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.

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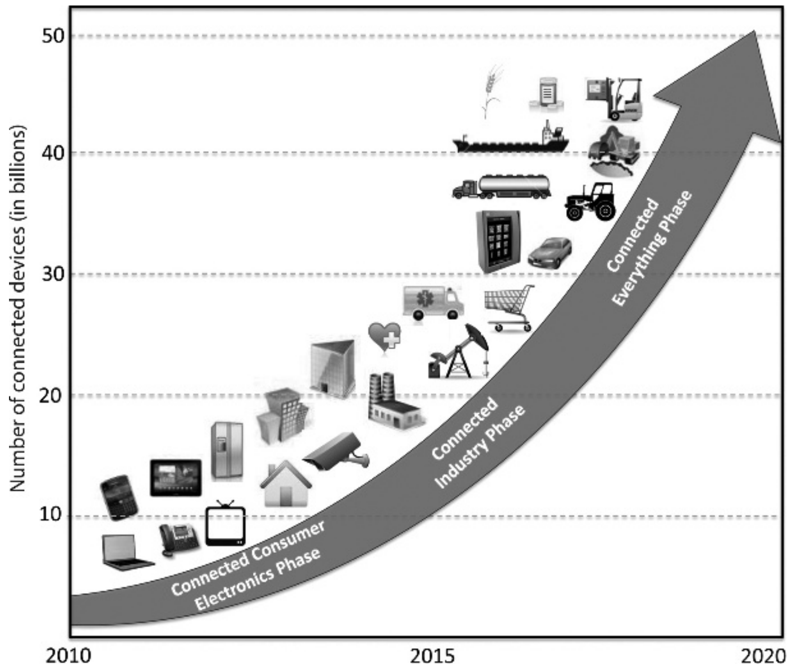


Figure 1.1 The evolution of the population of wireless devices.

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

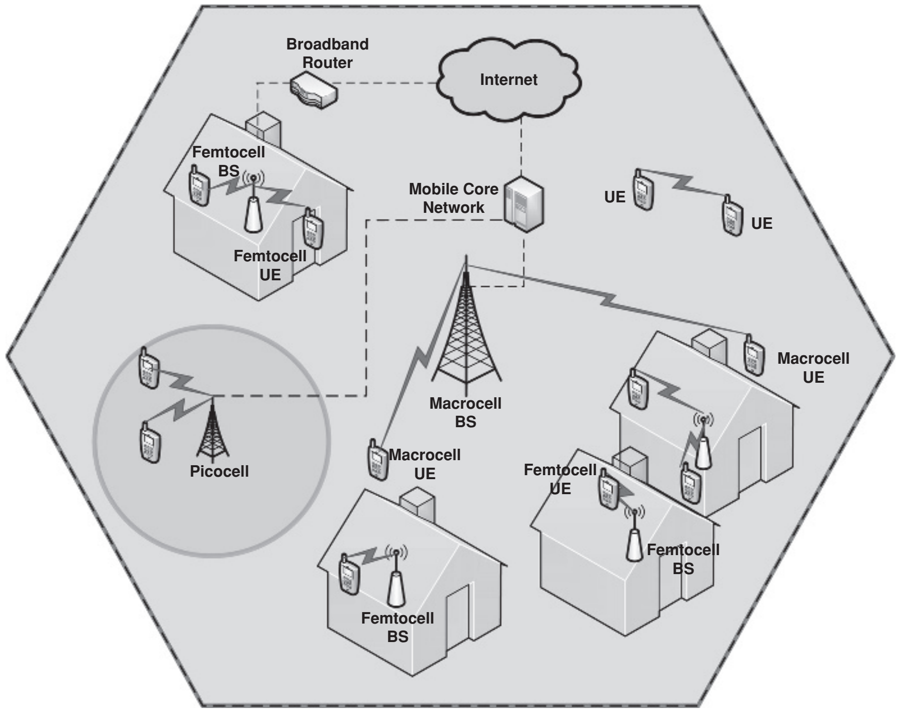


Figure 1.2 A heterogeneous cellular wireless network.

approach using a hierarchical cell deployment model where *small cells* are overlaid on the macrocells. The resulting network architecture is also referred to as a heterogeneous network (HetNet) architecture.[1] Such a deployment approach is beneficial to both the operators and end users. This approach is expected to not only increase the coverage and capacity of the cell but also improve the broadband user experience within the cell in a ubiquitous and cost-effective manner [6].

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,

[1]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$\sim$100 mW), small coverage range (10 $\sim$ 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 omnidirectional 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/km^2), 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

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

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]

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

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)

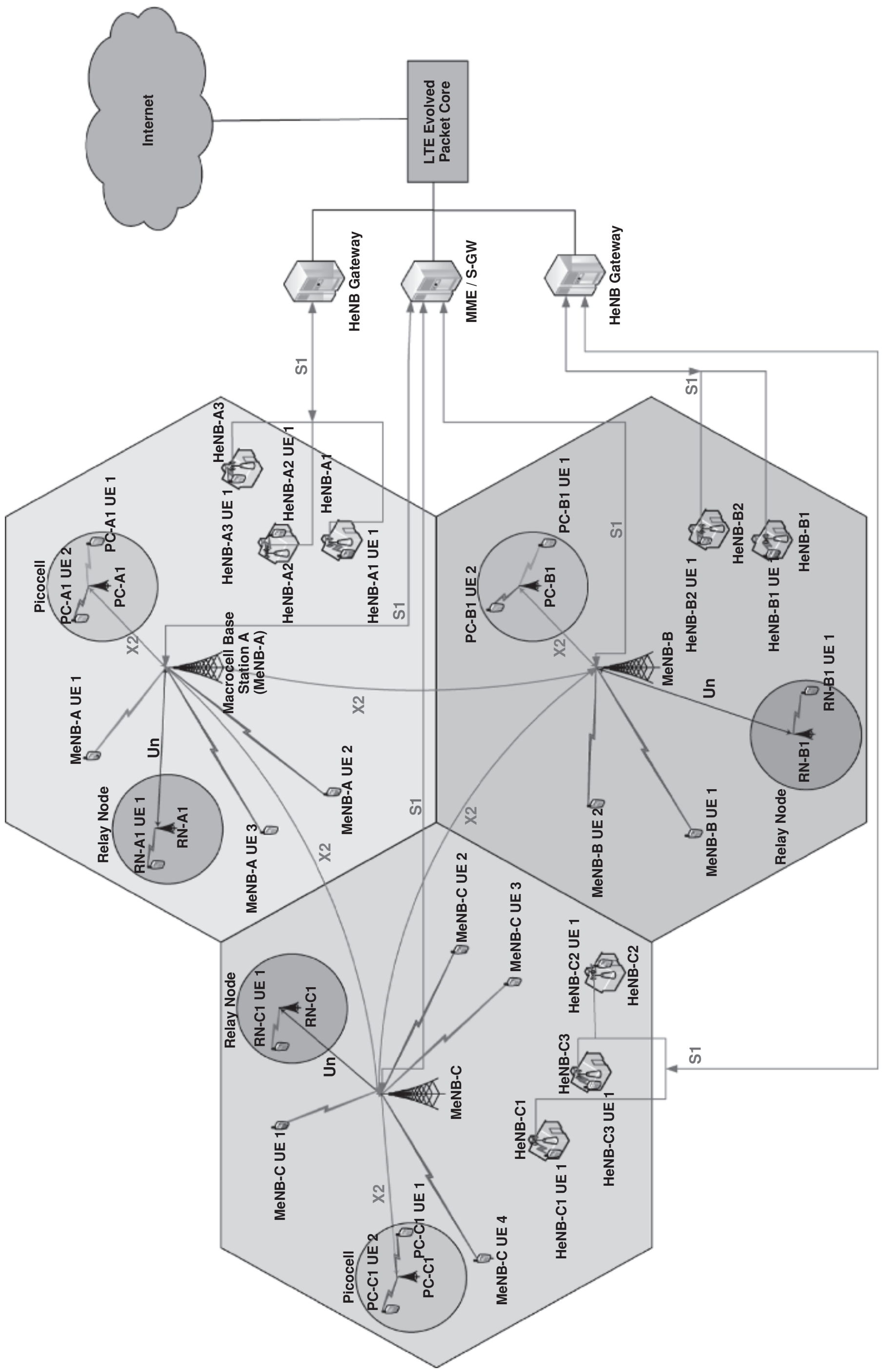


Figure 1.3 A generic LTE cell architecture [3].

and Serving GateWay (S-GW), and at the RAN are evolved Node-Bs (referred to as eNBs), that is, radio BSs.

1.4.1 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,[2] (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

[2]NAS 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 μs for short cell coverage and a long CP of 16.7 μs 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, 2×2 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) × 7 (OFDM symbols) × 100 (RBs) × 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) × 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 × 2 MIMO, the peak data rate: 100.8 (Mbps) × 2 = 201.6 Mbps.
- Considering 25% overhead, the peak date rate is approximately 150 Mbps (= 201.6 Mbps × 0.75).

1.4.4 Radio Base Stations in LTE

Although 3GPP-LTE employs a flat architecture, the radio BSs or cells in LTE can be classified in terms of their transmission powers, antenna heights, the type of an access mechanism provided to UEs, the air-interface and the backhaul connection to other cells, or the core network. In this regard, the radio BSs in LTE can be classified as follows.

- Macrocell base stations or Macrocell e-Node Bs (MeNBs) have a large coverage area (e.g., cell radius of 500 m–1 km) with high transmission power (∼46 dBm or 20 W) and provide service to all the UEs in its coverage area [3].
- Picocells are usually deployed to eliminate coverage holes in a homogeneous cellular network and 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 low transmission powered (in comparison to MeNB) antennas with about 5-dBi antenna gain providing significant indoor coverage to the UEs in the public places such as airports and shopping malls [7].
- Similar to picocells, relay nodes are also used to improve coverage in new areas (e.g., events, exhibitions, etc.). However, relay nodes transfer their data traffic via wireless link to a Donor eNodeB (e.g., MeNB). There are two types of relay nodes: inband relays and out of band relays. In the case of inband relay nodes, the same frequency spectrum is used for relay link (relay node to UE) and backhaul link (relay node to donor eNB). On the other hand, in case of out of band relaying, the relay nodes use different frequency spectrum for relay link and backhaul link.
- Femtocells or Home e-Node Bs (referred to as HeNBs) are short-range (10 ∼ 30 m), low power (10 ∼ 100 mW), and cost-effective ($100 – $200) home BSs deployed by the mobile subscribers.

1.4.5 Mobility Management

In LTE, the mobility management functionalities are divided into three categories: (i) intra-LTE mobility, (ii) inter-3GPP mobility, and (iii) inter-radio access technologies (RAT) mobility. The intra-LTE mobility corresponds to the UE mobility within the LTE system, whereas mobility to other 3GPP systems (e.g., UMTS) is referred to as Inter-3GPP mobility. Mobility of UEs between the LTE system and other non-3GPP (e.g., Global System for Mobile communications or GSM) is referred to as inter-RAT mobility. Intra-LTE mobility is handled via S1 or X2 interface. The mobility through X2 interface occurs when a UE moves from one MeNB to another MeNB within the same RAN connected to the same MME. On the other hand, when the serving MeNB and the target MeNB are not connected through X2 interface, then the mobility of UE between the MeNBs takes place over the S1 interface. In addition, when the UE moves from one MeNB to another MeNB belonging to different RAN attached to different MME, then the mobility is handled via the S1 interface. Figure 1.4 illustrates

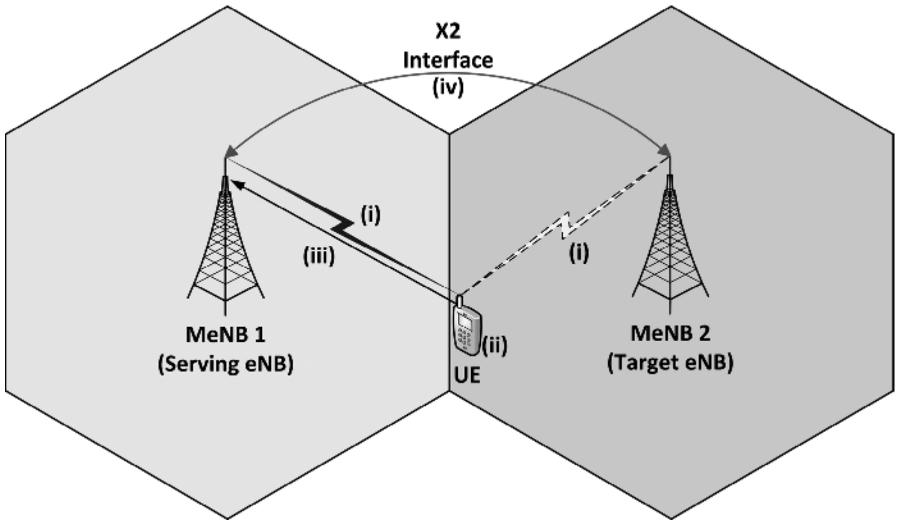


Figure 1.4 A generic diagram for intra-LTE mobility.

a generic intra-LTE mobility via X2 interface. In this handover scenario, the basic mechanism comprises the following steps.

1. The UE measures the DL signal strength.
2. The UE processes the measurement results.
3. The UE sends the measurement report to the serving MeNB (i.e., MeNB 1).
4. The serving MeNB makes the handover decision via X2 interface.

The mobility over the X2 interface comprises three phases [18]: (i) handover preparation phase, (ii) handover execution phase, and (iii) handover completion phase. A generic handover call flow for inter-MeNB mobility is shown in Figure 1.5.

Handover preparation phase: The serving MeNB makes the handover decision based on the UE measurement report. Once the handover decision is made by the serving MeNB, it sends a handover request message to the target MeNB. Based on the handover request message, the target MeNB allocates the resources to the UE. Once the preparation for admission control of the UE is completed, a handover request acknowledgment (ACK) message is sent back to the serving MeNB.

Handover execution phase: As the serving MeNB receives the handover request ACK, it sends a handover command to the UE. At the same time, the serving MeNB transfers the buffered data packets of UE to the target MeNB. Upon receiving the handover command from the serving MeNB, the UE synchronizes with the target MeNB.

Handover completion phase: The UE sends a handover confirmation message to the target MeNB when the handover procedure is completed. Upon receiving this confirmation message, the target MeNB sends a path switch request message to the MME/S-GW. Then, the S-GW switches the GTP from the serving MeNB to the target

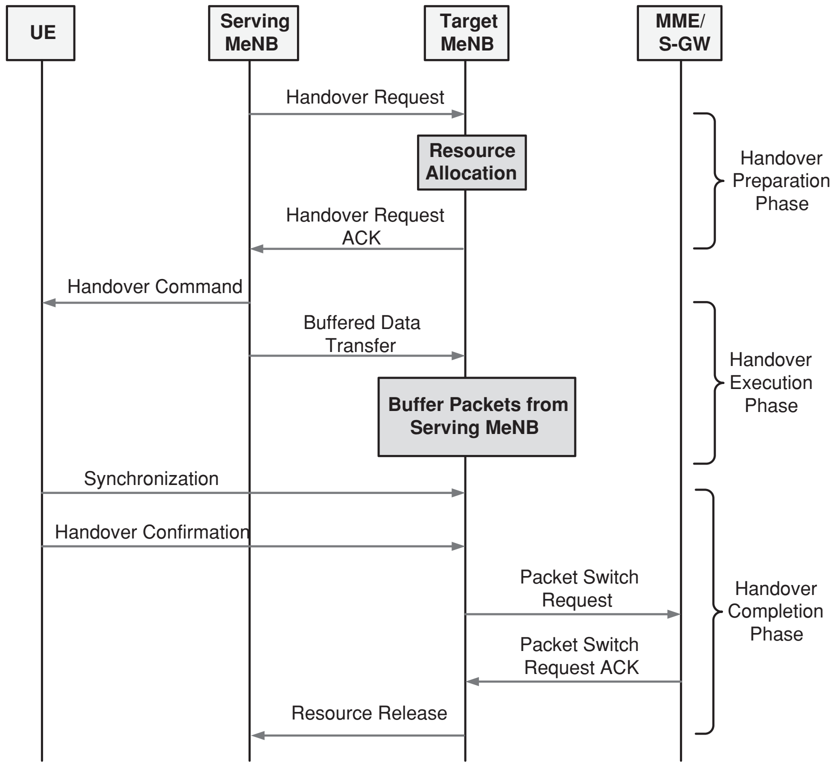


Figure 1.5 Inter-MeNB mobility management via X2 interface.

MeNB. As the data path in the user-plane for the UE is switched, the target MeNB sends a message to the serving MeNB to release the resources that were used by the UE.

The mobility via the S1 interface is similar to the mobility over the X2 interface and the details are elaborated in [18–20].

1.5 OVERVIEW OF LTE-ADVANCED NETWORKS

3GPP has been working on various aspects to improve LTE performance in the framework of LTE-Advanced [18, 24]. The summary of the LTE-Advanced target requirements is listed in Table 1.3. Some of the technologies that are being considered in LTE-Advanced include the following [18].

- In LTE-A multi-tier networks, orthogonal frequency-division multiplexing (OFDM) is used for DL and single-carrier FDM (SC-FDM) waveform is used for UL communications over 20 MHz bandwidth. The OFDM (SC-FDM) symbols are grouped into sub-frames of 1-ms duration. Each sub-frame is composed of two 0.5-ms slots. The minimum scheduling unit for the DL and

TABLE 1.3 Major specifications of the LTE-Advanced standard [18, 24]

Standard	Target Requirements of LTE-Advanced
Peak data rate	Uplink : 500 Mbps Downlink : 1 Gbps (Assuming low mobility and 100-MHz channel bandwidth)
Peak spectral efficiency	Uplink : 15 b/s/Hz (up to 4 × 4 MIMO) Downlink : 30 b/s/Hz (up to 8 × 8 MIMO)
Average downlink cell spectral efficiency	2.4 b/s/Hz (up to 2 × 2 MIMO) 2.6 b/s/Hz (up to 4 × 2 MIMO) 3.7 b/s/Hz (up to 4 × 4 MIMO)
Average downlink cell-edge spectral efficiency	0.07 b/s/Hz (up to 2 × 2 MIMO) 0.09 b/s/Hz (up to 4 × 2 MIMO) 0.12 b/s/Hz (up to 4 × 4 MIMO)
Mobility	Considered up to 500 km/h
Duplexing	FDD and TDD
User-plane latency	Less than 10 ms

UL of LTE is referred to as an RB. One RB consists of 12 sub-carriers in the frequency domain (180 kHz) and one sub-frame in the time domain (1 ms). The sub-frames are further grouped in 10-ms radio frames (Figure 1.6 [25]). A reference or pilot signal, referred to as a common reference signal (CRS), is used for mobility measurements as well as for demodulation of the DL control and data channels. The CRS transmissions are distributed in time and frequency.

- Higher order MIMO-based system (up to 8 × 8 MIMO) along with beamforming technique: Multiple antennas at the macrocell base stations can transmit the same signal with appropriate weight for each antenna element in such a way that the transmitted beam focuses in the direction of the receiver to improve the received signal-to-interference-plus-noise ratio (SINR) at the mobile station (MS) or UE [18]. The beamforming technique provides improvement in macrocell coverage and network capacity, and reduces the power consumption at the macrocell base stations.
- Increase in spectrum-efficiency and network throughput by using carrier aggregation (CA) mechanism: The available spectrum in LTE is divided into component carriers (CCs) with bandwidth of 1.4, 3, 5, 10, 15, and 20 MHz. The CA technique involves aggregation of the CCs at the macrocell base stations to allow higher data rates for the UEs. The current LTE-Advanced standard allows up to five 20-MHz CCs to be aggregated resulting in a maximum aggregated channel bandwidth of 100 MHz.
- Network MIMO to improve the overall system performance: Network MIMO corresponds to macrocell diversity and efficient coordination among macrocell base stations. In the DL transmission mode, multiple macrocell base stations transmit to a UE and in the UL transmission mode, the transmitted signal from the UE is received by one or more macrocell base stations. The network MIMO

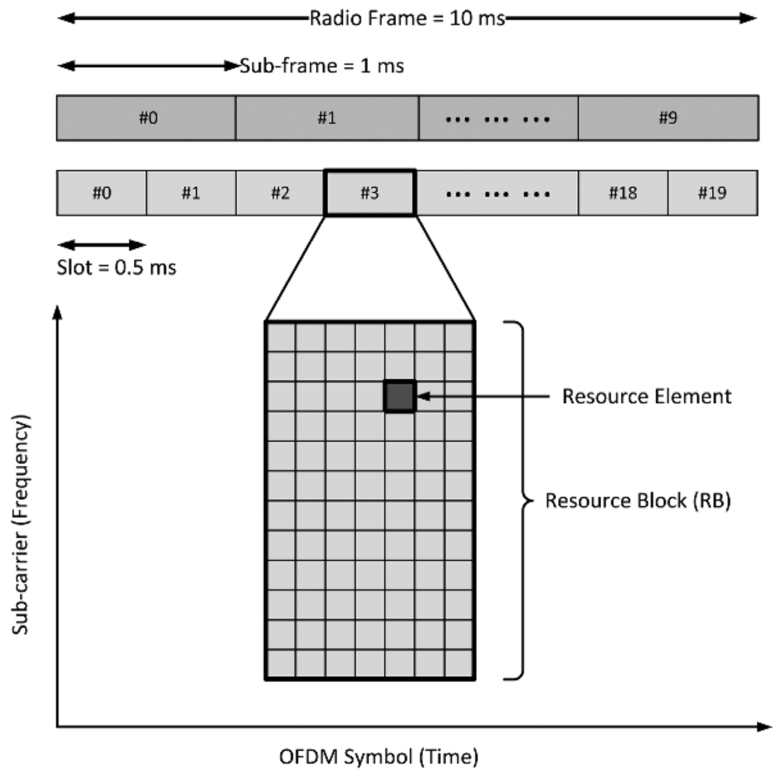


Figure 1.6 LTE-advanced frame structure.

allows the cooperating macrocell base stations to use the spectrum efficiently so that the interference from the adjacent macrocells is minimal.

- Implementation of multi-tiered network, that is, macrocell base stations overlaid with small cells, for example, femtocells, picocells, and microcells, to improve network coverage and increase the network capacity.
- Efficient inter-cell interference coordination (ICIC) and inter-cell interference (ICI) cancellation techniques: ICIC involves techniques such as spectrum splitting, power control, etc. Inter-cell interference cancellation techniques involve decoding or demodulation of the desired information, which is further used along with the channel estimates to eliminate (or reduce) the interference from the received signal [26]. Successive interference cancellation (SIC) and parallel interference cancellation (PIC) are the two techniques that are extensively used in wireless communication systems.
- The eNB serving the RN denoted as donor eNB (DeNB): The same eNB can be the DeNB for one RN and the regular serving node for UE. The X2 interface, defined as a direct eNB-to-eNB interface, allows for ICIC. The S1 and S11 interfaces support transfer of user and data traffic between the corresponding

nodes. The Un interface refers to an air interface between the DeNB and RN. Un is based on a modified interface between the eNB and UE in order to allow half duplex operation of the RN.

- Backward compatibility to ensure the reuse of the LTE architecture to coexist with other 3GPP and non-3GPP systems: The LTE devices should comply with the standards of LTE-Advanced system.

1.6 LTE FEMTOCELLS (HeNBs)

LTE or 3GPP Release-8 onward and LTE-Advanced (or Release 10 onward) femtocells use OFDMA as the air-interface technology. In LTE femtocells, resource allocation can be done in a more flexible manner due to dynamic allocation of time and frequency slots; however, large amount of coordination may be necessary. Also, semi-static allocation of frequency channels can be performed for interior, edge, and femtocell users, along with power control.

The major motivations behind the deployment of HeNBs are as follows.

- Unlike Wi-Fi, HeNBs operate in licensed spectrum offered by the mobile operator to extend the indoor coverage, improve QoS provisioning to the UEs, and off-load the indoor mobile data traffic.
- HeNBs offer increased spectrum utilization. Since the HeNBs are short-ranged BSs, the same licensed frequency band can be efficiently reused multiple times within the service area of the MeNB.
- HeNBs reduce the MeNB load which results in more resources (i.e., frequency and power) for macrocell UEs (referred to as MUEs). At the same time, the expected battery life of mobile phones are extended since the UEs do not require to communicate with the distant MeNBs.
- HeNBs are deployed by the mobile users on “plug-and-play” basis and they are self-organizing. Such deployment saves the additional macrocell base station installation cost for mobile operators. In addition to that, HeNB corresponds to low cost home BS that is capable of providing fixed mobile coverage and high rate to the UEs.

1.6.1 Access Network for HeNBs

The Home eNodeB Subsystem (HeNS) (Figure 1.3) consists of a Home eNodeB (HeNB) and optionally a Home eNodeB Gateway (HeNB-GW). An HeNB connects to the EPC through the S1-U and S1-MME interfaces. To support large number of HeNBs, an HeNB gateway is employed between the HeNBs and EPC. The HeNB gateway appears as an HeNB to the MME. S1 interface is used between the HeNBs and HeNB gateway as well as between the HeNB gateway and EPC. The basic functionalities of HeNB are the same as the eNBs. In addition, an HeNB performs access control or CAC for UEs based on the access modes incorporated with the HeNB. More detailed architectural overview of HeNBs can be found in [27].

1.6.2 Access Modes of HeNBs

In general, femtocells are designed to operate in one of three different access modes, that is, closed access mode, open access mode, and hybrid access mode [10]. In closed access mode, a set of registered UEs belonging to Closed Subscriber Group (CGS) are allowed to access a femtocell. This type of femtocell access control strategy is usually applicable to residential deployment scenarios. However, in public places such as airports and shopping malls, open access mode of femtocells can also be used where any UE can access the femtocell and benefit from its services. This access mode is usually used to improve indoor coverage and minimize the coverage holes in macrocell footprint. In hybrid access mode, any UE may access the femtocell but preference would be given to those UEs which subscribe to the femtocell. In small business or enterprise deployment scenarios hybrid access mode of femtocells may be used [10].

1.6.3 Mobility Management

The mobility management functions in a two-tier femtocell network can be categorized into three groups (Figure 1.7): (i) hand-in or inbound mobility (i.e., mobility from MeNB to HeNB), (ii) hand-out or outbound mobility (i.e., mobility from HeNB to MeNB), and (iii) inter-HeNB mobility (i.e., mobility between HeNBs). The mobility management in femtocell networks is handled over the S1 interface.

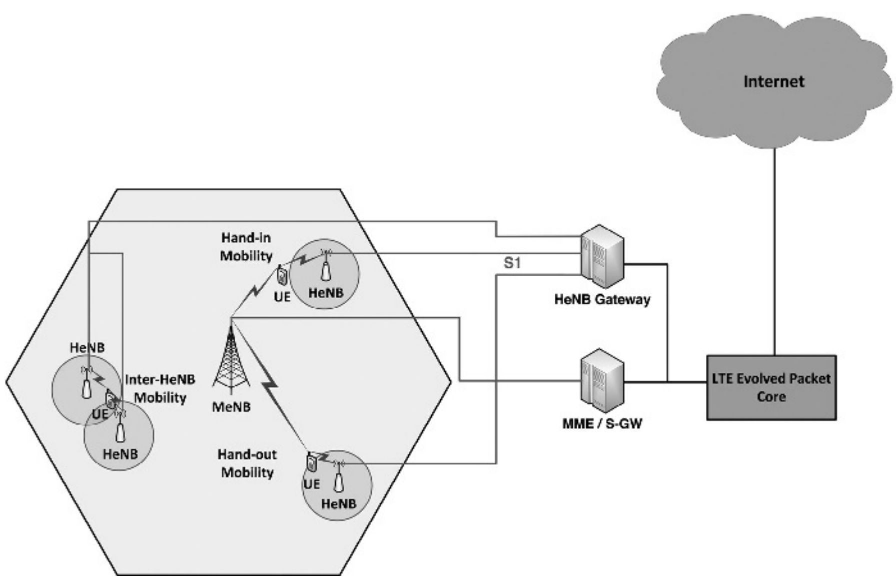


Figure 1.7 Mobility management in a femtocell network.

The handover procedure may be triggered based on different attributes such as received signal strength indicator (RSSI), QoS, UE velocity, etc. The mobility over the S1 interface consists of three phases: (i) handover preparation phase (measurement control/report, admission decision, resource allocation), (ii) handover execution phase (synchronization with target BS), and (iii) handover completion phase (path switch and resource release). The message/signaling involved in the mobility management for femtocell network is elaborated in [21].

1.7 3G FEMTOCELLS

A generic network architecture for cdma2000 femtocell enabled systems is shown in Figure 1.8. A brief description of the major network entities and the air interfaces is provided below.

1.7.1 Network Entities

Femtocell Access Point (FAP): The femtocell access point is a short-ranged, low power wireless access point that operates in licensed frequency to connect a MS or HRPD AT (known as High Rate Packet Data Access Terminal, a device to provide data connectivity to a user) to the Internet. The FAP provides access control for the MSs and supports cdma2000 1x packet data and HRPD services [28].

Security Gateway (SeGW): The SeGW provides secure access for the femtocell access point to access services within the network [28].

Femtocell Gateway (FGW): The FGW provides aggregation, proxy, and signal routing functions for the FAP to access cdma2000 1x packet data and HRPD services within the cellular network [29].

Femtocell Authentication, Authorization, and Accounting Server (F-AAA): The Femtocell AAA is a server that sends authorization policy information to the SeGW in order to provide the FAP authentication and authorization functions within the cellular network [29].

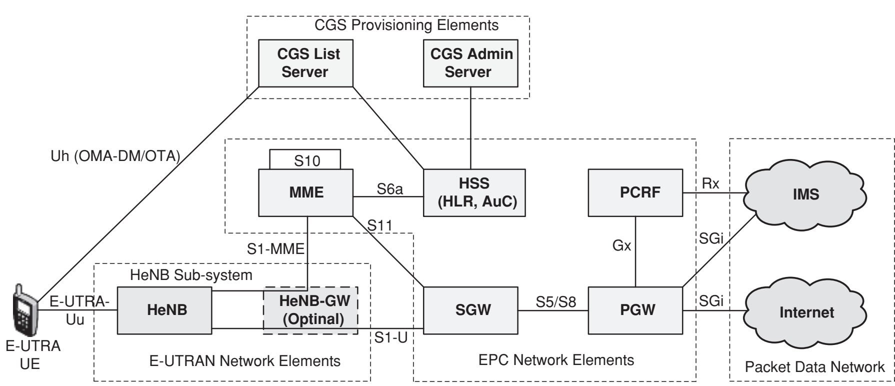


Figure 1.8 3G femtocell sub-system architecture [28].

Femtocell Management System (FMS): The FMS facilitates the auto-configuration of the FAP within the network [29].

Packet Data Serving Node (PDSN): The PDSN is a network entity that routes the HRPD AT based packet data traffic through the Internet.

Home Agent/Local Mobility Anchor (HA/LMA): This network entity acts as a mobility anchor within the network to provide the mobility management based on the location information of the MS and HRPD ATs and supports Proxy Mobile IP (PMIP) Version 6 (IPv6) [29].

Access Network Authentication, Authorization, and Accounting (AN-AAA) Server: The AN-AAA is a network entity that performs access authentication and authorization functions for the FAP. It also provides authorization function for local IP access to allow an MS to access either local IP networks or the Internet through the local interface [29].

1.7.2 Air Interface

The interface that carries user traffic between the FAP and the FGW or the PDSN is called A10 interface. On the other hand, the A11 interface is used for carrying signaling information between the FAP and the FGW or the PDSN. The A12 interface carries signaling information for access control and authentication between the FAP and the AN-AAA [29]. The A13 interface is used to provide HRPD idle session handoff between the FAP and the HRPD AN [28]. The A16 interface carries signaling information between the FAP and the HRPD AN for HRPD active session handoff (known as hard handoff) [28]. The A24 interface carries buffered data traffic for the user during idle session handoff between the FAP and the HRPD AN. The Fm interface is used for the auto-configuration of the FAP by femto user equipment (FUE). Fx4(AAA) interface is used to enable the authorization procedure for the FAP with in the network. The Fx5(AAA) interface is used for remote IP access authentication for FAP.

Note that the air-interface performance of 3G femtocells primarily depends on the power control method. However, in a large-scale deployment scenario, centralized power control would be infeasible for these femtocells.

1.8 CHANNEL MODELS FOR SMALL CELL NETWORKS

The propagation channel model can be represented by a combination of path-loss, log-normal shadowing, and multipath fading. For example, for an outdoor link (e.g., link between a macro base station and a macro user) or an indoor link (e.g., link between a FAP and a femto user), the channel gain g_{ji} of user j to BS i can be modeled as

$$g_{ji} = K_{ji} d_{ji}^{-\alpha_j} \chi_{ji} f_{ji} \tag{1.1}$$

where K_{ji} is a constant factor (depends on carrier frequency, antenna gains, reference distance), d_{ji} is the distance from user j to BS i, α_j is the path-loss

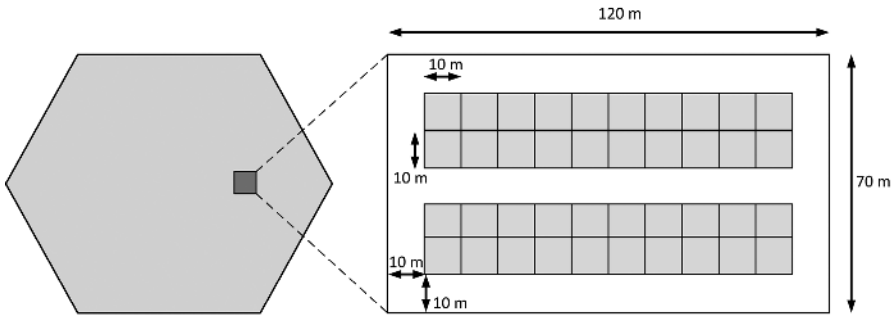


Figure 1.9 3GPP dual-stripe model.

exponent corresponding to the propagation environment (e.g., cellular, indoor, and indoor–outdoor), χ_{ji} is the log-normal shadowing between the BS and the user (i.e., $10 \log \chi \sim N(0, \sigma^2)$), and f_{ji} is the channel power gain due to multipath fading.

For an outdoor-to-indoor link (e.g., link between a macro base station and a femto user), the penetration loss (L_w) needs to be taken into account, in which case the link gain can be given by

$$g_{ji} = K_{ji} d_{ji}^{-\alpha_j} \chi_{ji} L_w^{-1} f_{ji}. \tag{1.2}$$

For an indoor-to-indoor link (e.g., link between an FAP and a femto user in another femtocell), the link gain can be given by

$$g_{ji} = K_{ji} d_{ji}^{-\alpha_j} \chi_{ji} L_w^{-2} f_{ji}. \tag{1.3}$$

In the following sections, we briefly outline the channel models defined by 3GPP for hierarchical networks and by ITU (International Telecommunication Union) for indoor propagation channels.

1.8.1 3GPP Model

For system simulations, 3GPP has defined the different physical-layer aspects and channel parameters for different deployment scenarios (e.g., homogeneous and heterogeneous deployment[3] scenarios) [30]. The path-loss between a small cell base station (SBS) and users takes into account-free space loss, indoor path-loss, indoor wall penetration loss, floor penetration loss, and outdoor wall penetration loss.

The dense urban deployment model for HeNBs, which is useful to model environments with many femtocells, is referred to as the dual-stripe model (Figure 1.9), where each block of deployment represents two stripes of apartments. Each stripe has $2 \times N$ apartments ($N = 10$ in Figure 1.9) and each apartment is of size $10\,\text{m} \times 10\,\text{m}$, and there is a street of width 10 m between the two stripes of apartments.

[3]In a heterogeneous deployment scenario, low power nodes such as femtocells, pico eNB, relays, and remote radio heads (RRHs) are placed throughout a macrocell.

For the dual-stripe model, the path-loss from a femto base station (FBS) to an FUE) is calculated as follows:

$$\begin{aligned} PL(dB) = 38.46 + 20\log_{10} D + 0.7 d_{2D,indoor} \\ + q \times L_{iw} + 18.3 n^{\frac{n+2}{n+1} - 0.46} \end{aligned} \tag{1.4}$$

where D (in m) is the distance between femtocell and user, $d_{2D,indoor}$ (in m) is the indoor distance, L_{iw} is the penetration loss of the indoor walls (5 dB), q is the number of indoor walls, and n is the number of penetrated floors.

The path-loss from FBS to FUE in another femtocell is calculated as

$$\begin{aligned} PL(dB) = \max(15.3 + 37.6\log_{10} D, 38.46 + 20\log_{10} D) + 0.7 d_{2D,indoor} \\ + q \times L_{iw} + 18.3 n^{\frac{n+2}{n+1} - 0.46} + L_{ow,1} + L_{ow,2} \end{aligned} \tag{1.5}$$

where $L_{ow,1}$ and $L_{ow,2}$ represent the penetration loss of outdoor walls (e.g., 20 dB).

The path-loss from FBS to MUE is calculated as

$$\begin{aligned} PL(dB) = \max(15.3 + 37.6\log_{10} D, 38.46 + 20\log_{10} D) + 0.7 d_{2D,indoor} \\ + q \times L_{iw} + 18.3 n^{\frac{n+2}{n+1} - 0.46} + L_{ow,1}. \end{aligned} \tag{1.6}$$

For macrocells, the path-loss from MBS to MUE is calculated as $15.3 + 37.6\log_{10}(D)$ [dB], where D (in m) is the distance. The path-loss from MBS to FUE/FBS can be calculated as $15.3 + 37.6\log_{10}(D)$ + Penetration loss (in dB).

For picocells, the distance-dependent path-loss from BS to UE is calculated as

$$\begin{aligned} PL_{LOS} = 103.8 + 20.9\log_{10} D \\ PL_{NLOS} = 145.4 + 37.5\log_{10} D \end{aligned} \tag{1.7}$$

where D is in km and the carrier frequency is 2 GHz.

1.8.2 ITU Model

For indoor environments, the ITU indoor propagation model estimates the path-loss of radio propagation which is applicable for carrier frequency ranging from 900 MHz to 5.2 GHz and for buildings with one to three floors [31]. According to this model, the indoor propagation path-loss is given by

$$PL_{indoor}(dB) = 20\log f + N\log D + L_{floor}(n) - 28 \tag{1.8}$$

where N is the distance power loss coefficient (which denotes the loss of signal power with distance), D is the distance (in m), L_{floor} is the floor penetration loss factor (an empirical constant which depends on the number of floors the radio waves need to penetrate), n is the number of floors between the transmitter and the receiver, and f is the transmission frequency (in MHz). When installed outdoor, the path-loss can be calculated as

$$PL = PL_{indoor} + L_{wall} \tag{1.9}$$

where L_{wall} is the exterior wall loss.

1.9 MULTI-TIER CELLULAR WIRELESS NETWORK MODELING AND ABSTRACTION

In a wireless network, the coverage and interference statistics highly depend on the network geometry. That is, the locations of the network entities and the users with respect to each other highly impact their performances[4]. Therefore, to model and design multi-tier cellular wireless networks, the network topology should be abstracted to a general baseline model that is able to capture the interactions among the coexisting network entities. For instance, the hexagonal grid-based model has been used traditionally for modeling, analysis and design of cellular networks.

In the grid-based model, it is assumed that the locations of the MBSs are known, follow a deterministic hexagonal grid, and all MBSs have the same coverage area. For macrocells, the hexagonal grid model is easy to simulate along with outdoor channel model considering path-loss, shadowing, and fading. However, due to the variation of the capacity demand across the service area (i.e., downtowns, residential areas, parks, sub-urban areas, etc.), and the infeasibility of deployment of MBSs in some locations (i.e., rivers, hills, rails, buildings, etc.), there are spatial randomness in the locations of MBSs and all MBSs do not have the same coverage area [32]. Hence, the assumption of hexagonal grids is violated, and therefore, is considered to be very idealized. Moreover, the grid-based model does not provide tractable results for ICI (i.e., interference from different BSs) for the simple one-tier cellular networks and the performance metrics of interest are usually obtained via Monte Carlo simulations [33].

Recently, a new network model based on stochastic geometry has been used to model homogeneous cellular networks as well as multi-tier cellular networks [32, 34]. In that model, it is assumed that the locations of the network entities are drawn from some realizations of a stochastic point process in the $\mathbb{R}^2$ plane. Although the locations of the MBSs are planned through a sophisticated network planning procedure and hence their locations are known, the locations of the MBSs with respect to each other highly vary from one location to another. The stochastic geometric network models not only explicitly account for the random locations of the network entities, but also provide tractable yet accurate results for the performance metrics of interest [32, 34]. Moreover, the results from the stochastic geometric network models are general and topology independent. The simplest, the most tractable and well-understood stochastic point process in the literature is the Poisson point process (PPP). A point process in $\mathbb{R}^d$ is a PPP if and only if the number of points within any bounded region has a Poisson distribution with a mean directly proportional to the d-dimensional volume of that region, and the numbers of points within disjoint regions are independent [35]. That is, the PPP assumes that the positions of the points are uncorrelated. Although the assumption on uncorrelated MBS locations is not realistic, it was shown in [32] that the PPP assumption provides a lower bound on coverage probability (i.e., the complement of the outage probability) and average achievable rate that is as much tight as the upper bound provided by the idealized

[4]Network entity is a generic term that will be used to denote both the MBSs or the SBSs.

grid-based model. In [34], it was shown that the PPP assumption is accurate to within 1–2 dB of the performance of an actual LTE network overlaid by heterogeneous tiers modeled as PPP.

A two-tier network is shown in Figure 1.10. Figure 1.10(a) shows a coexistence scenario for 5 MBSs and 14 SBSs.[5] As shown in the figure, the coverage of each network entity highly depends on its type (i.e., an MBS or an SBS) and the network geometry (i.e., its location with respect to other network entities). That is, assuming that each user will associate with (i.e., covered by) the network entity that provides the highest signal power, the coverage of each network entity will depend on its transmission power as well as the relative positions of the neighboring network entities and their transmission powers. For instance, if two MBSs have the same transmission power, a line bisecting the distance between them will separate their coverage areas. However, for an MBS with 50 times higher transmission power than an SBS, a line dividing the distance between them with a ratio of 50:1 will separate their coverage areas, and so on. Hence, it can be seen how the coverage of the network entities highly depends on the network geometry. In the same manner, if we have a test receiver at a generic location, it can also be shown that the interference statistics at that receiver also depends on the network geometry. Stochastic geometry can mathematically model these location-dependent phenomena and provide tractable results for the network performance metrics. For instance, assuming that both MBSs and SBSs follow independent PPPs, the network can be modeled via a weighted Voronoi tessellation as shown in Figure 1.10(b), and performance metrics such as outage probability and minimum achievable rate can be analyzed [34].

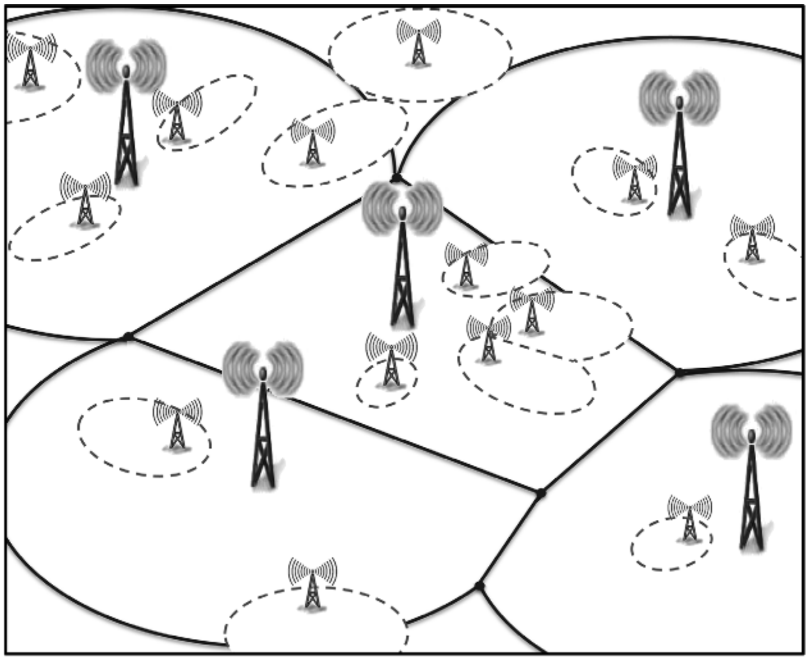
1.10 TECHNICAL CHALLENGES IN SMALL CELL DEPLOYMENT

The mass deployment of small cells gives rise to several technical challenges which are outlined below.

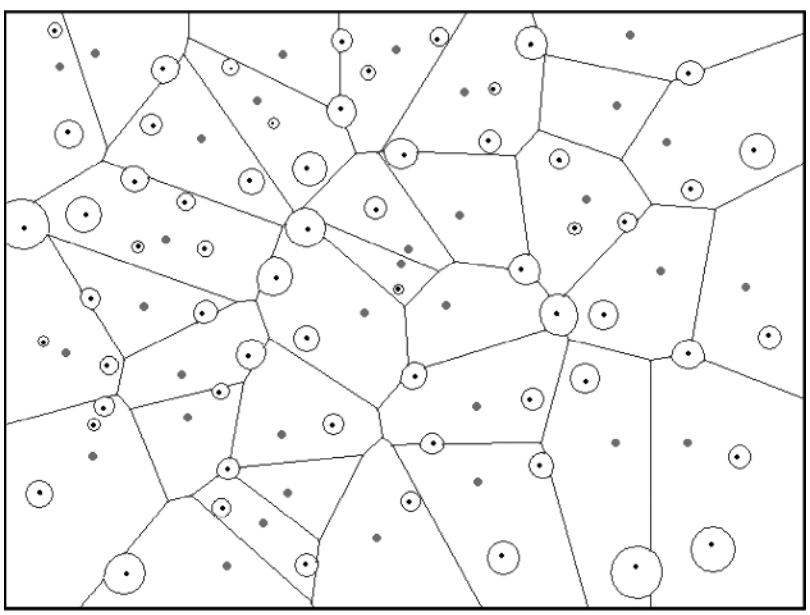
- *Resource allocation and interference management*: One of the major challenges is interference management between neighboring small cells and between small cells and macrocell. In general, two types of interferences that occur in a two-tier network architecture (i.e., a central macrocell is underlaid/overlaid with 3G/OFDMA femtocells, respectively) are as follows.

  Co-tier interference: This type of interference occurs among network elements that belong to same tier in the network. In case of a two-tier macrocell–femtocell network, co-tier interference occurs between neighboring femtocells. For example, a femtocell UE (aggressor) causes UL co-tier interference to the neighboring femtocell base stations (victims). On the other hand, a femtocell base station acts as a source of DL co-tier interference to the neighboring

[5] This figure is drawn for deterministic channel gains. For random channel fading, the same concept applies but the boundaries will be randomly curved lines and the coverage area of each network entity may be disjoint.



(a)



(b)

Figure 1.10 (a) A two-tier network model and (b) the network modeled as a weighted Voronoi tessellation (the larger dots represent the MBSs).

femtocell UEs. However, in OFDMA systems, the co-tier UL or DL interference occurs only when the aggressor (or the source of interference) and the victim use the same sub-channels. Therefore, efficient allocation of sub-channels is required in OFDMA-based femtocell networks to mitigate the co-tier interference.

Cross-tier interference (CTI): This type of interference occurs among network elements that belong to the different tiers of the network, that is, interference between femtocells and macrocells. For example, femtocell UEs and macrocell UEs (also referred to as MUEs) act as a source of UL CTI to the serving macrocell base station and the nearby femtocells, respectively. On the other hand, the serving macrocell base station and femtocells cause DL CTI to the femtocell UEs and nearby macrocell UEs, respectively. Again, in OFDMA-based femtocell networks, cross-tier UL or DL interference occurs only when the same sub-channels are used by the aggressor and the victim.

Distributed interference management schemes are required which satisfy the QoS requirements of the macrocell and small cell (e.g., femtocell) users and at the same time enhance the capacity and coverage of the network. In a CDMA femtocell network, interference caused to the macro users need to be controlled such that the QoS requirements of the macro users are satisfied while provisioning soft QoS for femtocell users. Also, the trade-off between the throughput and the power can be optimized for femtocell users. ICIC for femtocell networks is a major issue in 3GPP LTE-Advanced standardization. In LTE femtocells, backhaul-based coordination, dynamic orthogonalization, sub-band scheduling, and adaptive fractional frequency reuse (FFR) can be used for interference coordination. Advanced techniques such as interference cancellation and cooperative communication among BSs can be also used for ICI mitigation. In both open- and closed-access modes, signaling for coordinating CTI may be difficult. Since femtocells are not typically connected directly to the operator's core network, increased delay may occur in the backhaul signaling.

- *Cell association and admission control*: A simple approach for cell association is to assign each user to the "strongest" BS. With open-access and strongest cell selection, heterogeneous and multi-tier deployments may not worsen the overall interference conditions or even change the SINR statistics [5]. However, a better approach is *biasing* in which users are pushed into small cells. In OFDMA femtocells, biased users can be assigned orthogonal resources to the macrocell. The problems of optimal cell association, load balancing, optimal biasing, and admission control are open research issue. The optimal admission control decision should depend on factors such as distribution of users and locations of BSs, traffic patterns, information available to the mobiles and femtocell access points, etc.
- *Backward compatibility*: It may be infeasible to extensively modify the existing wireless infrastructure to accommodate the newly deployed SBSs. Hence, majority of the coexistence issues should be burdened to the SBSs.

Therefore, the protocol stacks at the SBSs need to take care of the convergence and backward compatibility issues.

- *Backhaul for small cells*: Designing a high capacity backhaul network (in particular, a wireless backhaul) for small cells is a big challenge. Lower cost backhaul solutions will be required for cost-effective deployment of small cells. The physical attributes of the backhaul solutions should be such that they are space-optimized. Also, due to the non-line-of-sight (NLOS) propagation environment, traditional point-to-point wireless backhaul solutions may not be suitable. In the backhaul network, the interference among the cell sites needs to be managed.
- *Limited cross-tier signaling and lack of completely centralized control*: Due to the large number of deployed SBSs, centralized control and optimization are infeasible. Moreover, cross-tier signaling via the IP network may be infeasible due to the large delay. Therefore, the resource allocation and interference management methods developed for multi-tier cellular networks with small cells should be developed such that they only involve limited signaling and take into consideration the limited capacity of the backhaul network.
- *Network performance analysis*: Precise characterization of interference in heterogeneous and multi-tier networks is important for the performance analysis and network dimensioning. By modeling the aggregate interference in a multi-tier set up under general fading scenarios, the coverage, outage, and capacity in the network can be analyzed. In this context, the analysis of UL SINR by modeling user location and BS location simultaneously, is a significant problem. Also, modeling and analysis of the effects of traffic burstiness (which affects interference) and packet-level performance analysis are crucial for design and optimization of multi-tier networks.
- *Handoff and mobility management*: An effective and efficient mobility management and handover scheme (macrocell-to-small cell, small cell-to-macrocell, and small cell-to-small cell) is necessary for mass deployment of small cells in UMTS and LTE networks [36]. The scheme should be able to reduce the network complexity and signaling cost, deal with different access modes and exhibit proper resource management beforehand to perform efficient handover. Also, vertical handoffs between licensed small cells and non-cellular access technologies such as Wi-Fi need to be considered. Lack of a low delay connection to the core network may result in significant handoff signaling delays. CDMA femtocells are typically unable to share a radio network controller (RNC) with a macrocell or other small cells for coordinating soft-handoffs. Therefore, architectural changes are required in the core network and small cell gateway functions.
- *Auto-configuration/self-organization, self-optimization, self-healing*: Since small cells are randomly deployed by the subscribers and are not location constrained, they must support a "plug-and-play" operation with automatic configuration and adaptation for their scalable deployment and maintenance

[37]. Therefore, efficient methods are required for automatic channel selection, power adjustment, and frequency assignment for autonomous interference coordination and coverage optimization. Also, the procedures for automatic registration and authentication, neighbor discovery, cell ID selection will be required for small cells. Self-organizing small cells will reduce the operational expenditure (OPEX). In this context, the *cognitive radio* concepts will be particularly useful to design these methods. The self-organizing and self-optimizing small cells will then be referred to as *cognitive small cells*. Cognitive small cells should be able to dynamically sense spectrum usage by the macrocell and adapt their transmissions accordingly. Cognitive small cells should be able to optimize the network parameters for transmission power, physical resources, access modes, admission control, handoff control, etc. For better convergence of the cognitive methods, semi-distributed schemes may be better. The small cells may also have the capability of shutting down and waking up autonomously to improve the energy efficiency (EE) performance of the FBSs. These type of small cells can be referred to as *green small cells*.

To deploy cognitive SBSs, there should be little or no modification required either in the existing MBSs or the mobile terminals so that backward compatibility is maintained. All the frequency bands are accessible to both the network tiers. Since the cognitive SBSs avoid interference from major interference sources by opportunistic access to orthogonal channels, topology-aware adaptive sub-channel allocation is achieved, and the spatial frequency reuse can be maximized via optimizing the spectrum sensing threshold for the cognitive SBSs. However, for the cognitive SBSs to be robust and adaptive to topological changes, the design parameters should be independent from the topology and account for the topological randomness. For instance, the spectrum sensing threshold is a very critical design parameter that should be tuned carefully while considering the topological randomness to achieve the required trade-off between the spatial frequency reuse and the experienced interference (which translates to outage probability).

- *Security*: The small cells (e.g., femtocells) need to be secured to prevent unwanted users from accessing them [38]. For example, femtocells are usually connected to the core network via DSL or broadband connection or wireless links (e.g., WiMAX) and vulnerable to a variant of malicious attacks such as masquerading, eavesdropping, and man-in-the-middle attack. Enhanced authentication and key agreement mechanisms are required to secure the femtocell networks [39].
- *Timing and synchronization*: SBSs such as the femto access points (FAPs) need to connect to the clock of the core network and use that clock for synchronization with the rest of the network. Also the packets need to be synchronized for transmission. Timing and synchronization is one of the major challenges for femtocells since synchronization over IP backhaul is difficult and inconsistent delays may occur due to varying traffic congestion [40].

  There are a number of options available for synchronization which include the following: timing over packet, global positioning system (GPS), and network listening over the air. Each of the options has its merits and demerits. For example, the GPS signals and the BS signals may not penetrate indoors. Therefore, a combination of methods may be required.

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