1 Introduction

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Mobile broadband demands are increasing rapidly, driven by the popularity of various connected mobile devices with data services, such as smartphones, tablets, vehicles, machines and sensors. The notion of connected devices actually expands to encompass basically everything that can take benefits from a wireless connection. A true mobile broadband experience of high quality everywhere can be expected by consumers in the near future.

Mobile applications have become an indispensable part of people's everyday life, with requirements on seamless access to social media, video contents and cloud-based contents anytime, anywhere. To provide services that meet these requirements is of top priority for operators with ambitions to be a key wireless communications provider in the networked society. These requirements can only be met by mobile networks with sufficient capacity and coverage. Mobile broadband today is mainly provided via networks based on *UMTS Terrestrial Radio Access* (UTRA) or *Evolved UTRA* (E-UTRA), and solutions differ in the details. Mobile networks need to evolve through improving the existing mobile broadband networks and adding more cells in an optimal way to migrate to a *heterogeneous cellular network* (HCN). The migration path could be different for different operators. A thorough understanding of the various components involved is vital for a cost-efficient, spectrum-efficient and energy-efficient network evolution.

This chapter provides an introduction to the whole book. First, the need for more capacity and mobile broadband forecasts are discussed in Section 1.1. Then, Section 1.2 reviews different network evolution solutions, Section 1.3 describes the HCN nodes, and Section 1.4 provides a brief discussion about related standardization work. Finally, Section 1.5 addresses technical challenges associated with HCNs. These challenges will then be addressed in more detail by reviewing the remaining chapters of the book.

1.1 Mobile data explosion and capacity needs

Mobile data demands increase at exponential rates. Market analyses [1, 2] agree that this trend will continue as mobile data is becoming a larger and larger part of people's daily lives. Based on measurements over several years using a large base of live networks that cover almost all regions of the world, the statistics provide strong evidence of a mobile data explosion.

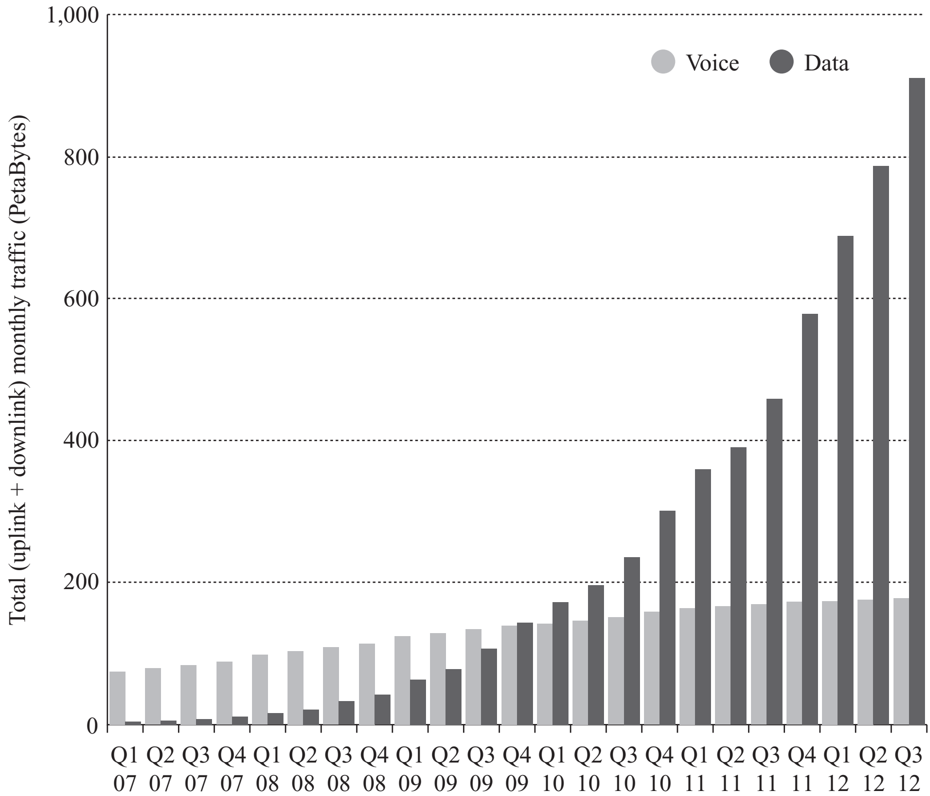

Figure 1.1 Global total traffic in mobile networks, 2007–2012.
Source: Ericsson (November 2012)

One key milestone was passed in the fourth quarter of 2009, when the volume of mobile data surpassed that of voice, as illustrated in Fig. 1.1. Not much later, in the first quarter of 2011, the volume of mobile data doubled that of voice.

The forecasts in Fig. 1.2 indicate that mobile data will continue to grow at exponential rates. Portable personal computers still dominate the traffic in mobile networks nowadays, but smartphones and tablets are increasing in popularity. The forecast for latter years even splits between mobile data via smartphones and via personal computers/tablets. It has been predicted [1] that mobile data will grow 12-fold between 2012 and 2018, corresponding to a compound annual growth rate of about 50%.

Moreover, users are increasingly aware of the connection speed, data rate, coverage and availability of their mobile broadband services. This has already led to disputes about whether the available capacity and coverage are sufficient to meet the increasing demands.

In order to meet or even exceed subscriber expectations, operators need to analyze the capacity and coverage challenges in their networks. Fig. 1.3 illustrates the capacity and coverage expansion needs that operators foresee to different extents. First, there is an overall need for enhanced capacity in the network, essentially across the entire service

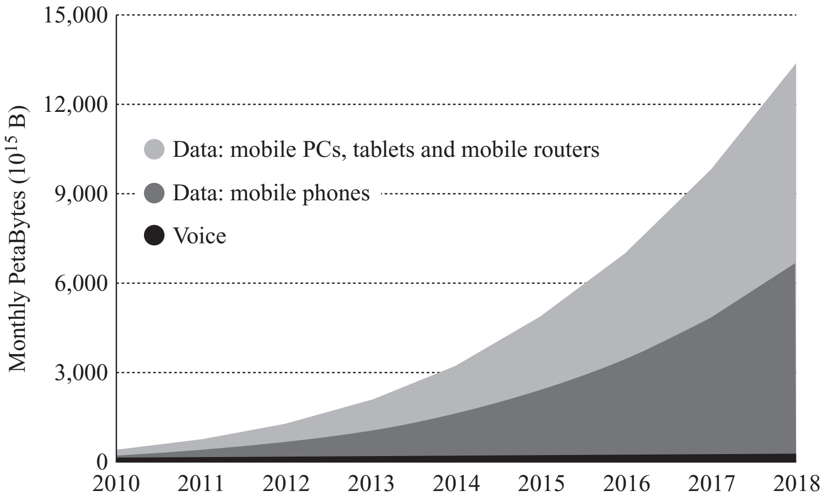

Figure 1.2 Global mobile traffic, voice and data, 2010–2018.
Source: Ericsson (November 2012)

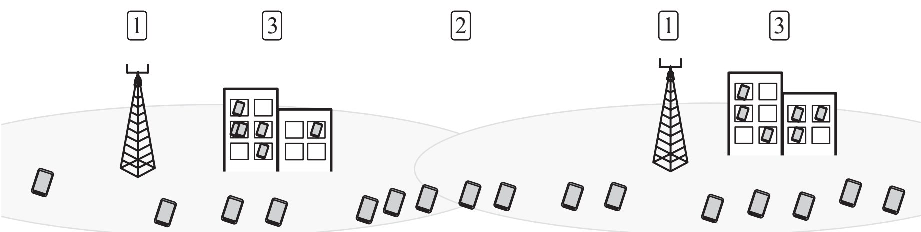

Figure 1.3 Different capacity and coverage challenges in mobile networks, characterized by (1) a need for an overall capacity increase, (2) a need for more favorable radio conditions far from current site installations and (3) adequate coverage and capacity indoors, where most of the mobile data is consumed.

area. Second, some of the capacity need comes far away from currently deployed site installations, resulting in poor user experiences over unfavorable radio links. Third, part of the capacity need comes from indoor environments with both coverage and capacity issues. For example, in most urban areas, most of the traffic is consumed indoors. There are different solution approaches to meet all these aspects, as will be discussed in the following section.

1.2 Capacity and coverage solutions

The challenges in terms of capacity and coverage illustrated by Fig. 1.3 can be addressed in different ways. In this section, we discuss some popular solutions.

1.2.1 Improving existing macrocell networks

To improve the existing macrocell network [3–5] is a cost-efficient way to address the overall capacity needs indicated by (1) in Fig. 1.3. Adding more spectrum to the existing sites together with interfrequency load sharing directly gives a capacity boost with limited efforts. Such interfrequency load sharing is facilitated by mobile terminals capable of supporting multiple carriers simultaneously, which is known as Multi-Carrier in UTRA and Carrier Aggregation in E-UTRA. Furthermore, cell sites can be upgraded with additional sectorization and improved radio link utilization, such as modulation and coding schemes corresponding to higher data rates. In fact, the capacity needs in one of the highest traffic density regions in the world have been met by improving the macrocell sites with additional spectrum [6].

Further improvement can be obtained via coordination between existing sites. Some signaling coordination is already available in the first releases of the radio technologies such as internode signaling in *Evolved UTRAN* (E-UTRAN) and *Radio Network Controller* (RNC) signaling in *UMTS Terrestrial Radio Access Network* (UTRAN). Additional benefits can be achieved through tighter coordination of data packet transmission and reception.

1.2.2 Network base station densification

The challenges indicated by (2) in Fig. 1.3 are difficult to address with improvements only to the existing cell sites, since the distances between *user equipments* (UEs) and cell sites cause the main problem. Accordingly, the alternative solution is to densify the network by installing new outdoor cell sites [3–5]. Large capacity gains in cellular networks are obtained through the shrinking of cell sizes and universal frequency reuse, and thereby the spatial frequency reuse is greatly improved by increasing the network node density.

The nature and properties of new site proposals depend on the radio propagation environment and installation limitations. The number of needed additional sites depends on the transmission power [7, 8], and is related to the deployment and maintenance costs. It is preferable to use node transmission power as high as possible to keep the number of needed sites small. Another important factor to consider is the spatial distribution of traffic. By identifying traffic hotspots and considering this information in the site selection process, the number of needed sites can be reduced [9].

When installing new cell sites, there are also advantages from intersite coordination. Some important coordination can be obtained via internode signaling in E-UTRAN and the RNC in UTRAN, and further gains can be achieved by introducing tighter coordination between sites.

1.2.3 Indoor capacity and coverage

Indoor areas are typically characterized by fairly good isolation from the macrocell network. *Low-power nodes* (LPNs) constitute a very attractive network expansion alternative to meet the indoor coverage and capacity needs [4, 5, 10], as indicated by (3) in Fig. 1.3, where the distances between the indoor LPNs and UEs are short and low transmission powers would be sufficient.

Indoor site installations should take benefit from considerations of the traffic density to keep the number of needed sites small [9]. Deployment considerations could be different if the LPNs are not intended to be used by all UEs but only a *closed subscriber group* (CSG) of UEs. There are also advantages from site coordination either between indoor nodes or between indoor and outdoor nodes. Such coordination can be obtained via internode signaling in E-UTRAN and the RNC in UTRAN, as well as via tighter coordination between nodes.

1.2.4 Heterogeneous cellular networks

Most likely, the optimal solution would be a combination of the approaches discussed above, and would also depend on specific network, propagation environment and traffic demand aspects. With the exponential traffic increase, uneven traffic distribution and limited spectrum availability, it will not be possible to address network evolution aspects only with *macrocell base stations* (MBSs) [11, 12]. More specifically, MBSs are inadequate to meeting the mobile data demands in certain scenarios, for example the following.

- Large outdoor areas with a high traffic density, for example urban commercial areas and town squares, where the network is already dense and the intercell interference could be high. Moreover, there can also be requirements of limited size to make the site equipment almost invisible.
- Large indoor areas with a high traffic density, such as enterprises, shopping malls, airports, subway stations and hotel lobbies, where it could be difficult to reach from an outdoor macrocell network.
- Small indoor areas and coverage holes, such as private apartments and houses, restaurants, small stores and offices, where the macrocell coverage is insufficient with respect to the mobile data demands. There may also be an interest to provide wireless access only to a CSG.

Hence, LPNs play an important role in the solution in combination with the existing macrocell network to meet future coverage and capacity needs. The most popular LPNs will be described in the next section.

1.3 Heterogeneous cellular network nodes

A *base station* or *node* is deployed at a geographical *site*, serving one or more *cell(s)*. When the discussion is specific for E-UTRAN a base station is referred to as an *evolved NodeB* (eNB), and for UTRAN a base station is denoted *NodeB* (NB).

HCN nodes are distinguished by their transmit power, coverage area, physical size, backhaul and radio propagation characteristics. MBSs will be operator-deployed with fairly large coverage areas, having transmit power levels per served macrocell that typically vary between 5 W and 40 W, plus large antenna gains. The transmit power of an LPN ranges from 250 mW to approximately 5 W if it is deployed outdoors and falls below 100 mW for indoor deployment [4, 5, 10, 12]. As will be discussed in the following subsections, LPNs include *remote radio heads* (RRHs), micro and pico base stations, femtocell access points and *relay nodes* (RNs).

1.3.1 Remote radio heads

RRHs are radio equipment typically connected to the MBS via a fiber optic cable. This enables a tight coordination between RRHs and the MBS, analogous to the coordination between cells served by the same *base station* (BS). RRHs can also be seen as a *distributed antenna system* (DAS) [13], even though the term more commonly refers to analog signal distribution over distributed antennas. Modern RRHs have the analog to digital converter in the RRH, which means that the interface to the RRH is digital, and that base band processing can be centralized. The transmission power levels depend on the deployment scenario, and can thus be in the range from macro- to picocells.

1.3.2 Micro base stations

Micro base stations or nodes, serving microcells, are regular BSs that provide standardized interfaces over the backhaul, but with lower transmit power than traditional macrocells. The transmit power of a microcell is typically of the order of 5–10 W for outdoor deployment. Micro base stations are deployed outdoors in an operator-planned fashion, particularly popular for providing outdoor hotspot coverage. They can be equipped with omnidirectional antennas, but may have antenna directivity as well, for example radiating outwards from a house wall deployment. Micro base stations can be coordinated with the macro network via the X2 interface in E-UTRAN and the RNCs in UTRAN, where tighter intersite coordination is possible.

1.3.3 Pico base stations

Pico base stations or nodes, serving picocells, are similar to micro nodes, but with even lower transmit power per picocell served, and possibly also of smaller size. This ranges from 250 mW to approximately 2 W for outdoor deployment, while it is typically 100 mW or less for indoor deployment. Pico base stations are deployed indoors or outdoors, often in an operator-planned fashion, particularly popular for providing hotspot coverage. They can be equipped with omnidirectional antennas or with some antenna directivity. Pico nodes can be coordinated with the macro network via the X2 interface in E-UTRAN and the RNCs in UTRAN, and tighter intersite coordination is also possible.

1.3.4 Femtocell access points

Femtocell access points (FAPs), base stations or nodes, serving femtocells, are small low-power BSs that are generally consumer deployed with a network backhaul facilitated by the consumer's own wired broadband connection [11]. They are typically provided by wireless operators as a managed service. Originally envisioned as a means to improve voice coverage in indoor environments, femtocells can also be viewed as one way to offload data traffic from macrocells. FAPs are typically equipped with omnidirectional antennas, and their transmit power is 100 mW or less. There are dedicated procedures for FAPs; in LTE, an FAP is denoted a *Home evolved NodeB* (HeNB), and in *Universal Mobile Telecommunication System* (UMTS) it is named a *Home NodeB* (HNB). The HeNBs or HNBs can be coordinated and controlled by a *Home NodeB/evolved NodeB Gateway* (HGW), which also can be used to interface the macro and core networks.

1.3.5 Relay nodes

In scenarios where a wired backhaul is not available, RNs can be deployed with the air interface used for both backhaul connection and access to UEs [14]. RNs can be deployed either indoors or outdoors. Their transmit power ranges from 250 mW to approximately 2 W for outdoor deployments, and is typically 100 mW or less for indoor deployments [12]. An RN can be considered as a full-fledged BS but without a wired backhaul. An RN appears as a UE to its *donor eNB* (DeNB) and as a regular BS to the UEs that it serves. The link between the RN and the DeNB is denoted the backhaul link, the RN to UE link is denoted the access link and the MBS to UE link (without relay participation) is denoted the direct link. RNs are typically equipped with directional antennas in the backhaul link (pointing to the DeNB) and may have omnidirectional or directional antennas in the access link. If the backhaul link uses the same frequency band as the access link, then the relay is an in-band relay; otherwise, the relay is an out-of-band relay.

1.4 3GPP LTE-Advanced heterogeneous cellular networks

The first release of *Long Term Evolution* (LTE), i.e., *3rd Generation Partnership Project* (3GPP) Release 8 [15], was published in December 2009. Subsequently, LTE evolved into LTE-Advanced (LTE-A), i.e., 3GPP Release 10 [16] and onwards, which are developed to meet the *International Mobile Telecommunications* (IMT)-Advanced requirements of the *International Telecommunication Union* (ITU). LTE-Advanced introduces carrier aggregation of up to five 20 MHz component carriers to provide a peak data rate of more than 1 Gb/s. Moreover, it features additional support for using multiple antennas in both the receiver and transmitter, enabling spatial multiplexing of data streams.

The physical layer is based on *Orthogonal Frequency Division Multiple Access* (OFDMA), which enables orthogonal intra-cell waveforms. However, interference from other cells can limit the performance. Therefore, LTE-Advanced features enhanced interference management and suppression techniques, in particular to address HCN interference scenarios. The *Self-Organizing Network* (SON) has also been part of LTE from the first release to facilitate deployment, installation, operation and maintenance – something that is important when the number of BSs increases. Throughout the releases, there has been increasing support for home eNBs, for example via dedicated mobility procedures and a specific architecture, as well as mechanisms to enable restricted access to CSGs. Later releases also have featured different interference management components, from intersite signaling mechanisms to interference suppression recievers, as well as mobility robustness support.

The book aims at a general treatment of HCN, but with an ambition to refer to related concepts in 3GPP. Concepts in 3GPP Release 11 and earlier releases are considered.

1.5 Heterogeneous cellular network challenges

HCNs have the potential to provide benefits over homogeneous network deployments [17]. These include the ability to place nodes close to the end users, enabling a dense node deployment, which in turn can provide unprecedented mobile network capacity to homes, enterprises and urban hotspots, where most mobile traffic is generated.

The deployment of LPNs also poses technical challenges, as will be discussed in this section. Most of the challenges are then addressed in the rest of this book, with the exception of backhaul, which is beyond the scope of the book. Another challenge not addressed in the book is interworking with *Wireless Fidelity* (WiFi), which is an important component in a mobile broadband offer.

1.5.1 Optimal network evolution path

As discussed before, the best network evolution path is individual to each network with its specific characteristics and traffic needs. It also depends on the cost structure for the investment in terms of *capital expenditure* (CAPEX), and the deployment, operation and maintenance costs in terms of *operational expenditure* (OPEX). The time needed for different kinds of site acquisition and planning activity is also a critical factor. Since the number of needed LPNs increases significantly with decreasing transmission power [9, 11], the total cost of ownership needs to match this. Clearly, this is not only about CAPEX, since a more expensive smart node would be more prepared to meet the other challenges discussed in this section, and can lead to lower OPEX. Overall, it is about evolving the network in a cost-efficient way.

One way to reach a better understanding of different deployment options is via simulations of HCN scenarios. Chapter 2 describes radio propagation models from empirical models with low computational complexity and reduced accuracy to fully deterministic models with high accuracy at the expense of large computational efforts. Semi-deterministic models act as a tradeoff between the two, and hybrid models combine two or more models. The ambition is to model indoor and urban radio propagation within an acceptable complexity. In addition to propagation models, antenna models, land-use models and detailed channel models are also central, especially for assessing *multiple-input multiple-output* (MIMO) components properly.

Chapter 3 describes static and dynamic system-level simulations, including the building blocks, link models, antenna models, shadowing and multi-path fading, with a focus on the models defined by ITU and 3GPP. Different 3GPP HCN deployment scenarios are described, together with a node placement discussion. Moreover, traffic models and mobility models are described as well. All models and scenarios are described with tabulated model parameters.

The propagation model can be tuned to match the characteristics of a particular network. The tuning can be based on radio signal strength and quality measurements provided by UEs as to be discussed in Section 6.6. These measurements may be geolocalized either based on location information provided by the UEs, or by network-based localization. With a geolocalized view of the network, it is possible to better analyze a particular network, and to propose suitable candidate sites for network evolution with LPNs.

1.5.2 Access control

Some deployments of LPNs are motivated by the need for restricted access to services. Such LPNs are not primarily for all subscribers but for the corresponding CSGs, such as enterprise employees or members of a household. Depending on whether an LPN allows access to all UEs or to a set of pre-registered UEs only, it can be classified into open access and closed access, respectively. With closed access, users on the CSG white list of the LPNs have exclusive rights to the LPN resources. Fewer resource allocation retrictions with open access enables a freedom that can be exploited to increase network capacity. An alternative is hybrid access, where all UEs can access the LPN but with a higher priority given to the UEs belonging to the CSG, while any other UEs are allowed with only a limited service grade.

Such access control mechanisms are supported by the 3GPP and are described in Chapter 4 together with details about the UMTS and LTE architectures. Both the core network and radio access network components are covered, including support for femtocells. The three different access modes (i.e., open, closed and hybrid access) are defined together with the CSG white list concept. The chapter reviews the different CSG components per 3GPP LTE release and describes the differences when it comes to UMTS.

1.5.3 Mobility and handover

Mobility is a challenge in the HCN, where the main difference from homogeneous networks is that the link connection to an LPN degrades quickly when moving out of the LPN coverage. Furthermore, very limited LPN coverage area may lead to short stays and frequent handovers by highly mobile users, which may increase both signaling and risk of handover failures. Efficient mobility is also a challenge with CSG LPNs in the HCN, since it is desirable to prevent unauthorized UEs from reporting CSG cells as handover candidates to avoid unnecessary signaling.

Chapter 9 describes the mobility and handover procedures in 3GPP LTE connected mode as well as in idle mode. The UE measurement report mechanisms are detailed, including the different configuration and report triggering options. Moreover, cooperation between LPNs is mandatory for any form of mobility management.

1.5.4 Self-organizing networks

As the number of LPNs is expected to be orders of magnitude greater than that of MBS, the costs associated with planning, deploying, configuring, optimizing and managing the LPNs become a critical issue. Manual deployment and maintenance associated with the LPNs should be reduced to a minimum. Especially for FAPs, which are likely installed by customers or private enterprises without traditional *radio frequency* (RF) planning, site selection or maintenance by the operator, plug-and-play operation becomes essential. Therefore, there are strong requirements on smart nodes, which self-organize in the network and simplify the network operations and maintenance.

Chapter 6 describes the network management architecture and the area of SONs, with a focus on the SON requirements and mechanisms in E-UTRAN, but also with respect to UTRAN and the use cases defined by *Next Generation Mobile Networkss* (NGMNs). SON functionalities can be divided into self-configuration, self-optimization and self-healing. Self-configuration concerns tasks that are carried out to introduce new or re-plan existing site installations, and automates installation and configuration procedures. While in operation, self-optimization tunes parameters that dictate algorithmic behaviors based on empirical network observations. Self-healing concerns tasks that are carried out to detect, and if possible compensate for, failures and disruptive events (e.g., malfunctioning equipment). Most SON aspects are equally applicable to macrocell networks. However, mobility and load sharing imply some aspects specific to HCNs. Moreover, there are needs for dedicated mechanisms to ensure mobility robustness and the sufficient utilization of LPNs through efficient load sharing. SON also includes aspects concerning spectrum and interference management. Specific SON aspects for femtocells are also discussed in Section 8.4.

As stated before, mobility is a critical issue in HCNs. Section 9.4 will address the tuning of mobility procedures for improving mobility robustness, and discuss the impact of interference management mechanisms.

1.5.5 Intercell interference

When densifying the radio networks they may become increasingly limited by interference. Orthogonal waveform multiplexing such as via OFDMA avoids intracell interference, which means that the primary source of interference would be intercell interference. The massive deployment of LPNs overlaying macrocells will create a large number of new cell boundaries, where UEs may suffer from strong intercell interference if LPNs and MBSs use the same operational carriers. In addition to the large number of newly