions, if a timeout for a redundancy test for $f_j$ was active, it is reset. Femtocell $f_i$ then initiates a handoff for the users it is
Algorithm 5: GreenFemto user detection

Input: a new user, $u_j$, attaching to the network $\bar{X}$, the current femtocell activation vector

Result: a femtocell is selected for $u_j$

1. user $u_j$ is detected by sentinel femtocell $f_s$;
2. $F^{u_j} :=$ user $u_j$’s active cell list;
3. $B_s :=$ femtocell $f_s$’s neighbors;
4. if $c_s \geq b_{sj}(\bar{X})$ then
   5. $c_s := b_{sj}(\bar{X})$;
   6. return $f_s$
5. if $c_i \geq b_{ij}(\bar{X}): i \in F^{u_j}$ then
   7. $f_i :=$ user $u_j$’s selection of best femtocell in $F^{u_j}$;
   8. $c_i := b_{ij}(\bar{X})$;
   9. return $f_i$
10. */ at this point, $c_s = b_{sj}(\bar{X})$ and $c_i = b_{ij}(\bar{X}) \ \forall i \in F^{u_j}$ */
11. wake up neighbors in $B_s$;
12. $f_n :=$ user $u_j$’s selection of best femtocell in $B_s$;
13. $F(u_j) := f_n$;
14. $t_m := [0, \tau_{max}]$;
15. schedule redundancy test at $t_m$;
16. return $F(u_j)$

transferring to $f_j$. This ensures that users will not be handed off to femtocells that no longer have sufficient capacity. The reassignment handoff must occur within a time, $T_R$, after which users are accepted according to the standard method\textsuperscript{2}.

### 4.5.4 Redundancy Test

The full redundancy test algorithm is listed in Algorithm 6. Redundancy tests take place when timeouts occur in newly awakened femtocells. A femtocell $f_i$ is redundant if it can be turned off without creating an area coverage hole, and if all the users served by $f_i$ can be reassigned to the other active femtocells in $F^*$. In the following section we describe how these tests can be performed.

\textsuperscript{2}The timeout is introduced to take into account possible changes to the network, such as user movement, which may prevent the application of the reassignment. However, since the reassignment can be performed at a small time scale relative to user movement, these changes are unlikely.
Algorithm 6: The RedundancyTest algorithm

Input: femtocell $f_i$ on which to perform the redundancy test
Result: $T_f := true$ if $f_i$ is redundant, false otherwise

1 begin coverage test
2 \hspace{0.5em} $T^c_f := true$;
3 \hspace{0.5em} $B^*_i :=$ femtocell $f_i$’s active neighbors;
4 \hspace{0.5em} $I_i :=$ femtocell $f_i$’s intersection points with neighbors $f_n \in B^*_i$;
5 foreach $p_i \in (R_i \setminus I_i)$ do
6 \hspace{1.0em} if $p_i$ not covered by a femto $f_n \in B^*_i$ then
7 \hspace{1.5em} $T^c_f := false$;
8 begin reassignment test
9 \hspace{0.5em} $T^r_f := true$;
10 \hspace{0.5em} perform generalized assignment of users $U_i$ to neighboring femtocells $B^*_i$;
11 if no feasible solution then
12 \hspace{1.0em} $T^r_f := false$;
13 return $T_f \rightarrow T^c_f \land T^r_f$

4.5.4.1 Coverage Test

Theorem 4.4.1 can be used to determine whether a femtocell is redundant in terms of coverage, as stated by the following corollary.

**Corollary 1.** A femtocell $f_i$, with area coverage range $R^a_i$, is redundant in terms of coverage if the intersection points in $R^a_i \cap P$ are covered by its set of active neighbors $B^*_i$.

Note that this test can be performed locally provided that femtocells are aware of the intersection points that lie in their coverage range, as we assume in this paper.

4.5.4.2 User Reassignment

User reassignment can be modeled as a generalized assignment problem \[56\] with unit costs, where all the users $u_j \in U_i$ on $f_i$, with respective RB requirements $b_{ij}(\bar{X}) \forall u_j \in U_i$, must be assigned to $|B^*_i|$ neighboring femtocells, with respective residual capacities $c_k, \forall f_k \in B^*_i$. This is an NP-complete problem, therefore there is no exact polynomial-time algorithm. However, there are both efficient, bounded approximation algorithms, and exact algorithms \[56\] that perform well on small problem sizes. In our experiments, the number of active neighbors $|B^*_i|$ is always less than ten, and the problem can be solved exactly.
4.5.5 User Departures and Handoffs

When a user $u_j$ served by femtocell $f_i$ leaves the network, $f_i$ increases its capacity and broadcasts an Info message to its neighbors, to alert them of this change. If $f_i$ is not serving any users and is not needed for area coverage, it broadcasts a Sleep message and enters the OFF state.

If a mobile user is leaving the coverage area of its attached femtocell, as detected by decreasing signal quality reports, and there are no active femtocells with available capacity to which the user can be handed off, the current femtocell broadcasts a WakeUp message to its sleeping neighbors. This awakens those neighbors, and allows them to be the target of a handoff from the current femtocell. Specifically, the WakeUp message is triggered when the current user’s SINR drops below a threshold $t_{\text{handoff}}$. $t_{\text{handoff}}$ is larger than $t_u$, so a handoff WakeUp is triggered before the user loses coverage.

4.6 Algorithm Properties

In this section we prove that GreenFemto converges. We assume that GreenFemto is run with an exact generalized assignment algorithm.

GreenFemto reconfigures the network as long as users move, join or leave the network. In the following we prove that the algorithm converges to a stable configuration after the last dynamic event, provided that no new event occurs during the execution of the algorithm.

Recall that an activation policy state is a vector $\bar{X} = \{x_1,\ldots,x_n\}$, where $x_i = 1$ if $f_i$ is active and 0 if it is inactive. In a network with $n$ femtocells and $m$ users, the space of possible activation vectors $X$ is finite and its size is bounded by $|X| < 2^n$.

**Theorem 4.** The algorithm GreenFemto converges to a stable configuration.

**Proof.** We define the function $g : X \rightarrow \mathbb{N}^+$:

$$g(S) = \sum_{i=1}^{n} x_i$$  \hspace{1cm} (4.15)

The function $g$ is trivially lower bounded by 0.

---

3Recall that each femtocell is aware of the residual capacity of its active neighbors.
Now consider the three possible network events: joining, leaving, or moving. Events can occur in any order, but we assume that events themselves are atomic. If a femtocell is scheduled for a redundancy test, any further redundancy test timeouts at that femtocell are ignored, therefore events will be sequentialized by the length of each femtocell’s initial non-overlapping timeout. Since any combination of events leads to a sequence of redundancy tests, it suffices to show that all events lead to redundancy tests, and redundancy tests cannot change a state $S$ to a state $S'$ such that $g(S) < g(S')$, and if $g(S) = g(S')$, $S = S'$.

Consider a user $u_j$ joining the network. If $u_j$ can be served by the sentinel femtocell $f_s$, or another currently active femtocell, the algorithm halts and no changes to the network state are made. If $u_j$ cannot be served by any active femtocell, $f_s$ wakes up its inactive neighbors $B_{o,s}$, and $g(S)$ increases by $|B_{o,s}|$. Each femtocell $f_k \in B_{o,s}$ schedules a timeout for a redundancy test.

Consider a user $u_j$ leaving the network. When $u_j$ leaves the network, one of two cases are possible; redundancy tests are performed in both. If $u_j$ is not the last user on a femtocell $f_i$, $f_i$ broadcasts an Info message. If $u_j$ is the last user on a femtocell $f_i$, $f_i$ broadcasts a Sleep message and disables itself. Neighboring femtocells receiving either message start a timeout for a redundancy test.

Consider a user $u_j$ moving from femtocell $f_i$ to femtocell $f_k$. The actions of $f_i$ are identical to when a user leaves the network. If $f_k$ has sufficient capacity to serve $u_j$, $u_j$ is handed over to $f_k$, and no more state changes occur. If $f_k$ does not have sufficient capacity to serve $u_j$, neighboring femtocells $B_{o,k}$ are woken up. The remainder of the proof is identical to when a user joins the network.

Finally, consider a femtocell $f_i$ performing a redundancy test, with initial state $S$, and final state $S'$. $f_i$ checks if it is needed for satisfaction of the area coverage constraint and if its users can be reassigned to neighboring femtocells. If one of the two tests fails, $f_i$ remains active, and $g(S) = g(S')$ and $S' = S$. If the tests are successful, $f_i$ is disabled and the new state $S'$ is such that $g(S) > g(S')$. Since the network state space is finite and the function $g$ is lower bounded, GreenFemto eventually converges to a stable state where no more state transitions are possible.

We now prove that the final configuration to which GreenFemto converges is locally Pareto-optimal, defined as follows:
Definition 4 (Local Pareto-Optimality). A network state $S$ is locally Pareto-optimal if any of the two following conditions holds:

1. For all active femtocells $f_i \in F^*$, deactivating $f_i$ violates the area coverage constraint

2. For all active femtocells $f_i \in F^*$, there does not exist a reassignment of all the users of $f_i$ to its active neighbors

A locally Pareto-optimal configuration cannot be unilaterally improved by a femtocell; that is, the energy consumption of the network cannot be reduced by any active femtocell based only on its knowledge and coordination with its immediate neighbors. A global reconfiguration may still reduce the number of active femtocells, but this requires global information on the network state which is not available to individual femtocells.

Theorem 5. GreenFemto converges to a locally Pareto-optimal network state.

Proof. We proceed by contradiction. Let us assume that the final network state $S_f$ is not locally Pareto optimal, i.e. there exists at least one active femtocell $f_o$ such that turning off $f_o$ does not violate the area coverage constraint, and there exists a reassignment of all of $f_o$'s users to its active neighbors.

$f_o$ performs a redundancy test if any of three events occurs:

1. $f_o$ detects a new user

2. A user assigned to $f_o$ leaves the network

3. $f_o$ receives an Info, Awake, or Sleep message from one of its neighbors

Consider, $T$, the most recent redundancy test performed by $f_o$. Since $f_o$ is active in $S_f$, $T$ was not successful, either because turning off $f_o$ would violate the area coverage constraint, or because $f_o$ was unable to find a reassignment of all of its users. Therefore, immediately after $T$, the network state, $S_T$, is locally Pareto optimal. Since no further redundancy tests occur between $T$ and $S_f$, we can assume that none of the three events listed above occurred, since if one of the events had occurred, a test $T'$ would have occurred between $T$ and $S_f$, which violates the assumption that $T$ is the most recent test performed by $f_o$. Since none of the
events occurred, no changes to the local Pareto optimality of the network could have occurred. As a result, $f_o$ cannot be disabled, and $S_f$ is locally Pareto optimal, contradicting the hypothesis.

\section{4.7 Simulation Results}

Next we describe our simulations and present results.

\subsection{4.7.1 Simulation Details}

We use a Matlab LTE system-level simulator from the Vienna University of Technology \cite{57}. A full description of the simulator is available in the reference. The simulator models an LTE system with multiple eNodeBs and user equipments (UEs), using three radio link quality factors: large-scale pathloss, shadow fading, and small-scale link-level fading. Parameters used in the simulation are listed in Table 4.2.

We consider a dense femtocell deployment with no underlying macrocell coverage. Femtocells use unidirectional antennas in a one-sector configuration. Since the femtocells are densely deployed, we assume that they are connected to the same local network, through which they can communicate using either a local management server or directly in a peer-to-peer fashion. Users are uniformly randomly distributed, with minimum rate targets.

\subsection{4.7.2 Results}

We compare three algorithms: \textsc{GreenFemto}, \textsc{Global}, a computed global reassignment optimization based on GreenFemto, and \textsc{IDLE}, which is a modification of an algorithm for femtocell power saving described in \cite{5}. We begin with results on stationary users to highlight the performance of the algorithms as the number of users changes, and discuss mobile users at the end of the section.

\textsc{Global} uses the Gurobi \cite{58} solver to solve the \textsc{MinActivation} problem in Section 4.3, given the activation vector $\bar{X}$ found by \textsc{GreenFemto} and the functions $b_{ij}(\cdot)$ for all femtocells $f_i$ and users $u_j$ as input. It then iterates on
Table 4.2: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\mathcal{L}</td>
<td>$</td>
</tr>
<tr>
<td>$n_{TX}$</td>
<td>2</td>
<td>Number of transmit antennas</td>
</tr>
<tr>
<td>$n_{RX}$</td>
<td>2</td>
<td>Number of receive antennas</td>
</tr>
<tr>
<td>$f$</td>
<td>2140 Mhz</td>
<td>System frequency</td>
</tr>
<tr>
<td>$b$</td>
<td>20 Mhz</td>
<td>System bandwidth</td>
</tr>
<tr>
<td>$p_{tx}^M$</td>
<td>40 dBm</td>
<td>Macrocell transmission power</td>
</tr>
<tr>
<td>$p_{tx}^F$</td>
<td>24 dBm</td>
<td>Femtocell transmission power</td>
</tr>
<tr>
<td>$\mu_s$</td>
<td>0 dB</td>
<td>Shadow fading mean</td>
</tr>
<tr>
<td>$\sigma_s$</td>
<td>10 dB</td>
<td>Shadow fading standard deviation</td>
</tr>
<tr>
<td>$n_r$</td>
<td>9 dB</td>
<td>Receiver noise figure</td>
</tr>
<tr>
<td>$T_k$</td>
<td>-174 dBm/Hz</td>
<td>Thermal noise density</td>
</tr>
<tr>
<td>$t^u$</td>
<td>19 dB (SNR)</td>
<td>Area coverage threshold</td>
</tr>
<tr>
<td>$t^u$</td>
<td>-7 dB (SINR)</td>
<td>User coverage threshold</td>
</tr>
<tr>
<td>$t_{\text{handoff}}$</td>
<td>-6 dB (SINR)</td>
<td>Handoff threshold</td>
</tr>
<tr>
<td>$N$</td>
<td>100</td>
<td>Resource blocks per base station</td>
</tr>
</tbody>
</table>

this solution until convergence. In the case that the problem is infeasible due to user coverage or femtocell capacity, the users that cannot be served are rejected one-by-one and the problem is reattempted without them until a solution is found. G	extsc{lobal} prioritizes serving users over reducing the number of active femtocells: users are only rejected if there is no femtocell that can serve them.

G	extsc{lobal} is used to evaluate the femtocell activation and user assignment that G	extsc{reenFemto} finds. It finds the optimal assignment of users to femtocells given a set of active femtocells, but it does not find the solution to the larger problem of determining which set of femtocells should be active. By using the solution that G	extsc{reenFemto} finds as input, we can determine whether there is a global reassignment of users to femtocells that uses fewer femtocells, improves SINR, or rejects fewer users. The performance difference between G	extsc{lobal} and G	extsc{reenFemto} highlights the impact of limiting G	extsc{reenFemto} to local reassignments.

The IDLE algorithm partially disables a femtocell’s electronics when no users are present, leaving only a low-power user detection mode active. When a user enters the network, it is detected by all of the femtocells in range. The user connects to the femtocell that can serve it with the highest SINR, while the remaining femtocells turn off. In IDLE, each femtocell is independent and does not communicate with other femtocells on the network. We modify the IDLE algorithm by requiring that area coverage is provided, as in G	extsc{reenFemto}.

4Since M	extsc{inActivation} can only activate as many or fewer femtocells as were active in the
Figure 4.3 shows the number of active femtocells, with 50 total femtocells, as the number of users in the system increases. All graphs show the average of 10 runs, with error bars indicating the 95% confidence interval. At low load, the number of femtocells activated by GreenFemto is dominated by area coverage. The difference between GreenFemto and Global is small, since most of the femtocells activated by GreenFemto are also needed for area coverage. IDLE activates three times the number of femtocells activated by GreenFemto.

As the number of users increases, the number of femtocells activated by GreenFemto increases linearly, while the number of femtocells activated by IDLE increases by the inverse square. IDLE turns on the best femtocell for a user, which in most cases is the nearest femtocell. Therefore, IDLE’s performance is dominated by the number of femtocells that are the nearest femtocell to a user, which is determined by the user and femtocell distribution. The gap between the global optimal and GreenFemto’s solution increases slightly due to the additional input activation vector, it is clear to see that it converges.
degrees of freedom in the ILP problem made available by the activation of more femtocells to cover users. With more femtocells, the probability of a superior global reassignment increases, and the local reassignment limitation of GreenFemto hurts its performance more.

Figure 4.4 shows the average user wideband SINR with 100 femtocells total. This SINR measurement is an average of the user SINR measured across the entire channel bandwidth; due to small-scale fading, individual subchannels may have SINRs above or below the wideband SINR. The lowest user SINR threshold is -7 dB, and all three algorithms find femtocell activations that achieve this target on average. Since IDLE activates the best femtocell for each user, it reaches a high average SINR. The difference between GreenFemto and Global can be explained by the path-dependence and local reassignment limitations inherent in the design of GreenFemto. GreenFemto focuses on reducing femtocell power consumption, therefore GreenFemto will not reassign a users to improve their SINR.

Figure 4.4: Average SINR, 50 femtocells, increasing user scenario
Figure 4.5 shows the user rejection rate. IDLE rejects a large number of users because it activates a large number of femtocells when new users enter the network, which increases interference. GLOBAL’s performance indicates that for approximately 50% of the users that GREENFEMTO rejects, there exists a way to serve them given the current active set of femtocells, however, it is not possible for GREENFEMTO to find these solutions. For example, this could occur if a new user can only be served by one femtocell, which is full of users that could be served on other femtocells. Since GREENFEMTO does not preempt users, the new user is rejected, while an assignment is possible using GLOBAL.

Figure 4.6 shows the throughput CDF for users across all ten runs. IDLE performs poorly in terms of throughput, with 35% of users achieving 0 throughput, due to rejection, insufficient resources, or poor subchannel SINR. Despite using more femtocells on average, IDLE performs only slightly better than GREENFEMTO, with only the top 5% attaining higher throughput than GREENFEMTO. The top 10% of users in GREENFEMTO and IDLE reach the same throughput of 6 Mbps.
Figure 4.6: Throughput ECDF, 50 femtocells, increasing user scenario

Figure 4.7 shows the number of active femtocells as the total number of femtocells varies, with 100 users. Up to 90 femtocells, the number of active femtocells increases with the total number of femtocells, because not all users can be served, as can be seen in the rejection graph in Figure 4.9. IDLE scales poorly as the number of femtocells increases, with the number of user rejections increasing with the total number of femtocells. This increase is due to the naive way that IDLE wakes up femtocells to serve users, with all femtocells that detect the presence of a user waking up, rather than only a sentinel femtocell’s neighbors. The larger number of woken up femtocells cause significant co-channel interference, which leads to high user rejections.

Figure 4.8 shows the average SINR as the total number of femtocells increases. As the number of femtocells increases, the distance between femtocells and users decreases on average. IDLE directly benefits from this increase, because it turns on each user’s best femtocell. GREENFEMTO performs poorly when the relative load is high, finding solutions with average SINRs below GLOBAL, despite using
more femtocells. However, as the number of femtocells increases, GreenFemto’s solutions improve. GreenFemto’s sensitivity to the total number of femtocells is due to the local search it performs for alternative femtocells. When there are a small number of femtocells, the local search performs poorly.

Figure 4.10 shows the number of active femtocells with 50 total mobile users joining and leaving the network using a Poisson arrival process with exponential call times and $\lambda = 3$, and moving at 3 m/s using a random waypoint mobility model. This scenario allows the algorithms’ behavior in a realistic setting to be analyzed. The number of active femtocells varies significantly with the number of users in the system when using the IDLE algorithm. GreenFemto exhibits much lower variation in the number of active femtocells; with around 9 femtocells active for the majority of the simulation time, which is half the number that IDLE uses. Despite using fewer femtocells, GreenFemto rejects far fewer users than IDLE, as seen in Figure 4.11. Figure 4.12 shows the mean SINR in the mobile user scenario.
Figure 4.8: Average SINR, 100 users, increasing femtocell scenario

Under the IDLE algorithm, mean SINR is higher, but this comes at the expense of a higher rejection rate. Overall GREENFEMTO finds solutions that use significantly fewer femtocells than IDLE, and within 15% of an optimal reassignment.

4.8 Related work

Reducing the energy consumption of femtocell networks has received significant attention in the recent literature.

Several works design power control schemes for femtocell networks [42–44]. In particular, [42] proposes a distributed algorithm based on game theory to adjust the transmission power of femtocells. The authors of [43] introduce a distributed algorithm to jointly optimize the power consumption of femtocells and the scheduling order for serving users. The work in [44] studies a Pareto optimal power control and scheduling algorithm which aims at improving the spectral efficiency. The above
Figure 4.9: Number of user rejections, 100 users, increasing femtocell scenario

mentioned papers mainly focus on adjusting the transmission power and do not consider the possibility of turning off femtocells, thus achieving less energy saving.

The problem of minimizing the energy consumption of a two-tier network composed by a macrocell and several femtocell has been addressed in [45–48]. The works [45,46,48] design centralized algorithms, while in [47] a hierarchical reinforcement learning approach is proposed. On the one hand, centralized algorithms do not scale in dense and dynamic scenarios such as the one considered in this paper. On the other hand, these works aim at optimizing the energy consumption of a network composed by a macrocell and several femtocells. In this paper we focus on the more challenging scenario, with less degree of freedom, in which the femtocell network does not belong to the service provider, but to a different institution which aims at reducing its own energy expenses.

The problem of reducing the energy consumption of densely deployed femtocell networks through selective activation has been considered in [49–51]. The authors
of [49] propose a low complexity sleeping mechanism which makes use of user traffic prediction. This work is complementary to ours, as traffic prediction can be used to further improve the performance of GreenFemto. The approach proposed in [50,51] is instead used in this paper as a comparison against GreenFemto.

Other works focus on problems related to ours. The authors of [59] consider the problem of user scheduling in self-organizing femtocell networks. The approach does not focus on network power consumption while it looks for the femtocell channel settings and user scheduling to reduce interference and provide better quality of service to the users. In [60] the authors propose an analytical model to characterize the power consumption of macrocell, microcell, picocell and femtocell based networks. The authors of [61] study the tradeoffs between network energy consumption and terminal energy consumption. The tradeoffs between user perceived quality of service and network energy consumption are instead studied in [62]. In [63] the authors investigate solutions for reducing the number and size of active macrocell to reduce the network energy consumption. Finally, in [64] the
authors study heterogeneous networks with cognitive radio capabilities in order to reduce the energy consumption exploiting spectrum sharing.

4.9 Conclusion and Future Work

This chapter introduced GreenFemto, a novel distributed algorithm that finds a solution to MinActivation, a femtocell selective activation problem. Selective activation has not been extensively studied in femtocell networks. However, due to the nature of femtocell power consumption, we find that it is a promising approach to reducing the energy consumption of these networks. Our simulations show that selective activation can be used in these networks to reduce total energy consumption, and improve outage probability. We find that selective activation algorithms, if designed correctly, can improve network performance with low network churn. Our solution to MinActivation makes only local changes. Potential future work can be done on a solution that makes global changes. Furthermore, there are
other interesting problems in this area, such as joint activation and scheduling or predictive activation.
Chapter 5  |  Power Management and Scheduling in Dense Femtocell Networks

5.1 Introduction

Femtocells are small, locally-deployed wireless base stations that have become popular as a means of supporting or replacing existing wireless macrocells. Their key features are: a small coverage area, on the order of 100 square meters; automatic setup and the use of the customer’s Internet connection for backhaul, which allow them to be deployed by customers rather than service providers; customer-defined access control.

Densely deployed femtocells can be used to establish wireless networks that operate in a similar manner to public or enterprise WiFi networks, but serve users using 3G or 4G wireless technology. These types of networks face different challenges than both WiFi networks and independently deployed femtocells. The load on such networks is typically much higher than on isolated femtocells, and co-channel interference between femtocells can cause service degradation. Due to these issues, recently dense femtocell networks have been an active topic in the research community. For instance, Arslan, et al. [65] introduce FERMI, a system for interference mitigation in dense OFDMA femtocell networks, that uses concepts from fractional frequency reuse to mitigate the negative performance impact of interference. Wang, et al. [66] present a joint power-and-fairness optimization algorithm for dense femtocell networks.

Due to the network environment, edge users in dense femtocell networks can be
exposed to high interference, leading to reduced throughput and fairness. Fairness in wireless networks refers to the ability of the network to share its resources amongst all users, rather than using its resources to serve only the users with the best signal quality, which maximizes system throughput but can starve some users. Fairness has typically been approached as a scheduling or resource management \[67, 71\] problem. See \[72\] for a comprehensive discussion of fairness in wireless networks.

This chapter takes a different approach, and introduces a new algorithm, RADIUS REDUCTION AND SCHEDULING (RRS), that increases fairness in densely deployed femtocell networks using a combination of power management and resource block scheduling.

Given the locations of users and femtocells, RRS determines the network configuration in two phases. In the first phase, it uses a Voronoi-Laguerre geometry-derived framework to reduce femtocell coverage overlaps and co-channel interference. At the same time, this preliminary phase seeks to maximize the number of users that can be served within their quality of service requirements. The first phase of the algorithm provides an iterative adjustment of each femtocell radius, on the basis of only local information on the setting of neighbor cells. We prove the termination of this phase in a finite number of steps, and we show that it preserves either area or user coverage while reducing transmission power and femtocell radio coverage overlaps and interference. In the second phase, RRS provides a resource block scheduling scheme that uses vacancy requests to improve resource sharing and service of users that are unable to meet their performance targets.

Simulations of an LTE-based network are used to compare RRS to previous approaches. We show that RRS can reduce the outage probability, the percentage of users that cannot meet their throughput requirements, by up to 100% over a baseline algorithm working with fixed cell radii and best-effort scheduling. Furthermore, our algorithm increases the Jain’s index \[73\] of the network, a common measure of fairness, by up to 190%.

The contributions of this chapter can be summarized as follows:

- We propose a new algorithm, called RRS, for reducing femtocell coverage radii and scheduling resource blocks among users. This algorithm can be formulated in several variants to consider different performance objectives

- We prove that RRS terminates in a finite time and preserves either area or
user coverage, despite radius reduction

- We provide simulation results from a dynamic, interfering OFDMA system simulator showing that our algorithm reduces outage probabilities and increases fairness.

### 5.2 Network Model and Problem Formulation

In this section we define the femtocell network model and introduce our assumptions and notation. Table 5.1 summarizes the notation used throughout the chapter. We consider an OFDMA network with several femtocells $f_i \in F$, interfering with each other. Femtocell $f_i$ may adjust its power $\pi_i$ within a range $\mathcal{P}$ of possible values. We consider a set of users $\mathcal{U}$, and we assume that femtocells are deployed densely enough to cover all users of $\mathcal{U}$ when they work at maximum power. We assume that users preferentially associate with femtocells. Nevertheless, in order to have a realistic model, we also consider the presence of a macrocell. Thanks to the joint presence of both the macrocell and the femtocells in our model, we are able to capture the interference generated by the macrocell.

A femtocell’s available bandwidth is time- and frequency-divided into resource blocks (RB), with $B^\text{max}$ numbered resource blocks per femtocell, as in an LTE system.

Resource blocks deliver a varying number of bits, depending on the signal-to-interference-and-noise ratio (SINR) received by a user on that resource block, and on the subsequent channel quality indicator (CQI) measured on the resource block itself. CQIs are a measurement of the channel quality between a user and its serving base station. CQIs are determined by a step-wise function defined on the SINR of an individual resource block.

The estimated SINR $\varsigma_j$ of a user $u_j$ is measured using reference signals. Notice that, since OFDMA signals are spread across a wide spectrum range, individual subchannel SINRs may differ significantly from $\varsigma_j$. The instantaneous throughput $t_j$ of user $u_j$ is the sum of the throughput achieved on each resource block assigned to the user during a transmission frame.

We tackle the problem of increasing the fairness of a wireless network, with the ancillary goal of decreasing power consumption. We consider users having
Notation & Description
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<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
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<tbody>
<tr>
<td>$F$</td>
<td>set of femtocells</td>
</tr>
<tr>
<td>$f_i \in F$</td>
<td>$i$-th femtocell</td>
</tr>
<tr>
<td>$U$</td>
<td>set of users</td>
</tr>
<tr>
<td>$u_j \in U$</td>
<td>$j$-th user</td>
</tr>
<tr>
<td>$\mathcal{P}$</td>
<td>possible power values of a femtocell</td>
</tr>
<tr>
<td>$\pi_i \in \mathcal{P}$</td>
<td>power level of $f_i$</td>
</tr>
<tr>
<td>$B_{\text{max}}$</td>
<td>number of resource blocks for any femtocell</td>
</tr>
<tr>
<td>$\varsigma_j$</td>
<td>estimated SINR of user $u_j$</td>
</tr>
<tr>
<td>$t_j$</td>
<td>instantaneous throughput of user $u_j$</td>
</tr>
<tr>
<td>$\tau_j$</td>
<td>throughput requirement of user $u_j$</td>
</tr>
<tr>
<td>$\mathcal{V}(\mathcal{C}_i)$</td>
<td>Laguerre polygon of circular range $\mathcal{C}_i$</td>
</tr>
<tr>
<td>$\mathcal{V}(f_i)$</td>
<td>Laguerre polygon of femtocell $f_i$</td>
</tr>
<tr>
<td>$\mathcal{V}^{(k)}(f_i)$</td>
<td>polygon $\mathcal{V}(f_i)$ at iteration $k$</td>
</tr>
<tr>
<td>$\hat{U}^{(k)}(f_i)$</td>
<td>farthest user of $\mathcal{V}^{(k)}(f_i)$</td>
</tr>
<tr>
<td>$\hat{V}^{(k)}(f_i)$</td>
<td>farthest vertex of $\mathcal{V}^{(k)}(f_i)$</td>
</tr>
<tr>
<td>$r^{(k)}_i$</td>
<td>radius of femtocell $f_i$ at iteration $k$</td>
</tr>
<tr>
<td>$S^{(k)}$</td>
<td>area covered at iteration $k$</td>
</tr>
<tr>
<td>$\mathcal{U}^{(k)}$</td>
<td>users covered at iteration $k$</td>
</tr>
<tr>
<td>$\mathcal{U}^{(k)}(f_i)$</td>
<td>set of users inside $\mathcal{V}^{(k)}(f_i)$</td>
</tr>
<tr>
<td>$\alpha_i^{(k)}$</td>
<td>radius reduction rate of $f_i$ at iteration $k$</td>
</tr>
<tr>
<td>$\epsilon_{\alpha}$</td>
<td>minimum reduction rate</td>
</tr>
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</table>

Table 5.1: Summary of notations

heterogeneous requirements. We define a hard throughput requirement $\tau_j$ for each user $u_j$, used to determine whether a user is served or not. Our goal is to serve the maximum number of users under this constraint, at the possible expense of reduced global throughput.

We address this problem by means of a new algorithm, RADIUS REDUCTION AND SCHEDULING (RRS) that determines power and resource block scheduling, given femtocells and users positions. The algorithm RRS runs in all femtocells across the network at network initialization, and in local femtocells when users arrive or move between femtocells. It works in two phases.

The first phase of RRS determines the femtocell transmission power. Each femtocell configures its own transmission power on the basis of a distributed coordination protocol that allows neighboring femtocells (femtocells that are in radio proximity with each other) to exchange information and adapt their working setting cooperatively. By using this distributed coordination protocol, neighboring femtocells determine their respective responsibility regions, namely the regions where each cell is responsible for providing enough radio resources to serve users.

In the second phase of RRS the algorithm provides a resource block scheduling
Figure 5.1: Voronoi and Voronoi-Laguerre cell boundaries

scheme, so that users working on conflicting radio resources are able to share them and to perform non conflicting transmissions.

In Sections 5.4 and 5.5 we describe the two phases of radius reduction and scheduling, respectively. In the next Section, we introduce the mathematical background of Laguerre geometry to motivate the design of the radius reduction phase.

5.3 Background on Voronoi-Laguerre diagrams

In typical wireless networks, users associate with the base station that has the strongest reference signal. Under the assumption of homogeneous transmission power, the coverage cells resulting from this type of user association can be approximated using Voronoi cells, where $f_i$’s Voronoi cell consists of all points closer to $f_i$ than to any other femtocell. The Voronoi cell approximation has been extensively studied and shown to be good under certain wireless network scenarios [74].

In a Voronoi diagram, cell polygons are defined by the axis of the segments generated by two femtocells, that is the locus of the points that are equidistant from them and perpendicular to their connecting segment (Voronoi line in Figure 5.1). Given any two femtocells, this line divides the plane into two halves. If the femtocell transmission power is homogeneous, the two femtocells would have the same coverage radius, and the Voronoi line would properly delimit their responsibility regions. Nevertheless, when the cells have different radio coverage capabilities, the Voronoi line may not determine the responsibility region correctly, as shown in Figure 5.1.

In both the diagrams the Voronoi cell assigns some points that are better served
by the femtocell on the right, located at $P_2$, to the femtocell on the left, at $P_1$. The desired partition of the plane into responsibility regions is through the intersection of the circles representing the radio coverage range of the two cells, labelled the Voronoi-Laguerre line in Figure 5.1. This line is perpendicular to the segment connecting the positions $P_1$ and $P_2$ of the two femtocells, and equidistant in the Laguerre geometry. Voronoi-Laguerre cells are defined using the Laguerre distance, $d_L^2$, which defines a radius-dependent distance between two circles, or between a circle and a point. Consider the circles $C_1$ and $C_2$, with respective radii $r_1$ and $r_2$, with $r_2 > r_1$, in Figure 5.1. The boundary between the Voronoi cells of $C_1$ and $C_2$ is indicated by the dashed line, while the boundary between the Voronoi-Laguerre cells is indicated by the solid line.

The Laguerre distance between two circles $C_1$ and $C_2$ centered on points $P_1$ and $P_2$, with radii $r_1$ and $r_2$, respectively, is defined as:

$$d_L^2(C_1, C_2) = ||p_1 - p_2||^2 - (r_1 - r_2)^2.$$ 

This definition can also be used to calculate the distance between a circle and a point, by considering the point as a circle with null radius. It is straightforward to see that under the Laguerre geometry, given two circles with distinct centers and possibly different radii, the locus of the points equally distant from them is a line, hereby called the Voronoi-Laguerre line, that is perpendicular to the segment connecting the centers, with the following properties: if the two circles intersect each other, their Voronoi-Laguerre line crosses their intersection points, as in the left side of Figure 5.1, while if two circles are disjoint, the Voronoi-Laguerre line lies between them, as in the diagram on the right of Figure 5.1.

Notice also that this definition implies that, depending on the overlap between two circles, in the Laguerre geometry the two centers may fall on the same side of the Voronoi Laguerre line, which would imply that the responsibility region of one femtocell would be located on the opposite side of the Voronoi Laguerre line with respect to its center [75]. The notion of Voronoi diagrams can be extended to the Laguerre geometry, as follows: given $N$ circles $C_i$ with centers $C_i = (x_i, y_i)$ and radii $r_i$, $i = 1, \ldots, N$, the Voronoi-Laguerre polygons $V(C_i)$ of the circles $C_i$ are defined as

$$V(C_i) = \{P \in \mathbb{R}^2 | d_L^2(C_i, P) \leq d_L^2(C_j, P), j \neq i\}.$$ 

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Notice, that unlike with traditional Voronoi diagrams, this extension to the Laguerre geometry may lead to the case that some polygons are either null or empty \[75\], reflecting a situation of high coverage redundancy that is not captured by traditional Voronoi diagrams. Null and empty polygons are described in more detail in Section 5.4.

Voronoi-Laguerre diagrams are extraordinarily powerful in modeling the responsibility regions of heterogeneous femtocells. Indeed, a fundamental property of the Voronoi diagrams in Laguerre geometry is the following:

**Theorem 6.** \((76)\) Let us consider \(N\) circles \(C_i\), with centers \(C_i = (x_i, y_i)\) and radii \(r_i\), \(i = 1, \ldots, N\), and let \(V(C_i)\) be the Voronoi-Laguerre polygon of the circle \(C_i\). For all \(k, j = 1, 2, \ldots, N\), \(V(C_k) \cap C_j \subseteq C_k\).

Less formally, if a point \(P\) is in the coverage range of at least one femtocell, it is certainly covered also by the femtocell \(f_i\) that generates the Voronoi-Laguerre polygon \(V(C_i)\) that includes \(P\).

In the following, we refer to \(V(f_i)\) as to the Voronoi-Laguerre polygon of femtocell \(f_i\), or alternatively, the responsibility region of cell \(f_i\). Likewise, we denote with \(V^{(k)}(f_i)\) the Voronoi Laguerre polygon of femtocell \(f_i\) at iteration \(k\).

### 5.4 Radius Reduction

This section describes the radius reduction phase of RSS. First, we prove that our coverage criteria preserve either user or area coverage, then we describe their use in the algorithm in detail. After that, we prove that the algorithm terminates, and discuss the reduction rate parameter, \(\alpha\).

The goal of this phase is to obtain a network configuration with less overlap in the radio coverage of neighboring femtocells, so as to limit co-channel interference which would reduce radio resource availability. This is done by eliminating unnecessary femtocells and reducing the transmission power of the remaining femtocells. This phase is executed in a distributed manner and governs the reduction of a femtocell’s transmit power and consequently, its radio coverage range. Since the range reduction is performed in a distributed manner, it is necessary to design an algorithm that allows neighboring cells to coordinate with each other, so as to avoid conflicting decisions that may lead to a loss of service in some regions.
Each femtocell calculates its transmission power iteratively. The algorithm begins with all femtocells transmitting at maximum power. At any iteration \( k \), each femtocell \( f_i \) reduces its transmission power \( p_i^{(k)} \) and its transmission radius \( r_i^{(k)} = r_i(p^{(k)}) \) correspondingly. It must be noted that since every cell potentially reduces its radius by some amount, the Voronoi-Laguerre diagram determining the responsibility regions of each cell is recalculated locally at any iteration \( k \) until the algorithm converges.

The amount of radius reduction at each iteration is determined according to one of two criteria:

- **Radius reduction preserving user coverage (UCR)** Each femtocell reduces its radius ensuring that it does not leave uncovered any of the users residing in its responsibility region at the current iteration. It does so by limiting the amount of reduction so as to preserve coverage of the farthest user located in its polygon.

- **Radius reduction preserving area coverage (ACR)** Each femtocell reduces its radius ensuring that it does not reduce the coverage of its current iteration Voronoi-Laguerre polygon. It does so by limiting the amount of reduction so as to preserve radio coverage of the farthest point of its polygon.

The ACR approach is inspired to the works of Gupta et al. \[77\] and Bartolini et al. \[78\] that are designed for selective activation and radius adaptation of sensor networks to provide sensing coverage, and aim at preserving coverage completeness of a continuous area of interest. By contrast, UCR is meant to ensure radio coverage where it is actually needed, that is in the discrete points of the area where users are located. Note that UCR does not aim to ensure completeness of area coverage.

### 5.4.1 Preservation of Coverage

In this subsection, we establish our criteria for eliminating femtocells while maintaining either user or area coverage. Let us consider a femtocell \( f_i \), located at \( P_i \). Let \( \hat{U}_i^{(k)} \) be the position of the farthest covered user lying in the Voronoi-Laguerre polygon of \( f_i \), and let \( \hat{V}_i^{(k)} \) be the farthest covered point of the same polygon at the current iteration \( k \).
According to the UCR criterion, \( f_i \) can reduce its radius for the \((k + 1)\)-th iteration to a value \( r_i^{(k+1)} \leq r_i^{(k)} \) such that it still covers the position of the farthest user of its polygon:

\[
r_i^{(k+1)} \geq ||P_i - \hat{U}_i^{(k)}||. \tag{5.1}
\]

Similarly, according to the ACR criterion the next iteration value of \( r_i^{(k+1)} \) must meet the area coverage constraint:

\[
r_i^{(k+1)} \geq ||P_i - \hat{V}_i^{(k)}||. \tag{5.2}
\]

Note that in the description of these two criteria for radius reduction we only considered non-empty and non-null polygons. An empty polygon is a Voronoi-Laguerre polygon that does not contain its generating point, that is the polygon \( V(f_i) \) for which the position \( P_i \) of the femtocell \( f_i \) is such that \( P_i \notin V(f_i) \). A null polygon is a degenerate polygon, with no points, that is \( V(f_i) = \emptyset \).

The Corollaries 2 and 3 follow from Theorem 6 and characterize the redundancy of femtocell \( f_i \) in the aforementioned situations.

**Corollary 2 (User coverage redundancy).** If femtocell \( f_i \) has an empty polygon \( V(f_i) \) and it does not cover any of the users contained in it, or it has a null polygon, then \( f_i \) is redundant, that is, for any user \( u \) with position \( P_u \) covered by \( f_i \), there is another femtocell \( f_j \) that also covers \( P_u \).

**Proof.** This corollary extends Corollary 3.1 of [78] to the case in which a femtocell \( f_i \) may cover a part of its polygon but does not cover any user. We recall that the Voronoi-Laguerre diagram of a region \( \mathcal{R} \), constitutes a partition of \( \mathcal{R} \). Let \( \mathcal{C}(f_i) \) be the radio range of \( f_i \). Any user positioned in \( P_u \in \mathcal{C}(f_i) \) does not belong to \( V(f_i) \) because, by assumption, \( f_i \) does not cover any user lying in its polygon. Hence the location of any user covered by \( f_i \) must belong to the Voronoi cell of some other femtocell \( f_j \). By Theorem 6 and since \( P_u \) is covered by assumption, we can conclude that the user location \( P_u \) is also covered by femtocell \( f_j \). As this is true for any user in \( \mathcal{C}(f_i) \) we can conclude that \( f_i \) is redundant. \( \square \)

In less formal words, user coverage redundancy captures the situation in which femtocell \( f_i \) covers only users that are better served by other femtocells (cells that are closer according to the Laguerre distance), or the situation in which \( f_i \) is located
such that it is too far away to cover the uncovered users located in its polygon, even at maximum transmission power. Analogously, we can prove Corollary 3 which directly derives from Corollary 3.1 of [78]; we omit the proof for space.

**Corollary 3** (Area coverage redundancy). *If femtocell $f_i$ has an empty polygon $V(f_i)$ and it does not cover any point of it, or it has a null polygon, then $f_i$ is redundant, that is, for any point $Z$ covered by $f_i$, there is another femtocell $f_j$ that covers $Z$.*

Area coverage redundancy captures the situation in which a femtocell $f_i$ covers only points that are better covered by other femtocells (cells that are closer according to the Laguerre distance), or is located such that it cannot cover the points of its area of responsibility.

Corollaries 2 and 3 allow us to define two situations of *eliminable redundancy* in which a femtocell (the *eliminable femtocell*) can be immediately disabled. Note that these corollaries define only sufficient conditions for redundancy and some femtocells can be redundant without meeting the criteria in Corollaries 2 and 3. In these cases a gradual iterative reduction of femtocell radio coverage range is needed to find redundant femtocells, a process which addresses possible conflicts in the concurrent elimination of several potentially redundant femtocells.

The following theorems show that if all femtocells apply an iterative radius reduction under the limits posed by the constraints in Equation 5.1 for the UCR criterion and Equation 5.2 for the ACR criterion, user coverage and area coverage are respectively preserved and eliminable femtocells are turned off. We define a *distributed execution of radius reduction* according to the UCR or the ACR criterion as the following: every non eliminable femtocell reduces its radius under the constraints given by Equation 5.1 or Equation 5.2 and every eliminable femtocell is turned off.

**Theorem 7** (User coverage preservation under UCR). *Let us consider a set $F$ of femtocells, randomly spread over a region $\mathcal{R}$. Let us also consider a set $\mathcal{U}$ of users over the same region. Let $\mathcal{U}^{(k)} \subseteq \mathcal{U}$ be the subset of users that the femtocells of $F$ are able to cover when each femtocell $f_i$ works with radius $r_i^{(k)}$. Let $\mathcal{U}^{(k+1)}$ be the set of users covered by the same femtocells of $F$ after a distributed execution of a radius reduction according to the UCR criterion. Then $\mathcal{U}^{(k)} = \mathcal{U}^{(k+1)}$, so the radius reduction preserves coverage of the users within the region $\mathcal{R}$.***
Proof. For simplicity of notation let us consider the set $\mathcal{U}$ as a finite set of points in $\mathcal{R}$, representing user positions. The Voronoi-Laguerre diagram determined by the positions and radii of the femtocells of $F$ at iteration $k$ creates a partition of the set of $U^{(k)}$ as follows: $U^{(k)} = \bigcup_{f_i \in F} U^{(k)}(f_i)$, with $U^{(k)}(f_i) \cap U^{(k)}(f_j) = \emptyset$, for $i \neq j$, and where $U^{(k)}(f_i)$ is the set of users inside $V^{(k)}(f_i)$. By altering the radii of the femtocells the Voronoi-Laguerre diagram is also altered, and consequently users that were in the polygon of a cell at iteration $k$ may find themselves in another cell at iteration $k+1$. Nevertheless, in order to prove the theorem we need to ensure that any user that was covered at iteration $k$ will still be covered by at least one of the available femtocells even after the radius reduction performed at iteration $k+1$. To this purpose, it is sufficient to prove that such a radius reduction preserves coverage of all the covered user positions of each polygon according to the partition determined by the diagram at the $k$-th iteration. Thanks to Theorem 6 we know that the covered users of each polygon $V^{(k)}(f_i)$ are also covered by $f_i$ itself, and therefore we can write $U^{(k)}$ in terms of the union of the covered sets of user positions of each polygon as follows: $U^{(k)} = \bigcup_{f_i \in F} C^{(k)}(f_i) \cap U^{(k)}(f_i)$.

Each non-eliminable cell performs a radius reduction that, according to constraint (5.1), preserves coverage of the users of its polygon.

Therefore, $U^{(k)}(f_i) \cap C^{(k+1)}(f_i) = U^{(k)}(f_i) \cap C^{(k)}(f_i)$. The same is trivially true also for eliminable femtocells as they do not have any covered user in their polygons at iteration $k$. This concludes the proof, as

$$U^{(k+1)} = \bigcup_{f_i \in F} C^{(k+1)}(f_i) \cap U^{(k)}(f_i) =$$

$$= \bigcup_{f_i \in F} C^{(k)}(f_i) \cap U^{(k)}(f_i) = U^{(k)}.$$ \hfill \Box

The following Theorem also holds for the criterion ACR and can be proved using a similar argument.

**Theorem 8 (Area coverage preservation under ACR).** Let us consider a set $F$ of femtocells, randomly spread over a region $\mathcal{R}$. Let $S^{(k)} \subseteq \mathcal{R}$ be the portion of $\mathcal{R}$ that the femtocells of $F$ are able to cover when each femtocell $f_i$ works with radius $r^{(k)}_i$. Let $S^{(k+1)}$ be the area covered by the same femtocells of $F$ after a distributed execution of a radius reduction according to the ACR criterion. Then $S^{(k)} = S^{(k+1)}$, so the radius reduction preserves coverage of the region $\mathcal{R}$.

We underscore that even though the radius reduction preserves area coverage and user coverage, according to criteria ACR and UCR, respectively, the modification
in the femtocell radii significantly alter the shape of the Voronoi-Laguerre polygons at any iteration. Consequently, users can be logically reassigned at any given iteration. We will show later in this section that the iterative radius reduction rapidly converges to the final setting of the femtocell radii.

Thanks to Theorems 7 and 8, we are able to guarantee that even if every femtocell performs a radius reduction to the minimum value provided by Equations 5.1 and 5.2, user and area coverage is preserved. Nevertheless the range of possible values for each femtocell radius can be exploited to prioritize the radius reduction of some femtocells over the others according to a given performance objective.

5.4.2 Radius Reduction

We propose that the radius reduction be performed gradually, at every iteration \( k \), with only a partial reduction \( \alpha_i(k) \in [0, 1] \) for every femtocell \( f_i \), at each step, as we describe in Algorithm 7. We call the parameter \( \alpha_i(k) \) the **radius reduction rate** of femtocell \( f_i \) at iteration \( k \). The formulation of this parameter is described in detail in Section 5.4.4. It requires neighboring femtocells to exchange additional information regarding their current iteration setting.

Under this approach, femtocell \( f_i \) starts working at maximum power \( p_i(0) = p_i^{\text{max}} \) at iteration \( k = 0 \). Let \( p_{\text{min}}(i)_{\text{UCR}|\text{ACR}} \) be the minimum value of power that ensures that \( f_i \) covers either the farthest covered user \( \hat{U}_i(k) \) (under the UCR criterion) or the farthest covered point \( \hat{V}_i(k) \) (under the ACR criterion) of \( V(k)(f_i) \).

This value can be expressed as follows: under the UCR criterion it is \( p_{\text{min}}(i)_{\text{UCR}} = \min \{ \pi : r(\pi) \geq ||P_i - \hat{U}_i(k)||, \ \pi \in \mathcal{P} \} \), while under the ACR criterion, \( p_{\text{min}}(i)_{\text{ACR}} = \min \{ \pi : r(\pi) \geq ||P_i - \hat{V}_i(k)||, \ \pi \in \mathcal{P} \} \). At any given iteration \( k \), the transmission power of \( f_i \) is reduced to \( p_i^{k+1} \leq p_i^k \), with:

\[
p_i^{(k+1)} = p_i^{(k)} - \alpha_i^k \cdot (p_i^{(k)} - p_{\text{min}}(i)_{\text{UCR}|\text{ACR}}).
\] (5.3)

According to Equation 5.3, the maximum reduction of power is obtained for \( \alpha_i^k = 1 \). We consider a positive lower bound \( \epsilon_\alpha \) to \( \alpha_i^k \), such that \( \epsilon_\alpha > 0 \) and \( \epsilon_\alpha \ll 1 \) to ensure that all the femtocells that can reduce their radius are actually able to do so, regardless of the behavior of their neighboring cells.

A preliminary exchange of information among neighboring femtocells is needed to let each cell know the position and current radius of its neighbor femtocells to
calculate the current iteration Voronoi-Laguerre polygon, and the current value of
the radius reduction rate \( \alpha_i^{(k)} \), as indicated in line 4 of Algorithm 7.

In most cases femtocells only allow tuning of the transmission power within a
discrete set of values. In such cases, the algorithm should take the minimum of
these discrete values that exceeds the calculated value of \( p_i^{(k+1)} \). For the sake of
clarity and without loss of generality we neglect this aspect in the following.

When femtocells have overlapping coverage ranges, the radius reduction algo-
rithm can lead some femtocells to reduce their transmission powers to zero. When
this occurs, femtocells with zero transmission power serve no users, and do not
transmit at all during the next frame, until a network reconfiguration, which may
occur as a consequence of user movement, arrival, or departure.

The distributed radius reduction procedure is described in detail in Algorithm
7. This procedure guarantees that \( f_i \)'s transmission power, \( p_i^{(k)} \), is reduced to
the minimum value of power that ensures either area or user coverage according
to criterion ACR or UCR, respectively. The speed of \( f_i \)'s radius reduction is
determined by the parameter \( \alpha_i^{(k)} \). Section 5.4.4 is devoted to a discussion of
possible ways to set the parameter \( \alpha_i^{(k)} \).

### 5.4.3 Termination of RRS

The radius reduction algorithm provably terminates provided that the radius
reduction at each step is a finite amount, which is always the case when radius
reduction is limited to discrete steps.

**Theorem 9** (Convergence of UCR). *Given a set of \( F \) femtocells with tunable radii,
executing the radius configuration phase of the algorithm RRS under the UCR
criterion, each femtocell converges [in a finite time] to a final radius configuration.*

**Proof.** If \( V^{(k)}(f_i) \) is not covered, \( f_i \) is eliminable and goes to sleep. If \( V^{(k)}(f_i) \) is at
least partially covered, then \( f_i \) can reduce its radius up to an extent that preserves
coverage of the farthest covered user. As \( \alpha_i^{(k)} \geq \epsilon_{(\alpha)} > 0 \), the algorithm performs a
reduction at any iteration, until the radius becomes null or equals the distance to
the farthest user covered exclusively. Termination follows by setting a finite and
positive minimum value of radius reduction \( \epsilon_r \) that can be performed in a single
iteration. \( \square \)
Algorithm 7: Radius Reduction Algorithm

Result: Power configuration $p_i$ for femtocell $f_i$

1. $k = 0$;
2. $p_i^0 = p_i^{\text{max}}$;
3. while !termination condition do
   4. exchange info with neighbor cells;
   5. local construction of $V^{(k)}(f_i)$;
   6. if $f_i$ is eliminable (Corollaries 2, 3) then
      7. termination condition := true;
      8. go to sleep;
   else
      9. calculate $p_{\min}^{(k)}(i)_{\text{UCR/ACR}}$;
      10. if $p_{\min}^{(k)}(i)_{\text{UCR/ACR}} = p_i^{(k)}$ then
          11. termination condition := true;
          12. $p_i := p_i^{(k)}$;
      else
          13. calculate $\alpha_i^{(k)}$;
          14. $p_i^{(k+1)} := p_i^{(k)} - \alpha_i^{(k)} \cdot (p_i^{(k)} - p_{\min}^{(k)}(i))$;
          15. $k := k + 1$;
      end
   end
4. end
5. end

Theorem 10 (Convergence of ACR). Given a set of $F$ femtocells with tunable radii, executing the radius configuration phase of the algorithm RRS under the ACR criterion, each femtocell converges [in a finite time] to a final radius configuration.

Proof. The proof follows similarly to the proof of Theorem 9 with the only exception that if $V^{(k)}(f_i)$ is only partially covered, then $f_i$ cannot reduce its radius as it needs to preserve coverage of the farthest covered point. So the algorithm immediately terminates for those femtocells covering their polygons only partially. \qed

5.4.4 Radius Reduction Rate $\alpha_i$

The radius reduction rate $\alpha_i$ controls the priority with which $f_i$ reduces its transmission power with respect to its neighbor femtocells. In the following we introduce three different prioritization criteria, that correspond to different ways to calculate $\alpha_i^{(k)}$. In all the approaches, only the femtocells with reduction rate $\alpha_i^{(k)} = 1$ are allowed to perform the maximum allowed radius reduction.
5.4.4.1 Prioritization based on throughput increase (TI)

Let \( t^{(k)}(f_i) \) be the estimated increase in total throughput that would be achieved by femtocell \( f_i \) if it decreases its transmission power to the minimum value.

We use \( \mathcal{N}_i \) to denote the set of femtocells in radio proximity to \( f_i \), and define \( t^{\text{min}}_{\text{TI}}(\mathcal{N}_i) \) and \( t^{\text{max}}_{\text{TI}}(\mathcal{N}_i) \) as the minimum and maximum value of the same metric in the neighbor cells of \( f_i \). Namely, \( t^{(k)}_{\text{min}}(\mathcal{N}_i) \triangleq \min_{f_j \in \mathcal{N}_i} t^{(k)}(f_j) \). Similarly, \( t^{(k)}_{\text{max}}(\mathcal{N}_i) \triangleq \max_{f_j \in \mathcal{N}_i} t^{(k)}(f_j) \). The value of \( \alpha^{(k)}_i \) under the TI criterion of prioritization is therefore the following:

\[
\alpha^{(k)}_i = \frac{t^{(k)}(f_i) - t^{\text{min}}_{\text{TI}}(\mathcal{N}_i)}{t^{\text{max}}_{\text{TI}}(\mathcal{N}_i) - t^{\text{min}}_{\text{TI}}(\mathcal{N}_i)}.
\] (5.4)

5.4.4.2 Prioritization based on number of users meeting throughput requirements (UTR)

When the metric of interest in the prioritization is the number of users that achieve their quality requirements, we use \( u^{(k)}(f_i) \) to denote the number of users that would be able to meet their throughput requirement if the radius of cell \( f_i \) were reduced to its minimum. Similarly to what we did for the throughput increase criterion, we denote with \( u^{(k)}_{\text{min}}(\mathcal{N}_i) \) and \( u^{(k)}_{\text{max}}(\mathcal{N}_i) \), the minimum and the maximum of the same metric over the neighbors of \( f_i \). Under the UTR criterion of prioritization we define the value of \( \alpha^{(k)}_i \) as follows:

\[
\alpha^{(k)}_i = \frac{u^{(k)}(f_i) - u^{(k)}_{\text{min}}(\mathcal{N}_i)}{u^{(k)}_{\text{max}}(\mathcal{N}_i) - u^{(k)}_{\text{min}}(\mathcal{N}_i)}.
\] (5.5)

5.4.4.3 Prioritization based on load (Load)

According to this last criterion we aim at prioritizing the femtocells which currently have the highest load in their neighborhood. Hence we denote \( \ell^{(k)}(f_i) \) as the number of users that are attached to \( f_i \) when the radius of the cell is the one provided at iteration \( k \).

We denote \( \ell^{\text{min}}_{\text{Load}}(\mathcal{N}_i) \) and \( \ell^{\text{max}}_{\text{Load}}(\mathcal{N}_i) \) as the minimum and the maximum of the same metric over the neighbors of \( f_i \). Under the Load criterion of prioritization we define
the value of $\alpha_i^{(k)}$ as follows:

$$\alpha_i^{(k)} = \frac{\ell^{(k)}(f_i) - \ell_{\min}^{(k)}(N_i)}{\ell_{\max}^{(k)}(N_i) - \ell_{\min}^{(k)}(N_i)}.$$  \hfill (5.6)

5.5 Resource Block Scheduling

In the second phase of RRS, users are scheduled onto femtocells using an interference- and throughput-aware algorithm. The algorithm divides users into two classes: regular and borderline users. Regular users are users whose measured and estimated SINRs are sufficient to meet their throughput targets. Borderline users have SINRs that are close to, but below their targets.

Regular users are scheduled first, in ascending order of the estimated number of resource blocks they require to meet their throughput targets. If a user is unable to be scheduled enough resource blocks to meet its throughput target, it is rejected. Regular users are assigned first to even-numbered resource blocks; if needed, they are scheduled on odd-numbered blocks as well.

Under all algorithm variants, borderline users are defined as users whose SINRs are within 3 dB below the lowest SINR threshold for service. They are scheduled after all regular users have been scheduled. Borderline users are scheduled first on odd-numbered resource blocks; they are only scheduled on even-numbered resource blocks if there is excess capacity. Borderline and regular users are scheduled in this fashion to increase the probability that borderline user vacancy requests will be satisfied. If free resource blocks remain after all regular and borderline users have been scheduled, both regular and borderline users are scheduled on them in a round-robin fashion.

5.5.1 Vacancy Requests

Borderline users are unable to meet their throughput targets as-is. Therefore, we introduce vacancy requests, which allow a femtocell to ask its neighbors to release scheduled resource blocks. Vacancy requests consist of a list of resource block identifiers and durations. Durations are determined by the estimated number of transmission frames each user will need.

Femtocells receiving vacancy requests will only honor them on resource blocks
Algorithm 8: Vacancy Scheduling Algorithm

Data: Users $U(f_i)$ assigned to femtocell $f_i$
Result: Schedule $S_i$ of resource blocks on femtocell $f_i$

1. $R \leftarrow \emptyset$;
2. $B \leftarrow \emptyset$;
3. $\phi \leftarrow B^{\text{Max}}$ for $u_j \in U(f_i)$ do
   4. if $\varsigma_{u_j} > \psi$ then
      5. $R \leftarrow R \cup \{u_j\}$;
   6. else
      7. $B \leftarrow B \cup \{u_j\}$;
   8. end
9. end
10. sort $R$ and $B$ by number of RBs required;
11. for $u_j \in R$ do
   12. if $b(\varsigma_{u_j}) \leq \phi$ then
      13. assign $b(\varsigma_{u_j})$ odd-numbered RBs in $S_i$ to $u_j$;
      14. $\phi \leftarrow \phi - b(\varsigma_{u_j})$;
   15. else
      16. reject $u_j$;
   17. end
18. end
19. for $u_j \in B$ do
   20. if $b(\varsigma_{u_j}) \leq \phi$ then
      21. assign $b(\varsigma_{u_j})$ even-numbered RBs in $S_i$ to $u_j$;
      22. $\phi \leftarrow \phi - b(\varsigma_{u_j})$;
   23. else
      24. reject $u_j$;
   25. end
26. end
27. if $\phi > 0$ then
   28. assign remaining RBs in $S_i$ to users in $R \cup B$;
29. end
30. for $f_n \in N_i$ do
   31. request vacancies for $u \in B$;
32. end

that are assigned to users that exceed their throughput targets. This ensures that users will not fall below their throughput targets due to vacancy requests. Vacancy requests increase fairness at the expense of capacity by trading resource blocks from users that exceed their throughput targets to users that are close to meeting their throughput targets.
| Variable \n\hline | Value | Description |
\hline
\text{L} & 20 \log_{10}(f) + \log_{10}(d) - 28 \text{ dB} & \text{Path loss} [79] \\
\text{f} & 1900 \text{ Mhz} & \text{Carrier frequency} \\
\text{p}^{tx}_M & 40 \text{ dBm} & \text{Macrocell tx power} \\
\text{p}^{tx}_F & 24 \text{ dBm} & \text{Femtocell tx power} \\
\mu_s & 0 \text{ dB} & \text{Shadow fading mean} \\
\sigma_s & 10 \text{ dB} & \text{Shadow fading std dev} \\
n_r & 9 \text{ dB} & \text{Receiver noise figure} \\
T_k & -174 \text{ dBm/Hz} & \text{Thermal noise density} \\
B^{\text{max}} & 100 & \text{Max RBs per base station} \\
\hline

Table 5.2: Simulation details

Since borderline users are preferentially scheduled to odd-numbered resource blocks, and regular users are preferentially scheduled to even-numbered resource blocks, if all regular users can be served at their throughput targets without spilling over to the odd-numbered resource blocks, any vacancy requests from borderline users on neighboring femtocells will be satisfied.

5.6 Simulations and Results

5.6.1 Experimental Details

The algorithms described in Section 5.4 and 5.5 address two aspects of network operation: transmit power, via radius reduction, and resource block scheduling. Recall that the radius reduction phase can be performed according two criteria: area coverage reduction (ACR) and user coverage reduction (UCR). Additionally, recall that the radius reduction of a femtocell is performed with different priority with respect to its neighbor femtocells, according to different performance criteria, that are: estimated increase in total user throughput (TI), number of users meeting throughput requirements (UTR) and load of the femtocell (Load).

Of the six possible variants, in the following experiments, we consider the ACR-TI, the UCR-UTR, and the UCR-load variants. For each of these variants we considered both the variants for the scheduling phase, namely with or without vacancy requests. Our experiments showed that the variants UCR-TI and ACR-UTR and ACR-load performed worse than UCR-UTR, ACR-TI, and UCR-load, respectively. For the sake of brevity, we omit these results. We denote with ACR-TI-V, UCR-UTR-V, UCR-load-V the variants of our algorithms in which we schedule with vacancy requests.
We evaluated a baseline algorithm that does not perform any radius reduction, and uses a naive scheduling algorithm that schedules users in a best-effort manner without vacancy requests. In the figures the baseline algorithm is referred to as *Baseline*. We also evaluated vacancy request scheduling on its own, with no radius reduction, indicated in the graphs as *Vacancy*.

To compare the performance of our algorithms to existing work, we implemented the *Interfering Link Conflict* algorithm, in the figures referred to as *Link Conflict*, from [70]. This algorithm uses graph coloring to produce mutually exclusive resource block schedules, while allowing unused resource blocks to be assigned if they meet certain interference requirements. The original paper describes a system with binary interference, where interference during a transmission results in zero throughput. By contrast, our simulated system is an SINR-based system, where interference reduces signal quality, but does not necessarily cause transmission failure. Our results show that the coloring approach of the link conflict algorithm is unsuited for SINR-based systems.

These algorithms were evaluated in a simulation of an OFDMA network modeled using LTE design principles. Details of the simulation parameters are in Table 5.2. Users and femtocells are uniformly distributed across a 50m×50m area of interest.

To quantitatively measure fairness, we use Jain’s index [73], defined as

\[
    f(X) = \frac{[\sum_{j=1}^{[d]} x_j]^2}{|U| \sum_{j=1}^{[d]} x_j^2}
\]

where \(0 \leq f(X) \leq 1\), and \(x_j = \frac{t_j}{\sum_{j=1}^{[d]} t_j}\). Jain’s index is a commonly used measure of fairness, with \(f(X) = 1\) when each user gets a \(\frac{1}{|U|}\) share of total throughput, and \(f(X) = \frac{1}{|U|}\) when one users gets all throughput. A higher value for \(f(X)\) indicates a more fair throughput distribution in the network.

### 5.6.2 Results

Figure 5.2 shows the network outage probability, defined as the percentage of users who are unable to reach their throughput targets, as the number of concurrent users increases. We considered a network composed of 30 femtocells, where user throughput requirements are distributed uniformly random between 10 kbps and 50 kbps.
The Baseline algorithm exhibits uniform performance as the number of users increases, indicating that the network is underloaded. However, due to interference, edge users are unable to meet their throughput targets. UCR-UTR-V performs the best, closely followed by UCR-Load-V. The versions of the algorithms that do not use vacancy scheduling have higher outage probabilities, but vacancy scheduling on its own does not significantly reduce outage probabilities over the baseline.

Vacancy scheduling benefits users at cell boundaries the most, since they experience the most interference from other cells. However, when femtocell transmit powers are fixed, the reduction in interference from vacancy scheduling is typically not enough to increase an unserved user’s throughput over its throughput minimum.
Figure 5.3: Femtocell transmit power level requirement. It is the combined reduction in interference due to both reduced transmit powers and vacancy scheduling that increases throughput enough for more users to meet their throughput requirements.

The Link Conflict algorithm results in outage rates that are unacceptably high. Since the algorithm eliminates conflicting transmissions between neighboring femtocells, it leaves a large number of resource blocks unassigned to prevent interference. In a system where conflicts cause transmission failure, this leads to near-optimal performance, however, in systems that can tolerate co-channel interference, the Link Conflict algorithm severely underutilizes available resources.

Figure 5.3 shows femtocell power levels as the number of users increases. UCR-
Figure 5.4: Global throughput

UTR and UCR-Load consistently use less power than ACR-TI, resulting in smaller cells and lower interference. The vacancy variants decrease outage probabilities without consuming more power, but give up some resource block usage for reduced interference. This tends to reduce the throughput of high-throughput users while increasing the throughput of lower throughput users who are unable to reach their minimum throughput without assistance. The Baseline, Link Conflict, and Vacancy algorithms all use a constant amount of power as the number of users increase.

Figure 5.4 shows the total sum of throughput across all users. Initially, the Link Conflict and Baseline algorithms result in the highest global throughput, although the Link Conflict algorithm’s global throughput falls quickly as the number of users increases. As the number of users increases, the throughput of the ACR-TI
increases over the baseline. The ACR-TI algorithms always use less power than the baseline, indicating that the ACR-TI algorithms are able to reduce interference and increase efficiency. The UCR-UTR and UCR-Load algorithms decrease global throughput with respect to the baseline, but do so while increasing the number of users who meet their throughput targets.

The Jain’s index of each algorithm, a measure of fairness, is shown in Figure 5.5. Recall that a Jain’s index of 1 indicates a perfectly uniform throughput distribution, with each user being allocated \( \frac{1}{|U|} \) of the throughput, and a Jain’s index of \( \frac{1}{|U|} \) indicates a completely unfair throughput distribution, with one user being allocated all of the throughput. The UCR-Vacancy algorithms exhibit a U-shaped Jain’s index curve, with fairness increasing again as the number of users increases. The increase in fairness at high load is due to the increased use of vacancy scheduling in the UCR variants as transmission powers increase. Vacancy has a higher Jain’s index than Baseline, despite serving the same number of users, indicating a fairer throughput distribution. Due to its overall poor performance, the Link Conflict algorithm has a very low fairness index, as most users get no service at all.

Figure 5.6 shows the outage probability with 30 femtocells and 60 users as users mean throughput targets increase. Throughput targets are uniformly distributed in a range of 50 kbps above and below the mean. At lower throughput targets, the UCR-Load-V and UCR-UTR-V algorithms perform the best. As throughput targets increase, the ACR-TI algorithms begin to perform better. However, at these higher throughput targets, the outage probability approaches 50\%, which is far above the level for which a wireless network would be designed.

Overall, the UCR-Load-V and UCR-UTR-V algorithms are able to trade off some total throughput to increase the number of users that are able to connect to the network.

5.7 Summary

In this chapter we presented RRS, a distributed algorithm for network management. RRS consists of two parts: an algorithm for increasing fairness in dense femtocell networks by managing femtocell transmission power using a Voronoi-Laguerre geometry-based cell radius reduction, and a scheduling algorithm that allows femtocells to request vacancies on resource blocks that are experiencing heavy
interference. Simulations show that RRS reduces outage probabilities by up to 50%, and increases Jain’s index, a measure of fairness, by up to 190%.
Figure 5.6: Outage probability, increasing throughput target
Chapter 6  |  Conclusion and Future Work

This dissertation presented four methods for interference and power management in dense femtocell networks.

First, we presented a game-theoretic algorithm for managing femtocell pilot signals in CDMA networks. The algorithm finds the Nash equilibrium of an n-player game played amongst femtocells to determine an equilibrium pilot signal strength that reduces pilot pollution across the network, then dynamically reduces femtocell pilots while users are connected to neighboring femtocells. Simulation results showed a total reduction of outage probability of up to 43% relative to an existing femtocell transmission power management scheme.

Next, we presented a set of greedy algorithms for femtocell deployment. The algorithms use coverage, area spectral efficiency, or a combination of the two as metrics to determine the location of the next femtocell. The combined algorithm was shown to reduce outage probability by up to 30% relative to naive greedy approaches, while reducing power consumption by up to 14%.

We presented GREENFEMTO, a femtocell selective activation algorithm designed for over-provisioned femtocell networks. By deactivating all femtocells except those needed to maintain area coverage, and activating them only when necessary, GREENFEMTO requires up to 55% fewer femtocells than an existing femtocell power management scheme. Furthermore, we proved that GREENFEMTO finds a locally Pareto-optimal solution, and comes within 10% of an optimal solution for a given set of active femtocells.

Finally, we presented Radius Reduction and Scheduling, a femtocell transmission power management and resource block scheduling algorithm. RRS determines initial femtocell cell sizes and user assignments via a distributed cell coverage
radius reduction algorithm. It then schedules user transmissions using a vacancy request algorithm, where femtocells can request that certain resource blocks be vacated to reduce interference for certain users. We show that RRS decreases outage probability by up to 50%, and increases a fairness measure by up to 200%.

There are a number of potential ways to extend the work presented in this dissertation. Foremost is experimental validation of our results, as the majority of the work in this dissertation is based on simulations. Since the pilot adjustment algorithm relies on the interaction between pilot signal strength and interference for data transmission, experiments could be performed using femtocell development kits and wireless adapters for laptops to act as mobile devices. **GreenFemto** and the radius adjustment portion of RRS can be performed using generic wireless devices, since they are not dependent on the characteristics of a specific air interface. The scheduling portion of RRS is specific to the resource scheduling mechanism in OFDMA systems, and would require either an OFDMA development kit or emulation via another wireless medium.

The scheduling algorithm used in RRS is another area of this work that could be extended. The current scheduling algorithm is dynamic and distributed, but straightforwardly designed. A more complex algorithm could potentially improve the overall performance of the algorithm, or emphasize certain performance characteristics, such as fairness or total throughput.

The broader thrust of the work in this dissertation is the design and analysis of algorithms for dense femtocell networks. The work in the last two chapters applies algorithm design strategies from sensor networks to dense femtocell networks. Although there are differences in scope, application, and design between the two types of networks, enough similarities exist that principles from sensor networks can be successfully adapted to dense femtocell networks. There exists the potential for more work to be done by examining dense femtocell networks through the lens of sensor networks.
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