1

An Introduction to Heterogeneous Networks

1.1 Introduction

We have witnessed the wireless telecommunications revolution in the last decade, and it is still very much alive. Wireless technologies have enabled new services that have empowered human beings and transformed social interactions. From the days when advance booking was necessary to make a long-distance voice call, we have come to an era when we can film a high-definition video, upload it to Facebook via a wireless network, and receive almost instant feedback from our friends all over the globe. The services we use today consume more bandwidth than before and we want them to be fast, reliable, and affordable.

Various market surveys all concur about the rapid proliferation in mobile broadband data. The Strategy Analytics [1] estimates that mobile data traffic grew by 100% in 2012. As shown in Figure 1.1, the data traffic is expected to increase by about 400% by 2017. The major contributors to the traffic are bandwidth-intensive real-time applications such as mobile gaming and video. In 2013, the number of mobile-connected devices exceeded the world population and by 2017 there will be about 1.4 mobile devices per capita [2].

Are mobile operators prepared to meet this enormous surge in demand, however? It is quite a formidable challenge. It has been shown that network capability using traditional macrocell-based deployments is growing at about 30% less than the demand for data [3]. The profit margins of most operators have also been decreasing globally [4]; there are two main reasons for this. The first is that the flat rate pricing policies that customers have become accustomed to prevent the mobile data revenues of an operator to scale proportionately with the increased usage of mobile broadband data. The second is the cost (capital expenditure or CAPEX versus operating expenses or OPEX) incurred as a result of setting up more base stations to provide increased capacity and coverage, connecting them via backhaul and their operation and maintenance.

To cater for the increasing data traffic and also enhance profits, the operators therefore need to fundamentally rethink methods of operating their networks. The key principle is to deliver higher capacity at a reduced cost.
As mentioned by Mallinson [5], a 1000× increase in capacity is required to support the rising demand. High capacity can be achieved by improving spectral efficiency, employing more spectrum, and by increasing network density. The first two are related to link level enhancements where radical gains cannot be expected over current networks that are already functioning at near optimal. Instead, as Figure 1.2 from [5] shows, the major gains are expected through increasing network density by deploying an overlay network of small cells over the macro coverage area. A small cell could be an indoor femtocell or an outdoor picocell. It could be a
compact base station or a distributed antenna system (DAS) controlled by a central controller. The different types of small cells have low transmit power and coverage and together with the macro are referred to as Heterogeneous Networks or simply HetNets.

The reason why heterogeneous networks improve capacity is intuitive. Mobile broadband data is highly localized as the majority of current traffic is generated indoors and in hotspots such as malls and convention centers. It therefore makes sense to add capacity where it is needed by deploying an overlay of small cells in those regions of the macro coverage area which generates heavy data demand. Small cells offload data from the macro coverage area and improve frequency reuse. Additionally, they can also offer higher capacity than the macro as they can better adapt to the spatio-temporal variations in traffic by dynamic interference management techniques.

Besides improving network capacity, small cells also address the second concern of operators: cost reduction. A small cell-based heterogeneous network is much more energy efficient than a macrocell network. The power amplifier in a macrocell consumes the most energy and requires a fixed DC power supply even if there are no data being transmitted. The high transmit power requires a cooling unit which also consumes energy. The low transmit power of the small cell reduces the impact of both. It can be shown that deployment of picocells reduces overall energy consumption by 25–30%, compared to macrocell-only baseline [6]. Due to rising energy costs (electricity bills could be as high as 17% of an operator’s OPEX), there is a substantial reduction in the operator’s expenditure. Reducing energy consumption, a greener alternative, also helps to drive down the total carbon footprint of the operator. According to a Bell Labs study, incorporating small cells into the network can save service providers 12–53% in CAPEX and 5–10% in OPEX, depending on traffic loading.

Small cell-based heterogeneous networks are therefore being increasingly adopted by wireless operators globally. In February 2013, Informa Telecoms & Media announced at the Mobile World Congress (MWC) that, for the first time, femtocells make up the majority (56%) of all base stations deployed globally. This trend is set to continue with an 8x increase expected in the total number of deployed small cells by 2016. Clearly, small cells and heterogeneous networks play a critical role in the global mobile infrastructure.

1.2 Heterogeneous Network Deployments

As mentioned in the previous section, there are many different kinds of small cells which result in different kinds of heterogeneous networks. Each heterogeneous network has unique deployment, coverage, and capacity characteristics. The needs of the operator and their customers determine what type of heterogeneous network is optimum for a given situation. A broad classification of the different types of heterogeneous networks is provided in the following sections [7].

1.2.1 Distributed Antenna Systems

A Distributed Antenna System (DAS) consists of a network of nodes that are connected via fiber to a central processing unit. These nodes, also called DAS nodes, contain antennae/remote radio heads (RRH) that perform all the radio functionalities. The central processing unit contains the baseband transceiver module. DAS systems are usually technology agnostic,
which means that the same DAS network can support multiple frequency bands and multiple technologies such as high-speed packet access (HSPA) and long-term evolution (LTE). DAS network installations usually require significant upfront capital investment and careful planned deployment by the DAS vendor. They can be deployed both outdoors and indoors and often cover large areas such as sports stadiums and convention centers.

Each DAS node is capable of supporting up to 16 frequency bands and up to 300 simultaneous connections for an area of 5000–25 000 square feet when driven by a macrocell. LTE and Worldwide Interoperability for Microwave Access (WiMAX) operators utilize an optical driver-to-fiber-to-RF (radio frequency) DAS configuration, where the optical transceiver at the central processing unit transmits the baseband signal along the fiber to remote sites where the signal is converted to RF for the first time. Other DAS solutions can be configured as RF-to-optical-to-RF systems, where the central processor converts RF signals generated by the radio transceiver of the wireless service provider to optical signals that are transported to the DAS nodes where the optical signal is converted back to RF.

The planned nature of DAS deployments leads to higher flexibility and customization according to the needs of the customer. However, it lacks the simple plug-and-play architecture that makes other small cell deployments, such as femtocells, attractive.

### 1.2.2 Public Access Picocells/Metrocells

As the name suggests, these small cells are deployed by operators to target specific public access areas such as railway stations and aircraft. They are open to all members of the public, although there could be a preferential grade of service for first responders such as police and public safety personnel.

The term metrocell is sometimes used to denote small cells (usually picocells) installed in a high-traffic urban area. They have less transmit power and coverage than the macrocell. Pico/metrocells are planned installations in the same way as DAS systems. Unlike DAS however, they cover a smaller area and are specific to a particular wireless access technology such as LTE or HSPA. Each picocell is capable of supporting only a few frequency bands and up to 80 simultaneous connections for an area of about 10 000–20 000 square feet. To increase coverage over a large area, an operator may install multiple picocells; they are not typically interconnected like DAS, however.

Public-access pico/metrocells have more features and are typically priced higher than consumer-grade femtocells (discussed in the following section). They will also be produced in lower numbers than femtocells. According to ABI research, the reason for this is that public-access metrocells are deployed for rugged outdoor use and need advanced features to handle simultaneous subscribers at higher RF power levels than a femtocell.

### 1.2.3 Consumer-Grade Femtocells

Femtocells are small stand-alone low-power nodes that are typically installed indoors. Unlike picocells, femtocell services are available only to paid subscribers who are said to form a Closed Subscriber Group (CSG). They support simple plug-and-play architecture and do not require professional installation by operators. The femtocells connect to the operator’s network through the subscriber’s internet service.
Like picocells, femtocells also support a single wireless access technology. The coverage and number of supported users in a femtocell vary depending on the nature of their installation. Femtocells could be residential, also known as Small Office/Home Office (SOHO) or enterprise. Some typical values are listed in Table 1.1. It can be seen that, although enterprise femtocells have a smaller share of the market, they yield more revenue per unit than residential femtocells. Further, enterprise femtocells can be categorized into Small and Medium Businesses/Enterprises (SMB or SME), Medium to Large (MLE) or large enterprises.

### 1.2.4 WiFi Systems

Unlike other types of small cells, WiFi systems operate in the unlicensed band. Devices such as personal computers and smartphones can use WiFi to connect to the internet when in a residential environment. WiFi systems are inexpensive to use and install. WiFi usage is widespread in many countries and often used by businesses such as coffee shops and airports to offer free wireless access to their customers. WiFi can also integrate with an existing cellular network by offloading some of its load. The number of operators and vendors utilizing this option is steadily growing.

WiFi is based on the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards. Unlike cellular standards, the basic version of 802.11 is based on carrier sense multiple access (CSMA) technology. Latest releases of 802.11 have incorporated many quality of access (QoS) features not present in the basic CSMA version. WiFi has a range of 20–200 ft.

### 1.3 Features of Heterogeneous Networks

Heterogeneous networks have several features that set them apart from macro-only networks, some of which have already been alluded to in previous sections. This section presents a broad overview of some of the important features.

#### 1.3.1 Association and Load Balancing

One of the main functions of small cells is to offload user equipment (UE) traffic from the macro. The amount of offloading depends on the criterion by which a UE associates with a base station. Downlink reference signal received power (RSRP) is the most basic criterion but this does not lead to much offloading since the transmit power of a macrocell is much greater than that of the small cell. Adding a bias to the small cell RSRP is an example of an association method that increases offloading.
The macrocell and the picocell can operate at different carrier frequencies. This is especially true for future heterogeneous networks, where small cells will be deployed in newly available spectrum in higher-frequency bands. RSRP does not capture the information about the difference in the levels of interference in the macrocell and small cell carrier frequencies. The interference information is captured in a reference signal received quality (RSRQ) based association and hence leads to better load balancing.

Association is also tied to the network load. For highly loaded systems, load balancing will distribute the UE load across all base stations uniformly. This will homogenize the intercell interference and lead to a fair distribution of a base station’s resources among all its associated UEs. For networks with low load, it may however be better to concentrate the load on a few base stations as this will reduce intercell interference from the base stations with little or no associated UEs. This principle is opposite to load balancing and is sometimes called *load shifting*.

Association can also be based on UE application or speed. For example, associating a voice user or a UE with high velocity to the macrocell will lead to better performance.

### 1.3.2 Interference Management

The dense deployment of small cells increases interference; unless interference mitigation techniques are applied, the gains of heterogeneous networks will not be realized. For example, when a CSG femtocell is deployed, it may interfere with the UEs that are close but cannot associate with it as they are not part of its subscriber group. Another example could be a UE that is originally connected to a macrocell but is later handed over to a picocell with a cell range expansion (CRE) bias for the purpose of load balancing. In this case, the UE will experience an interference level that is higher than the desired signal. The system performance will degrade if the intercell interference is not managed properly.

In order to coordinate the intercell interference, various techniques have been proposed and adopted in LTE Releases 8–12. Frequency-domain techniques were proposed in Release 8, where two neighboring cells can coordinate their data transmission and interference in frequency domain. Time-domain techniques and their enhancements were proposed in Releases 10 and 11, where a cell can mute some subframes to reduce its interference to its neighboring cell. In Release 12, a small cell can perform dynamic activation/deactivation based on its traffic load and interference situation. Implementation of full-dimension (FD) multiple-input-multiple-output (MIMO), where a base station can direct a narrow and focused beam directed towards the three-dimensional location of the UE, is a new area for interference management in dense heterogeneous networks. Interference can also be mitigated by coordinated multipoint transmission/reception (CoMP) technology where a macrocell and a small cell can cooperate to simultaneously serve a UE.

### 1.3.3 Self-Organizing Networks

Self-organizing networks (SON) are an important class of base station functionalities through which the various base stations in the network (notably the small cells) can sense their environment, coordinate with other base stations and automatically configure their parameters such as cell ID, automatic power control gains, and so on. Previously these properties formed part of the network configuration tools and processes which were configured by
the operators manually. The manual methods work for a small number of homogeneous macrocell deployments but do not scale in a dense small-cell-based heterogeneous network. SONs are therefore critical to small cell deployments.

A SON optimizes network parameters for controlling interference which has a major impact on performance. It also manages the traffic load among different cells and different radio access networks and provides the user with the best possible service while maintaining an acceptable level of overall network performance. SONs reduce OPEX and thus save money for operators.

1.3.4 Mobility Management

In a cellular network, handover is performed between cells to ensure that a mobile UE is always connected to the best serving cell. The general handover process is as follows. A UE measures the signal strength of its neighboring cells. If the signal strength of a neighboring cell is higher than that of its serving cell plus an offset for a particular time period called the time to trigger (TTT), the UE will report this information to its serving cell. The serving cell then initiates the handover process.

In a homogeneous network, the handover parameters such as the handover offset and TTT are common for all cells and all UEs. However, using the same set of handover parameters for all cells/UEs may degrade the mobility performance in a heterogeneous network. It is desirable to have a cell-specific handover offset for different classes of small cells. Furthermore, for high-mobility UEs passing through a dense heterogeneous network, the normal handover process between small cells will lead to very frequent changes in the serving cell. This can be solved by associating this UE to the macrocell at all times, leading to UE-specific handover parameter optimization. Both cell-specific and UE-specific handover functionalities therefore need to be considered for heterogeneous networks.

1.4 Evolution of Cellular Technology and Standards

Performance optimization in dense small-cell heterogeneous networks is one of the most important topics in LTE. LTE-compliant small cells will see the maximum growth when compared to small cells belonging to other radio access technologies. This provided the inspiration for this book.

An evolution of various cellular standards over the years to LTE-Advanced is shown in Figure 1.3. The first generation of cellular systems, not shown in the figure, were analog systems. Second-generation cellular networks were hybrid Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) systems. Third-generation systems had Code Division Multiple Access (CDMA) as their primary radio access technology. The fourth generation of cellular networks underwent a major revolution with the introduction of Orthogonal Frequency Division Multiple Access (OFDMA) as the radio access technology and a flat, all-IP (internet protocol) core network design [8]. The first Third-Generation Partnership Project (3GPP) release with this technology was called Release 8, popularly known as LTE. Each successive release has seen gradual evolution, although there have been major leaps in technology such as the introduction of coordination among different base stations of a HetNet in LTE Release 11. A summary of some of the requirements for different 3GPP releases is provided in Table 1.2.
These requirements are influenced by the guidelines of the International Telecommunications Union (ITU) which is the apex worldwide regulatory body in telecommunications. The ITU allocates spectra on a worldwide basis and decides the technologies for which the spectra are to be used. The high-level requirements that these technologies should meet are also stipulated by ITU. The family of technologies that meet ITU’s International Mobile Telecommunication (IMT) requirements are popularly known as 3G technologies. Similarly, LTE is an example of a technology that meets (in fact exceeds) the requirements of ITU’s IMT-Advanced
class of technologies (popularly known as 4G). WiMAX and 3GPP2 are other examples of technologies that meet the IMT-Advanced requirements.

As the capabilities being offered by the network changes, changes are also needed in the specifications of the user equipment (UE). Accordingly, 3GPP has introduced the notion of UE categories as listed in Table 1.3. A higher-category UE can receive and transmit data at a higher rate. It can avail the advanced features of a LTE release which a lower category UE may not be able to. For example, the categories 6–8 were added in LTE Release 10 to address the bandwidth increase due to Carrier Aggregation. UE categories thus lead to service and price differentiation.

### 1.4.1 3GPP Standardization Process

A major change from initial generations of cellular systems to latter releases is increased collaboration among various companies leading to the process of standardization. At present, 3GPP has close to 400 member companies from all over the world from network operators, base station, UE vendors, and chipset manufacturers to industrial and academic laboratories. During the standardization process, technical proposals are debated and discussed from different angles. A consensus-driven process decides which portions should be included in the next release of the standard. A large and complex system such as LTE has multiple functional components – from digital signal processing to core network optimization – and it is not possible for everything to be discussed in one group. Accordingly, 3GPP has a well-structured organization. As shown in Figure 1.4, 3GPP comprises four major working groups each in charge of a specific area. Each working group is further divided into subgroups for more specialized focus.

An understanding of standardization provides an insight into the features and timeline of future cellular systems. In the following chapters, the development of heterogeneous networks within the LTE-Advanced standardization framework will be presented in detail. The focus of this book will be on RAN working group 1 which pioneers the physical layer signal processing and related standardization aspects. Wherever applicable, issues related to the other Radio Access Network (RAN) working groups will also be presented.
Figure 1.4 3GPP organizational chart showing various working groups

References


