RADIO RESOURCE MANAGEMENT IN MULTI-TIER CELLULAR WIRELESS NETWORKS
Wiley Series on
Adaptive and Cognitive Dynamic Systems

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The phenomenal increase in mobile data traffic and the high data rate and improved quality-of-service (QoS) user requirements has created a huge demand for network capacity in the cellular wireless networks. Multi-tier cellular wireless networks, consisting of macrocells overlaid with “small cells,” will provide a fast, flexible, cost-efficient solution to satisfy this capacity demand.

“Small cell” is an umbrella term for low-power radio access nodes that operate in both licensed and unlicensed spectra and have a range of ten to several hundred meters. These contrast with a typical mobile macrocell, which might have a range of up to several kilometers or even higher. The term “small cell” encompasses femtocells, picocells, microcells, and metrocells. The multi-tier cellular wireless networks, including macrocells and small cells of all types (which are also referred to as heterogeneous networks (HetNets) or small cell networks (SCNs)), are expected to provide improved spectrum efficiency (bps/Hz/km²), capacity, and coverage in future wireless networks.

Small cells can support wireless applications for homes and enterprises as well as metropolitan and rural public spaces. Small cell technology is applicable to the entire range of licensed spectrum mobile technologies, such as those standardized by the 3GPP, the 3GPP2, and the WiMAX forum. When compared with unlicensed small cells (e.g., Wi-Fi), small cells operating in the licensed band (i.e., licensed small cells) provide support for legacy handsets, operator managed QoS, seamless continuity with the macro networks through better support for mobility/handoff, and improved security.

Deployment of small cells poses many challenges, among which the radio resource management (i.e., interference management, admission control, load balancing) is the most significant. The aim of this book is to provide an in-depth overview of the radio resource management problem in multi-tier networks considering both code-division multiple access (CDMA)-based (e.g., 3G) and orthogonal frequency-division multiple access (OFDMA)-based (e.g., LTE, WiMAX) small cells, and the state-of-the-art research on this problem.

The book consists of ten chapters. In Chapter 1, after a brief overview of the multi-tier cellular networks, LTE-Advanced networks, LTE, and 3G small cells (femtocells, in particular), we outline the major challenges in the successful deployment of small cells in next generation cellular wireless systems. In particular, the challenges related to resource allocation, co-tier and cross-tier interference management and admission control, mobility and handoff management, auto-configuration, timing and synchronization, and security are discussed.

In Chapter 2, after discussing the design issues for resource allocation in multi-tier networks, we provide a comprehensive overview of state-of-the-art techniques
for resource allocation and interference management in small cell networks. In particular, several concepts for resource allocation and interference management in two-tier macrocell-femtocell networks, including the femto-aware spectrum arrangement approach, the graph-based clustering approach, the adaptive power control approach, the transmit beamforming approach, the collaborative frequency scheduling approach, the cognitive radio-based approach, the game theoretic approach, and the fractional frequency reuse (FFR)-based approach are discussed. Several important research directions are also outlined.

Since the adoption of OFDMA as the radio transmission technology for LTE/LTE-Advanced networks, radio resource allocation in the OFDMA-based cellular networks has become a significant research topic. In Chapter 3, we provide a review of the resource allocation methods for OFDMA-based single-tier cellular wireless networks. Then, a resource allocation framework for uplink transmission in a two-tier OFDMA-based macrocell–femtocell network is discussed which provides max–min fairness to the femtocell users and robust SINR (signal-to-interference-plus noise ratio) protection to macrocell users. The complexity of solving the problem for optimal solution is discussed. Subsequently, a suboptimal and distributed solution is proposed. To this end, several open issues related to adaptive radio resource allocation in OFDMA-based multi-tier networks are discussed.

Cooperation of small cells through clustering (or grouping) is an effective technique to mitigate both the cross-tier and co-tier interferences in OFDMA-based two-tier networks, especially in dense deployment scenarios. When the small cells in a cluster cooperate, the co-tier interference among these small cells in the same cluster is completely eliminated. In Chapter 4, we study the problem of radio resource allocation (i.e., subchannel and power allocation) in clustered femtocells in a two-tier macrocell–femtocell network. The problem of joint subchannel and power allocation in a clustered femtocell network is formulated as an optimization problem (more specifically, as a mixed-integer non-linear program) under constraints on both cross-tier and co-tier interferences, as well as constraints on data rates. To solve the problem suboptimally, different approaches are proposed, which offer close to optimal performances, but incur much lower computational complexity. The effects of different cluster configurations (in terms of cluster size) are evaluated.

In Chapter 5, we address the FFR-based interference management method in OFDMA-based two-tier networks. The concept of FFR is to partition a macrocell service area into regions and assign different frequency sub-bands to each region. When operating on a large timescale, this is referred to as a static FFR scheme. A static FFR scheme for interference management through spatial channel allocation requires minimal cooperation among the base stations and has a simple operational mechanism. We discuss four FFR schemes for OFDMA-based two-tier macrocell–femtocell networks and compare their performances in terms of outage probability of users, average network sum-rate, and spectral efficiency.

An important network functionality, closely related to radio resource allocation, is the call admission control (CAC), which is responsible for admission or rejection of an incoming call request from a user. The decision of admission or rejection is made based on the current network load and the QoS requirements of the existing users and the potential incoming user. An efficient CAC scheme will be required
for multi-tier networks to achieve high spectrum utilization while satisfying the QoS requirements of the users in all network tiers. In Chapter 6, we present a CAC method for a two-tier macrocell–femtocell network, which uses a sector-based FFR for spatial channel allocation for macrocells and femtocells. For this sector-based FFR, the system parameters (i.e., spatial channel allocation parameters) are optimized to maximize the total network throughput, subject to a minimum rate requirement for every user. The CAC method can be executed in a decentralized manner at each macro base station (i.e., MeNB) or femto access point (i.e., HeNB) and the CAC policy determines whether to admit or reject the arriving calls in the MeNB and HeNBs. All types of calls in the network (e.g., new calls to MeNB, new calls to HeNB, inter-sector macro–macro handoff calls, inter-sector femto–femto handoff calls, intra-sector macro–macro handoff calls, intra-sector femto–femto handoff calls, inter-sector macro–femto and femto–macro handoff calls) are considered, as is the random mobility of the users. The CAC problem is formulated as a semi-Markov decision process (SMDP), and a value iteration algorithm is used to obtain the admission control policy.

Game theory, which provides a rich set of mathematical tools to analyze interactions among independent rational entities, can be used to model and analyze radio resource management problems in multi-tier cellular networks. In Chapter 7, we discuss the applications of game theory for radio resource management in two-tier macrocell–femtocell networks. A basic introduction to the different game models is provided, and subsequently, several examples of game formulations for resource/interference management (subchannel and power allocation), spectrum sharing, and pricing in two-tier cellular networks are discussed. Several potential research directions are outlined.

In Chapter 8, we focus on the radio resource allocation problem in CDMA-based multi-tier networks. We provide a review of the existing literature on resource allocation and QoS support in single-tier CDMA networks. Then we demonstrate how game theory and optimization theory can be used to develop distributed resource allocation algorithms for CDMA-based multi-tier cellular networks, considering the tradeoff between efficiency and signaling complexity. We present example resource allocation algorithms for such networks, which provide robust QoS protection for macro users and converge to desirable operating points. Several open issues are outlined.

To reduce the capital expenditure (CAPEX) and operation expenditure (OPEX) of the deployment of small cells in multi-tier cellular networks, the small cells are required to have self-organizing network (SON) functionalities. Self-organizing small cells are expected to have self-configuration, self-optimization, and self-healing properties. While the self-configuration functionality is related to the preoperational stage of the network (e.g., installation and initialization), the self-optimization and self-healing functionalities are required at the operational stage. Different techniques can be adopted (e.g., from control theory, game theory) to implement the SON functionalities in small cells. In Chapter 9, we focus on self-organizing SCNs. We discuss the motivations behind self-organization and the use cases of self-organizing SCNs. We also classify these networks based on the timescale of self-organization and the deployment phase. We review selected works in the literature on self-configuration,
self-optimization, and self-healing of two-tier macrocell–femtocell networks. Also, we outline several open research challenges.

The concept of cognitive radio for dynamic spectrum access in wireless networks can be exploited in designing self-organizing SCNs. For example, cognitive small cell base stations (SBSs) should be able to monitor the radio environment (i.e., spectrum usage) and opportunistically access the radio spectrum so that major interference sources can be avoided. In Chapter 10, we focus on cognitive small cells. We discuss the approaches for traffic offloading to small cells, which affects the resource allocation performance in the network. Then we discuss two spectrum access techniques for the cognitive small cells and compare their performances, and outline future research directions.

Multi-tier wireless networking has emerged as a new frontier in cellular radio technology. This is a fertile area of research and offers significant challenges to “wireless” researchers. We would be pleased to learn that researchers find this book useful in their pursuit of progress in this area.

Last but not least, for this book project, we acknowledge the research support from the Natural Sciences and Engineering Research Council of Canada through the Strategic Project Grant (STPGP 430285).

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CHAPTER 1

OVERVIEW OF MULTI-TIER CELLULAR WIRELESS NETWORKS

1.1 INTRODUCTION

The demand of wireless services (e.g., data, voice, multimedia, e-Health, online gaming, etc.) through the cellular networks is ever-increasing. A recent statistics in [1] shows that, in March 2009, there were approximately 4.8 billion of mobile subscribers all over the world and this number is expected to reach 5.9 billion by 2013. The Global Mobile Data Traffic Forecast Report presented by Cisco predicts 2.4 exabytes (1 exabyte = \(10^{18}\) bytes) mobile data traffic per month for the year 2013 [2]. It has been indicated in [3] that the global mobile data traffic has tripled each year since 2008 which is projected to increase up to 26-fold between 2010 and 2015. This results up to 6.9 exabytes of mobile data traffic per month for the year 2015 [2].

Satisfying the posed capacity demand has become very challenging, and the challenge has been even more acute with the introduction of the machine-to-machine (M2M) communications and the Internet of Things (IoT). With the introduction of M2M, the network usage goes beyond the conventional voice and data usage and needs innovative solutions to handle the growing amount of traffic and user population. It is expected that by 2020 there will be more than 50 billion connected devices, which is almost 10 times the number of currently existing connected devices [4]. Note that at least 60% of the Internet traffic will be transferred via wireless access [5].

Figure 1.1 shows the three evolution phases of the user population defined by the industry, namely, the connected consumer electronics phase, the connected industry phase, and the connected everything phase [4]. In the connected consumer electronics phase, the majority of the connected devices are smart phones, tablets, computers, IP TVs, and phones. In the connected industrial phase, sensor networks, industry and buildings automation, surveillance, and e-Health applications contribute significantly to the population of wireless devices. Finally, in the connected everything phase or the IoT phase, every machine we know will have a ubiquitous Internet connectivity to be remotely operated and/or to periodically report its status.
One of the major challenges for next generation cellular wireless communication networks is therefore to accommodate the exponentially growing mobile data traffic by improving the capacity (e.g., spectral efficiency per unit area) of the networks. Also, the coverage (both indoor and outdoor) of the presently available cellular systems needs to be improved and high data rate services with enhanced quality-of-service (QoS) need to be provided to the subscribers. The current cellular standards and technologies such as the High Speed Packet Access (HSPA), Long-Term Evolution (LTE), LTE-Advanced (LTE-A), and Worldwide Interoperability for Microwave Access (WiMAX) systems are evolving toward meeting these requirements.

The conventional cellular systems use a macrocell-based planned homogeneous network architecture, where a network of macrocell base stations (referred to as Macrocell evolved Node B or MeNBs) provides coverage to user equipments (UEs) in each cell. In such a homogeneous network, the MeNBs have similar transmission power levels, antenna patterns, access schemes, modulation technique, receiver noise floors, and backhaul connectivity to offer similar QoS to the UEs across all cells [6, 7]. However, such a deployment especially degrades the coverage and capacity of the cell-edge users.

One of the approaches to solving this problem is to use the concept of cell splitting. However, this approach may not be economically feasible since it involves deploying more MeNBs within the network, and site acquisition for MeNBs in dense urban areas becomes a difficult proposition for the operators [6]. Therefore, the evolving LTE-Advanced systems are adopting a more flexible and scalable deployment
1.2 SMALL CELLS: FEMTOCELLS, PICOCELLS, AND MICROCELLS

Small cells can support wireless applications for homes and enterprises as well as metropolitan and rural public spaces. Different types of small cells include femtocells, picocells, and microcells. Due to the smaller coverage area, the same licensed frequency band can be efficiently reused multiple times within the small cells in a HetNet (Figure 1.2), thus improving the spectral efficiency per unit area (and hence the capacity) of the network. In a HetNet, small cells are envisioned as traffic off-loading spots in the Radio Access Network (RAN) to decrease the congestion in macrocells,

Throughout this book, the terms “HetNets,” “multi-tier networks,” and “small cell networks” are used interchangeably.
and enhance the users’ QoS experience [5]. The small cells in the licensed bands can be used in the cellular networks standardized by 3GPP, 3GPP2, and the WiMAX forum. When compared to unlicensed small cells (e.g., Wi-Fi), the small cells operating in the licensed band (i.e., licensed small cells) provide support for legacy handsets, operator-managed QoS, seamless continuity with the macro networks through better support for mobility/handoff, and improved security.

A femtocell is a small area covered by a small base station, called the femtocell access point (FAP), intended for residential indoor applications, which is installed and managed by the customers. The FAP is characterized with its limited transmission power (10~100 mW), small coverage range (10 ~ 30 m), IP backhauling, and low deployment cost. Femtocells operating in the licensed spectrum owned by the mobile operator providing Fixed Mobile Convergence (FMC) service (i.e., seamless transition for the user between wired and wireless communication devices) by connecting to the cellular network via broadband communication links (e.g., digital subscriber line [DSL]) [8].

One of the main advantages of femtocell deployment is the improvement of indoor coverage where macrocell base station or MeNB signal is weak. Femtocells provide high data rate and improved QoS to the subscribers or UEs. It also lengthens the battery life of the mobile phones since the mobile phones do not need to communicate with a distant macrocell base station. By off-loading traffic to the femtocells, the macrocell load can be reduced and hence more resources can be made available to each macro user. Deployment of femtocells can improve the utilization of radio frequency spectrum significantly. Femtocells can easily be deployed by the end users in indoor environments on a “plug-and-play” basis. It saves the backhaul cost for the mobile operators since femtocell traffic is carried over wired residential broadband connections and reduces the traffic intensity at the macrocell network. Femtocell technology has the potential to offer new services to the mobile phone users. Finally, femtocells can also be considered as an option toward the convergence of landline and mobile services. A recent study conducted by a market research company Informa Telecoms & Media estimates that by 2014, 114 million mobile users will be accessing mobile networks through femtocells [9]. This signifies that in the upcoming years femtocells could be an integral part of the next generation wireless communication systems.

In recent years, different types of femtocells have been designed and developed based on various air-interface technologies, services, standards, and access control strategies. Different operators such as Sprint Nextel, Verizon, and AT&T in the United States, Vodafone in Europe, NTT DoCoMo, Softbank mobile, and China Unicom in Asia have already successfully deployed their femtocell systems. Due to the flexibility in spectrum allocation, LTE-Advanced femtocells will use orthogonal frequency-division multiple access (OFDMA) as the air-interface technology. This is one of the most innovative technologies that will shape the future generations of the cellular wireless systems. In this standard, the FAPs are referred to as Home evolved Node Bs (HeNBs). The FAPs can use different access modes [10] as will be discussed in Section 1.6.2.

The term picocell is typically used to describe low power compact base stations (BSs) used in enterprise or public indoor areas and sometimes in outdoor
areas as well. Picocells are usually deployed to eliminate coverage holes in a homogeneous system and to improve the capacity of the network. The coverage area of picocells usually varies between 40 and 75 m [7]. The picocells consist of omni-directional antennas with about 5-dBi antenna gain providing better indoor coverage to the UEs in the public places such as airports and shopping malls [7].

The term *microcell* is used to describe an outdoor short-range BS aimed at enhancing the coverage for both indoor and outdoor users where macro coverage is insufficient. The term *metrocell* has recently been used to describe small cell technologies designed for high capacity metropolitan areas and can include technologies such as femtocells, picocells, and microcells. The evolving HetNets including macrocells and small cells of all types (and in some cases Wi-Fi access points operating in the unlicensed bands as well) with handoff capabilities among them are envisioned to provide improved spectrum efficiency (bps/Hz/km²), capacity, and coverage in future wireless networks.

A comparison among the different types of small cell specifications is provided in Table 1.1.

Among all the small cells, femtocells or HeNBs, are of great interest and importance to the research community and mobile operators. A study by ABI research shows that in the future, more than 50% of voice calls and more than 70% of mobile data traffic are expected to originate from indoor UEs [11]. Another survey shows that 30% of business and 45% of household users experience poor indoor coverage [12]. From now on, our discussions will focus on femtocells; however, the concepts and techniques to be discussed throughout this book can apply to other types of small cells.

### Table 1.1 Small cell specifications

<table>
<thead>
<tr>
<th>Attribute</th>
<th>MeNB</th>
<th>Picocell</th>
<th>HeNB</th>
<th>Wi-Fi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage</td>
<td>Wide area</td>
<td>Hot spot</td>
<td>Hot spot</td>
<td>Hot spot</td>
</tr>
<tr>
<td>Type of coverage</td>
<td>Outdoor</td>
<td>Outdoor, indoor</td>
<td>Indoor</td>
<td>Indoor</td>
</tr>
<tr>
<td>Density</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>BS installation</td>
<td>Operator</td>
<td>Operator</td>
<td>Subscriber</td>
<td>Customer</td>
</tr>
<tr>
<td>Site acquisition</td>
<td>Operator</td>
<td>Operator</td>
<td>Subscriber</td>
<td>Customer</td>
</tr>
<tr>
<td>Transmission range</td>
<td>300–2000 m</td>
<td>40–100 m</td>
<td>10–30 m</td>
<td>100–200 m</td>
</tr>
<tr>
<td>Transmission power</td>
<td>40 W (approx.)</td>
<td>200 mW–2 W</td>
<td>10–100 mW</td>
<td>100–200 mW</td>
</tr>
<tr>
<td>Band license</td>
<td>Licensed</td>
<td>Licensed</td>
<td>Licensed</td>
<td>Unlicensed</td>
</tr>
<tr>
<td>System bandwidth</td>
<td>5, 10, 15, 20 MHz</td>
<td>(up to 100 MHz)</td>
<td>(up to 100 MHz)</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Transmission rate</td>
<td>up to 1 Gbps</td>
<td>up to 300 Mbps</td>
<td>100 Mbps–1 Gbps</td>
<td>up to 600 Mbps</td>
</tr>
<tr>
<td>Cost (approx.)</td>
<td>$60,000/yr</td>
<td>$10,000/yr</td>
<td>$200/yr</td>
<td>$100–200/yr</td>
</tr>
<tr>
<td>Power consumption</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Backhaul</td>
<td>S1 interface</td>
<td>X2 interface</td>
<td>IP</td>
<td>IP</td>
</tr>
<tr>
<td>Mobility</td>
<td>Seamless</td>
<td>Nomadic</td>
<td>Nomadic</td>
<td>Nomadic</td>
</tr>
<tr>
<td>QoS</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Best-effort</td>
</tr>
</tbody>
</table>
CHAPTER 1 OVERVIEW OF MULTI-TIER CELLULAR WIRELESS NETWORKS

1.3 HISTORICAL PERSPECTIVE

The concept of self-optimizing home BSs is not completely new [13]. In March 1999, Alcatel first announced its plan to launch a GSM home BS in 2000 which would be compatible with existing standard GSM phones. Although demonstration of these home BSs, which were basically dual mode DECT/GSM units, was successful, they were not commercially viable due to the high cost of 2G chipsets. In 2002, Motorola engineers in Swindon, UK, claimed to have built the first complete 3G home BSs. In 2004, two UK-based startup companies, namely, Ubiquisys and 3Way networks (now part of Airvana), were using 3G chipsets developed by the chipset design company picoChip to develop their own 3G cellular home BSs. Around 2005, the term femtocell was adopted for a standalone, self-configuring home BS. Rupert Baines, VP marketing of picoChip and Will Franks, CTO of Ubiquisys are both said to have coined the term during this period, although picoChip registered the website URL www.femtocell.com first (in April 2006). The femtocell products were demonstrated by several vendors in February 2007. The “Femto Forum” (www.femtoforum.org) was formed in 2007 and grew to represent industry players and to advocate this technology. The Femto Forum is active in standardization, regulation, and inter-operability issues as well as marketing and promotion of femtocell solutions.

In late 2007, Sprint Nextel started deployment of its 2G femtocell system in the United States which it developed by teaming up with Samsung Electronics. This system worked with all Sprint handsets. Sprint launched its commercial femtocell service in August 2008. In the United Kingdom, O2 is one of the leaders in femtocell technology who developed 3G femtocells by partnering with NEC. Vodafone is another player in this technology which has started deployment and testing of femtocells in Spain. In Asia, Softbank Japan launched their 3G femtocell systems in January 2009.

Recently, research on HetNets and small cell technology in general has attracted significant interest in both academia and industry [5] and standardization efforts are ongoing since the 3rd Generation Partnership Project (3GPP) Release-8 (http://www.3gpp.org/Release-8). In recent years, different types of femtocells have been designed and developed based on various air-interface technologies, services, standards, and access control strategies. For example, 3G femtocells use Wideband Code-Division Multiple Access (WCDMA)-based air interface of Universal Mobile Telecommunication System (UMTS), which is also known as UMTS Terrestrial Radio Access (UTRA). The 3GPP refers to these 3G femtocells as Home Node Bs (HNBs). On the other hand, WiMAX and LTE femtocells use OFDMA. The LTE femtocells are referred to as HeNBs.

1.4 OVERVIEW OF LTE NETWORKS

The LTE standard was first published in March 2009 as part of the 3GPP Release-8 specifications with the aim of providing higher data rates and improved QoS. LTE corresponds to a packet-switched optimized network that encompasses
TABLE 1.2 Major specifications of the LTE standard [15–18]

<table>
<thead>
<tr>
<th>Specifications</th>
<th>LTE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>3GPP Release 8</td>
</tr>
<tr>
<td>Frequency bands</td>
<td>700 MHz, 1.5 GHz, 1.7/2.1 GHz, 2.6 GHz</td>
</tr>
<tr>
<td>Access scheme – Uplink</td>
<td>Single Carrier Frequency Division</td>
</tr>
<tr>
<td></td>
<td>Multiple Access (SCFDMA)</td>
</tr>
<tr>
<td>Access scheme – Downlink</td>
<td>Multiple Access (OFDMA)</td>
</tr>
<tr>
<td></td>
<td>Orthogonal Frequency Division</td>
</tr>
<tr>
<td>Channel bandwidth (MHz)</td>
<td>1.4 3 5 10 15 20</td>
</tr>
<tr>
<td>Number of sub-channels</td>
<td>6 15 25 50 75 100</td>
</tr>
<tr>
<td>Number of sub-carriers</td>
<td>72 180 300 600 900 1200</td>
</tr>
<tr>
<td>(1 sub-channel consists of 12 sub-carriers)</td>
<td></td>
</tr>
<tr>
<td>IDFT/DFT size</td>
<td>128 256 512 1024 1536 2048</td>
</tr>
<tr>
<td>Data modulation</td>
<td>QPSK, 16 QAM, 64 QAM</td>
</tr>
<tr>
<td>Duplexing</td>
<td>Frequency-Division Duplexing (FDD)</td>
</tr>
<tr>
<td></td>
<td>Time-Division Duplexing (TDD)</td>
</tr>
<tr>
<td>Frame size</td>
<td>1-ms sub-frames</td>
</tr>
<tr>
<td>Sub-carrier spacing</td>
<td>15 KHz</td>
</tr>
<tr>
<td>Channel coding</td>
<td>Convolutional and Turbo Coding</td>
</tr>
<tr>
<td></td>
<td>Rate: 78/1024–948/1024</td>
</tr>
<tr>
<td>Cyclic prefix length – Short</td>
<td>4.7 μs</td>
</tr>
<tr>
<td>Cyclic prefix length – Long</td>
<td>16.7 μs</td>
</tr>
<tr>
<td>Peak uplink data rate</td>
<td>75 Mbps (Channel Bandwidth: 10 MHz)</td>
</tr>
<tr>
<td>Peak downlink data rate</td>
<td>150 Mbps (2 × 2 MIMO, Channel Bandwidth: 20 MHz)</td>
</tr>
<tr>
<td>User-plane latency</td>
<td>5–15 ms</td>
</tr>
</tbody>
</table>

high capacity, high spectral efficiency due to robustness of the air-interface technologies, co-existence and inter-networking with 3GPP and non-3GPP systems, low latency of the network (i.e., short call setup time, short handover latency, etc.), and supports for Self-Organizing Network (SON) operation [6, 14]. Some of the major specifications of LTE standard are listed in Table 1.2 [15–18].

A generic LTE cell architecture is shown in Figure 1.3. The LTE networks correspond to a much simpler RAN in comparison to its predecessor, the UMTS Terrestrial Access Network (UTRAN) [19]. LTE is designed to support packet-switched services based on Evolved Packet System (EPS). EPS aims to provide a uniform user experience to the mobile users or UEs anywhere inside a cell through establishing an uninterrupted Internet Protocol (IP) connectivity between the UE and Packet Data Network (PDN). The network core component of EPS is referred to as Evolved Packet Core (EPC) or System Architecture Evaluation (SAE) [20]. The major components of LTE at the EPC are the Mobility Management Entity (MME)
Figure 1.3  A generic LTE cell architecture [3].
and Serving GateWay (S-GW), and at the RAN are evolved Node-Bs (referred to as eNBs), that is, radio BSs.

### 1.4 OVERVIEW OF LTE NETWORKS

#### 1.4.1 The Core Network

The Core Network (CN) or the EPC of LTE comprises some logical nodes (e.g., MME and S-GW) which are responsible for the overall control of the UE and the establishment of the EPS bearer with desired QoS [20]. A brief description of the components of the CN is provided below.

**Mobility Management Entity**: The MME is a logical node that processes the control signaling in order to establish connection and security between the core network and the UE. Some of the major functionalities supported by the MME are as follows: (i) EPS bearer management, which includes the establishment, control, maintenance, and release of the bearers (an EPS bearer is an IP packet flow with a defined QoS [20]), (ii) Non-Access Stratum (NAS) security, (iii) mobility anchoring for UEs in the idle state, and (iv) inter-working with other 3GPP or non-3GPP networks which involves handing over the voice calls.

**Serving GateWay**: The S-GW works as a mobility anchor for the UEs and transfers the IP packets when UEs move between eNBs. The S-GW also gathers call charging information (e.g., the volume of data sent and/or received from the UE) and serves as the mobility anchor to enable handover of voice calls to other 3GPP or non-3GPP networks. The basic functionalities of eNBs include scheduling, radio access control, inter-cell radio resource allocation, mobility management, interference management, and call admission control (CAC). The detailed functionalities of the network components of LTE are elaborated in [21].

#### 1.4.2 The Access Network

The access network of LTE is referred to as E-UTRAN and consists of eNBs connected via different interfaces. The architecture of E-UTRAN is called a *flat architecture* since there is no centralized controller for data traffic in E-UTRAN. The eNBs are inter-connected with each other by an interface called X2 and with the core network via an interface called S1. More specifically, the eNBs are connected to the MME and S-GW through S1-MME (known as S1 control-plane) and S1-U interfaces (known as S1 user-plane), respectively. The S1-U interface carries data traffic between the serving gateway and eNB using General Packet Radio Service (GPRS) tunneling protocol which is referred to as GTP. On the other hand, the signaling information between eNB and the MME is carried via S1-MME interface which uses the Stream Control Transmission Protocol (SCTP). The network management functionalities of EPC, for example, radio access bearer management, load balancing between MMEs, paging, and instantaneous intra-LTE and/or inter-3GPP handovers

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2NAS are the protocols running between the UE and the core network [22].
are performed via S1 interface [19]. Similar to the S1 interface, the X2 interface is split into two parts: X2 user-plane (X2-U) and X2 control-plane (X2-C). Based on the User Datagram Protocol (UDP), the X2-U interface carries user data traffic between the inter-connected eNBs. The X2-C interface is used for error handling functionalities and intra-LTE mobility between the serving eNB and the target eNB. The specific functions supported by each components and interfaces are provided in [21, 23].

1.4.3 The Air Interface

LTE uses OFDMA for the downlink (DL) communication. However, for the uplink (UL) communication, it uses Single Carrier Frequency-Division Multiple Access (SCFDMA), which is a cost-effective and power efficient (saves the battery life of mobile terminal) transmission scheme. LTE supports both TDD and FDD duplexing modes. The frame duration in LTE is 10 ms. In case of FDD, the entire frame is used for UL or DL transmissions. In the case of TDD, the frame is divided for UL and DL communication. Each frame consists of 10 sub-frames and the transmission duration of each sub-frame is 1 ms. Each sub-frame is divided into 2 time slots. Each time slot has a duration of 0.5 ms. There are two types of cyclic prefix (CP) used in LTE, that is, a short CP of 4.7 $\mu$s for short cell coverage and a long CP of 16.7 $\mu$s for large cell coverage. The time slot will consist of seven and six OFDM symbols when short and long CPs are used, respectively. The resource block (RB) in LTE refers to a time slot spanned with 12 sub-carriers where the bandwidth of each sub-carrier is 15 KHz. LTE supports different types of modulation technique such as, QPSK, 16-QAM, and 64-QAM. The peak data rate in UL/DL transmission mode depends on the modulation used between eNB and UE. For example, the peak data rate of LTE in the DL transmission is approximately 150 Mbps (assuming 20 MHz channel bandwidth, short CP, $2 \times 2$ multiple-input and multiple-output (MIMO)-based system with 64-QAM). This can be obtained as follows.

- The number of resource elements per sub-frame is calculated first. Since the channel bandwidth is 20 MHz and the short CP is used, the number of resource elements per sub-frame is: 12 (sub-carriers) $\times$ 7 (OFDM symbols) $\times$ 100 (RBs) $\times$ 2 (time slots) = 16,800.
- Each resource element is carried by a modulation symbol. Since 64-QAM is used, one modulation symbol will consist of 6 bits. The total number of bits in a sub-frame is: 16,800 (modulation symbols) $\times$ 6 (bits/modulation symbol) = 100,800 bits.
- The duration of each sub-frame is 1 ms. The data rate is: 100,800 bits/1 ms = 100.8 Mbps. With $2 \times 2$ MIMO, the peak data rate: 100.8 (Mbps) $\times$ 2 = 201.6 Mbps.
- Considering 25% overhead, the peak data rate is approximately 150 Mbps ($= 201.6$ Mbps $\times$ 0.75).