PART I

INTRODUCTION

1

SMALL CELLS—THE FUTURE OF CELLULAR NETWORKS

1.1 INTRODUCTION

> *"Any sufficiently advanced technology is indistinguishable from magic."*
> —Arthur C. Clarke, *Profiles of the Future*

One of the most widely used devices that appears "magical" today is the smartphone, which allows the user to connect instantaneously with people anywhere on the planet, can provide professional answers to any question, has access to a map of the entire world, and can guide the user to any desired destination.

However, the "magic" does not occur in the smartphone but in the network, which enables its functionality, provides ultra-broadband wireless access, and processes information to deliver voice and data services, invisible to the user.

Popular user demand has thus fueled a remarkable growth of cellular network infrastructure and mobile devices. In 2014, the number of connected mobile devices for the first time exceeded the number of people on Earth, increasing rapidly from zero to 7.6 billion connected devices and 3.7 billion unique subscribers in only three decades [1, 2]. This has fundamentally transformed the way we communicate and access information.

Small Cell Networks: Deployment, Management, and Optimization, First Edition. Holger Claussen, David López-Pérez, Lester Ho, Rouzbeh Razavi, and Stepan Kucera.

Today, we are on the brink of another significant change. While up to now the network mainly served humans, in the future, this capability will increasingly be used by machines as well. The emergence of machine-originated data traffic not only drives further the demand for network capacity but also imposes additional requirements on network performance, mainly in the area of end-to-end latency, which currently is the limiting factor for many new applications.

Nowadays, most of the data services reside in the Internet, far away from the user where the speed of light becomes one of the main factors limiting latency. To address this problem, processing will have to move closer to the user into a cloud computing infrastructure as part of the network. In addition, adaptive network management and well-designed congestion control can help to control latencies and enable new real-time applications such as augmented reality or efficient machine communication.

With these changes, the future network is evolving to become our main interface with the virtual world, and increasingly also with the physical world, to simplify and automate much of life. This will allow us to effectively "create time" by improving the efficiency in everything we do [3].

Making this vision of the future network a reality will require both:

1. Ultra broadband wireless access, providing orders of magnitude improved performance and quality-of-service control, as well as
2. A flexible and programmable cloud computing infrastructure located close to the edge of the wireless network.

Throughout this book, we argue that small cells are the answer to the technological challenges of creating a wireless access network that connects the mobile devices, machines and objects to a processing cloud engine.

As an introduction to our technological philosophy and the content of the book, the remainder of this chapter first summarizes the industry challenge, followed by an overview of the small cell technology and its history. Then, individual parts and chapters of the book are introduced as well as their relationship to various aspects of deploying and operating small cell networks.

1.2 THE INDUSTRY CHALLENGE

The proliferation of highly capable mobile devices as well as the user expectation to be fully connected and have access to all services anywhere and anytime has resulted in an exponential increase in cellular capacity demand over the past few years. With the addition of wirelessly connected machines, which can send, receive, and process massive amounts of data, this trend will continue and is driving an explosion of cellular capacity demand. The expectations are that machines will significantly outnumber human users in the future.

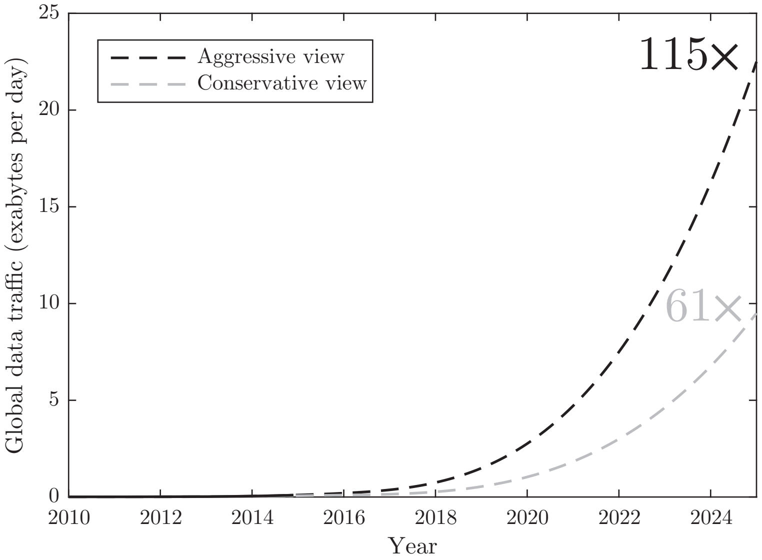

Figure 1.1. Growth in capacity demand [7].

Figure 1.1 shows the predicted increase in data traffic until 2025, taken from an analysis done by Bell Labs Consulting in 2014 based on LTE traffic models and drawing from multiple data sources, including Alcatel-Lucent field data and [1,4–6]. It is shown that the global bearer traffic is expected to grow by a factor between 61× and 115× over the next decade to 22.5 Exabytes per year [7].

Moreover, the control plane demand is predicted to increase proportionally to support an increasing number of short traffic messages generated by machines [7].

However, although the demand for capacity is increasing, users are not willing to pay substantially more for higher data rates, and the average revenues per unique subscriber in recent years have been stagnating [8]. This means we have to provide exponentially more capacity for the same costs as today, adding a significant commercial challenge to the already difficult physical challenge of scaling capacity by orders of magnitude.

A further difficulty is the energy consumption of networks. A report from Ofcom suggests that information communication technology (ICT) accounts for 2% of global CO2 emission with 0.7% contribution from mobile and fixed communication devices [9]. For example, British Telecom consumes 0.7% of all electricity usage in the United Kingdom [10]. The energy consumption already accounts for 7–15% of operational expenditure (OPEX), reaching up to 50% in developing countries. As a result, we cannot scale capacity using traditional macrocellular network technology, since this would quickly become unsustainable both from a commercial and environmental point of view.

In summary, we can state the industry challenge as *enabling orders of magnitude increase in wireless capacity without increasing costs.*

1.3 ARE SMALL CELLS THE ANSWER?

1.3.1 Dimensions for Capacity Scaling and Historic Capacity Gains

When aiming at orders of magnitude improvements of network capacity, it is important to understand the different dimensions of how capacity can be improved. In a simplified form, the Shannon–Hartley theorem

$$C = B \log_2 \left(1 + \frac{S}{N}\right) \tag{1.1}$$

provides an insight into what are the variables that influence the amount of information (capacity C) one can transmit over a communication channel of a specified bandwidth B with a signal received with power S in the presence of white Gaussian noise with power N [11].

Capacity C can be scaled by increasing the bandwidth B per user, and by increasing the signal-to-noise ratio S/N, or in a multi-user network the signal-to-interference-plus-noise ratio (SINR). Addressing the bandwidth is a more promising approach since this results in a linear scaling compared to the logarithmic scaling when increasing spectral efficiency by improving the SINR. In a network with multiple users, the bandwidth per user can be scaled by either increasing the frequency resources, or by network densification based on the reduction of cell size. This measure results in improved spatial reuse of frequency resources and less sharing of the available bandwidth between users.

An overview of how each of the three degrees of freedom governing wireless channel capacity—densification, bandwidth, and spectral efficiency—contributed to capacity gains between 1950 and 2000 is provided in [12]:

- 2700× from densifying to smaller cells,
- 15× by using more spectrum bandwidth (3 GHz vs. 150 MHz),
- 10× by improving spectral efficiency (coding, medium access control (MAC) and modulation methods).

From this, it is clear that the majority of the gain was achieved by increasing the spatial frequency reuse though densifying the network to small cells. This leaves us with the question: How much further can we increase the spatial reuse by reducing the cell size?

1.3.2 Densification

In a multi-user network, users in the coverage of a cell share the available bandwidth. Thus, reducing the cell size and deploying more cells also reduces the number of users per cell, and in turn increases the bandwidth available to each user. Through this approach, the bandwidth per user can be increased until each cell serves only a single user. When densifying further, only the SINR is improved by reducing the distance between the base station and user. As a result, the capacity scales linearly until the single user limit is reached by increasing the bandwidth per user, after which the scaling becomes logarithmic (see Eq. 1.1). This is illustrated in Fig. 1.2 showing that with increasing cell densities the capacity initially increases very quickly through cell splitting gains, but then slows down when the gains are mainly achieved via improving SINR through proximity gains. Note that if base stations (BSs) are not deployed following the user distribution, a large number of cells are required to achieve the one user limit.

A second aspect of densification is that the required transmit power reduces to an extent where its contribution to the total energy consumption becomes insignificant, and the processing power becomes the dominant factor. In addition, with smaller cell sizes the required number of cells increases such that many of them do not serve active users for most of the time. However, they still consume power and transmit unnecessary pilot signals which cause interference. This can be addressed by introducing

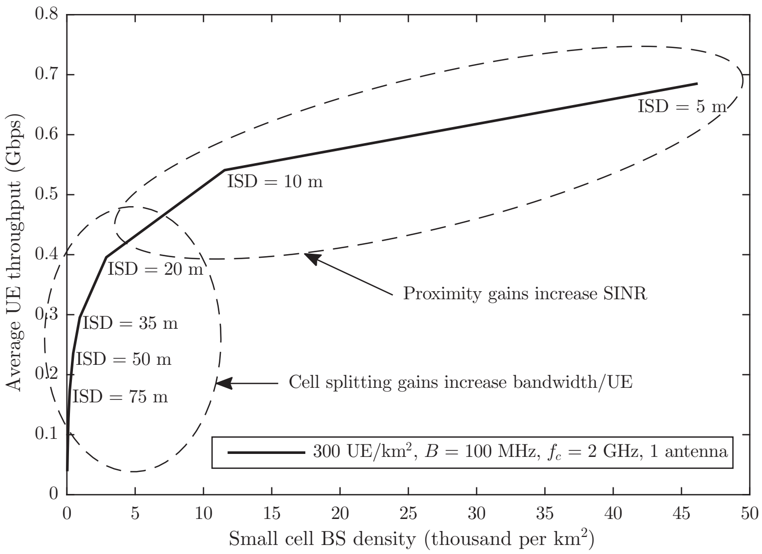

Figure 1.2. Capacity scaling with densification for different inter-site distances (ISDs).

idle modes, where cells are only woken up when actively serving users. With efficiently controlled idle modes, the SINR and network energy consumption improves significantly.

The main challenge of network densification is the issue of increasing costs for equipment, deployment and operational expenses. In this light, it is important to note that the costs of a small cell BS only accounts for approximately 20% of the total deployment costs associated with outdoor small cells in 2015. The majority of the costs are site leasing (26%), backhaul (26%), planning (12%), and installation (8%) [13], which can be addressed by changing the deployment model from operator deployment to a "drop and forget" user deployment, and reusing of existing power and backhaul infrastructure. The end user simply connects the base station to power and backhaul, which triggers a fully automatic configuration, and a continuous self-optimization process during operation. This user deployment model is feasible for both the residential and enterprise market. In addition, it becomes increasingly important to deploy the cells where the users are, since small cells cannot compensate for misplacement as well as larger cells. However, accurate user demand distributions are hard to derive today because the accuracy of conventional localization techniques in cellular networks such as triangulation is poor and the use of more accurate techniques such as the global positioning system (GPS) is not available indoors, where 80% [14] of the traffic demand is located.

In summary, densification continues to have a high potential to increase capacity until reaching one user per cell. In order to maintain high performance and energy efficiency, idle modes that switch off cells when they are not serving users are necessary. Transitioning to a "drop and forget" deployment by the user has a high potential to reduce the deployment and operational costs.

1.3.3 Bandwidth

Another dimension we can use to increase capacity is increasing the bandwidth, where we can achieve linear scaling (see Shannon–Hartley theorem, Eq. 1.1).

However, there are several challenges with this approach as well. First, the available bandwidth at lower frequencies is limited which implies that increasing bandwidth often requires an increase in the carrier frequency band as well, and higher frequencies lead to increased path loss (even line-of-sight requirements when moving to mm-wavelengths). Second, the required transmit power increases significantly when increasing bandwidth due to the higher path loss at higher frequency bands and the fact that more carriers need to be allocated. This is illustrated in Fig. 1.3, which shows that with increasing bandwidth, the transmit power also increases quickly, making higher bandwidths only usable for small cells.

Although increasing spectrum availability can provide high capacity gains, bandwidth is already used up at lower carrier frequencies. More bandwidth is available at higher carrier frequencies, but is mainly applicable to smaller cells due to the increasing transmit power requirements.

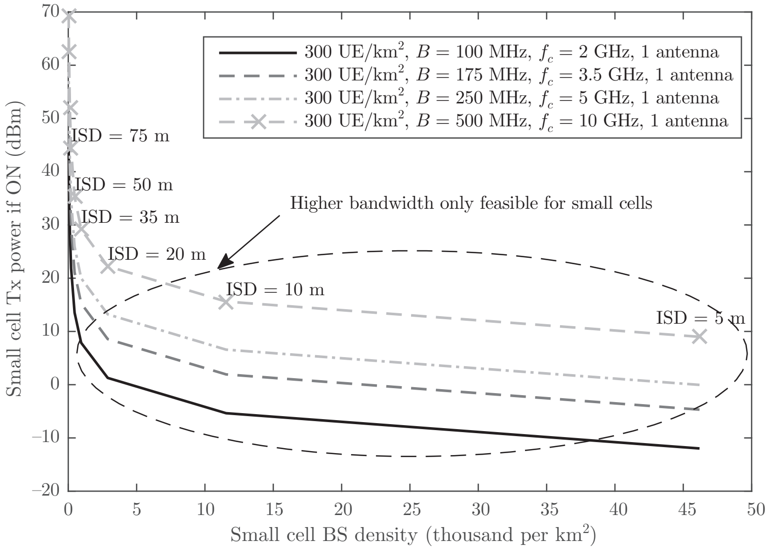

Figure 1.3. Transmit power for increasing bandwidth, small cell densities, and inter-site distances (ISDs).

1.3.4 Spectral Efficiency

The third dimension for increasing capacity is increasing the spectral efficiency, for example, by signal processing through error correction coding, increasing the SINR using interference mitigation, or with multiple antennas.

The progress in signal processing has already led to near-saturation of gains in this dimension. Current coding schemes already operate close to the Shannon–Hartley capacity limit, and further signal processing gains require significant overhead (e.g., Network multiple-input multiple-output (MIMO)). Multiple antennas can be used to increase SINR through beamforming or for spatial multiplexing, but the low number of antennas at the user equipment (UE) at cellular bands and issues with channel state information acquisition limit the gain for traditional MIMO systems.

Figure 1.4 shows the achievable gains exploiting densification, high bandwidth and different numbers of antennas used for beamforming. It is shown that increasing the number of antennas results in gains, but they are lower compared to densification and increasing bandwidth. This results from the fact that improving the SINR only leads to logarithmic gains (see Shannon–Hartley theorem, Eq. 1.1). Consequently, the gains in this dimension are more limited compared to densification and increasing bandwidth. A further challenge is that the gains from improving SINR are not fully complementary with densification. For example in an ultra-dense small cell network, with on average less than 1 user per cell, the SINR is already high due to low

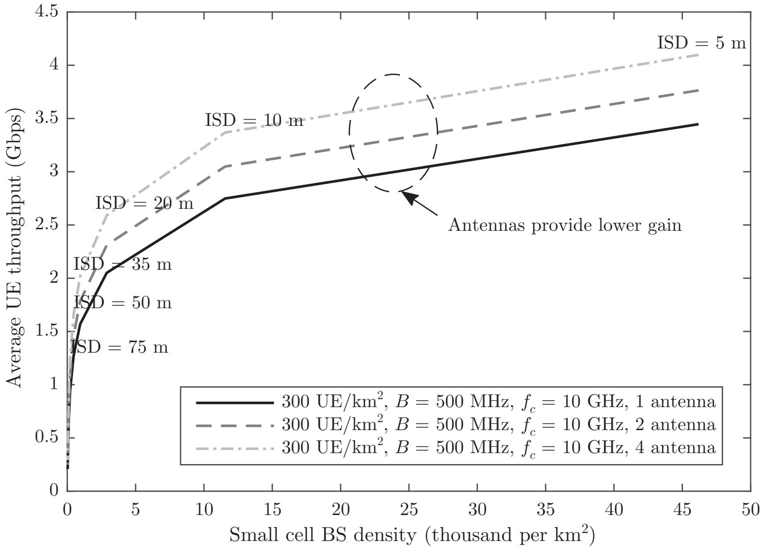

Figure 1.4. Increasing spectral efficiency through beamforming with multiple antennas for different small cell densities, and inter-site distances (ISDs).

interference resulting from empty neighboring cells. Further increasing the SINR leads to diminishing gains due to the logarithmic scaling.

As a concluding remark, techniques improving spectral efficiency should be exploited but any improvement in SINR leads to only logarithmic gains. Thus, the gains in this dimension are more limited compared to densification and increasing bandwidth.

1.3.5 The Answer

Figure 1.5 illustrates the three dimensions for scaling cellular capacity, summarizes their characteristics, and outlines the expected future gains in cellular bands. More spatial reuse by densifying the network with smaller cells continues to provide the highest potential for capacity gains with an expected increase of 18×. Increasing bandwidth can lead to 5× improvements, and improving spectral efficiency with multiple antennas can increase capacity by 2× at cell edges. The challenge of capacity scaling and all assumptions for these results are discussed in more detail in Chapter 2. By exploiting all dimensions, cellular capacity can be increased on the order of 180×. Beyond that we need to explore higher frequencies such as the unlicensed bands and mm-wave. In addition, a high increase in user density due to machine traffic will allow further gains through densification.

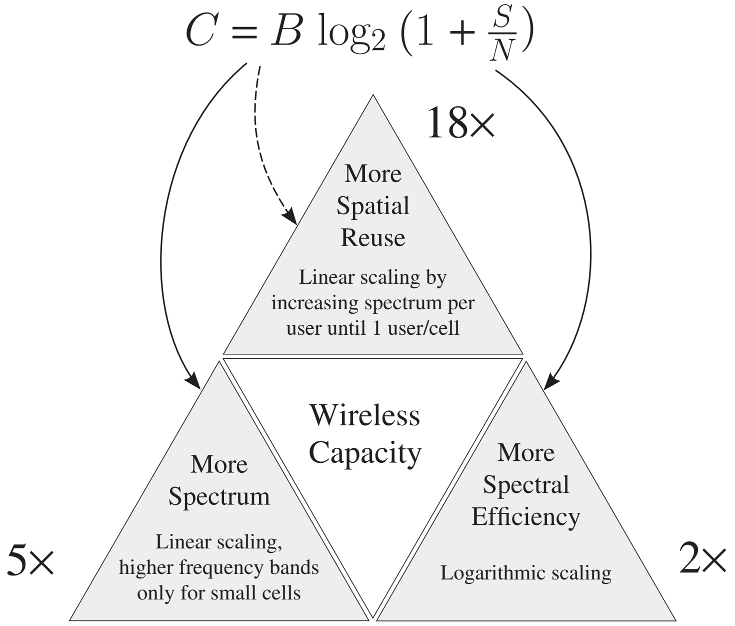

Figure 1.5. Dimensions for scaling wireless capacity and achievable future gains at cellular bands.

The discussion above outlines the physical feasibility of achieving orders of magnitude capacity gains. However, to make this commercially viable, it is necessary to be able to implement and deploy this future network at a cost point not much different from where we are today. This requires a significant increase in automation of the network, including all aspects from planning, deployment, configuration, and optimization.

In summary, orders of magnitude increases in wireless network capacity are possible. Small cells are a necessary topology evolution and will be the main solution to providing the future capacity growth until reaching one user per cell. The other dimensions of frequency and spectral efficiency should also be exploited. To make this future network commercially viable, significant changes are required in the way we deploy and operate the network. Many of these topics are covered in this book.

1.4 A BRIEF HISTORY OF SMALL CELLS

The idea of small cells has been around for over three decades [15]. Initially, "small cells" was the term used to describe the cell size in a metropolitan area, where a macrocell (on the order of kilometers in diameter) would be split into a larger number of smaller cells with reduced transmit power, known today as metropolitan macrocells or microcells. These cells have a radius of a few hundreds of meters.

In the 1990's picocells appeared [16] with a cell size between a few tens of meters and around a hundred meters. These "traditional" small cells are used for capacity and coverage infill, that is, where macrocell penetration was insufficient to give a good connection or where the macrocell was at its capacity limit. Moreover, these types of small cell BSs are essentially a smaller version of the macrocell BS. They had to be planned, managed, and interfaced with the network the same way as macrocell BSs. This last point alludes to why small cells (other than metropolitan microcells) have not gained in popularity for some time. Essentially, the costs associated with deploying and running a large number of small cells outweighed the advantage that this kind of cellular topology provided.

New thinking on the deployment and configuration of cellular systems began to address the operational and cost aspects of small cell deployment [17, 18], which enabled cost-effective deployment of even smaller cells. Early simulation results for femto- and small cells were presented by the authors [19–21], which were extended to self-optimization strategies, multiple antennas, energy efficiency, and offloading benefits shortly afterward [22–29]. On the academic side, early work included new mathematical models and analysis, specifically looking at the uplink interference problem in code division multiple access (CDMA)-based networks with closed access [30, 31].

Femtocells [22, 32, 33] emerged as the first step toward a heterogeneous network deployment model. Femtocells are low-cost cellular BSs with advanced auto-configuration and self-optimization capability, which allows them to be deployed by the user in the home in a plug-and-play manner. They use a broadband Internet connection as backhaul and connect to the cellular network via gateways, which allows better scaling to millions of BSs.

Following early research, the number of publications including femtocell or femtocells in the topic registered in the IEEE database [34] have increased from 3 in 2007 to 11 (2008), 52 (2009), 117 (2010), and a total of 1088 publications registered by the end of 2015.

In addition, the European Union has started funding research on femtocells, for example the ICT-4-248523 BeFEMTO project, which focuses on the analysis and development of long-term evolution (LTE)-compliant femtocell technologies [35].

In 2007, several industry players advocating small cell technology formed the Femto Forum, rebranded as the Small Cell Forum in 2012, to create a venue for promotion, standardization, and regulation.

The first commercial deployments of residential femtocells started in 2008 when Sprint launched a nationwide service in the US, followed in 2009 by Vodafone in Europe, and Softbank in Japan. Since then, small cell technology has proliferated quickly. The number of deployed 3G small cells for the first time exceeded those of macrocells in 2011 [36], and in 2015, over 77 operators used small cells worldwide [37]. The business impact of small cells with 4G LTE-Advanced is now considered by far the most important, but multi-mode cells with additional 3G as well as wireless fidelity (Wi-Fi) capability are becoming increasingly available [38].

The scope of femtocells was then extended from residential deployments to public indoor spaces, which generate most of the cellular traffic. By 2015, 71 carriers operated in-building small cells, known as pico- or microcells, in enterprise or public buildings [37]. Their design is tailored to reduce planning and deployment costs, decrease the need for large customer support teams, and eliminate the need for massive reprovisioning. The generally good availability of Internet protocol (IP) backhaul such as Ethernet in indoor spaces is an important deployment advantage. The overall system configuration as well as the overlap with outdoor macro- and metrocells must be monitored and well managed. To this end, in-building small cell deployments are equipped with quality of service (QoS) and per-call analytics, as well as self-organizing network (SON) features.

The expansion to the outdoor space is more difficult due to barriers such as backhaul availability and cost, site rental, network provisioning and management as well as monetization challenges. Nevertheless, even in this area, small cells proved to be a viable approach in the form of metrocells—smaller and more flexible versions of macrocells with whom they share many hardware and software features, most notably the support of a high number of simultaneous active users and the SON capability for self-configuration and self-optimization of inter-cell interference mitigation, neighbor relation management and handover parameter configuration.

By 2014, AT&T has deployed small cells in 30 US states, mainly to fill coverage gaps in areas with complex landscape or poor signal propagation [39]. Outdoor capacity-oriented trials using cloud radio access network (C-RAN) technology were announced in 2015 [40]. In Europe, the trend is similar with Vodafone rolling out metrocells for years and small cells being part of Orange's strategy, although the overall small cell penetration is still moderate as the available spectrum has not yet been fully utilized [41]. As of 2015, 23 operators have deployed metrocells in outdoor urban zones and large venues such as stadiums and shopping malls, while over 32 operators have used them in rural or remote scenarios [37].

By February 2016, 13.3 million small cells were shipped, and the small cell market size increased to more than \$1 billion annually [42]. However, the growth of the small cell technology evolution is nowhere near saturation given the ongoing capacity crunch. It is predicted that small cell densification will continue at a fast pace for both residential and enterprise networks, and the market revenue will reach \$6.7 billion by 2020 [42].

In addition, small cells are expected to play a big role in 5G, especially in terms of low latency and high data rates due to the close proximity to the user. Small cells also drive the discussion around long-term evolution (LTE) Unlicensed, a technology that may coexist with Wi-Fi in unlicensed bands and could substantially increase the LTE capacity.

1.5 SMALL CELL CHALLENGES AND OUTLINE OF THE BOOK

1.5.1 Part I: Introduction

Following the introduction and motivation provided in this chapter, the remainder of Part I focuses on the fundamental challenges of enabling 100× scaling of cellular capacity, and automating cellular networks, the key to cost-effective deployment and operation.

Chapter 2 extends the high-level discussion on scaling capacity, and provides an in-depth analysis on how to make it physically possible to scale the cellular capacity by orders of magnitude. The three dimensions of densification, bandwidth, and spectral efficiency are discussed in detail. The one user per cell concept is introduced as the sweet spot for densification. The importance of idle modes, both for reducing interference and improving the energy efficiency in small cell networks is discussed. The impact of increased bandwidth on the power consumption is evaluated and improving spectral efficiency with beamforming techniques is explored. In addition, the impact on scheduling and the resulting network energy efficiency is evaluated. Finally, the technology mix that can enable an average capacity of 1 Gbps per UE is derived.

In addition to making it physically possible to scale the network capacity, making such networks commercially viable is the second critical challenge. To achieve this, significant changes are required in the way networks are planned, deployed, configured, and optimized. Chapter 3 provides an overview of what parts of the network can be automated today. The main SON use cases introduced by Third-Generation Partnership Project (3GPP) and next-generation mobile networks (NGMN) are discussed. Then, key requirements for SON are described and different mechanisms for implementing intelligence across the network are explained. Finally, two examples are given as case studies for SON functionality. First, an antenna tilt angle optimization in a heterogeneous network with macrocells and small cells based on fuzzy-reinforcement learning is presented. Second, the online evolution of femtocell coverage algorithms using genetic programming shows how networks can become truly intelligent in the future and can even rewrite their own optimization code while operating.

The main optimization challenges in small cell networks are addressed in the following parts in more detail.

1.5.2 Part II: Coverage and Capacity Optimization

One of the initial challenges when deploying small cell networks is selecting the carrier frequency and access method, and optimizing the coverage of the cells.

One of the first choices an operator needs to make when deploying small cells is on the frequency allocation and the user access model. In Chapter 4, the different options for frequency allocation: separate, shared, and partially shared frequency resources are presented and their trade-offs and applicability to private and public access models discussed. Then, some of these concepts are illustrated using two examples. First, the feasibility of co-channel deployment of residential femtocells is demonstrated showing that co-channel femtocells with public access can achieve high performance while only causing negligible performance degradation for the macrocellular network. As second example, the optimization of a partially shared spectrum configuration using multi-carrier soft reuse (MCSR) for outdoor small cells is investigated. It is shown that correct optimization of macrocell power in the reduced power band is critically important to maximize offloading to small cells and overall network performance.

Once the initial parameters such as frequency and access model are configured, coverage optimization is a critical step that has significant impact on the overall network performance. Chapter 5 focuses on coverage and capacity optimization for both residential and enterprise small cells. For residential femtocells, the main objective is to minimize leakage of the coverage into busy public spaces, which can cause a significant amount of handover traffic and signaling for passing users, while maximizing indoor coverage of the home. Coverage optimization algorithms are presented that can reduce the number of mobility events by 90% for a single antenna configuration and by a further 31% for a multiple antenna configuration. For enterprise femtocells, the objective is different. Small cells need to jointly work together to provide full coverage and balance load, with the minimum necessary power to minimize interference. A distributed algorithm is presented that achieves this and improves capacity by 18% compared to a static configuration. An alternative approach to automatically evolving optimization algorithms for joint coverage optimization is already covered in Chapter 3.

Chapter 6 focuses on coverage optimization for outdoor small cells. Here, the problem is different again, since outdoor small cells are typically deployed to cover a hotspot area. When small cells reuse the macrocell frequencies, their coverage is often limited by their lower transmit power. This power imbalance can lead to insufficient traffic offloading particularly when small cell BSs are deployed close to a macrocell BS and also to high interference in the uplink. To address this problem, range expansion using a bias value is discussed and optimization strategies to calculate the bias value for the expanded coverage are presented. A second problem with outdoor small cells is that their placement is often sub-optimal due to deployment limitations and availability of backhaul and power. This problem is addressed using a switched multi-element antenna system, which allows better adaptation of the coverage to the user locations. The proposed solution can achieve an average SINR improvement of 5.1 dB, translating in a peak throughput improvement of 72% in the investigated scenario.

1.5.3 Part III: Interference Management

To achieve high spectral efficiency, small cells need to reuse the frequency resources of the macrocellular network in a shared or partially shared configuration, as discussed in Chapter 4. However, this can create high interference between macrocells and small cells resulting in degraded network performance at the cell boundaries. In this part, different interference management strategies for both downlink and uplink are presented and their trade-offs discussed.

Chapter 7 focuses on inter-cell interference management by frequency-domain multiplexing. Here, potentially interfering transmissions can be transmitted in different frequency bands using carrier aggregation. Different configuration options and aspects such as signaling, cell activation, power control, and mobility management are discussed. The main benefit of this approach is backward compatibility and its relative simplicity. This comes at the cost of limited flexibility and overhead for separate reference, synchronization and control signals on each component carrier.

In Chapter 8, time-domain interference coordination is discussed. In particular, the technique of almost blank subframes (ABSs) is examined, which allows an interfering cell to mute some of its non-critical transmissions in selected subframes to reduce interference in these resources to other cells. The benefit over carrier aggregation-based approaches discussed in Chapter 7 is the finer granularity of the blanking, which results in improved performance. Methods for optimizing ABS pattern, range expansion biases (REBs) and transmit power are presented, which achieve improvements of the median capacity of almost 60% in a simulated scenario with 132 macrocells and 72 metrocells.

In Chapter 9, a novel sector offset configuration for the macrocell tier is proposed, which can achieve interference coordination without reducing the frequency reuse factor. As a result, the approach can significantly enhance both macrocell and small cell UE throughput, and also improve mobility performance. For a single carrier LTE heterogeneous network (HetNet), cell-edge UE throughput has been shown to improve by 50%, while average and cell-edge macrocell UE throughput have been improved by 17% and 32%, respectively. The handover failure (HOF) rate decreased by 46% when adopting offset sectorization. This comes at the cost of an increased number of antennas at the macrocell site to achieve the sector offset configuration. The concept is fully compatible with current mobile devices and cellular standards, and is in general easy to implement.

Frequency dependent interference coordination, as described in Chapter 7, can be used to improve the quality of LTE data channels. However, the LTE standard does not allow this flexibility in the control channels. As a result, the performance of LTE control signaling under inter-cell interference can become the coexistence bottleneck in co-channel HetNets that limits the effective small cell coverage range and user capacity. In Chapter 10, the concept of orthogonally filled subframes (OFSs) is proposed where control channel interference is minimized by optimizing the pseudo-random allocation of control channel resources. It is shown that this method can either be used to double the small cell radius, enabling a significantly improved offload of the macrocell traffic by the small cell, or triple the control channel capacity—a feature demanded by the emerging high-load voice over LTE (VoLTE) applications.

While previous chapters have mainly focused on interference management in the downlink, Chapter 11 focuses in more detail on uplink-oriented optimization. In particular, conditions under which secondary base stations can share the same communication channel with the primary base stations are examined, assuming constraints such as common interference-limited channels and predefined quality of service such as a minimum SINR for each active transmission. Optimization methods for both CDMA and LTE networks are presented with up to 3× gains in mean uplink user data rates.

1.5.4 Part IV: Mobility Management and Energy Efficiency

Mobility management and energy efficiency are important challenges that highly impact the quality of experience for the user and the operating expenses for the operator. These problems are related since idle modes are the key to energy efficiency in small cell networks, and wake up procedures need to be able to activate idle cells in time that a handover can take place.

Due to the power imbalance and high number of small cells in HetNets, mobility issues are amplified, and if not addressed, they can result in a significantly increased number of dropped calls. In Chapter 12, the handover process in LTE is reviewed as well as the different mobility challenges in HetNets. Special attention is given to its main four stages: measurements and processing, triggering, preparation, and execution, together with important concepts such as radio link failure (RLF), HOF, and ping-pongs. Based on the significant impact of UE velocity on the handover (HO) performance in HetNets, a UE velocity-dependent HO scheme is presented. The need for a better mobility state estimation and new network architectures that consider small cells and the mobility management issue as a key design driver is also discussed.

Chapter 13 presents a framework that is used to quantify the energy saving gains of deploying small cells using a parametric model. It is shown that a power reduction gain of 46× can be achieved when compared to the baseline macrocell-only scenario, with traffic demand assumptions for 2016. With increasing traffic demand in the future, this gain will increase further significantly. Obtaining those gains in practice requires efficient idle mode control and a low idle power consumption. Two idle mode control methods are presented. A simple distributed approach is based on sniffing uplink transmissions to the macrocell and waking the cell up when the measured power exceeds an auto-configured threshold. This simple method can achieve the majority of the efficiency gains, but wakes up more cells than necessary in multi-tier HetNets. This is addressed by a centralized approach based on RF-fingerprinting which can overcome this problem.

1.5.5 Part V: Small Cell Deployment

The correct placement of small cells is important to maximize the gains of small cell deployments. This part focuses on providing backhaul and on placement optimization to maximize the return of investment.

One significant challenge for the deployment of small cells is the provisioning of backhaul, in particular for outdoor deployments where this represents a high cost factor. In Chapter 14, different backhaul options such as point-to-point and point-to-multipoint wireless backhaul, and wired backhaul options are presented and their capabilities and costs discussed.

Chapter 15 is focused on the placement optimization of small cells. The correct placement is important to maximize the gains of small cell deployments. Placing small cells in the wrong location can not only result in low gains in capacity but, in the worst case, can even cause a degradation due to increased interference. There are many factors which contribute to a good deployment location, but the main ones to consider are interference, offload, backhaul, and costs. In order to maximize the benefits of small cell deployments, they should ideally be placed in locations where the received signal strength from the macrocell underlay is low in order to minimize co-channel interference and maximize the small cell coverage area, while minimizing the costs for site and backhaul. A solution to achieve this is presented including the collection and processing of input data, together with different algorithms for solving the multi-objective placement optimization problem.

1.5.6 Part VI: Future Trends and Applications

This part provides a view into the future and discusses how a transition to ultra-dense networks could be realized, and what new applications could be enabled by the finer spatial information that small cells provide.

For scaling of capacity, densification is one of the most promising approaches as discussed in Chapters 1 and 2. When densifying to ultra-dense networks, one challenge is the transition to line-of-sight path loss resulting in increased inter-cell interference between small cells. Chapter 16 addresses this challenge by employing an attocell deployed at the ceiling with a downward facing patch antenna. It is shown that this significantly reduces inter-cell interference and increases capacity by 4× compared to a traditional small cell with an omni-directional antenna. In addition, aspects such as mobility in ultra-dense networks, and the applicability to higher frequency bands are discussed.

Owing to their special characteristics, such as their short coverage range, small cells can be used as the technology enabler for a number of other applications. Chapter 17 presents different application areas that can be addressed by small cells that can potentially reverse the trend of declining revenues per user for operators. Localized services can provide information and enhanced experience in areas such as museums and for public transport. Proximity detection can provide location-based notifications, for example, when children leave or enter their home. Small cells enable accurate indoor localization where GPS is not available, which can enable a variety of enterprise applications, navigation, tracking, interaction detection, and support E911 emergency call localization. Small cells could also connect devices with applications in home automation, light control, remote control, smart energy, remote care, security, and safety. A further application is enabling selective localized network access control, allowing to restrict the mobile service for specific user groups in hospitals, libraries, theatres, and cinemas without intrusive jamming that causes interference in neighboring areas.

1.5.7 Appendix A: Simulating HetNets

Finally, Appendix A explains how HetNets can be simulated, and describes how the results in this book were derived. Modeling of macrocell and small cell layouts are described, followed by modeling of antennas, path loss, fading, and the calculation of the received signal strengths and SINRs. Scheduling algorithms and the mapping SINR to throughput is also discussed. Then, user traffic and mobility models are presented. This provides the reader with a guide of how to analyze HetNets using computer simulations.

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