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# Preface

In the recent years, cellular networks have witnessed a significant increase in bandwidth-intensive and data-centric applications. Moreover, non-uniform user density and variations in the traffic types pose additional challenges to provide adequate Quality of Service (QoS) to all the users. With wireless communications approaching physical layer spectral efficiency limits, new approaches are being investigated at the network layer to address the requirements of QoS. Heterogeneous network or HetNet is one such approach. Heterogeneous network typically comprises of several low-power nodes which may be overlaid over an umbrella macro-cell network. Moreover, these low-power nodes may have different Radio Access Technologies (RAT). Thus, heterogeneous network could cover the span from cellular entities such as macro base stations, relay, pico, and femto nodes to non-cellular networks such as Wi-fi and plethora of sensor nodes eventually connecting to various Internet of Things (IoT) devices.

In this book, we consider the initial stage of heterogeneous networks and focus on meeting the mobility challenges posed by the overlay of low-powered cellular nodes in the context of Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) standard. This book is the first of its kind, compiling information on the LTE standard, which has been enhanced to address new mobility-related challenges in heterogeneous networks. Mobility management refers to the handover (HO) of a mobile user from one base station node to another in a cellular network. The objective of mobility management is to ensure continuous coverage by associating an appropriate base station node for a mobile user such that the desired QoS is maintained. While HetNets are intended to provide very high spectral efficiency and seamless coverage, the increased cell density and irregular network topology make mobility management a complex task in HetNets.

While mobility management in homogeneous networks is well understood, LTE standards are being enhanced to address the HetNet-specific mobility management challenges. This book identifies the related challenges and discusses solutions and the simulation methodology for modeling HetNet mobility cutting-edge information that was previously accessible only in the form of 3GPP specifications and documents and research papers. The book reviews the current LTE mobility framework, discusses some of the changes for enhancing mobility management in HetNets, and describes the measurement procedures, handover mechanisms and HO success/failure scenarios.

The book addresses these aspects in a succinct and easy to understand format, offering a valuable resource for researchers and professionals working in the area of HetNet mobility and a ready reference guide for practicing engineers and researchers. We have tried our level best to make this book self-contained and only for the well-known topics, have referred to the literature. Readers will find lucid explanation of the intricate mobility management related 3GPP procedures in this book.

In Chap. 1, we introduce the LTE cellular and heterogeneous network. We review the LTE architecture and describe the functionality split between different elements in the core and radio access networks. In Chap. 2, we emphasize the mobility management procedures as per the 3GPP standard. In this chapter, the network entry and connection setup procedures are explained along with details of the Radio Resource Control (RRC) states of the User Equipment (UE). We describe the handover procedures, signaling, and radio link management issues. Further, we explain the details of measurement performed by UE which assist in mobility management. We also discuss issues in mobility state estimation, which is required to appropriately set the measurement configurations in order to achieve improved handover performance.

In Chap. 3, we illustrate the 3GPP simulation and modeling aspects, which are important to understand the basic framework of LTE HetNets. The 3GPP specified models to illustrate the mobility scenarios in HetNet are discussed. It includes the models for topology, user mobility, handover, radio link failures, etc.

The initial releases of LTE focused on macro deployments but from Release 10 onwards, there has been increased emphasis on HetNets. HetNet deployment scenarios will differ depending on the network requirement in terms of coverage, traffic density etc. The coverage of low-power eNBs and macro eNB may be overlapping/non-overlapping. Based on the need of coverage/capacity improvement in indoor/outdoor environment, low-power eNBs may be deployed indoors/outdoors. Specifically, hotspot coverage can be provided by sparse deployment of low-power eNBs, while overall coverage improvement can be achieved by dense deployment of low-power eNBs. In Chap. 4, we consider all these HetNet deployment scenarios and the resulting system requirements and challenges associated with each of them. We discuss various deployment specific challenges and other issues such as mechanisms for small cell discovery and detection, and methods to achieve energy efficiency at network level and UE level. We also throw light on the features available in the 3GPP for cell range expansion and enhanced inter-cell interference coordination. Finally, we highlight the key performance considerations in HetNets including handover performance, achieving energy efficiency, and self-organization.

We then address the enhancements techniques that can be applied to the existing mechanism to improve the mobility performance for both UE and network. We begin with simple enhancements like consideration to handover failure events in the mobility state estimation because even the HO failure events are potential indicators of user mobility. Next, we consider assigning different weights for different HO events and analyze the behavior. Here, it is interesting to observe the role of cell sizes and different types of HO events in estimating UE speed. Finally, we illustrate the impact of UE trajectory on mobility state estimation. Thus, a couple of enhancement strategies for mobility state estimation are described, and their performances are compared in Chap. 5.

Lastly, we focus on how optimizations in the mobility-related parameters help in further improvement of the mobility performance. We elucidate those mobility-related parameters that can be optimized to improve the overall handover performance in HetNet scenarios. This includes scaling of various thresholds and timers, determining mobility state estimation procedures and various measurement configurations.

We hope you will enjoy reading this book and it will help you build the foundation to work on the mobility management aspects of heterogeneous cellular network. Happy reading!

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November 2016

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Nadeem Akhtar
Mahima Mehta

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May the journey of learning, sharing knowledge, and enjoying every bit of life continue in true spirit…

Mahima Mehta

# Contents

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Professor Karandikar is a founding member and currently the Chairman of the Telecom Standards Development Society (TSDSI), India's standards body for telecom set up in 2014. He holds several patents and has published contributions to IEEE standards, contributed chapters in books and a wealth of papers in international journals and conferences. Professor Karandikar is a two-time recipient of the award for excellence in teaching at IIT Bombay (2006 and 2011). He is a recipient of the IEEE-SA Standards Medallion, VASVIK Industrial Research Award 2010, and The National Academy of Sciences, India (NASI)-Reliance Industries Platinum Jubilee Award 2012.

**Dr. Nadeem Akhtar** is a principal wireless architect at Mojo Networks, where he works on Radio Resource Management (RRM) and Self-Organizing Networks (SON) algorithms for enterprise and carrier Wi-fi networks. He also provides guidance on planning and deployment of Wi-fi networks. Prior to this, Dr. Akhtar worked at the Centre of Excellence in Wireless Technology (CEWiT), Chennai, India where his research focused on L2 and L3 aspects of Long-Term Evolution (LTE) systems, particularly on issues related to mobility management, resource allocation, and interference coordination. He represented CEWiT at the 3GPP radio access network standardization meetings for five consecutive years. Dr. Akhtar has authored/co-authored a significant number of publications in international conferences, magazines, and journals and has contributed to two books.

Dr. Nadeem Akhtar received his B.Sc. (Eng.) degree in Electronics from Aligarh Muslim University in 1998, followed by an M.E. in Telecommunications from the Indian Institute of Science in 2000. He obtained his Ph.D. from the University of Surrey (UK) in 2007.

**Dr. Mahima Mehta** is an LTE Systems Engineer at Intel Mobile Communications, Bangalore. She works on the implementation of the latest 3GPP features in the cellular modem, focusing on L1 Controller. Earlier, she had been an academician and researcher for more than 12 years. She worked as Research Scientist at IIT Bombay for about a year. She led the India-UK Advanced Technology Centre (IU-ATC) project funded by Department of Science and Technology (DST), and also contributed to the Department of Electronics and Information Technology (DietY) funded project on Dual Connectivity LTE Wi-fi Solution for Broadband Wireless Networks. Dr. Mehta represented the IIT Bombay at 3GPP RAN2 standardization meetings. Having served as a Technical Program Committee member at various IEEE conferences, she has authored/co-authored several research publications in reputed journals and national/international conferences.

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# Acronyms

| | |
|---|---|
| 3GPP | Third Generation Partnership Project |
| AS | Access Stratum |
| BLER | BLock Error Rate |
| BSC | Base Station Controller |
| BTS | Base Transceiver Station |
| CAPEX | CApital EXpenditure |
| CDMA | Code Division Multiple Access |
| CN | Core Network |
| CP | Cyclic Prefix |
| CQI | Channel Quality Indicator |
| CRE | Cell Range Expansion |
| CRS | Cell-specific Reference Signal |
| CS | Circuit Switched |
| CSI | Channel State Information |
| eICIC | enhanced Inter-Cell Interference Coordination |
| eNB | Evolved Node B |
| EPC | Evolved Packet Core |
| EPS | Evolved Packet System |
| ETMSE | Enhanced Trajectory based Mobility State Estimation |
| GGSN | Gateway GPRS Support Node |
| GPRS | General Packet Radio Service |
| GSA | GSM Suppliers Association |
| GSM | Global System for Mobile communications |
| HARQ | Hybrid Automatic Repeat Request |
| HetNet | Heterogeneous Networks |
| HLR | Home Location Register |
| HO | HandOver |
| HOF | HandOver Failure |
| HSPA | High Speed Packet Access |
| ISI | Inter-Symbol Interference |

| | |
|---|---|
| LTE | Long Term Evolution |
| LTE-A | Long Term Evolution—Advanced |
| M2M | Macro to Macro |
| M2P | Macro to Pico |
| MAC | Medium Access Control |
| MCS | Modulation and Coding Scheme |
| MIB | Master Information Block |
| MIMO | Multiple Input Multiple Output |
| MME | Mobility Management Entity |
| MSC | Mobile Switching Centre |
| MSE | Mobility State Estimation |
| MTS/MToS | Minimum Time of Stay |
| NAS | Non-Access Stratum |
| OFDMA | Orthogonal Frequency Division Multiplexing |
| OPEX | OPerational EXpenditure |
| P2M | Pico to Macro |
| P2P | Pico to Pico |
| PAPR | Peak-to-Average-Power-Ratio |
| PBCH | Physical Broadcast CHannel |
| PDCCH | Physical Downlink Control Channel |
| PDCP | Packet Data Convergence Protocol |
| PDN-GW/P-GW | Packet Data Network Gateway |
| PDSCH | Physical Downlink Shared channel |
| PDU | Protocol Data Unit |
| PLMN | Public Land Mobile Network |
| PP | Ping-Pong |
| PRACH | Physical Random Access CHannel |
| PRB | Physical Resource Block |
| PS | Packet Switched |
| PSS | Primary Synchronization Signal |
| PSTN | Public Switched Telephone Network |
| PUSCH | Physical Uplink Shared Channel |
| QoS | Quality of Service |
| RAN | Radio Access Network |
| RAP | Random Access Procedure |
| RAT | Radio Access Technology |
| RE | Resource Element |
| RLC | Radio Link Control |
| RLF | Radio Link Failure |
| RLM | Radio Link Monitoring |
| RNC | Radio Network Controller |
| RRC | Radio Resource Control |
| RRM | Radio Resource Management |
| RSRP | Reference Signal Received Power |
| RSRQ | Reference Signal Received Quality |

| | |
|---|---|
| RSSI | Reference Signal Strength Indicator |
| SC-FDMA | Single Carrier Frequency Division Multiple Access |
| SGSN | Signaling GPRS Support Node |
| S-GW | Serving Gateway |
| SIB | System Information Block |
| SINR | Signal to Noise + Interference Ratio |
| SRB | Signaling Radio Bearer |
| SRS | Sounding Reference Signal |
| SS7 | Signaling System 7 |
| SSS | Secondary Synchronization Signal |
| TAU | Tracking Area Update |
| TB | Transport Block |
| ToS | Time of Stay |
| TTI | Transmission Time Interval |
| TTT | Time to Trigger |
| UE | User Equipment |
| UMTS | Universal Mobile Telecommunications System |
| UTRAN | UMTS Radio Access Network |
| VLR | Visitor Location Register |
| WLAN | Wireless Local Area Network |

# Chapter 1
# Introduction

Cellular wireless communication systems have witnessed significant technological advancements in recent years. The demand for ubiquitous, high-speed, always-on data connectivity has led to the rapid evolution of wireless technologies. In particular, the Third-Generation Partnership Project (3GPP) standards family has seen the evolution of Universal Mobile Telecommunications System (UMTS) into High Speed Packet Access (HSPA) and the more recent evolution to the Long-Term Evolution (LTE) and its advanced variant LTE-Advanced (LTE-A). LTE is expected to be a promising standard for mobile broadband. As per the estimates of the GSM Suppliers Association (GSA), there are 360 commercially launched LTE networks in 124 countries as of January 2015 and the deployment is gaining fast momentum.

LTE/LTE-A is designed to support very high data rates in both downlink (3 Gbps) and uplink (1.5 Gbps). This is achieved by a combination of carrier aggregation and advanced Multiple-Input Multiple-Output (MIMO) techniques. In addition, packet latency in the Radio Access Network (RAN) is significantly reduced by fast scheduling and fast Hybrid Automatic Repeat Request (HARQ). The minimum scheduling interval is reduced to 1 ms, whereas in HSPA, it is 2 ms. This requires tight coordination between physical and Medium Access Control (MAC) layers of the protocol stack. Another key aspect is the deployment of an end-to-end Internet Protocol (IP)-based network architecture with relatively fewer levels of hierarchy compared to 2G/3G networks. This reduces the end-to-end delay and at the same time, makes deployment more cost-effective in terms of OPerational EXpenditure (OPEX) and CApital EXpenditure (CAPEX). Furthermore, LTE supports inter-working with legacy 3GPP technologies such as Global System for Mobile Communication (GSM), HSPA and non-3GPP technologies such as Wireless Local Area Network (WLAN) and Code Division Multiple Access (CDMA).

LTE also supports Heterogeneous Network (HetNet) deployments, wherein macrocells are deployed for global coverage, while an underlay of pico/femto/relay cells is deployed for capacity/coverage enhancements and increased spectral efficiency per unit area. HetNets have their own unique challenges in terms of interference



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management and mobility. As a result, radio resource management in HetNets is one of the key research issues being addressed. In this book, we focus on mobility management in HetNets. The objective is to highlight some of the key issues in this area and describe a few indicative solutions.

This chapter provides an overview of LTE, highlighting major differences with respect to the legacy 2G/3G networks.

## 1.1 Overview of LTE Network

The first- and second-generation cellular networks have been designed primarily to carry voice traffic. The network architecture and the underlying radio protocols are inspired by Circuit-Switched (CS) systems in the Public Switched Telephone Network (PSTN). The first evolution in the form of General Packet Radio Service (GPRS) has introduced a Packet-Switched (PS) domain to the GSM network. GPRS employs Signaling System No. 7 (SS7)[1] protocol. Similarly, the 3G Universal Mobile Telecommunications System (UMTS) network features a dual CS/PS architecture to support both voice and data services. The GPRS/UMTS core network has further evolved to a completely packet-switched network in LTE, where there is no distinction between voice and non-voice traffic as both are carried as data packets. This is done by introducing an all IP core network, known as Evolved Packet Core (EPC) for signaling, voice and data traffic. This evolution is illustrated in Fig. 1.1.

Figure 1.2 shows the network architecture of GSM-GPRS and UMTS Radio Access Network (UTRAN). In case of GSM, Radio Resource Management (RRM) functions are distributed between Base Transceiver Station (BTS) and Base Station Controller (BSC) while in UTRAN, Node B and Radio Network Controller (RNC) are jointly responsible for RRM functions. Core Network (CN) is same in both cases. Voice traffic as well as call setup/management signaling are routed via a Mobile Switching Centre (MSC)-Gateway, while data traffic and session setup/management signaling are routed via Signaling GPRS Support Node (SGSN)-Gateway GPRS Support Node (GGSN).

Evolved HSPA (3GPP Release 7) enables direct tunneling in the user plane, which provides a direct connection from RNC to the GGSN, bypassing the SGSN, as shown in Fig. 1.3. This makes the network topology flexible and allows SGSN to be optimized for control plane. This has been taken one step further in 3GPP Release 8 by splitting the control and data planes in the core network, with dedicated nodes to handle control signaling and data.

[1]SS7 is a global standard for telecommunications defined by the International Telecommunication Union (ITU) Telecommunication Standardization Sector (ITU-T). SS7 standard is a signaling protocol which enables the network elements of telecommunication network to exchange control information and perform functions such as call setup and routing

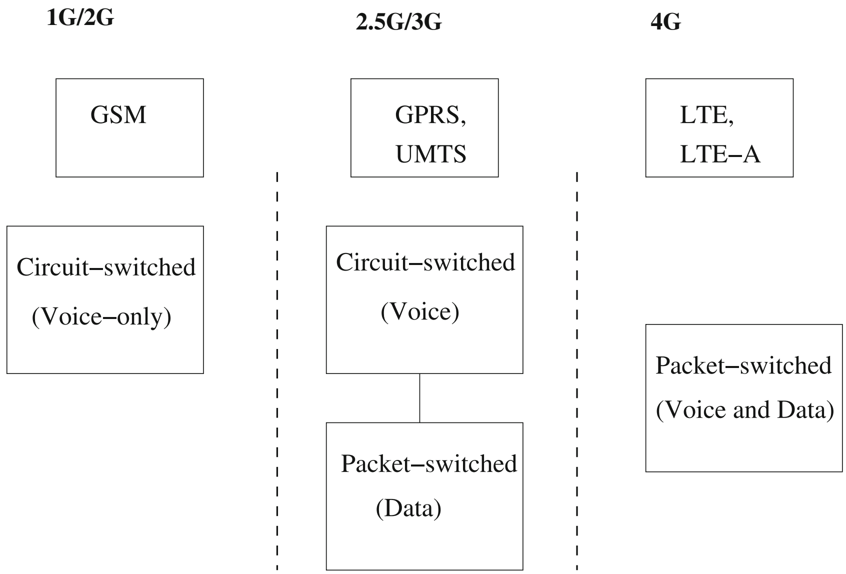


**Fig. 1.1** Evolution of cellular network architecture to LTE

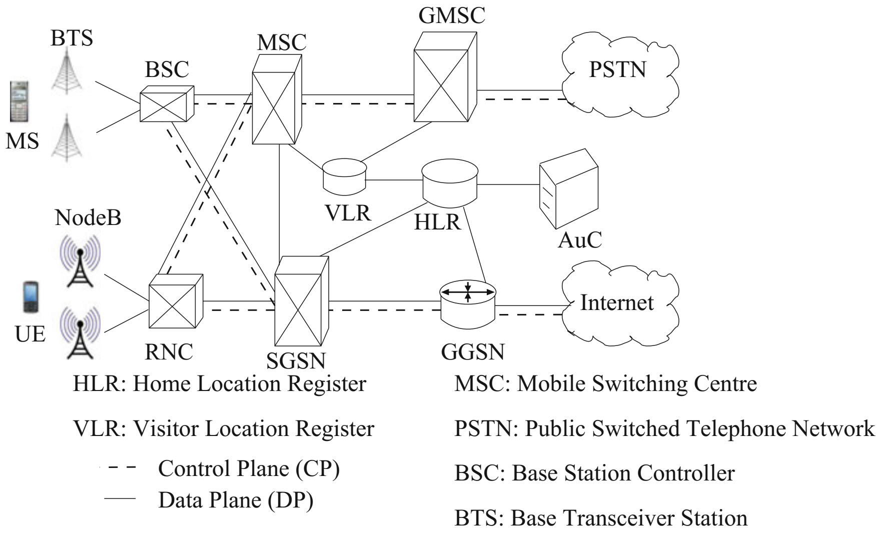


**Fig. 1.2** GSM-GPRS/UMTS network architecture

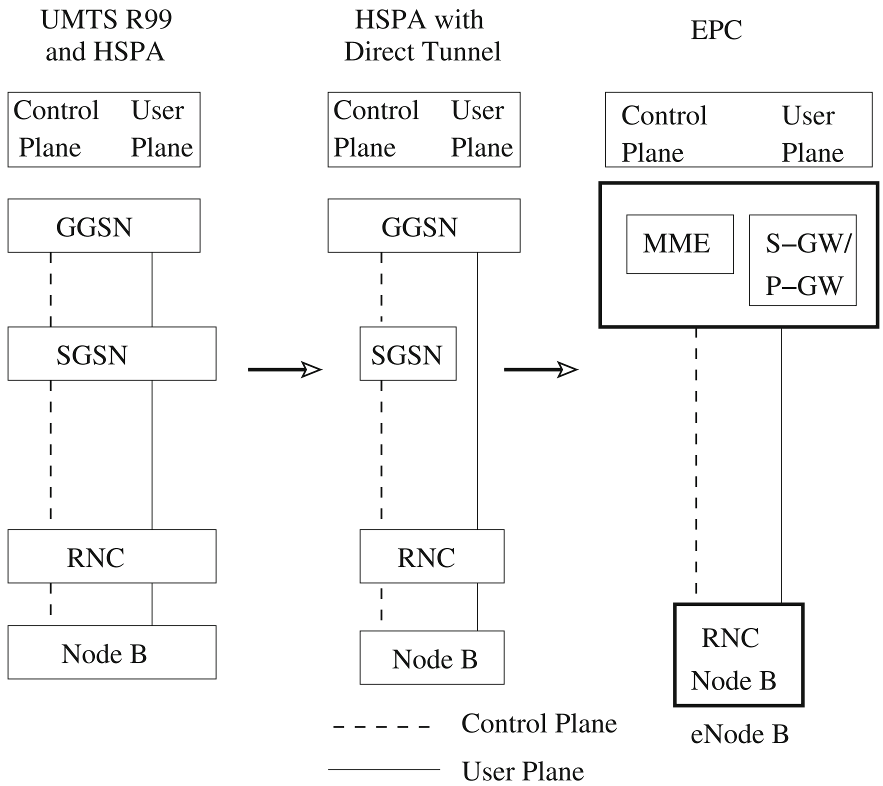


**Fig. 1.3** Evolution of 3G network architecture (to reduce latency in the data plane)

The core network evolution in 3GPP Release 8 has been driven by the following requirements:

1. Creation of a simplified network architecture,
2. Converged packet-based service delivery for real-time and non real-time applications,
3. Provision for end-to-end Quality of Service (QoS) management,
4. Inter-working with legacy 3GPP and non-3GPP radio access technologies, including mobility support.

The resulting network is referred to as Evolved Packet Core (EPC). EPC consists of the following network entities:

- Mobility Management Entity (MME),
- Serving Gateway (S-GW),
- Packet Data Network Gateway (PDN-GW or P-GW).

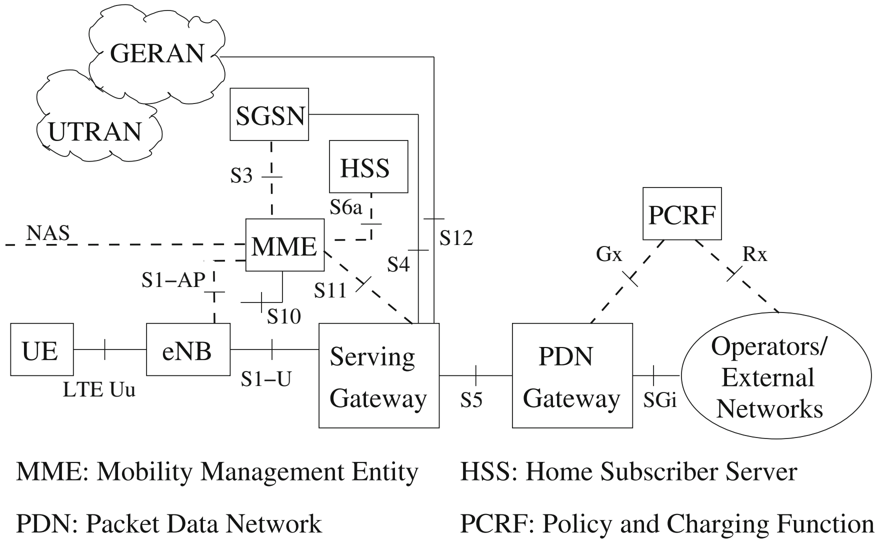


**Fig. 1.4** Network elements of EPS

EPC, along with a User Equipment (UE) and E-UTRAN is collectively known as the Evolved Packet System (EPS). Figure 1.4 shows a logical view of an EPS, including the connections with legacy 3GPP networks. The functions of EPS network entities are described in the following section.

## *1.1.1 Evolved Packet Core*

EPS follows the split control and data planes approach, with MME as the nodal control plane entity in EPC and S-GW and P-GW providing data forwarding functions.

Further details of the functions supported by the EPC entities are provided below.

### 1.1.1.1 Mobility Management Entity

The functions of MME can be divided into three groups:

1. Subscriber Management: At the time of network entry, UE is authenticated by MME. UE may support multiple ciphering and integrity protection algorithms. However, MME selects which algorithm(s) are to be used, and this procedure is referred to as ‘negotiation’. MME is connected to the Home Subscriber System (HSS), which stores user subscription information. MME also provides roaming management function.

2. Session Management: MME is responsible for the selection of appropriate S-GW and P-GW for associated UEs. It orchestrates signaling procedures for the establishment, modification, and deletion of the data bearers between an UE and P-GW. As part of bearer management, MME negotiates the associated QoS parameters and assigns the appropriate amount of resources.
3. Mobility Management: MME is the anchor for mobility between LTE and legacy 3GPP radio access networks such as GSM-GPRS and UMTS-HSPA. It is also responsible for location management of idle UEs via the tracking area update procedure. MME maintains the necessary network context for such UEs and pages them for incoming calls.

#### 1.1.1.2 Serving Gateway

S-GW interfaces EPC with the E-UTRAN and routes traffic between an UE and P-GW. There is always only one S-GW associated with UE. The selection of S-GW is performed by the MME, based on factors such as network topology and UE location. S-GW is typically chosen such that data path latency is minimized. If the S-GW supports multiple interfaces toward the eNB, then MME ensures that load is fairly distributed across the interfaces. S-GW acts as the mobility anchor for inter-eNB and inter-3GPP handovers. Incoming data packets are buffered at the S-GW, while bearer paths are being switched during inter-eNB handover. In the case of inter-3GPP mobility, S-GW plays the same role as the GGSN in GSM/UMTS networks (i.e., 2G/3G networks). For idle UEs, S-GW buffers incoming packets while MME attempts to page the UE. Data accounting and Lawful Interception (LI) functions are also hosted by S-GW.

#### 1.1.1.3 Packet Data Network Gateway

PDN-GW or P-GW connects the EPC with external public and private networks such as the global Internet. P-GW allocates IP addresses to a UE. In general, a UE may connect to multiple external networks. Therefore, a UE may be attached to multiple P-GW nodes. For instance, a user may need to simultaneously access the Internet and the operator's own portal. P-GW creates tunnels via GPRS Tunneling Protocol (GTP) to the S-GW for routing data traffic. It is responsible for packet filtering, enforcing QoS policies, and collecting and accounting data. For this purpose, it interfaces with the Policy and Charging Rules Function (PCRF).

MME, S-GW, and P-GW are logical entities only and their physical realizations are vendor-dependent. In the extreme case, a vendor may choose to combine the MME, S-GW, and P-GW in the same hardware.

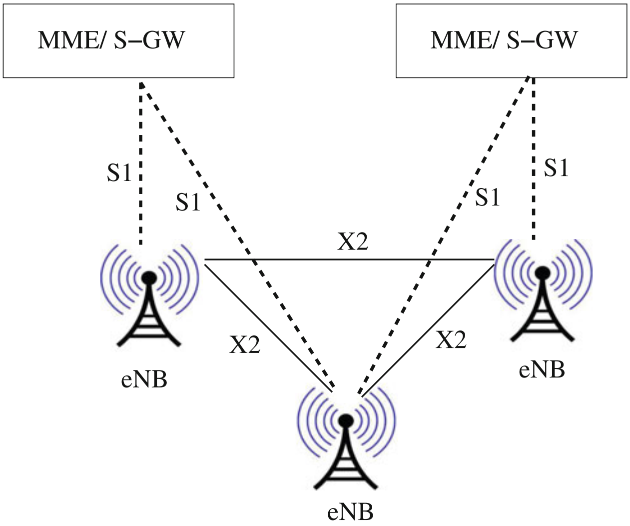


**Fig. 1.5** Evolved UTRAN (adapted from [2])

### *1.1.2 Evolved UTRAN*

The Evolved UTRAN (E-UTRAN) consists of eNodeBs (eNBs),[2] interconnected by X2 interface, as shown in Fig. 1.5. eNB is responsible for all Radio Resource Management (RRM) functions and terminates the Radio Resource Control (RRC) protocol. It periodically broadcasts system information, which facilitates initial network access for UEs.

During the network entry process, the eNB sets up an RRC connection with the UE, which is then used for all radio connection management-related control signaling between the two entities. RRC also provides the container for transporting signaling messages between UE and MME. The eNB performs radio admission control and manages the signaling and data radio bearers. It is also responsible for dynamic resource allocation and packet scheduling, taking into account QoS, channel quality, and UE capabilities. It configures the UE to report periodic/aperiodic Channel State Information (CSI), which are used while taking scheduling decisions. In addition, eNB also configures the UE to measure serving and neighbouring cells and report the measurements, if certain threshold criteria are met. At the time of handover, eNB uses these reports to determine the target eNB. During the handover process, the eNB is responsible for associated security handling and providing the necessary key and algorithm information to the target cell by sending UE context information to the target eNB over the X2 interface. Data buffered at the source eNB while handover is in progress, is also transferred to the target eNB on the X2 interface.

[2]eNodeB (eNB) is a base station in a cellular network. This nomenclature is as per 3GPP LTE standard.

eNB interfaces with EPC via S1 interface. The S1-U interface connects the eNB with a S-GW while the S1-C interface connects the eNB with an MME. There can be many-to-many connections between eNBs and MMEs as well as between eNBs and S-GWs. This approach, known as pooling, provides redundancy for connection and helps achieve load balancing.

From the UE perspective, the protocols can be divided into Access Stratum (AS) and Non-Access Stratum (NAS). AS is responsible for functions related to radio network access, radio connection control and data transfer between UE and eNB. NAS protocol is used to communicate control signaling for mobility and session management between the MME and UE, which is required to maintain IP connectivity between UE and PDN-GW. NAS messages are piggybacked onto AS control messages in the RAN.

### *1.1.3 LTE Radio Interface*

Orthogonal Frequency Division Multiplexing (OFDM) is used for the downlink transmissions in LTE. In OFDM, the carrier bandwidth is divided into a set of narrow-band subchannels (or *subcarriers*). The subcarrier bandwidth is such that each subcarrier experiences flat fading. This makes the system robust to frequency-selective fading. OFDM signal design also ensures that the subcarriers are orthogonal. In the time domain, the smallest unit of transmission is a symbol. The transmission of such symbols is distributed over a group of subcarriers. This type of resource structure enables flexible, channel-dependent dynamic scheduling. A guard interval is provided between symbols, known as the Cyclic Prefix (CP), to prevent Inter Symbol Interference (ISI) caused by delay spread.

In LTE, a radio resource is defined in terms of time, frequency as well as space dimension. The spatial dimension relates to the multiple antenna ports at eNB. For each antenna port, the time–frequency resource grid has the structure shown in Fig. 1.6. A 10 ms radio frame is divided into ten subframes, each of which has two 0.5 ms time slots. Each slot contains six or seven OFDM symbols, depending on the length of CP. In frequency domain, a group of 12 subcarriers with subcarrier spacing of 15 kHz constituting an overall bandwidth of 180 kHz, for one slot duration is known as a *Physical Resource Block* (PRB). The smallest resource unit is known as *resource element*, which comprises one subcarrier for one slot duration.

Instead of assigning all the subcarriers in a time slot to only one user, multiple users can be allocated different sets of subcarriers in the same time slot. Such an OFDM-based multiple access scheme, which allows simultaneous scheduling of multiple users, is known as Orthogonal Frequency Division Multiple Access (OFDMA). OFDMA exploits the fact that each subcarrier may exhibit different fading behavior to different users due to time-variant and frequency-selective wireless channel. Therefore, each user can be assigned the set of subcarriers, where it is experiencing good channel conditions. This opportunistic scheduling achieves multiuser diversity,

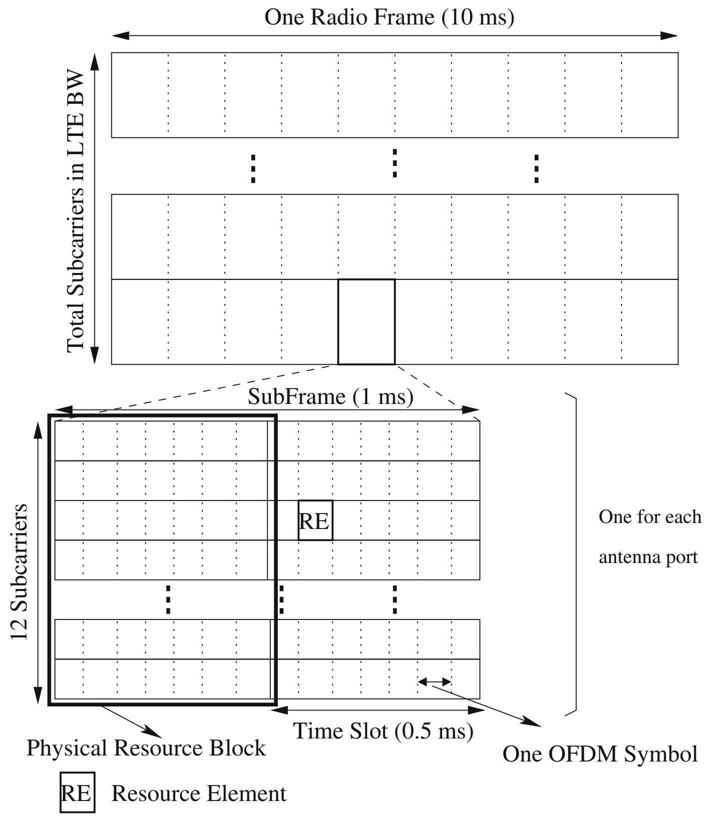


**Fig. 1.6** Resource structure in LTE

thereby improving spectral efficiency. The subcarriers allocated to a user maybe contiguous or non-contiguous.

Single-Carrier Frequency Division Multiple Access (SC-FDMA) is used for uplink transmissions. The reason for choosing a different uplink scheme is that OFDM has a high Peak-to-Average Power Ratio (PAPR), which makes it energy inefficient for the uplink transmission. The key difference in SC-FDMA as compared to OFDMA is that multiplexing of users across frequency domain in the same symbol is not possible.

Scheduling decisions for downlink and uplink transmissions are made by the eNB in every Transmission Time Interval (TTI), which is specified as 1 ms in LTE. These are communicated to UEs via Physical Downlink Control Channel (PDCCH), which is transmitted in every TTI. Physical Downlink Shared Channel (PDSCH) is used for transmission of user data and system information in downlink, while Physical Uplink Shared Channel (PUSCH) is for uplink data transmissions. The unit for data transmission at the physical layer is Transport Block (TB), which corresponds to a

Medium Access Control (MAC) layer Protocol Data Unit (PDU). One or two (in case of spatial multiplexing) transport blocks are passed from MAC to physical layer once per TTI. The size of a TB depends on the number of resource blocks allocated and the chosen Modulation Coding Scheme (MCS). eNB selects the modulation and coding scheme for downlink and uplink, based on downlink Channel State Information (CSI) feedback from UE and uplink CSI measurement done by the eNB, respectively.

## 1.2 Heterogeneous Network

The need for spectral efficiency improvement in cellular wireless networks arises due to the tremendous increase in bandwidth intensive and data-centric applications, which are witnessing a shift in focus from voice to data services. In addition, the non-uniform user density and variations in the traffic pattern make it difficult to ensure QoS guarantees to all users at all times. Hence, spectrally efficient and highly adaptive resource management techniques are needed. As the cellular networks are nearing theoretical capacity limits after implementing the possible physical layer enhancements, approaches based on network layer are being investigated for further capacity improvement. One such approach is that of Heterogeneous Network (HetNet), envisioned to address the area spectral efficiency challenge by deploying many low-power (or small cell) eNBs, overlaid on the umbrella macrocell network as shown in Fig. 1.7. Such a deployment may ensure ubiquitous coverage, QoS satisfaction to users and improved resource utilization, in addition to higher area spectral efficiency.

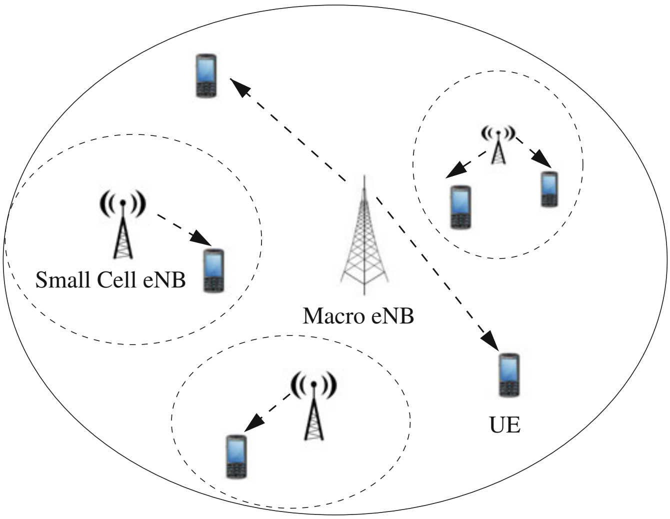


**Fig. 1.7** A heterogeneous cellular network

The low-power nodes comprising a HetNet may be relay, femto or pico base stations (eNodeB or eNB in LTE terminology). These are all distinct in terms of their functionality, deployment, and operational characteristics. Relays have wireless backhaul and are typically deployed for the purpose of coverage extension. However, these may be used for capacity enhancement also. Relays are operator-deployed nodes with open access.[3] In this respect, picos are similar to relays. However, picos are essentially low-power macro-eNBs, with similar backhaul connectivity. Picos achieve improved area spectral efficiency and QoS experienced by users, by offloading traffic from macro-eNB. Unlike relay and pico eNBs, femto eNBs are generally user-deployed with backhaul provided by an existing Internet connection, e.g., digital subscriber line or fiber at residential premises. Femto eNBs may support open, closed[4] or hybrid[5] access and are generally used to provide improved coverage and QoS to the indoor users. These distinctions in small cell nodes introduce different challenges in their deployment. Here, we discuss HetNets in the context of pico cells, although the discussion also applies to femtos and relays. Note that we refer to pico cells as small cells in this text. In HetNet deployment, small cells may deploy same or different Radio Access Technology (RAT) compared to that of the macrocell network. RAT could be one of these, GSM, CDMA, LTE, WLAN, etc.

The HetNet coverage/capacity gains come at the cost of increased network complexity. In particular, deployment of low-power nodes within the macrocellular coverage area dramatically alters the interference scenario by creating a vastly increased number of cell-edge zones. At the same time, the mobility scenario is also affected, because of a greater likelihood of handovers as a UE moves through a network of macro and relay/pico/femto cells. Thus, radio resource management in HetNets becomes much more challenging. Newer releases of LTE have attempted to address some of these issues. In particular, interference coordination and mobility management have received significant attention within the 3GPP standardization group.

## 1.3 Organization

The rest of this book is organized as follows. Chapter 2 gives a detailed view of mobility management procedures in LTE. Chapter 3 provides an overview of the aspects related to 3GPP simulation methodology and highlights the implementation considerations in such a model. Chapter 4 focuses on mobility in Heterogeneous Network (HetNets), highlighting the key technical challenges and related performance issues. Chapter 5 discusses some of the enhancements available in the literature for the mobility state estimation in HetNets. Chapter 6 illustrates the procedures available in the literature for the optimization on mobility related parameters.

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[3] In open access, there is no restriction on users for association.

[4] In closed access, only a restricted set of users are allowed association.

[5] In hybrid access, a set of users have closed access, while others are allowed access to limited resources.

**Bibliographic Notes**

The overall description of E-UTRA and E-UTRAN is given in [2]. The estimate of the number of commercially launched LTE networks across the world is given in [40]. An overview of LTE/LTE-A networks and the associated benefits and challenges are discussed in [17]. The description of LTE radio interface is from [42]. The definition of radio resource and other physical layer aspects of LTE is adapted from the 3GPP specifications document [1]. The aspects related to spectral efficiency improvement in an OFDMA based LTE network are discussed in [22, 42]. An introduction to the heterogeneous network environment and its deployment scenarios is given in [5–7, 36].

# Chapter 2
# Mobility Management in LTE Networks

To provide ubiquitous coverage, it is essential to ensure that cellular users are able to access the service as they move across the network coverage area. While the LTE radio interface is optimized to support low-to-medium mobility scenarios, it can also support very high-speed users. At the same time, the higher layer protocols must also be able to handle UE mobility by finding an appropriate serving cell, which offers the best radio link condition for a moving UE such that the ongoing application sessions are not disturbed and the desired QoS is also maintained.

In general, a UE may be in idle or connected mode, with respect to the network. An idle UE has no signaling or data bearers associated with it. In other words, no network/radio resources are allocated to it. An idle UE's location is known to the MME only within a contiguous groups of cells, called tracking area. While an idle UE is not attached to any eNB, it is required to select a suitable cell and *camp* on it. The procedure of an idle UE selecting and camping on a cell is known as *Cell Selection*. An idle UE, while camping on a cell, continues to monitor other cells and may decide to camp on another cell if radio conditions change, for example, due to UE mobility. This process is known as *Cell Reselection*. The criteria to be adopted by an idle UE for selecting/reselecting a cell are communicated to the UE via the system information broadcast messages periodically by each cell.

While in connected state, a UE may need to switch to another eNB because of the degradation in the received signal power from the serving eNB, which may happen due to user mobility. The process of a connected mode UE changing its association from one eNB to another is referred to as *HandOver* (HO). In LTE, the HO process is controlled by the eNB. Mobility management refers to determining an appropriate cell for camping and an appropriate eNB for association, for an idle and connected mode UE, respectively, performing the required signaling exchange, and ensuring minimal delay while avoiding unnecessary cell changes.

In this chapter, we first describe the connection setup procedure for a UE that is admitted to an LTE network, followed by a discussion on the mobility management procedures for both idle and connected mode UEs. Further, in this chapter, we



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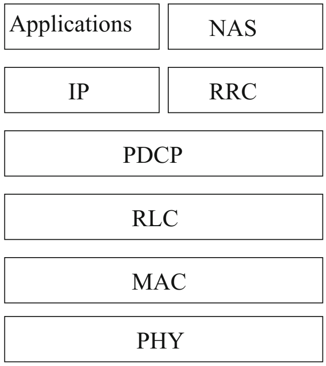


**Fig. 2.1** LTE protocol stack

explain the radio link management in LTE networks and illustrate the radio resource management and radio link monitoring procedures. We also discuss the mobility state estimation in an LTE network.

## 2.1 Connection Management in LTE Network

This section briefly reviews the LTE protocol stack (Fig. 2.1). In an LTE network, the physical layer implements Orthogonal Division Multiple Access (OFDM) in downlink and Single-Carrier Frequency Division Multiple Access (SC-FDMA) in uplink for communication on the access link (between UE and eNB). MAC sublayer maps the transport channels[1] to physical channels,[2] performs packet scheduling, and provides uplink timing advance to UEs. Radio Link Control (RLC) sublayer is responsible for providing reliable packet transport services, segmentation/concatenation and in-sequence delivery of upper layer data units. Packet Data Convergence Protocol (PDCP) sublayer handles the tasks of IP header compression/decompression, ciphering/deciphering of user data, and integrity protection of both user-plane and control-plane data.

The protocol stack is split into user plane and control plane above PDCP. In the control plane, there is RRC protocol which is used for signaling between UE and eNB. RRC layer is responsible for initial connection setup, radio resource configuration/reconfiguration, and mobility management of connected UEs. In addition, RRC serves as a transport protocol for NAS signaling messages between a UE and its MME.

In this chapter, we focus on RRC protocol. We briefly discuss the RRC states of a UE and review the connection setup and handover management procedures.

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[1]The data and signaling messages between MAC and PHY layer are communicated via transport channels.

[2]The data and signaling messages between different PHY layers are communicated via physical channels.

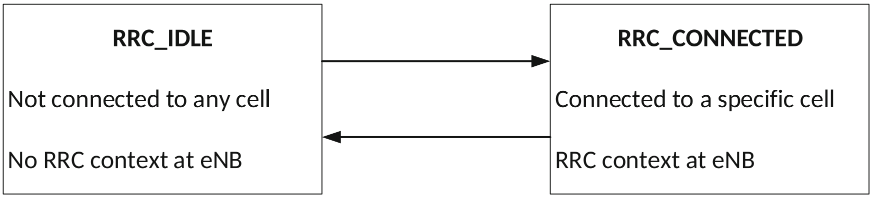



**Fig. 2.2** RRC states of user equipment

### *2.1.1 RRC States of UE*

A UE is considered to be in one of the two states, *RRC_IDLE* and *RRC_CONNECTED* and it can transit from one state to another as shown in Fig. 2.2. In both states, the UE is associated with a MME, which maintains the UE context. This context consists of UE-specific information such as its identity, mobility state, security parameters, and tracking area. When a UE transits from idle to connected state, the MME communicates this UE context to the chosen eNB, which is used to create signaling and data radio bearers for communication and manage the UE while it stays in connected state. When the RRC connection is released by the eNB, the UE context is deleted from the eNB while it is still maintained at the MME. The RRC connection may be released, for example, when the UE is handed over to another eNB or moves to idle state.

An *RRC_IDLE* UE needs to camp to an appropriate cell for two reasons: (1) to monitor the paging channel for notification regarding incoming service requests and (2) acquire System Information Block Type 1 (SIB1) which contains parameters to control the cell selection and reselection process. A UE in *RRC_IDLE* state is not connected to any specific cell, and, therefore, there is no RRC connection established for such UEs in the E-UTRAN. Such UEs wake up periodically to check whether there is any paging message for them from the network. In case of any paging message, the UE initiates the procedure (discussed in the next section) to establish RRC connection with the eNB controlling the cell on which the UE is camped. If the connection setup is successful, the UE moves into connected state. This transition from idle to connected state may also be triggered when: (1) UE initiates a request to send data on the uplink; (2) UE moves out of its current Tracking Area (TA) and performs the procedure to update the network about its new location. This procedure is called Tracking Area Update (TAU).

An *RRC_CONNECTED* UE requires association with an appropriate eNB to (1) monitor PDCCH for information about downlink scheduling assignments and uplink resource grants; (2) send/receive data and signaling on the shared data channels, as per the scheduling information received on PDCCH. In this state, RRC connection is available between UE and the serving eNB, which is used to exchange signaling messages via Signaling Radio Bearers (SRBs). The messages originating from the UE may terminate at the eNB or, in case of NAS signaling, forwarded to the MME. NAS messages originating from MME are forwarded to the UE by the eNB in RRC containers. eNB may create and send its own RRC messages to the UE. These typically carry configuration parameters, for example, channel state measurement configuration. After the establishment of RRC connection, corresponding RRC context is maintained at the eNB until UE moves out of the coverage of eNB leading to termination of RRC connection.

### 2.1.2 Connection Setup Procedure

The prerequisite for RRC connection setup is that UE acquires cell identity and obtains time and frequency synchronization with the eNB for both downlink and uplink. To do so, the UE needs to decode the Primary Synchronization Signal (PSS) and the Secondary Synchronization Signal (SSS). In addition, the UE has to receive and decode the Master Information Block (MIB) and a broadcast message periodically transmitted by the eNB on Physical Broadcast CHannel (PBCH). MIB contains parameters which are essential for the UE during initial access to the network, such as downlink system bandwidth and system frame number. Next, the UE acquires information about Public Land Mobile Network (PLMN), Tracking Area (TA) ID, cell ID, radio, and core network capabilities, via the system information broadcast messages. After this, the UE achieves uplink synchronization by performing Random Access (RA) procedure on Physical Random Access CHannel (PRACH).

The following triggers are there to initiate the random access procedure: (1) during initial access to network, (2) radio link failure, (3) handover, (4) to achieve UL synchronization and (5) to request for scheduling grant. RACH preamble contains information about the resources required by UE. These resources could be used for control and/or data signaling because RA Procedure (RAP) is also used by connected mode UEs to request eNB for scheduling grant. RAP is of two types: contention-based and non-contention-based. Contention-based RAP is used for uplink synchronization for UEs in the coverage of an eNB, whereas non-contention-based RAP is used for UEs undergoing handover, where a reserved set of RACH preambles are used to avoid contention. The completion of the RAP does not imply that UE is attached to the network. It requires UE to establish an RRC connection with eNB to initiate NAS attach procedure and request for resources. This attach procedure is mandatory for UE during the initial network access. After successful attachment with the network, UE can request for the network services by establishing RRC connection.

Having completed the RA procedure, the UE can initiate RRC connection setup, which involves the following steps:

- The RRC connection setup is initiated by sending *RRCConnectionRequest* message to the eNB. This message contains Temporary Mobile Subscriber Identity (TMSI) of that UE.
- If the eNB accepts the request, it sends *RRCConnectionSetup* message to the UE, which includes the initial radio resource configuration parameters. These parameters may be either UE-specific or follow a default configuration in which

the parameter values are as specified in the RRC specification. eNB may decide to reject the RRC connection request when the cell is congested.

- On receiving the initial radio resource configuration parameters, UE responds with the *RRCConnectionSetupComplete* message, which contains information like the selected PLMN identifier. Then, eNB determines an appropriate MME, which selects a Serving Gateway (S-GW) to which UE can connect. This connection is established via the S1–CP interface,[3] which is used for signaling between UE and MME.

The RRC connection establishment procedure is followed by initial security activation and Signaling Radio Bearer 2 (SRB2) establishment. SRB2 is used for subsequent NAS signaling.

### *2.1.3 Handover Procedure*

An *RRC_CONNECTED* UE continuously monitors the signal strength of its serving cell to ensure that link quality is sufficiently good to support the QoS requirements of its ongoing sessions. Whenever the signal strength begins to deteriorate, the UE is triggered to measure neighboring cells and hand over to an appropriate target cell at the opportune time. To illustrate the HO procedure, we consider the scenario in Fig. 2.3 where a UE moves from location-A in Cell-1 to location-B in Cell-2. Based on the link budget, a specific received signal power is sufficient to achieve a minimum acceptable service quality at the UE. A slightly stronger signal power ($+\Delta$), represented by *Handover Threshold* in the figure, is chosen as the trigger to initiate neighbor cell measurements. When the measured signal power from the serving node becomes less than the *Handover Threshold*, UE begins the measurement of received signal power from the neighboring nodes. These measurements from neighboring cells are compared, and the strongest cell is chosen as the target for HO. To ensure a successful HO, the process must be completed before the signal power from the serving cell becomes lower than the minimum acceptable level, else HO failure may happen due to the loss of radio connectivity. Figure 2.3 shows a situation where the HO process is completed before the measured signal from Cell-1 drops below the minimum acceptable signal power, resulting in successful HO. This scenario is represented by *Signal-1* while the handover failure scenario is indicated by *Signal-2* in the figure.

The choice of $\Delta$ can affect the HO performance in two ways: (1) if $\Delta$ is too low, it may result in late HO, increasing the chance of HO failure due to insufficient time available to complete the HO, and (2) if $\Delta$ is high, it may cause premature HO, which may be unnecessary too. In addition, UE speed impacts the HO performance. Higher the speed, lesser is the time available for measurements and HO processing and vice versa. The mobility management challenge is to ensure fast and timely handover while minimizing signaling overhead and unnecessary HO.

[3] S1 is the interface between eNB and MME, and between eNB and S-GW.

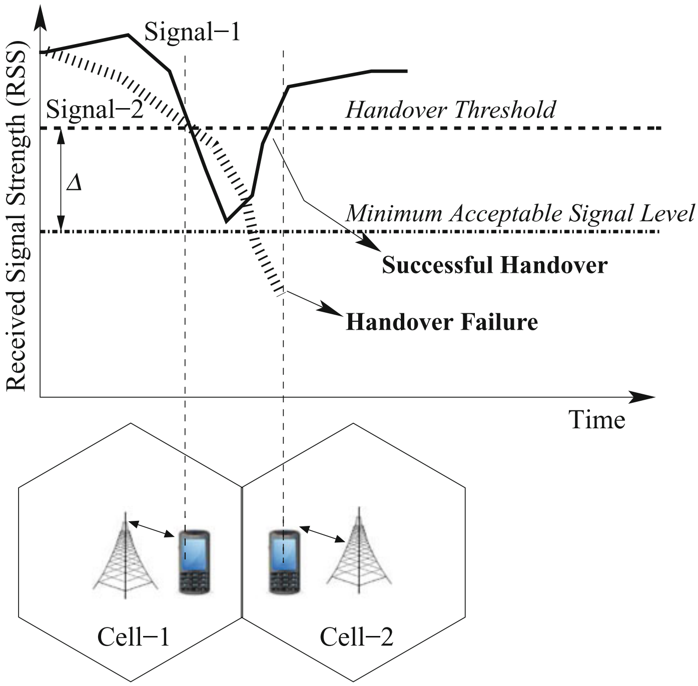



**Fig. 2.3** Coverage-based handover in cellular networks

#### 2.1.3.1 Handover Classification

There are several ways to categorize handovers. Depending on the handover triggering event, it can be classified as:

- *Quality-based*: HO based on signal quality is initiated when better signal quality is experienced from the neighboring cell(s), even if the signal quality from the serving node is above the acceptable threshold.
- *Coverage-based*: HO based on coverage is initiated when the serving node is unable to provide coverage to a UE. In this case, HO becomes essential to ensure uninterrupted service. An illustration of the coverage-based HO is given in Fig. 2.3.
- *Load-balancing*: HO based on load balancing is initiated by the network to balance the traffic load across different cells to improve resource utilization.

Based on the frequency of operation and deployed radio access technology, HOs can also be classified as:

- *Intra-RAT*: Intra-RAT HO includes all HOs that are performed on cells that use the same radio access technology:

- *Intra-frequency*: HO that is performed when the carrier frequency of the serving cell and that of the target cells are same is called Intra-frequency HO. In an LTE-specific scenario, we can classify intra-frequency handovers in the following way. Based on the signaling interface used, there can be two types of HOs for Intra-LTE case: X2-HO and S1-HO. The X2-HO is used for inter-eNB HOs, while the S1-HO is triggered only when either there is no X2 interface between the two eNBs or the configuration of source eNB indicates S1-HO to be triggered.
- *Inter-frequency*: HO that is performed when the carrier frequency of the serving cell and that of the target cells are different is called Inter-frequency HO. In this case, UE needs to withhold all its ongoing uplink and downlink transmissions, switch radio to the carrier frequency of the target cells, and then perform measurements.

- *Inter-RAT*: HOs that are performed on cells using different radio access technologies (such as GSM and CDMA.) are classified as inter-RAT HOs.

## 2.2 Idle State Mobility

E-UTRAN provides a list of neighboring frequencies and cells which can be considered for cell reselection by an idle mode UE. This list is known as *white-list*. The network assigns priority to each listed frequency and cell, which is communicated to UE via System Information Block Type 1 (SIB1) message[4] or during RRC connection release procedure. Thus, UE must measure frequencies and RAT in the order of priority indicated by the eNB. When the received signal power measured by UE from the camped cell falls below a threshold $S_{intraSearch}$ [21], UE can start measuring the received signal power from other cells on the same frequency (intra-frequency measurements). If the received signal power from the camped cell falls below another threshold $S_{nonintraSearch}$, UE can measure other frequencies or RATs (inter-frequency and/or inter-RAT measurements) with equal or lower priority. If priority is not assigned to any cell by E-UTRAN, it is not eligible to be considered for cell reselection. In case of equal priority assignment to multiple cells, the cells are ranked based on the radio link quality and those with better link quality become the potential candidates for reselection. UE performs measurement on the frequencies of all the candidate cells and selects that cell for reselection whose measurement is consistently better than that of all other cells. Note that more the frequencies UE performs measurement on, greater is the UE battery power consumption.

[4]In addition, the parameters used to control intra/inter-frequency and inter-RAT cell reselection are communicated via SIB3-SIB8 messages.

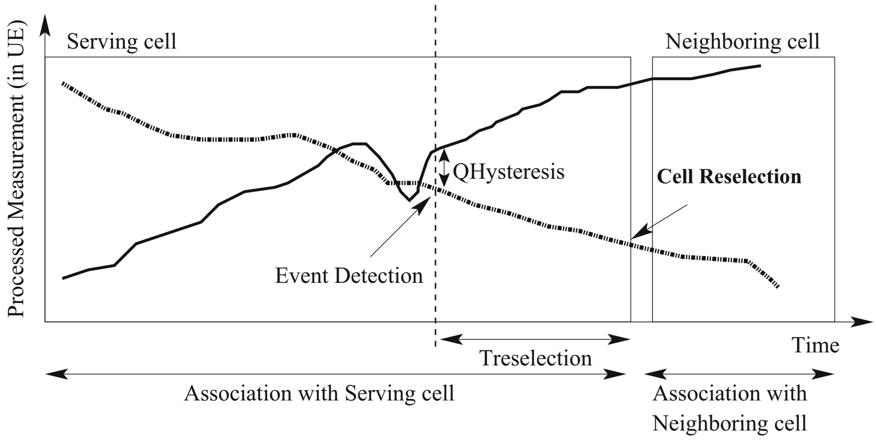



**Fig. 2.4** Cell reselection or camping

## *2.2.1 Cell Selection/Reselection*

After camping on a suitable cell, UE may need to initiate the process of cell reselection in case it moves out of the coverage of the camped cell. To determine an appropriate eNB for reselection, UE measures the received signal power from the currently camped cell as well as from other candidate cells which qualify to be considered for cell reselection. When the received signal power measured from any of the qualifying cells becomes better than that of the currently camped cell by an amount (*Qhysteresis*) and this condition remains true for a predefined time duration (*Treselection*), then UE changes the camping cell to the neighboring cell. This is known as *cell reselection* or *camping* (Fig. 2.4). Note that the camping decision is made by UE autonomously, but thresholds (*Qhysteresis*, *Treselection*) are configured by eNB through system information messages.

Instead of the radio link quality-based ranking, other ranking criteria can also be applied in order to limit the number of frequencies to be measured, making the cell reselection process faster and power efficient. For instance, in case of inter-frequency/inter-RAT reselection, criteria other than signal quality, such as the type of UE or service required may be considered for cell reselection decision. As an example, it may be preferable to keep an M2M[5] device, which typically transmits small amounts of data infrequently, camped on a GSM cell, instead of LTE. The network may also enforce cell reselection decision for idle mode UEs to achieve load balancing and thus, ensure that idle mode UEs are evenly distributed across cells.

[5]M2M device maybe a sensor for recording temperature, location, movement etc. These sensors have a Subscriber Identity Module (SIM) card to ensure data connectivity with a centralized M2M server.

## 2.3 Connected State Mobility

UE is always connected to a single cell in LTE. When the received signal power measured by a connected state UE from the serving cell deteriorates, the responsibility of E-UTRAN is to determine an appropriate cell to which UE should handover so as to maintain the QoS of the ongoing session. It may consider factors such as radio link quality, UE capability, subscriber type, and access restrictions to take this decision. E-UTRAN configures UE to perform and report measurements for the potential target cells. When a connected mode UE approaches cell boundary, the received signal power experienced by that UE from the serving eNB is likely to deteriorate. If signal power from any neighboring cell becomes better than that of the serving cell, by an amount (*Hysteresis*) and this condition remains true for a predefined time interval (*timetotrigger* or TTT), then network triggers UE to change association to ensure session continuity as shown in Fig. 2.5. This change of association for a connected mode UE is known as handover.

### 2.3.1 Handover Procedures and Signaling

The handover procedure or sequence includes signaling exchanges between UE, source eNB, target eNB, and EPC. The procedure (Fig. 2.6) can be divided into the following three phases:

1. *HO preparation*
   The time duration from the instant when UE reports the received signal measurements from the neighboring eNBs to its serving eNB till the time when the serving (or source) eNB issues *HO command* to UE is considered as HO preparation phase.

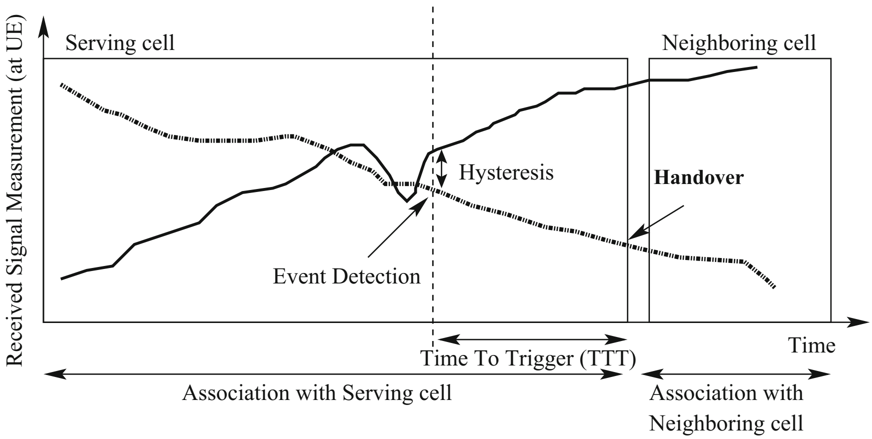



**Fig. 2.5** Measurement triggers for handover. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084910)

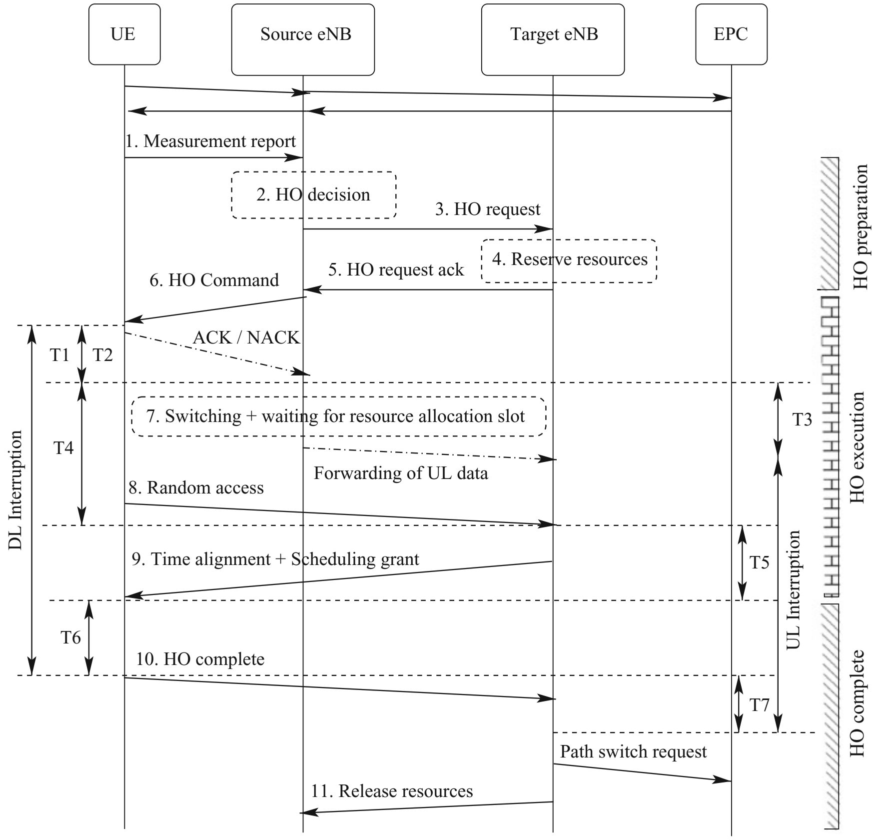



**Fig. 2.6** LTE handover sequence (adapted from [14])

As a part of HO preparation, the source eNB requests one or more target cells (identified based on the measurements reported by the UE) to prepare for the HO. The source eNB communicates UE's RRC context information (i.e., radio resource configuration) about the UE capabilities, the current AS-configuration, and UE-specific RRM information to the target eNB. In response, the target eNB generates *HO command*, which is then forwarded by the source eNB to the UE in *RRCConnectionReconfiguration* message. User-plane tunnels are established between source and target eNBs so that all data packets pending for transmission to the UE at the source eNB are forwarded to the target eNB.

2. *HO execution*
*RRCConnectionReconfiguration* message which carries *HO command* also contains the mobility control information i.e., identity and frequency of target cell, common radio resource configuration information which is required to perform random access in the target cell, security configuration, Cell Radio Network Temporary Identifier (C-RNTI), dedicated radio resource configuration information, and measurement configuration.

After source eNB issues *HO command*, UE initiates a random access procedure using the Random Access CHannel (RACH) configuration to the target cell. Successful completion of the random access procedure implies that UE obtains the timing synchronization and scheduling grant from the target eNB. In this phase, user data packets are forwarded from the source eNB to the target eNB. This continues till either S-GW stops sending packets to the source eNB for that UE or the buffer at the source eNB gets emptied.

The intermediate processing steps are indicated in the figure. T1 denotes the processing time of *HO command* when it is received by the UE from the corresponding source eNB. After issuing *HO command*, eNB withholds all downlink transmissions to the UE till the HO completion time, to prevent any loss of data packets. T2 indicates the time taken by UE to send acknowledgment for the successful reception of *HO command* to source eNB. This is the last control message on uplink from UE to source eNB. T3 denotes the processing time of the last uplink data at the eNB. T4 denotes the time required to switch radio to the frequency of target eNB and wait for the random access slots to be granted from the target eNB. T5 (also indicated by T304 timer) indicates the time taken by target eNB to process the random access grant and send the first downlink transmission to UE indicating timing alignment and granted slots information.

3. *HO completion*

After obtaining scheduling grant, UE sends *HO complete* message to the target eNB. Then, target eNB sends a *Path Switch* message to MME to inform that UE has obtained scheduling grant. Then, MME requests S-GW to switch the user-plane path from source eNB to target eNB. Finally, all resources used for communication like user-plane tunnels established between target and source eNBs are released.

Time duration T6 indicates the time taken by UE to process the downlink message, time alignment, and granted slots information obtained from target eNB. The time to process the first uplink transmission at eNB is indicated by T7. Both downlink interruption (T2+T4+T5+T6) and uplink interruption (T4+T5+T6+T7−T3) indicated in the figure depends on the waiting time for resource allocation slots.

## 2.4 Radio Link Management

A connected mode UE estimates the radio link quality by tracking BLock Error Rate (BLER) of Physical Downlink Control Channel (PDCCH). If the link quality is observed to be bad consistently for a predetermined time interval, UE starts the Radio Link Failure (RLF) timer, also known as T310 timer. The notion of bad radio link condition corresponds to the observed BLER exceeding some threshold say, 10%. After turning ON T310 timer, UE continues to monitor the link quality for another pre-defined time interval. If the radio link quality improves, i.e., BLER exceeds another threshold say, 2%, RLF timer is stopped and the usual periodic link quality measurement process continues. On the contrary, if there is no improvement in the radio link quality, i.e., BLER remains above 10% and RLF timer expires, then radio link failure is declared and recovery procedures are initiated.

Radio link failures can be classified in the following ways:

- *True RLF events*: This occurs when UE encounters shadowing/dead zone and failure happens due to the extremely bad radio link condition that UE continues to encounter for a pre-defined time interval.
- *HandOver Failure (HOF) events*: This occurs when UE encounters radio link failure while the handover procedure is going on and in particular, when UE is undergoing the HO execution phase.

## 2.5 RRM and RLM Measurements

In this section, we describe the measurements performed for radio resource management and radio link monitoring (RLM).

***RRM Measurements***

UE is configured by E-UTRAN to report the received signal measurement information to eNB. It is done via *RRCConnectionReconfiguration* message which includes the following:

- Measurement Object: List of cells (and their frequencies of operation) on which measurements are to be performed,
- Reporting Configuration: It comprises periodic or event-driven triggers to send measurement report and the information (received power etc.) to be included in the report,
- Measurement Identity: This identifies a measurement and defines the applicable measurement object and reporting configuration,
- Filtering to be used on measurements,
- Measurement Gaps: This indicates the time period when no downlink or uplink transmissions are performed. The objective of this time gap is to enable UE to switch radio and perform measurements from the neighboring cells when they operate on frequencies other than that of the serving cell.

### *2.5.1 Measurement Procedures*

UE is configured by the eNB to perform one or both of the following measurements from the serving and neighboring eNBs:

- *Reference Signal Received Power* (*RSRP*): This is the average received power on the resource elements that carry Cell-specific Reference Signals (CRSs). The interference and noise components are not considered in the computation of RSRP.
- *Reference Signal Received Quality* (*RSRQ*): This is the ratio of RSRP to Received Signal Strength Indicator (RSSI), where RSSI is the total received power including interference from all sources (serving and non-serving cells) and thermal noise. Due to the consideration of interference and noise in RSRQ measurement, a UE may experience different received signal qualities at different locations.

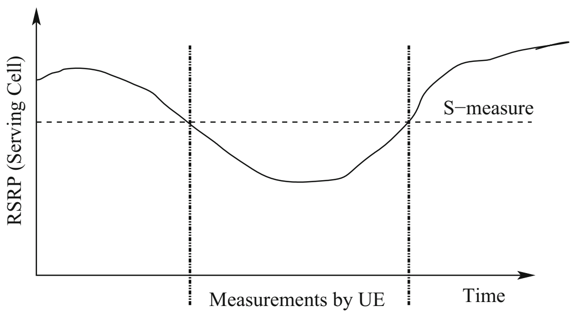
Both RSRP and RSSI measurements are performed over a specified set of subcarriers that span over a certain bandwidth, known as the *measurement bandwidth* $M_{BW}$. Note that the minimum value for $M_{BW}$ is specified in the 3GPP LTE standard and the maximum value for $M_{BW}$ is implementation specific and any value can be chosen that is less than the system bandwidth.

UE may be configured to perform *triggered measurements* by the serving eNB, or it may autonomously perform *background measurements*. Triggered measurements are performed on the occurrence of the configured event and only when UE is configured by eNB. On the contrary, background measurements are performed autonomously by UE whenever it is not involved in any active communication.

When RSRP measurement from the serving eNB falls below a specified threshold, known as *S-measure*, UE starts measuring one or more neighboring eNBs (Fig. 2.7). The measurements are *intra-frequency* when the neighboring and serving eNBs operate on the same frequency and *inter-frequency*, when neighboring eNBs operate on different frequencies. Different values for S-measure threshold may be specified to initiate intra/inter-frequency measurements.

Based on the RSRP measurement performed by UE from the serving eNB, it is determined whether it should perform measurements from neighboring eNBs or not. Figure 2.8 illustrates the S-measure usage, where the inner and outer concentric circles indicate two threshold values of RSRP: Th1 and Th2, respectively. When the measured RSRP happens to be less than Th1 but more than Th2, UE performs intra-frequency measurement. When the measured RSRP goes below threshold Th2, UE performs both intra-frequency and inter-frequency measurement. S-measure thresh-

**Fig. 2.7** Purpose of S-measure for measurement configuration (adapted from [12])



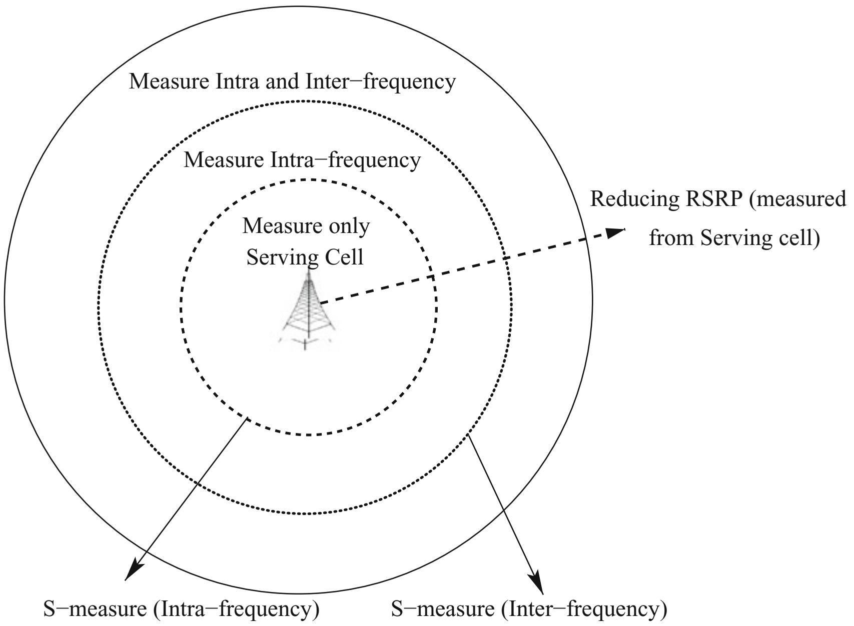



**Fig. 2.8** Usage of configuration parameter: S-measure (adapted from [12])

olds ensure that UE performs measurements only when it is required and reduces its battery power consumption.

To facilitate the measurement of received signal power from the neighboring cells, downlink data transmission to the UE is suspended for the duration specified by *Measurement Gap* (also referred to as *Gap Length*). The structure of measurement gap is given in Fig. 2.9, where *margin time* is the time required by the receiver to switch to another carrier frequency. Measurement gap patterns are configured by eNB, which includes gap length, gap interval $M_{interval}$ (also known as gap repetition period), and number of measurements to be performed in the specified *measurement period* $M_{Period}$.

### 2.5.2 *Reporting Mechanisms*

UE measures the received signal power from the serving cell periodically. However, the received signal power measurement from the neighboring cells is performed only when the measured power from the serving cell becomes less than the S-measure threshold. These measurements undergo averaging and filtering before they are reported to the eNB for HO decision:

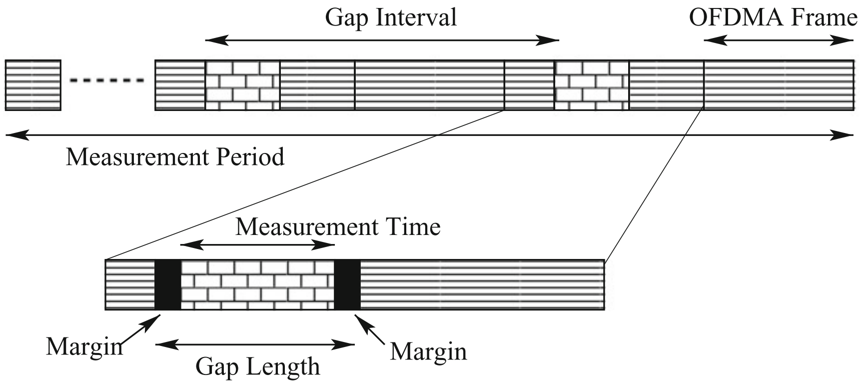



**Fig. 2.9** Measurement gap pattern (adapted from [27])

- *Layer-1 averaging*
  The number of measurements ($M_{num}$) that can be performed in a specified measurement period $M_{Period}$ (also known as averaging window) for a given gap interval $M_{interval}$ is given by

$$M_{num} = \frac{M_{Period}}{M_{interval}}.$$

  Average RSRP/RSRQ measurements (denoted by $R_{L1}^{n}$) at $n$th instant are given by

$$R_{L1}^{n} = \frac{R_1 + R_2 + \cdots + R_n + \cdots + R_{M_{num}}}{M_{num}},$$

  where $R_n$ indicates $n$th RSRP or RSRQ measurement.
- *Layer-3 filtering*
  The updated filter measurement result (denoted by $R_{L3}^{n}$) at $n$th instant is given by

$$R_{L3}^{n} = (1-\alpha)R_{L3}^{n-1} + \alpha R_{L1}^{n},$$

  where $\alpha = \frac{1}{2^{k/4}}$ determines the weightage of layer-1 average measurement at $n$th instant and past layer-3 filtered value.

The averaged RSRP/RSRQ measurements are known as *processed measurements*. The processing eliminates the effects of fading and estimation inaccuracies in the measurement.

UE may be configured to report the processed measurements in one of the two ways: (1) periodically or (2) based on event triggers. Both the configurations are done by setting the parameters *reportAmount* (the number of periodic reports) and *reportInterval* (the time interval between two reports). In case of periodic reporting, UE reports the measurements immediately while in case of event-triggered reporting, UE reports the measurement only after the specified event has occurred. The S-measure threshold condition ensures that the measurements are performed only when required and the event-based reporting ensures that the measurements are reported only when the specified threshold conditions are satisfied, thereby conserving UE's battery life and reducing signaling overheads. Note that the triggering events manifest the radio link condition experienced by UE.

#### 2.5.2.1 Events and Timers

An *event* is triggered when the corresponding *entering condition* is satisfied. These conditions are signaled by eNB in the form of parameters such as thresholds, offset, and hysteresis. For example, the entering condition for event $A1$ is that the RSRP measurement from the serving eNB becomes more than the specified threshold. If this event has been configured and the entry condition holds for the TTT duration, event A1 gets triggered and measurement report is communicated to the eNB (Fig. 2.4). Based on the received measurement reports, eNB takes appropriate mobility management decisions, such as handing over to the target eNB. The events defined for mobility management in 3GPP LTE standard to facilitate measurement report triggering for intra-RAT and inter-RAT HOs are given in Table 2.1.

*Timers*, in general, assist in the triggering of various events. The timers relevant to mobility management in LTE are T304, T310, and T311, each having distinct entry and exit conditions. T304 indicates the ongoing process of reconfiguration of radio resource connection. It is started when the reconfiguration of radio resource connection is triggered and stops upon successful completion of either cell reselection or HO. On expiry, it initiates RRC connection re-establishment procedure. Timers T310 and T311 are responsible for radio link management. T310 is known as RLF timer and is triggered when the radio link quality is observed to be bad consistently

**Table 2.1** List of mobility-related events in the 3GPP LTE standard

| Event | Triggering condition |
|---|---|
| $A1$ | Measurement from serving eNB becomes better than the specified threshold |
| $A2$ | Measurement from serving eNB becomes worse than the specified threshold |
| $A3$ | Measurement from neighboring eNB becomes offset better than serving eNB |
| $A4$ | Measurement from neighboring eNB becomes better than the specified threshold |
| $A5$ | Measurement from serving eNB becomes worse than the specified threshold1 and measurement from neighboring eNB becomes better than the specified threshold |
| $A6$ | Measurement from neighboring eNB becomes offset better than neighboring eNB |
| $B1$ | When the measurements from neighboring eNB deploying distinct RAT from that of the serving eNB (known as inter-RAT neighbor) becomes better than the specified threshold |
| $B2$ | When the measurements from serving cell becomes worse than threshold1 and the measurements from inter-RAT neighbor becomes better than threshold2 |

for a pre-defined time interval, i.e., BLER observed on PDCCH exceeds 10%. The timer stops when one of these happens: (1) when the radio link quality improves and the observed BLER exceeds only 2%, (2) when handover process is triggered or (3) when connection re-establishment procedure is initiated. When none of these conditions is met and timer expires, then it triggers connection re-establishment procedure. T311 timer starts when RRC connection re-establishment procedure is initiated and stops when a suitable cell is selected. If the timer expires before suitable cell selection, it switches UE to RRC idle state.

## 2.6 Handover Model

While the handover process gets executed, UE goes through the following three states, as shown in Figs. 2.10 and 2.11:

- **State 1**: The state before the entering condition for event A3 is met is considered as State-1.
- **State 2**: The state when the entering condition for event A3 is met but UE is yet to receive HO command successfully is considered as State-2.
- **State 3**: When UE receives HO command successfully from the serving eNB, but it is yet to send HO complete message to the target eNB is considered as State-3.

Next, we illustrate scenarios when HO failure may happen:

- Case-1: Timer T310 is triggered (Fig. 2.10) when the current state of UE is as follows:
  - Monitoring of measurements is ongoing and
  - At least one candidate target node for handover is identified

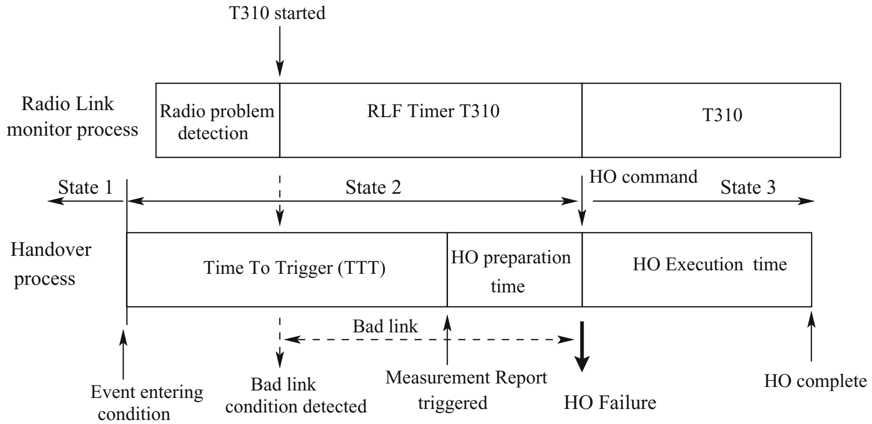



**Fig. 2.10** Case-1: handover failure when T310 is triggered in state 2 (adapted from [4])

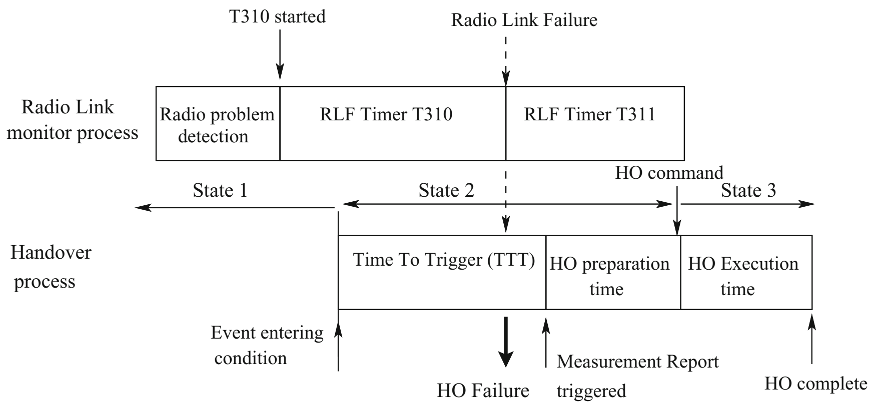



**Fig. 2.11** Case-2: handover failure when RLF occurs in state 2 (adapted from [4])

In this case, HO command is not delivered to UE and HO process remains incomplete.
Note that the start, stop, and expiry of timer T310 are governed by following rules:

- T310 gets triggered when radio link condition is bad
- Timer stops only when one of the following conditions is true:
  Improvement in radio link condition
  HO process gets triggered
  Initiation of connection re-establishment procedure
- When T310 expires, one of these two things happen based on the status of security activation:
  Connection re-establishment procedure is triggered
  UE switches to idle mode

- Case-2: This scenario, shown in Fig. 2.11, occurs when the following two events happen simultaneously:

  - A candidate target node for handover is identified
  - Radio link condition is bad already

  In such a case, measurement reporting may not be successful, resulting in HO failure, even before the HO command is dispatched from source eNB.
  Note that the start, stop, and expiry of timer T311 are governed by following rules:

  - T311 gets triggered on initiation of connection re-establishment procedure
  - Timer stops on successful completion of the procedure
  - When T311 expires, UE switches from RRC_CONNECTED to RRC_IDLE mode

- Case-3: In this case, PDCCH failure happens while UE is in State-3 of HO process. Thus, UE receives neither uplink grant information nor timing advance command from eNB. Such a scenario occurs when the target eNB power measurements on downlink become less than the threshold at the end of HO execution time.

## 2.7 RLM Model

Radio link management requires monitoring BLER of PDCCH, as discussed in Sect. 2.4. An equivalent way to model PDCCH reception quality is to consider the wideband Signal-to-Noise Interference Ratio (SINR), based on measurements of Cell-specific Reference Signal (CRS), which is transmitted very frequently by the eNB. The scenario of BLER equal to 10% is indicated by $Q_{out}$ threshold, which is also known as "out-of-sync" condition of an *RRC_CONNECTED* state UE. $Q_{out}$ can be modeled by averaging 20 samples of the wideband SINR, where the samples are obtained over a 200 ms window and the $Q_{out}$ threshold may be set as $-8$ dB. Similarly, the scenario of BLER equal to 2% is indicated by $Q_{in}$ threshold, which is also known as "in-sync" condition of an *RRC_CONNECTED* state UE. This can be modeled by averaging 10 samples of the wideband SINR, where the samples are obtained over a 100 ms window and the $Q_{in}$ threshold may be set as $-6$ dB.

## 2.8 Mobility State Estimation

The speed of UE has a significant influence on the handover performance. For instance, a high-speed user needs a faster HO processing to ensure that call drop does not happen due to rapidly deteriorating signal strength. One way to achieve faster HO processing may be to use smaller TTT value for high-speed users compared to the value being used for low-speed users. With the knowledge of UE speed, it is possible to prevent call drops and improve HO performance. In actual practice, the precise estimation of UE speed is not required for HO processing. Rather, it is sufficient to estimate the rate at which UE is changing association with cells. This is referred to as Mobility State Estimation (MSE).

Mobility state of UE is detected by counting the number of HOs (# HOs) over a specified period of time. The number of cell changes is compared with two thresholds (*N_H* and *N_L*, configured by eNB) to determine one of the three mobility states: high, medium, and normal. These states are determined as:

$\# HOs > N\_H$ implies high,

$N\_L < \# HOs < N\_H$ implies medium, and

$\# HOs < N\_L$ implies normal mobility state, respectively.

UE is allowed to autonomously scale its mobility parameters based on the detected mobility state. For example, a UE may add an offset to *Hysteresis* or scale *TTT*.

A HO from cell B to cell A and then back to cell B is defined as *ping-pong* if the '*Time of Stay*' (ToS) in cell A is less than a predetermined *minimum time of stay* (MTS). Note that MTS represents the time required for UE to establish reliable connection with the serving eNB and begin data transmission. To ensure good HO performance (reduced *HandOver Failure* and *Ping-pongs*), accurate estimation of mobility state of UE is paramount.

**Bibliographic Notes**

The radio resource management protocols in an LTE network and related RRC timers are described in [21]. The architecture description of E-UTRAN is given in [11]. The procedures for RRC connection and radio link monitoring, and the measurement methodology for RRM and RLM are detailed in [41]. An overview of M2M communication is available in [20]. The handover procedure and message flows are illustrated in [14]. The RSRP and RSRQ measurement procedures are from [9]. The description of three states that UE transits during the handover process is from [4]. It also addresses the mobility management issues in an LTE heterogeneous network. The threshold values for various mobility-related parameters like $Q_{in}$ and $Q_{out}$, values for various RLM timers and definition of handover performance metrics are given in [4]. The procedure for 3GPP specified mobility state estimation is from [13].

# Chapter 3
# Methodology for 3GPP Modeling

In this chapter, we illustrate 3GPP modeling for the mobility scenarios in heterogeneous networks. This includes the topology model, user mobility model, handover procedure, and modeling of radio link failure and ping-pongs. It is followed by a description of the implementation framework of LTE HetNet simulator which is based on 3GPP modeling considerations and is used for the simulation of various mobility aspects in an heterogeneous environment.

## 3.1 3GPP Simulation Methodology

### *3.1.1 Topology Model*

Based on the 3GPP-specified evaluation methodology, there is provision to support both Urban Macro (UMa) and Urban Micro (UMi) deployment scenarios, where the inter-site distances are 500 and 200 m, respectively. The macrocellular network is modeled such that there is uniform distribution of macro-eNBs with their coverage defined by hexagonal geometry as shown in Fig. 3.1.

For overlay network, there are following possible drop methods:

- Pico-eNBs on the fringes of macrocell as shown in Fig. 3.2a.
- Pico-eNBs inside the macrocell as shown in Fig. 3.2b.

Note that the pico-drops are shown only for the first tier of cells in the figure.

The macro-eNB has a trisector antenna with fixed horizontal and vertical antenna patterns, while pico-eNB has an omnidirectional antenna. The distance-dependent path loss, three-dimensional antenna pattern, correlated shadowing, and fast fading are implemented as per the 3GPP evaluation model.



A. Karandikar et al., *Mobility Management in LTE Heterogeneous Networks*,
DOI 10.1007/978-981-10-4355-0_3

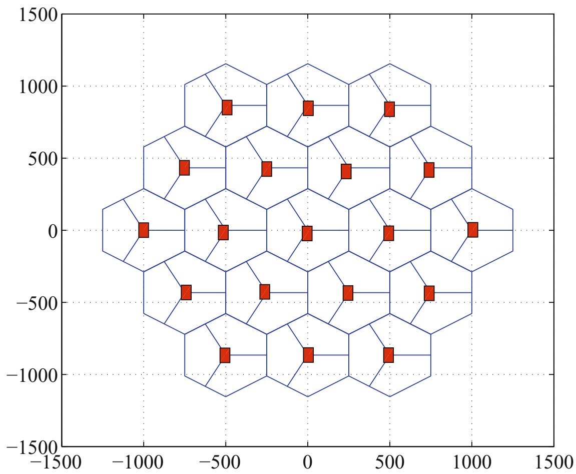



**Fig. 3.1** Deployment of macro-only network with uniformly distributed hexagonal grids

### *3.1.2 UE Mobility Model*

Users can be dropped in each sector with uniform or any other distribution, as required. The "bouncing circle" mobility model, where each user moves with a fixed speed in a randomly chosen direction toward the bouncing circle. The direction of movement, once chosen by UE remains fixed until it reaches the boundary of the bouncing circle, from where it again selects a random direction for traversal such that UE remains within the bouncing circle. As shown in the example in Fig. 3.3, UE is dropped initially in the central cell, follows the trajectory shown by blue color dotted lines, and the final location of UE is shown by the arrow in blue color. Thus, each UE follows a different trajectory.

### *3.1.3 Radio Link Failure Model*

The radio link failures are determined based on the wideband SINR measurement. The wideband SINR measured by the UE is compared with two thresholds, $Q_{in}$ and $Q_{out}$. When the wideband SINR falls below the $Q_{out}$ threshold, timer T310 starts, thereby indicating bad radio link condition. This timer gets incremented every TTI if the wideband SINR continues to be less than $Q_{in}$. However, if the measured SINR exceeds $Q_{in}$ before the expiry of T310, radio link is considered to have become good and T310 is stopped. Otherwise, if the measured SINR continues to be less than $Q_{in}$ when T310 expires, RLF is declared and re-association process is initiated for that user.

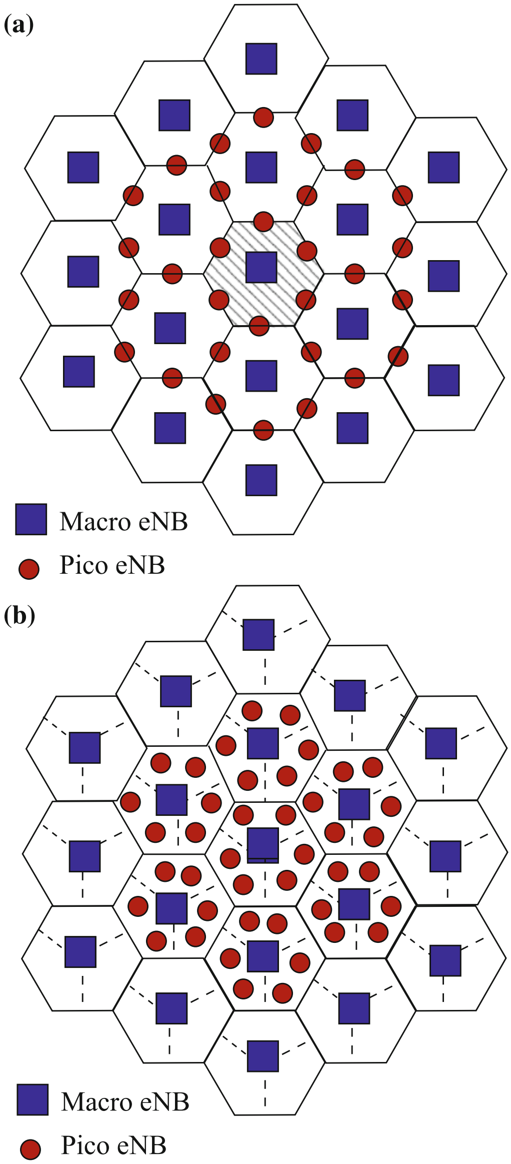



**Fig. 3.2** Network deployment of macro-pico network with: **a** Pico-eNBs on fringes of macrocell and **b** Pico-eNBs in the macrocell. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084910)

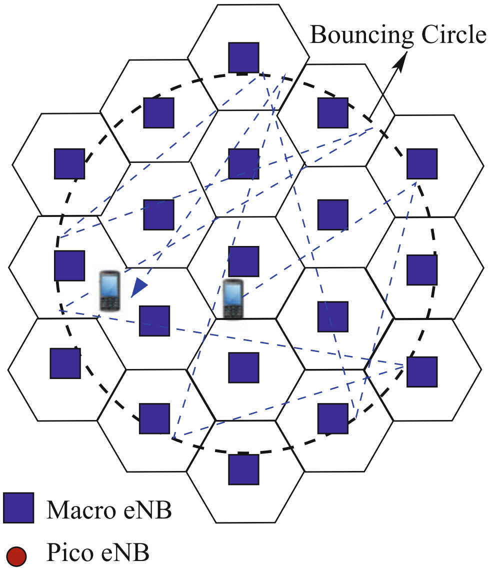



**Fig. 3.3** Bouncing circle mobility model. © 2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084910)

### *3.1.4 Handover and Ping Pong Model*

The measurements from neighboring cells are not performed unless the serving eNB measurement is below S-measure threshold. RLF at such times is considered as *State-1 RLF*. When L3 measurement from serving eNB falls below the S-measure threshold, UE starts performing measurements from the neighboring eNBs. If RLF is encountered during the TTT interval, *State-2 HOF* is declared. Otherwise, based on the measurement reports at the end of TTT, one or more potential target eNBs are identified for handover processing. This marks the beginning of handover preparation phase during which the wideband SINR measurements from the serving eNB are monitored. If T310 gets triggered or it is already running in this phase, it is considered as a pure *State-2 HOF* case. On successful completion of this phase, HO command is received by the user and it gets attached to the target eNB. The end of HO preparation phase marks the beginning of HO execution phase. Now, the wideband SINR measurements from the target eNB are observed. Any RLF is this phase leads to *State-3 HOF*, otherwise successful handover is recorded. Note that the HO failures in different states are recorded separately.

Between any two successful HOs, i.e., from node A to B and then, B to C, if the final target node C and the original source node A happens to be the same, the Time of Stay (ToS) in node B is measured. If this ToS is less than Mean Time of Stay (MToS), the event is recorded as ping-pong.

## 3.2 Implementation Framework

We describe the framework of simulator that has been developed for mobility modeling in LTE networks. The simulator has been developed following the 3GPP-specified HetNet mobility evaluation methodology. It supports heterogeneous deployment with an overlay of pico-cells. Figure 3.4 illustrates the basic building blocks of this simulator.

The simulator is capable of modeling interference from multiple sectors up to two tiers with wraparound. Also, there is a provision to change the mobility model as required in the simulator. The simulator allows a wide range of scenarios by appropriately configuring the following parameters:

1. Terrain: UMa and UMi
2. Carrier frequency
3. System bandwidth
4. Antenna configuration
5. Transmit power of pico-eNB
6. Number of pico-eNBs per sector
7. Number of users per sector
8. Pico-drop: random and planned
9. User drop: random and clustered
10. User speed
11. Mobility model
12. Choice of mobility state estimation algorithm (discussed in the next chapter)

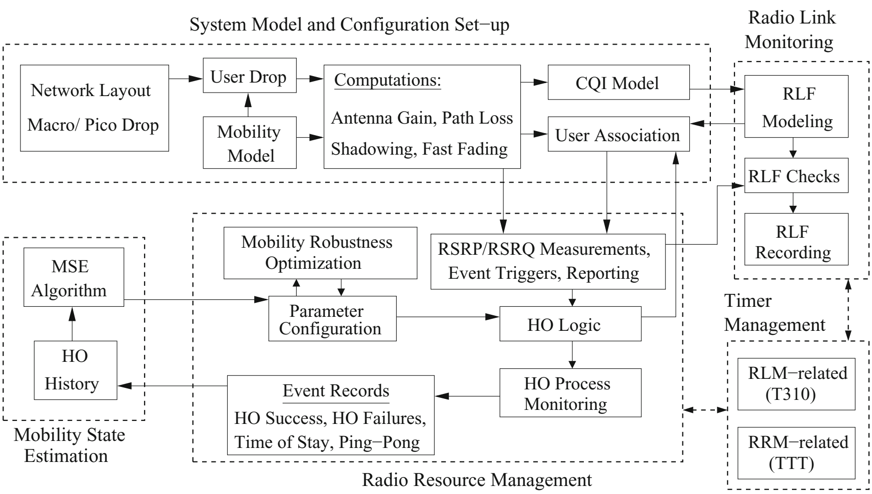



**Fig. 3.4** Building blocks of Matlab simulator for mobility modeling in HetNets

**Table 3.1** Radio link monitoring and HO-related parameters

| Parameters | Value |
|---|---|
| *Measurement and radio link monitoring* | |
| $Q_{out}$ | −8 dB |
| $Q_{in}$ | −6 dB |
| T310 | 500 ms |
| L1 sampling interval | 40 ms |
| L1 window for L3 sample | 200 ms |
| L3 filter coefficient | 1 |
| Measurement error modeling | Normal distribution with S.D. 1.216 dB |
| *Handover-related parameters* | |
| Time to trigger (TTT) (ms) | {240, 320, 400, 480} ms |
| Mean time of stay (MToS) | 500 ms |
| HO preparation time | 50 ms |
| HO execution time | 40 ms |

For the simulation results presented in Chaps. 5 and 6, the network deployment-related parameters are given in Table 3.2.

The parameters associated with user mobility are listed in Table 3.1.

### 3.2.1 Measurement Model

The simulator supports both RSRP and RSRQ measurements. In general, the processed (Layer-3) measurements provide better averaging compared to Layer-1 measurement because of the moving average, as evident from the graph in Fig. 3.5. The figure gives a snapshot of both L1 and L3 RSRP measurements for a period of 800 TTIs.

The wideband SINR is the ratio of average received power from serving eNB to the sum of average interference power received from other eNBs and noise. It is evaluated by taking into consideration distance-dependent path loss, antenna gains, and shadowing (long-term fading).

### 3.2.2 CQI Computation

Channel Quality Indicator (CQI) is a metric which UE communicates to the network to indicate the radio link quality. The CQI reporting can be either periodic or aperiodic. For CQI computation, the average SINR experienced by a user on a given resource block is determined, which is mapped to one of the 15 CQI values in LTE.

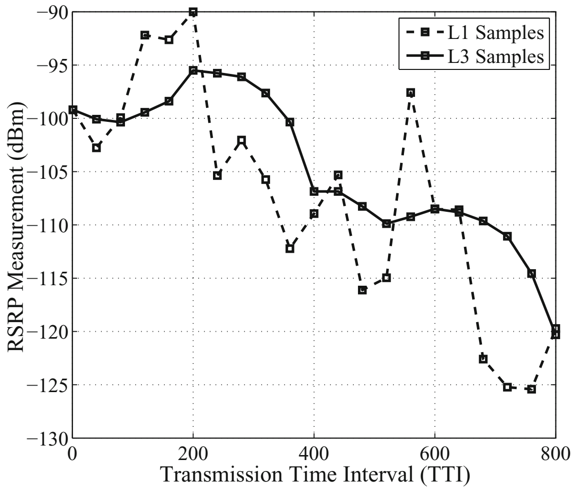



**Fig. 3.5** RSRP measurements

Based on the CQI index, appropriate modulation and coding scheme is chosen which determines the transport block size for that UE on the given resource block. The CQI information is essential for eNB to make appropriate resource allocations to that UE so that resources are efficiently utilized.

### *3.2.3 Calibration Results*

The simulator has been calibrated for (1) Wideband SINR and (2) Handover failure rate by comparing the results with those provided in the 3GPP Technical Reports 36.814 and 36.839, respectively. We consider UMa scenario for the calibration and use the parameter settings given in Tables 3.1 and 3.2. Other simulation parameters used specifically for the purpose of calibration are given in Table 3.3. Three iterations (different user drop) of simulation for 0.27 million subframes are performed, which is about 45 min of simulation time. These iterations are considered sufficient because the calibration results of simulator have been found to be within the range as provided by other 3GPP member organizations. For computing metrics like HOF rate, mobility events are recorded per UE and then, averaged over the total number of UEs and the total simulation time. For the simulation, co-channel deployment of pico-eNBs is considered to analyze the impact of interference on the HO performance. Interference is computed assuming 100% traffic load on the network.

The Cumulative Distribution Function (CDF) of wideband SINR is given in Fig. 3.6. The result closely matches the SINR distribution provided in the 3GPP Technical Report TR 36.814, specifically for the calibration purpose. Note that the calibration of wideband SINR ensures calibration of physical layer including channel model and network layout.

**Table 3.2** Configuration parameters: Matlab simulator for mobility modeling in HetNet

| *Radio configuration parameters* | | |
|---|---|---|
| Parameters | Macrocell | Pico-cell |
| System bandwidth | 10 MHz | |
| Carrier frequency | 2 GHz | |
| Inter-site distance | 250 m | NA |
| Number of pico-eNBs/Sector | 2 | NA |
| Transmit power | 43 dBm | 27 dBm |
| Min. distance bet. node and UE | 35 m | 10 m |
| Min. distance bet. macro- and pico-eNB | 75 m | |
| Min. distance bet. any two pico-eNBs | 40 m | |
| Distance-dependent path loss | $128.1 + 37.6 \log_{10}(R)$ | $140.7 + 36.6 \log_{10}(R)$ |
| Antenna type | Tri-sector | Omni-directional |
| Front to back ratio (max) $A_m$ | 20 dB | NA |
| $SLA_v$ | 20 dB | 0 dB |
| Electrical downtilt of antenna $\theta_{etilt}$ | 12° | NA |
| 3 dB beamwidth $\phi_{3\text{dB}}$ (horizontal plane) | 70° | NA |
| 3 dB elevation width $\theta_{3\text{dB}}$ (vertical plane) | 10° | NA |
| Height of mast | 32 m | NA |
| Antenna gain (eNB) | 15 dB | 5 dB |
| Antenna gain (UE) | 0 dBi | |
| Antenna configuration | 1 × 1 | |
| Shadowing | Map-based approach with grids and simple linear interpolation | |
| Shadowing standard deviation (dB) | 8 | 10 |
| Correlation distance | 25 m | |
| Shadowing correlation bet. cells | 0.5 | |
| Shadowing correlation bet. sectors | 1 | NA |
| Fast fading | Typical urban model | |
| Noise spectral density | −174 dBm/Hz | |
| Noise figure | 5 dB | |
| Cell loading | 100% | |

The HOF rate performance is compared with the results provided by 3GPP member organizations and is shown in Fig. 3.7. Note that HOF rate is defined as the ratio of the total number of HOFs per UE per second to the sum of the total number of HOFs per UE per second and the total number of successful HOs per UE per second. In addition to Macro to Macro (M2M) HOs, following HO cases are possible in an heterogeneous environment: Macro to Pico (M2P), Pico to Macro (P2M) and Pico to Pico (P2P). Note that our system model deploys pico-eNB such that the separation

**Table 3.3** Specifications for calibration of simulator

| Parameters | Value |
|---|---|
| Deployment scenario | UMa |
| Inter-site distance | 500 m |
| Transmit power macro-eNB | 46 dBm |
| Transmit power pico-eNB | 30 dBm |
| Simulation time | 45 min |
| No. of iterations | 3 |

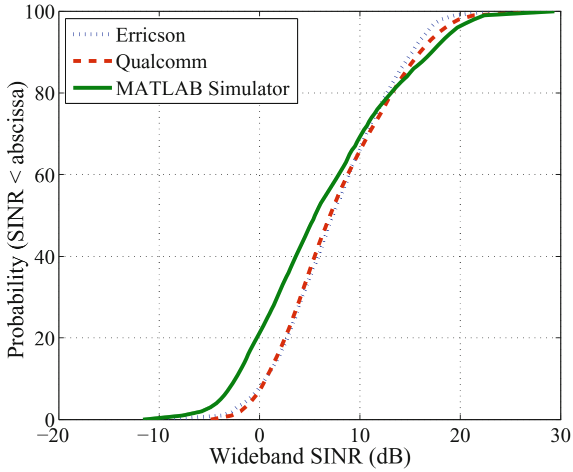



**Fig. 3.6** Calibration result: CDF of downlink wideband SINR for urban macro scenario

between them is at least 40 m (Table 3.2), which eliminates the possibility of P2P HOs to a large extent. Therefore, we ignore P2P HOF case in the figure. The graph shows that the results obtained from the implementation framework are well within the range of results provided by various other 3GPP member organizations for the scenario under consideration.

### *3.2.4 Simulation Parameters*

The simulation parameters specific to offsets, thresholds, and MSE are given in Table 3.4.

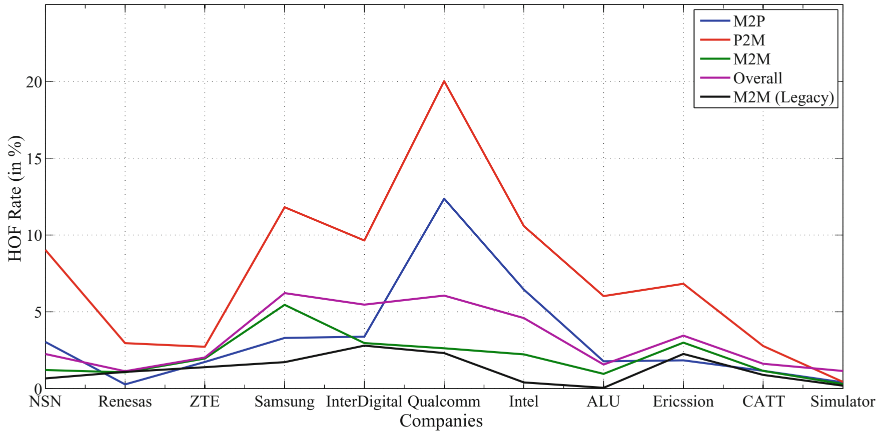



**Fig. 3.7** Calibration result: HO failure rate for urban macro scenario

**Table 3.4** Simulation parameters for evaluating mobility performance in HetNets

| Parameters | Value |
|---|---|
| Time to trigger (TTT) (ms) | 480 ms |
| A3 offset | 1 dB |
| Hysteresis | 0 dB |
| User speed | 60 km/h |
| Minimum time of stay (MToS) | 500 ms |
| MSE interval | 30 s |
| MSE thresholds: High $N\_H$, Low $N\_L$ | 8, 4 |
| Scaling factor: High $S_H$, Medium $S_M$ | 0.25 and 0.5 |
| Cell specific offset: M2P and P2M | 2 dB |
| Simulation time | 300 s |
| Number of iterations | 3 |
| Number of users in system | 3 |

## Bibliographic Notes

The 3GPP-specified evaluation methodology is given in [4]. The 3GPP evaluation model in [3] gives the implementation details of distance-dependent path loss, three-dimensional antenna pattern, correlated shadowing, and fast fading. The bouncing circle mobility model described in Sect. 3.1.2 is from [4]. The network deployment related parameters are adapted from [3]. The procedure for CQI computation is derived from [8]. The HOF rate performance results provided by 3GPP member organizations, given in [4] are compared with the results obtained using HetNet mobility simulator in Fig. 3.7.

# Chapter 4
# Mobility Challenges in LTE Heterogneous Networks

Homogeneous cellular networks are macrocentric and are deployed with careful planning. However, in a heterogeneous network, small cells are deployed to address the issues of coverage gaps and/or traffic hotspots. These small cells typically have uneven deployment which results in dense, localized frequency reuse. Therefore, HetNets introduce significant challenges from the Radio Resource Management (RRM) perspective, particularly with respect to interference and mobility management.

Non-uniform distribution of users with variation in their speeds and QoS requirements makes the traffic load uneven in different cells. This reduces the resource utilization efficiency, which adversely impacts the spectral efficiency performance of the network. In addition, there is a need to reduce the rate of handover failures and ping pongs. While UE in a macro-only network typically selects an eNB as the serving eNB from which it experiences the strongest received signal power, the serving eNB selection in HetNets requires more careful consideration. The complexity arises because the selection decision may have to take into account other factors such as offload requirement, loading at macro and small cells, and speed of users. This makes mobility management more challenging in HetNets. In this chapter, we give a brief introduction to the deployment scenarios in HetNets, which is followed by a discussion on the various challenges related to mobility management in HetNet.

## 4.1 Heterogeneous Network

The macrocellular network is augmented with an overlay of low power nodes, with localized radio footprint, giving rise to Heterogeneous Networks or HetNets, to meet the twin requirements of coverage enhancement and capacity improvement. These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low power nodes may be relay, pico, or femto eNBs. Relay eNBs can be used to extend cellular coverage while pico/femto eNBs can be deployed to augment capacity in hotspots, as discussed in Chap. 1.

In this section, we review the deployment scenarios in HetNets.

### *4.1.1 Deployment Scenarios in HetNets*

HetNet deployment scenarios can be classified as follows:

1. *Non-overlapping and Overlapping Deployment*:
   When the coverage of low power eNBs and macro-eNB is non-overlapping, low power eNBs ensure ubiquitous radio coverage by extending their cellular footprint to dead zones. This is a *coverage improvement scenario*. When the low power network is an overlay, it may be used for traffic offload and boost system capacity. This is a *capacity improvement scenario*.
2. *Sparse and Dense Deployment*:
   To provide coverage to hotspot areas (small areas with large user density), low power eNBs may be deployed specifically at such locations to ensure traffic offload. This is considered as *sparse deployment*. When large number of low power eNBs are deployed to improve overall coverage of a wider area with large user density, it is a *dense deployment* scenario.
3. *Indoor and Outdoor Deployment*:
   Low power eNBs may be deployed indoors like femto or outdoors like relay and pico for coverage/capacity improvement.
4. *Intra-frequency and Inter-frequency Deployment*:
   When the carrier frequency of both low power eNBs and macro-eNB is same, the deployment is considered to be intra-frequency. On the other hand, the operational frequencies are distinct in case of inter-frequency deployment. The former requires tighter interference management, while the latter needs more spectrum.

The objective of heterogeneous network deployment is to attain higher capacity and enhanced coverage while providing seamless connectivity and reduced cost per bit/Hz/km$^2$. Small cell deployment also results in reduced CApital and OPerational EXpenditure (CAPEX and OPEX). The overlapping coverage in HetNet makes it possible to opportunistically offload traffic from macronode to small cell nodes and gain in terms of improved network capacity as well as efficient resource utilization from network's perspective and seamless connectivity from the perspective of user.

One such requirement is that of adequate backhaul link in HetNet. The coexistence of different radio access technologies requires proper coordination and interaction between them to take appropriate decisions concerning resource allocation, node selection/re-selection, offloading etc. To facilitate this harmonization in an heterogeneous environment, high bandwidth, low latency, and reliable backhaul is required.

While offloading traffic from macrocell to small cell in an heterogeneous network, there should be scope for considering both operator deployed as well as user deployed small cell so as to maximize the achievable gains. There is also a need to handle plug and play kind of deployments in addition to planned deployments to achieve greater flexibility in resource planning. In addition, it is required to support multiple Radio Access Technologies (RATs) so that inter-RAT handovers can be performed.

The location and density of hotspots and the throughput requirements of users dictate the deployment of small cell eNBs. In addition, the availability and usage of radio resources in small cells is one of the planning considerations. *Inter-frequency* small cell deployment is feasible when sufficient amount of spectrum is available, while *intra-frequency* small cells are deployed when spectrum availability is limited. Intra-frequency small cell deployment requires appropriate resource partitioning and scheduling mechanisms to ensure minimum interference. The location of small cell eNB may be such that its cellular footprint may or may not overlap with that of the macro-eNB. Consequently, both *overlapping* and *non-overlapping* small cell deployments are possible, as shown in Fig. 4.1.

Dense deployment of eNBs in HetNet improves the area spectral efficiency in terms of bits per second per Hz per unit area. However, the aggressive spectral reuse reduces the reuse distance (distance at which the same frequency is being used) and results in increased inter-cell interference (Fig. 4.1). It also affects the handover performance of the network. In addition, it is essential to ensure that signaling load is minimum and there is not significant increase in the backhaul traffic due to large number of small cells.

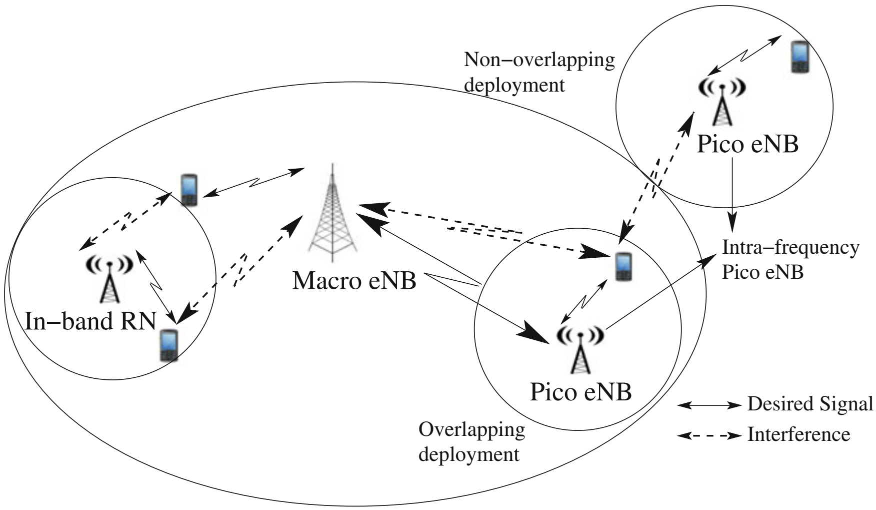


**Fig. 4.1** Interference scenario in HetNet

## 4.2 Mobility-Related Issues and Challenges

HetNets provide an economically viable solution to attain higher network capacity and QoS. However, many research issues need to be addressed from the implementation perspective. With this consideration, we describe below some of the challenges pertinent to mobility management in HetNets.

### *4.2.1 Small Cell Discovery and Detection*

In a macrocell network, it is relatively simple for the serving eNB to determine when a UE needs to be configured for measurements because the coverage area is well defined, and the handover is generally governed by cell coverage and link quality considerations. In contrast, offloading is the primary motive for handovers in HetNets and the situation is complicated by the fact that small cells may be deployed at multiple locations within the macrocell. As a result, even if a UE is in a good coverage zone with respect to the macro-eNB, it may still need to search for a suitable small cell for offloading purposes. Aggressive small cell discovery is required to maximize offloading opportunities which implies that UEs have to perform exhaustive search. This may cause excessive power consumption at the UE and the problem aggravates when small cell layer operates on different carrier frequency. In such cases, UE needs to perform inter-frequency measurements continuously which may also reduce its achievable throughput. Thus, the major challenge lies in determining the best trade-off between the need to minimize cell search duration to ensure power saving and the requirement for faster small cell discovery to achieve traffic offload. The three aspects related to small cell discovery are as follows:

1. *Determining S-measure*:
   S-measure is a threshold corresponding to the received signal strength experienced by UE from the serving eNB. This threshold determines the time when UE should begin performing measurements from the neighboring eNBs. Its significance in a macrocellular network has been described in Chap. 2 (Sect. 2.5.1). Now, we consider the same S-measure settings for small cell discovery in HetNet scenario (Fig. 4.2). Note that P1, P2, and P3 represent small cells that may require intra/inter-frequency or inter-RAT measurement. Based on the serving cell measurement, assume that UE lies in the innermost circle. In that case, UE will not be able to discover small cell P1 because the measurements are being performed from only the serving cell. Similarly if UE lies in zone I, P2 may be discovered only if it operates on the same frequency as that of the macrocell as only intra-frequency measurements are being performed by UE. When UE falls in zone II, P3 may be discovered if it operates on the same RAT as that of the macrocell because UE does not perform inter-RAT measurement in this case. The location of small cells and the frequency at which it operates relative to that of the macrocell is not known beforehand. Thus, cell discovery solely based on S-measure is not acceptable for HetNets.

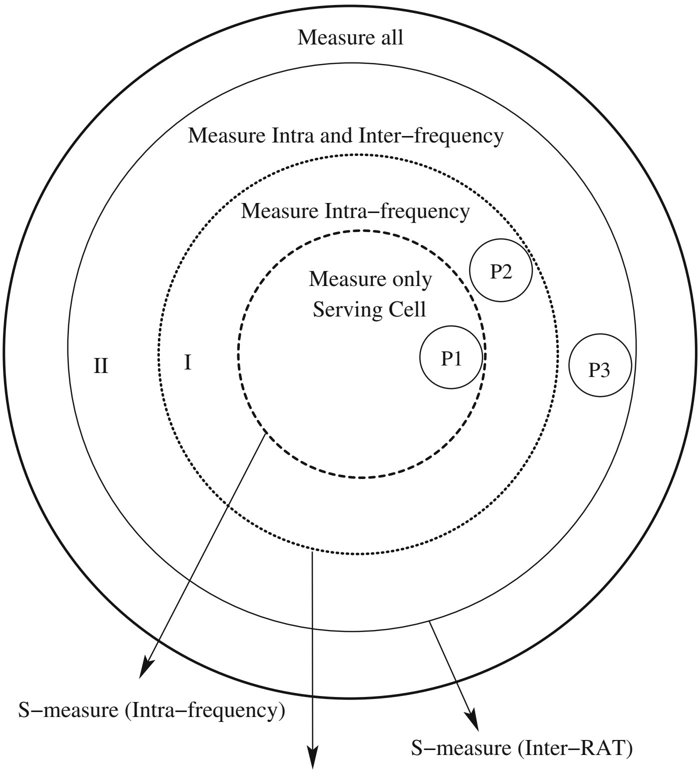


**Fig. 4.2** Challenges in using S-measure for measurement configuration in HetNets (adapted from [12])

One solution is to use S-measure based on the RSRQ measurements. However, the problem is not alleviated completely because it helps in the discovery of only those small cells which require intra-frequency measurements.

2. *Proximity Detection*:
It is a mechanism to detect the presence of small cells in the vicinity of UE and only then initiate explicit inter-frequency measurements. Based on the detection strategy, proximity detection may be classified as follows:

- *UE-Based Proximity Alert*—UE employs autonomous cell search and whenever it finds itself in the proximity of any small cell, it sends a proximity indication to the network. This indication is then used to initiate inter-frequency measurements. It is an efficient approach because it reduces the unnecessary inter-frequency handovers resulting in significant reduction in power consumption at UE.

- *Network-Based Proximity Alert*—This may be implemented in following ways: small cell and macro-eNB may sense the uplink transmissions such as Sounding Reference Signals (SRS) or Physical Random Access CHannel (PRACH) signals from macro and small cell UE, respectively. When the serving macro-eNB senses UE's vicinity to a small cell, it triggers UE to perform appropriate neighbouring cell measurements. When small cell eNB senses any macro-UE in its proximity, it sends proximity indication to the serving macro-eNB. Small cell eNB may transmit *discovery signal* on the frequency of macro-eNB for faster detection.

Based on the proximity indication reports, macro-eNB may either configure UE for inter-frequency measurements or trigger a HO to small cell immediately. In general, proximity detection is beneficial in reducing power consumption at UE and the signaling overheads required to switch radio path for inter-frequency measurements.

3. *Network-Controlled Background Inter-frequency Measurement*:
In this method, network initially configures UE for background inter-frequency measurements. When UE detects small cell, it reports to eNB which may decide to perform HO and offload UE or configure UE with existing inter-frequency measurements. Using background measurements, the network becomes aware of the offload opportunities faster. This is also a power-efficient method for small cell discovery.

However, the latency involved in *small cell discovery* manifests in the form of reduced offloading opportunity. In addition, it must be ensured that this mechanism is applied over only UEs with low or medium mobility state, else a large number of HOs may happen resulting in increased overheads.

### *4.2.2 Handover Issues*

Mobility management ensures that mobile users experience uninterrupted access to wireless services without compromising their expected QoS. Typically, this requires UE to measure the received signal power experienced from the neighbor cells either periodically or at the occurrence of some event and then report these measurements to its serving eNB. It is upto the latter to decide if and when the UE should be handed over to another eNB. With small cell deployment, a mobile UE happens to frequently cross cell boundaries generating many handover events. In addition, aggressive offload to small cells may be required to achieve capacity improvement. This calls for a change in the handover mechanism to reduce signaling overhead while maximizing the offloading gain.

The speed of user significantly influences the mobility-related decisions. For instance, it is not desirable to handover a high-speed UE to a small cell, because it may not stay in the cell for sufficiently long time, which may lead to increased number of handovers and signaling overhead.

Mobility state estimation of UE is a significant aspect of mobility management. In macro-only network, this estimate is based on the number of successful handovers UE undergoes. However, this logic may lead to either under-estimation or over-estimation of the mobility states in a HetNet because of the presence of different cell sizes and the fact that handovers in HetNets are based on offloading considerations and not just mobility. If the mobility states are determined accurately, certain measurement parameters can be optimized to improve the handover performance. For instance, small cell measurements can be disabled for high-speed users because the probability of their staying in small cell is very low, resulting in increased number of handover events and excessive overhead. This reinforces the necessity of accurate mobility state estimation to improve handover performance.

### 4.2.3 Impact of CRE and eICIC

In an heterogeneous network, signal strength-based user association may not be effective because connection with small cell may be required to achieve offload benefits even though user experiences lower SINR from small cell node. Mobility management in HetNet should, therefore, consider some cell-specific bias to the received signal from small cell eNB in order to enable steering of users to the small cell. The effective coverage area of small cell eNB increases with biasing, and this concept is known as *Cell Range Expansion* (CRE). While CRE helps in traffic offload, the users located in the extended coverage area of small cell eNB are likely to experience high downlink interference (from macro-eNB) in both data and control channels. It may deteriorate the handover performance in a network. This interference on data channels is mitigated by either interference cancelation at UE or by coordination-based resource allocation like implementing dynamic and self-organized interference mitigation techniques, as proposed in the literature. Another solution, which has not been exploited well in the literature is to optimize the mobility-related parameters to control traffic offload and improve handover performance. The objective of these propositions is to mitigate interference on data channels. However, interference mitigation for control channels is not addressed, which is more crucial.

A procedure called enhanced Inter-Cell Interference Coordination (eICIC) has been defined in Release 10 of 3GPP LTE specifications to mitigate the problem of increased interference in HetNets. In eICIC approach, macrocell configures certain subframes as blank subframes, during which no data transmission happens and only control information is transmitted at low power. While blank subframes are being transmitted from macrocell, data transmission can be scheduled by the small cells lying in its vicinity to and/or from its users, thereby eliminating interference between macrocell and small cell on both data and control channels.

## 4.3 Handover Performance Metrics

To analyze the mobility performance of a cellular network, following metrics are taken into consideration:

1. *MSE State Distribution*: The distribution of UE's mobility state is defined as the probability of a UE being estimated to be in a particular mobility state.
2. *Average Number of HO Failures*: It indicates the total number of HO Failures (HOFs) per UE per second, which is defined as the total number of HOFs averaged over the total travel time of all the simulated UEs.
3. *Average Number of Successful HOs*: It indicates the total number of successful HOs per UE per second, which is defined as the total number of successful HOs, averaged over the total travel time of all the simulated UEs.
4. *Average State-2 HOFs*: It is defined as the total number of State-2 HOFs averaged over the total travel time of all the simulated UEs. Note that State-2 HOFs, as described in Chap. 2 correspond to two cases of failure: (1) Radio link failure, marked by the expiry of T310 while TTT is running and (2) 'Out-of-sync' situation, marked by T310 running when 'HO Command' is being sent to UE by source eNB.
5. *Average State-3 HOF* is defined as the total number of State-3 HOFs averaged over the total travel time of all the simulated UEs. Note that State-3 HOFs, as described in Chap. 2 correspond to the scenario when the received signal power from the target eNB reduces below the acceptable threshold required for sustained connectivity. This results in PDCCH failure resulting in HOF.
6. *Overall HOF Rate*: It is defined as the ratio of the total number of HOFs per UE per second to the sum of the total number of HOFs per UE per second and the total number of successful HOs per UE per second.
7. *Time of Stay* (ToS): ToS in a cell A is the duration from the instant when an UE successfully sends a "HO complete" message to cell A till the instant when the UE successfully sends a "HO complete" message to another cell B. Note that when a HO is followed by a HOF, the ToS is not taken into consideration. ToS calculation for macro and pico follows this rule. Macro-ToS is considered only when one of these three situations arise: (1) a successful small cell to macro-HO is followed by a successful macro to macro-HO, (2) a successful macro to macro-HO is followed by a successful macro to small cell HO or (3) when there are two consecutive successful macro to macro-HOs happens. Small cell ToS is recorded only when a successful macro to small cell HO is followed by a successful small cell to macro-HO.
8. *Ping Pong Rate*: Ping Pong (PP) event occurs when an UE handovers from cell A to cell B and again to A within a short span of time, indicated by minimum ToS (Table 3.4). Ping pong rate is defined as the ratio of the number of ping pongs to the total number of successful HOs.

## 4.4 Summary

In this chapter, we have focused on the mobility-related challenges in HetNet. The accurate estimation of UE‘s mobility state can enable it to choose between the two options of speeding up or slowing down the HO process. This will eventually result in improved HO performance. Additionally, UE is required to opportunistically handover to small cells whenever possible and continue to stay in the small cell for good enough duration. Estimating the mobility state of UE in itself is challenging in HetNets because of variable cell sizes and frequent handover to and from small cells.

**Bibliographic Notes**
The benefits and challenges related to an heterogeneous network deployment are discussed in [36]. Various deployment scenarios in an LTE heterogeneous network are given in [7]. The definition of S-measure threshold and its role in the physical layer measurements are from [12]. The classification of proximity detection mechanism is given in [15]. The network-controlled background inter-frequency measurement procedure can be obtained in [16]. Some of the self-organized interference mitigation techniques available in the literature and discussed in this chapter are from [30, 38, 39]. The handover performance metrics are defined in [4].

# Chapter 5
# Enhancements for Mobility State Estimation in LTE HetNet

The heterogeneous cellular deployment improves the spectral efficiency of cellular network due to the dense spectral reuse. At the same time, mobility management becomes more complex due to the proliferation of small cells, resulting in increased number of cell crossings. In addition, user mobility impacts the HO performance. Therefore, mobility state of user needs to be taken into account to classify UEs in normal, medium, and high mobility states, respectively. The information about the mobility state of a UE can be used for the selection of handover parameters for that UE. The Mobility State Estimation (MSE) procedure as specified by 3GPP LTE standard is used to classify UEs in normal, medium, and high mobility states, respectively, based on their handover rate. This information is subsequently used to determine the appropriate handover parameters for each UE.

In this chapter, we discuss 3GPP MSE procedure which is used in LTE and analyze the impact of MSE thresholds on the mobility performance. We investigate the performance issues with 3GPP MSE procedure and give the motivation to address them. We analyze the performance using the HetNet mobility simulator that is based on the mobility evaluation methodology used in Release 12 of 3GPP LTE standard. Further in this chapter, we illustrate three enhancements to the existing MSE procedure which reduces handover failures and improves accuracy of the mobility state estimation.





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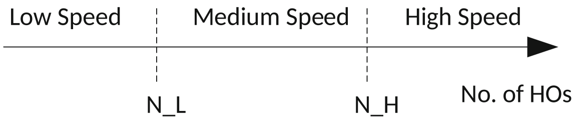


**Fig. 5.1** Mobility state estimation—based on HO counts. ©2016 IEEE. Reprinted, with permission, from IEEE Wireless Communications and Networking Conference (WCNC), 2016 (DOI: 10.1109/WCNC.2016.7564960)

## 5.1 3GPP Legacy MSE Procedure

In the existing MSE scheme, as defined in 3GPP LTE standard, the mobility state of a UE is detected by counting the number of HOs over a specified period of time. The number of cell changes is compared with two thresholds (*N_H* and *N_L*, configured by eNB) to determine one of the three mobility states: high, medium, and normal, as shown in Fig. 5.1.

UE can autonomously scale its mobility parameters (*hysteresis* or *TTT*) based on its detected mobility state. A predetermined value of TTT is used for all UEs, unless their mobility state is determined. UE detected in the normal mobility state continues to use the default value of TTT, while a UE in medium and high mobility states scales down the default value of TTT by half and one-fourth, respectively. The rationale behind this scaling down is to expedite the handover process for medium and high mobility users. As described in Chap. 2, the handover procedure can be divided into 3 states, where State 2 consists of Time To Trigger (TTT) and HO preparation time. The HO preparation time typically depends on the processing load at source and target eNBs and the availability of radio resources for sending the HO command. However, TTT being a configurable parameter, one way to speed up the HO process is to reduce the TTT. This is achieved using speed-dependent scaling. Reducing TTT ensures that the time taken by UE to complete State 2 of HO process is shortened. This increases the likelihood of a UE in high mobility state to complete the handover before the experienced received signal power deteriorates to the extent of causing a radio link failure.

In the next section, we discuss various performance issues with regard to the mobility state estimation.

## 5.2 Performance Issues in Mobility State Estimation

There are two main HO-related issues concerning the speed of the mobile users. First, users with medium-/high-speed traverse the HO region faster compared to low-speed users and therefore require faster HO processing to avoid HO failures. Note that high-speed UEs are likely to experience frequent HOs with short Time of Stay (ToS). This problem becomes more acute in HetNet because of the small cells whose coverage area is much smaller compared to the macro-cell. Such frequent HOs lead to increased signaling overhead, reduction in UE's battery life, and degradation in the overall mobility performance. To resolve this issue, handover to small cells may be avoided for the high-speed UEs. However, coverage-based handover to small cells may be required to minimize call drops due to radio link failure. To implement such a scheme, we need fairly accurate estimation of the UE's mobility state. Limited work has been done in this regard, in the context of HetNet.

The prime performance considerations relating to the mobility state estimation are as follows:

1. First, the 3GPP-specified MSE procedure (also referred to as the legacy scheme) considers only the successful HO events excluding ping-pongs, for the estimation of UE's mobility state. However, the HO failure events in states 2 and 3 (which correspond to the scenarios where A3 event has occurred but either the UE has not received HO command from the serving eNB or if it has received HO command, the HO complete message could not reach the target eNB, both due to radio link failure) also indicate user mobility, which needs to be taken into account in the mobility state estimation. This consideration is required because the mobility state estimation is performed based on the number of cell crossings that UE encounters in a given time period. In case of handover failure, in particular when it happens in states 2 or 3, the event of cell crossing cannot be neglected. This issue has been addressed in the enhanced MSE scheme in Sect. 5.3.
2. Second, 3GPP legacy MSE procedure is optimized for homogeneous networks or macro-only deployment where cells are of uniform sizes, i.e., the cellular footprint of eNBs is similar. However, the cells may be of vastly different sizes due to various deployment considerations. For instance, outdoor pico in a stadium may operate at higher power compared to an indoor pico inside an office building. In general, the number of HO events per UE is expected to be higher because of the increased cell density in HetNet. This results in the overestimation of UE's mobility state, i.e., HO count for MSE calculation may be high even if UE speed is low. This overestimation may result in improper selection of TTT and increased ping-pongs. To prevent this, different weights can be assigned to different types of HOs (macro-to-macro, macro-to-pico, pico-to-macro, or pico-to-pico) in the MSE computation. Such weighted MSE scheme is illustrated in Sect. 5.4.
   Alternatively, handover parameters can be determined based on source/target cell size, in addition to mobility state. The source/target cell size determines the HO region, which is that portion of the coverage regions of source and target eNBs which are traversed by UE from the instant HO is initiated up to the time of HO completion. Note that the size of HO region in homogeneous network (i.e., macro-only network) is more or less the same, whereas in HetNets, the HO region depends on the source and the target cell type. The size of HO region can assist in an appropriate selection of TTT for the UE, which in turn impacts the HO performance. However, 3GPP legacy MSE procedure does not take this into account.

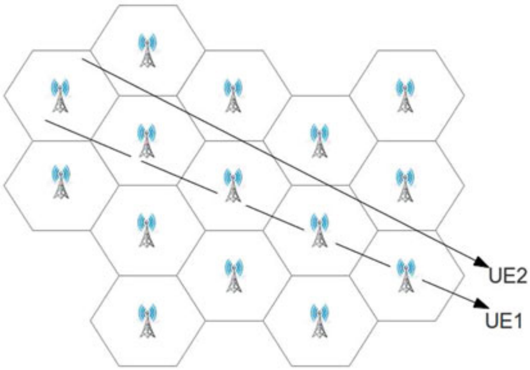


**Fig. 5.2** Impact of UE trajectory on MSE. ©2016 IEEE. Reprinted, with permission, from IEEE Wireless Communications and Networking Conference (WCNC), 2016 (DOI: 10.1109/WCNC.2016.7564960)

3. Third, inconsistency in the mobility state estimation may arise when the users follow different mobility paths. Consider Fig. 5.2 as an example to depict the impact of UE trajectory on the mobility state estimation. UE1 and UE2 are both moving with the same speed, but UE2 experiences more HO events compared to UE1 in the same observation interval. This may lead to the overestimation of mobility state for UE2. This problem is evident in HetNet deployment, even for smaller inter-eNB distances. Thus, there is a need to give consideration to the UE trajectory in the MSE computation. Trajectory-based MSE scheme is discussed in Sect. 5.5.

In the related works available in the literature, research focus has been on utilizing the mobility state information of UE to achieve either improved interference management or efficient handover decisions. See bibliographic notes for further details. Although these proposals claim improved mobility performance, there is no backward compatibility with 3GPP legacy MSE procedure.

However, the estimation of UE's mobility state is critical, which has not been considered in the literature, as per our knowledge. The thrust of this chapter is on addressing the procedure for mobility state estimation to improve the mobility performance in HetNet. In the next section, we describe enhanced MSE scheme.

## 5.3 Enhanced MSE Scheme

To understand the issues related to MSE performance in HetNets more clearly, we first consider 3GPP legacy MSE procedure and compare its performance in HetNet and macro-only network scenarios. Let TTT be set to 480 ms, A3 offset to 1 dB, and cell-specific offsets to 2 dB for this simulation. Note that A3 in 3GPP LTE standard refers to an event which triggers the reporting of measurements performed by UE from neighboring cells to the serving eNB. A3 event is triggered when the received signal power experienced from a neighboring eNB becomes higher than that of the

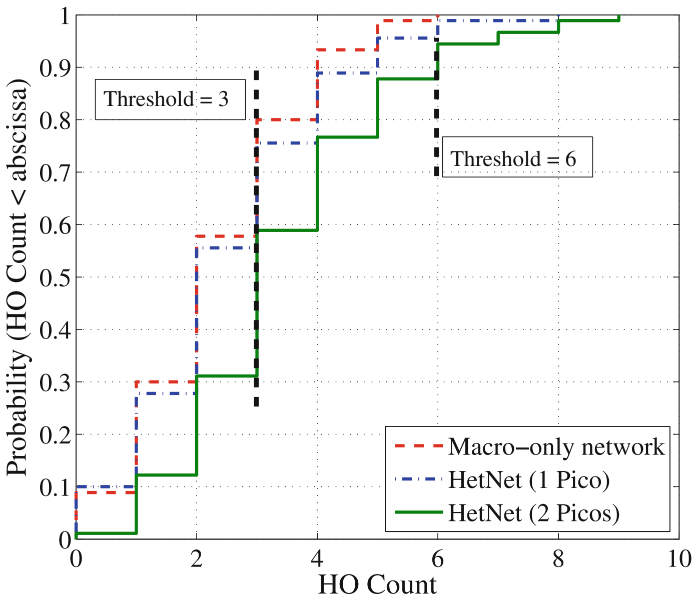


**Fig. 5.3** CDF of HO counts for macro-only and heterogeneous network. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084911)

serving eNB by an amount equal to A3 offset. Cell-specific offset is defined in 3GPP LTE standard as the bias added to small cell measurement to increase offloading and ToS in small cells.

Figure 5.3 gives the Cumulative Distribution Function (CDF) of HO event counts for both macro-only network and HetNet. It is clear that in HetNet case, HO event count tends to be on the higher side and this trend becomes more pronounced with an increase in the density of pico-cells. Assuming 6 and 3 as medium and high MSE thresholds to estimate UE's mobility state, we observe that in the macro-only network, 58% of the time, the UE will be considered to be in normal state and 42% of the time in medium mobility state, when the actual UE speed is 60 km/h (which can be considered as medium mobility state). On the contrary, as the pico-cell density per sector increases from 1 to 2, (a) the number of times UE is considered to be in high mobility state increases from about 1–5% and (b) the HO count for normal (low) mobility state reduces by about 25%. This happens because HOs are more likely in HetNet due to the presence of small cells and the HO count increases with an increase in the density of small cell. Thus, increased HO count in HetNet directly impacts the MSE, resulting in overestimation of mobility state. This motivates the need to modify the existing MSE scheme to ensure accurate mobility state estimation in HetNets.

3GPP legacy MSE procedure relies on counting the number of cell crossing a UE undergoes in a specified time interval (MSE interval) to estimate its mobility state. Then, based on the estimated mobility state, appropriate TTT scaling is applied for the subsequent MSE interval. For high and medium mobility states, TTT is reduced to expedite the HO process, while TTT remains unchanged for a UE in normal mobility state. This is to ensure that the HO processing of medium-/high-speed users gets completed before call drop situation arises. In 3GPP legacy MSE, the number of successful HOs during the MSE interval is compared with the given thresholds. However, there is no consideration given to HO failure, which is also a mobility event, as it stems from UE's attempt to change cell. Therefore, enhanced MSE scheme takes both successful as well as failed HO events into consideration while counting mobility events. Subsequently, the HO count is compared with the medium and high MSE threshold and UE's mobility state is estimated.

### *5.3.1 Results and Inferences*

We follow the system model and mobility scenario as specified in Chap. 3. Figure 5.4 highlights the difference in mobility state estimation for legacy and enhanced cases, when UE is moving with a constant speed of 60 km/h. In this figure, we represent the distribution of MSE states (in percentage) using histogram. Note that the distribution of MSE states is defined as the relative amount of time, a UE is designated to be in a particular mobility state (low, medium, or high) during the simulation duration. It is evident that 3GPP legacy MSE considers UE to be in normal mobility state 75% of the times, while the enhanced MSE tends to put users in medium/high mobility states almost 90% of the times. Note that the actual UE speed is 60 km/h in the simulator, which can be considered as medium mobility state. This happens because in the enhanced MSE, the count of mobility events increases due to HOF consideration. Thus, mobility event count in the MSE interval is likely to exceed medium/high threshold often, and therefore, estimated state happens to be medium or high more often compared to that of 3GPP legacy MSE. State estimation updates the TTT value, which in turn impacts the State 2 failures. Observing the reduction of about 15.4% in State 2 HOFs (Fig. 5.4) for the enhanced MSE, we can infer that because of smaller TTT, UE is able to complete the HO processing before its link with the serving node deteriorates significantly enough to cause RLF. Similar results for UE speed of 30 km/h, given in Fig. 5.6, are discussed later in the chapter. Thus, the enhanced MSE improves the mobility state estimation for UEs, resulting in improved HO performance.

Figure 5.5 compares the performance of both schemes in terms of HOF rate. We observe that for all HO scenarios, the failure rate is reduced in the case of the enhanced MSE compared to 3GPP legacy MSE. To understand the reason for this HOF rate reduction, we refer to Fig. 5.4, when the actual speed of user is 60 km/h (considered as medium mobility state). In this scenario, we recall the following two observations:

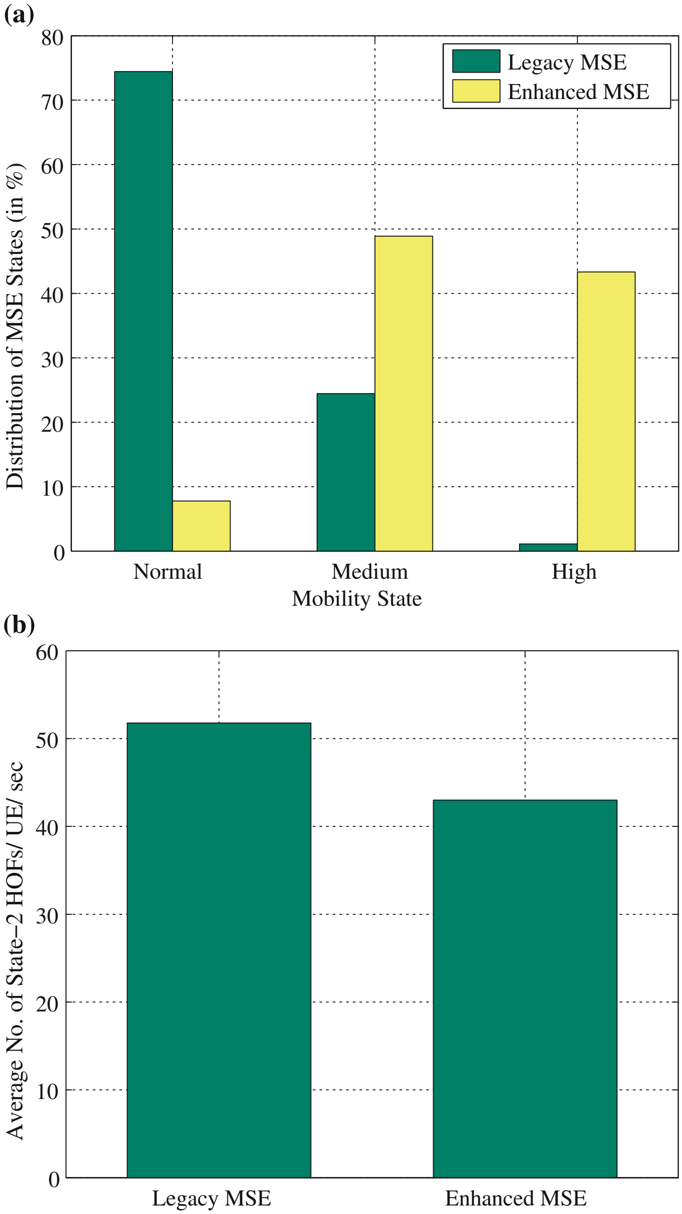


**Fig. 5.4** Comparison of legacy and enhanced MSE (UE speed = 60 km/h and TTT = 480 ms): **a** count of mobility states and **b** state 2 HOFs. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084911)

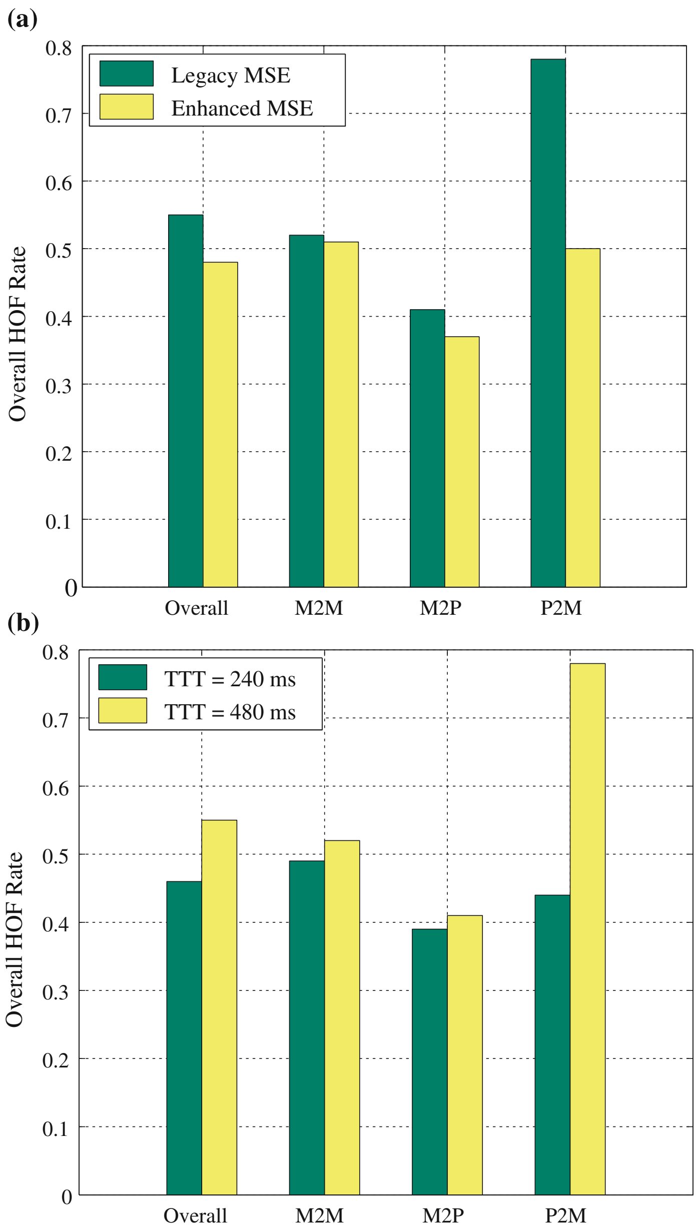


**Fig. 5.5** Comparison of HOF rate (UE speed = 60 km/h): **a** 3GPP legacy and enhanced MSE when TTT = 480 ms and **b** 3GPP legacy MSE. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084911)

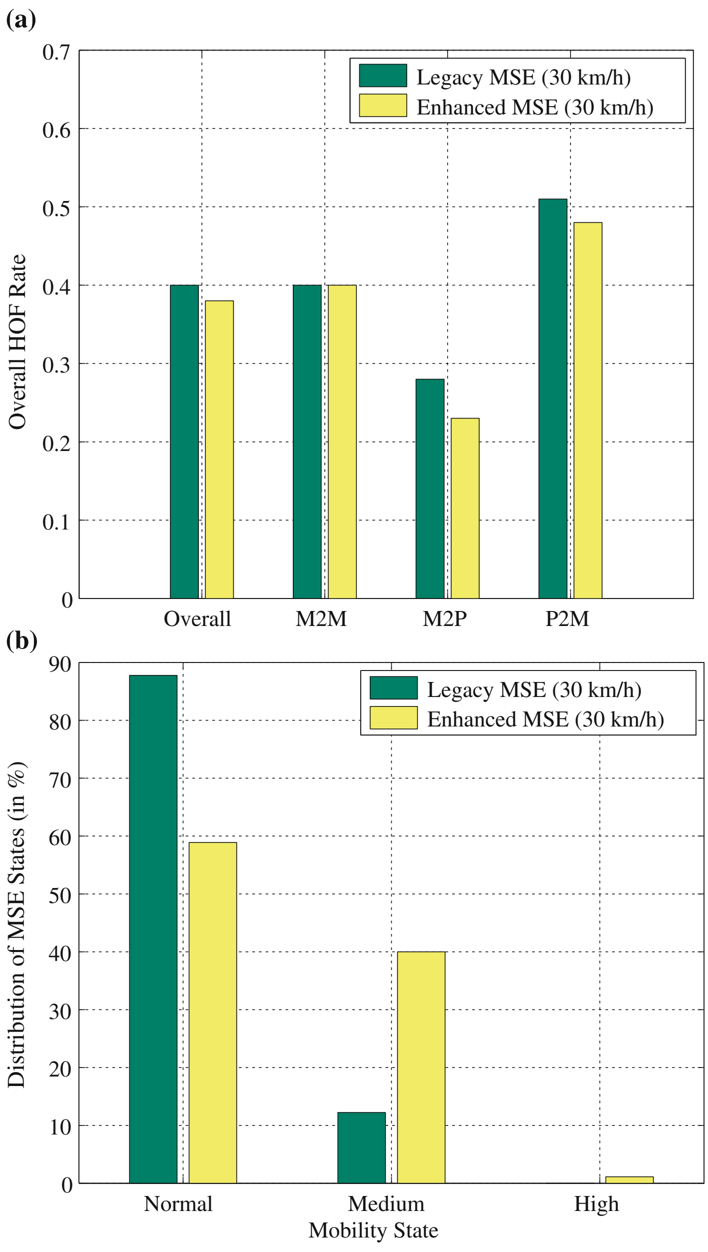


**Fig. 5.6** Comparison of 3GPP legacy and enhanced MSE (UE speed = 30 km/h): **a** HO failure rate and **b** count of mobility states. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084911)

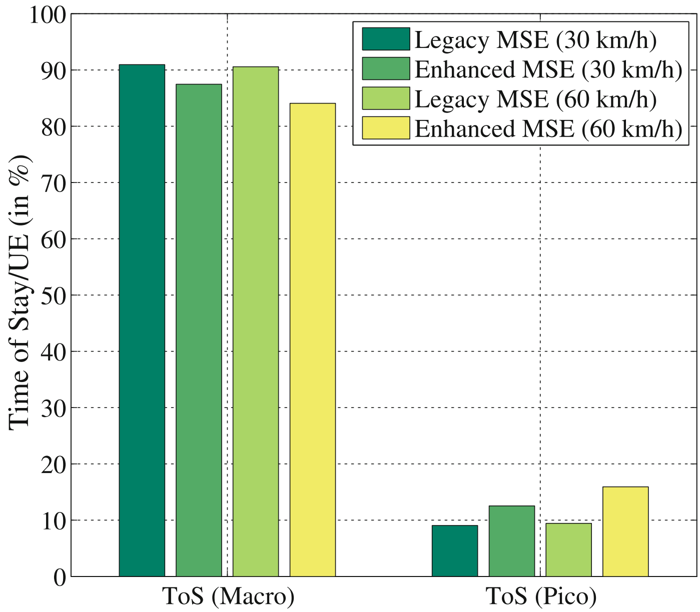


**Fig. 5.7** ToS comparison for 3GPP legacy and enhanced MSE. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084911)

- When 3GPP legacy MSE is used, approximately 75% of the time, UE is considered to be in normal mobility state. This implies that TTT remains fixed at 480 ms 75% of the time and downscaling happens only for the remaining 25% of the time in case of legacy MSE.
- With the enhanced MSE, approximately 50% of the times, UE is considered to be in medium mobility state. Therefore, for almost 50% of the times, TTT downscales from 480 to 240 ms. Note that this downscaling happens more often in the enhanced MSE compared to 3GPP legacy MSE.

Figure 5.5 shows the variation in HOF rate based on TTT. It is clear that lower value of TTT results in reduced HOF rate. Extrapolating this with Fig. 5.5, it is observed that with 3GPP legacy MSE, TTT remains 480 ms most of the time. Hence, HOF rate is higher compared to the scenario when enhanced MSE is used, where TTT is equal to 480 ms less than 10% of the time. Thus, with accurate state detection and resulting TTT scaling when enhanced MSE is implemented, the HO performance improves significantly, in particular for pico-to-macro HOs (Fig. 5.5).

We analyze the impact of enhanced MSE for UE with speed 30 km/h on HOF rate in Fig. 5.6 and occurrence of MSE states in Fig. 5.6. We observe that HOF rate reduces in enhanced MSE, in particular for pico-to-macro and macro-to-pico handovers. We also note that the HOF rates are lower for 30 km/h speed users, compared to 60 km/h speed users (Fig. 5.5). The MSE state distribution result in Fig. 5.6 shows that more users are considered to be in the medium mobility state (when the actual UE speed is modeled as 30 km/h) when the enhanced MSE is used compared to when 3GPP legacy MSE is used. This is because the HO count for the enhanced MSE is higher compared to that of the legacy MSE, as shown in Fig. 5.3 earlier.

Figure 5.7 shows reduction in ToS for macro and increased ToS for pico-cell when the enhanced MSE is used compared to when 3GPP legacy MSE is used. The trend is same for both UE speeds, 30 and 60 km/h, with the only difference that the percentage reduction in macro-ToS and increase in pico-ToS are higher for 60 km/h speed. This happens because the probability of crossing pico-cells and encountering more HOs is more for users with higher speed (60 km/h in this case).

## 5.4 Weighted MSE Scheme

One of the solutions to improve mobility performance in HetNet scenario is to prevent high-speed UEs to hand over to small cells. However, it is not feasible to prevent all high-speed UEs from handing over to small cell. For instance, when UE is in outage with reference to macro-eNB but experiences sufficiently high received signal power from small cell. Another instance could be when UE experiences severe interference from small cell. In that case, it becomes essential to perform handover to small cells to prevent call drop due to radio link failure.

However, the legacy MSE procedure is not capable of implementing such use cases when we allow handover of high-speed UE to small cell and prevent it at all other times. This is because legacy MSE procedure does not give any consideration to cell type in the mobility state estimation. Legacy MSE procedure only provides the mechanism to expedite the HO process for high-speed UEs by downscaling TTT appropriately.

In weighted MSE scheme, we suggest three different approaches to prevent overestimation of UE's mobility state in HetNet deployments, which are described in the following sections.

### *5.4.1 Weight Assignment to HO Events*

To distinctly identify the high-speed users, it is required to accurately estimate the user's mobility state. As discussed in Sect. 5.2, handovers occur between cells of different sizes in HetNet deployment, such as macro-to-macro, macro-to-pico, pico-to-macro, and pico-to-pico. This may lead to increased count of handovers during the evaluation period, resulting in the overestimation of UE's mobility state. The overestimation may be significant when the density of small cells in HetNet is high. To prevent overestimation, the weighted MSE scheme performs different weight assignments to different HO events and the final HO count for MSE is computed using a weighted sum of the HO events as

$$MSE = n_{mm} * w_{mm} + n_{mp} * w_{mp} + n_{pm} * w_{pm} + n_{pp} * w_{pp} \quad (5.1)$$

where $w_{mm}$, $w_{mp}$, $w_{pp}$, $w_{pm}$ represent the weights assigned to each type of HO event. As the coverage area of pico-cells is smaller compared to that of macro-cells, lesser weight is assigned to the HO events involving pico-cells. Thus, the weighted MSE employs the weights 1, 0.45, 0.25, and 0.1 for macro-to-macro, macro-to-pico, pico-to-macro, and pico-to-pico HO events, respectively.

### 5.4.2 HO Avoidance to Small Cells—Restricting Measurement Reporting

In this step, we restrict the reporting of small cell measurements to the serving eNB for high-speed users. The network specifies the Physical Cell Identity (PCI) of the pico-cells, known as Gray list. UEs perform the RSRP/RSRQ measurements on all cells, but the measurement reporting for gray listed cell is not done when UE is a high-speed UE. This prevents the HO triggering to a small cell for high-speed UE. The battery drain due to performing the measurements on small cells is inevitable in this case. However, this mechanism allows handover to a pico-cell in two cases: (1) when there is no suitable macro-cell available as the target cell for handover or (2) when UE experiences severe interference from pico-cell. Thus, handover of high-speed UE to pico-cell is allowed only for the coverage reasons and to prevent call drop due to radio link failure. The implementation is done based on comparing the RSRQ measurement from serving cell with that from the neighboring macro- and pico-cells.

### 5.4.3 HO Avoidance to Small Cells—Cell-Dependent TTT Scaling

We focus on appropriate scaling of the handover parameter, TTT, to regulate the HO process timing and prevent high-speed users to hand over to small cells, while ensuring that the mobility performance of low-/medium-speed users are not adversely affected. In the legacy MSE procedure, the choice of TTT does not depend on the target cell under consideration during the HO process. On the contrary, in this approach, it is emphasized that the requirement of upscaling and downscaling TTT is based not

**Table 5.1** Cell-dependent TTT scaling (adapted from [18])

| TTT (ms) | Macro-to-macro | Macro-to-pico | Pico-to-macro | Pico-to-pico |
|---|---|---|---|---|
| Normal MSE | 256 | 256 | 256 | 256 |
| Medium MSE | 128 | 256 | 128 | 128 |
| High MSE | 128 | 480 | 128 | 128 |

solely on the serving cell, but on the combination of serving and target cells. TTT scaling for four HO events and all possible source and target cell combination are given in Table 5.1.

The strategy is to downscale TTT when the mobility state is estimated to be medium or high and the target cell is a macro-cell. For macro-to-pico handover, no scaling is applied when the estimated mobility state of UE is medium but upscaling of TTT is done when MSE is high, to reduce the probability of triggering handover to a pico-cell. For pico-to-pico handovers, TTT is downscaled to ensure timely handover.

### *5.4.4 Results and Inferences*

The simulations have been done for heterogeneous deployment with four pico-cells located randomly within each tri-sectored macro-cell. User moves in a random direction at constant speed along a straight line. Figure 5.8 compares the rate of handovers for UEs with different speeds for the legacy MSE, weighted MSE, MSE with GrayList option, and MSE with cell-dependent TTT scaling option. Rate of handover is proportional to UE speed, but we can observe that with GrayListing option, there occurs fewer HOs for high-speed UEs because of preventing high-speed UEs to hand over to pico-cells.

Figure 5.9 compares the offloading percentage for the four variants of MSE schemes discussed in this section. The offloading percentage for high-speed UEs reduces for MSE with cell-dependent TTT scaling, but this reduction is more evident for MSE with GrayList option, compared to all other schemes.

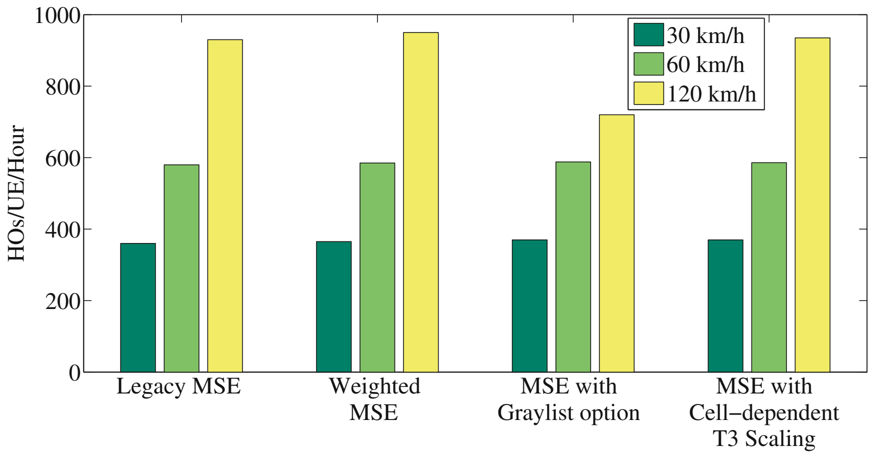


**Fig. 5.8** Number of handovers/UE/hour for legacy MSE, weighted MSE, MSE with GrayList option, and MSE with cell-dependent TTT scaling option (adapted from [18])

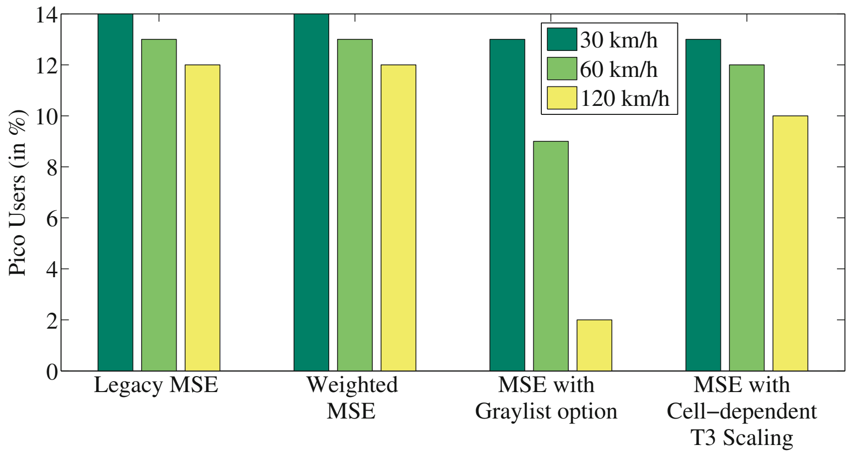


**Fig. 5.9** Percentage of pico-users for legacy MSE, weighted MSE, MSE with GrayList option, and MSE with cell-dependent TTT scaling option (adapted from [18])

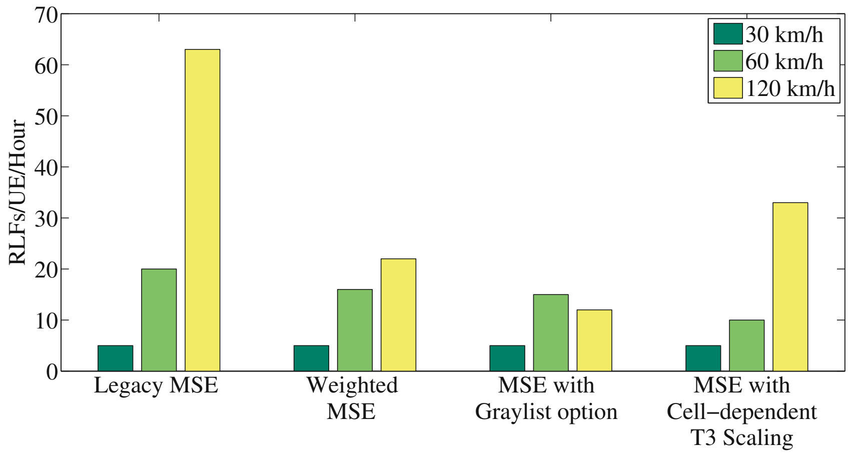


**Fig. 5.10** Radio link failure comparison for legacy MSE, weighted MSE, MSE with GrayList option, and MSE with cell-dependent TTT scaling option (adapted from [18])

Figure 5.10 shows reduction in RLF for weighted MSE compared to legacy MSE, as expected. MSE with cell-dependent TTT scaling option also shows this reduction, except for high-speed UEs. Comparing the RLF metric, MSE with GrayList option gives the best performance.

Figure 5.11 compares the percentage of pico-users in case of legacy MSE procedure with weighted MSE using GrayList option and MSE with GrayList option. Note that this simulation is performed for a denser heterogeneous network, where there are 10 pico-cells per macro-cell. The results show that combination of weighted MSE with GrayListing option outperforms the other two schemes and results in increasing the offloading percentage of users in the network.

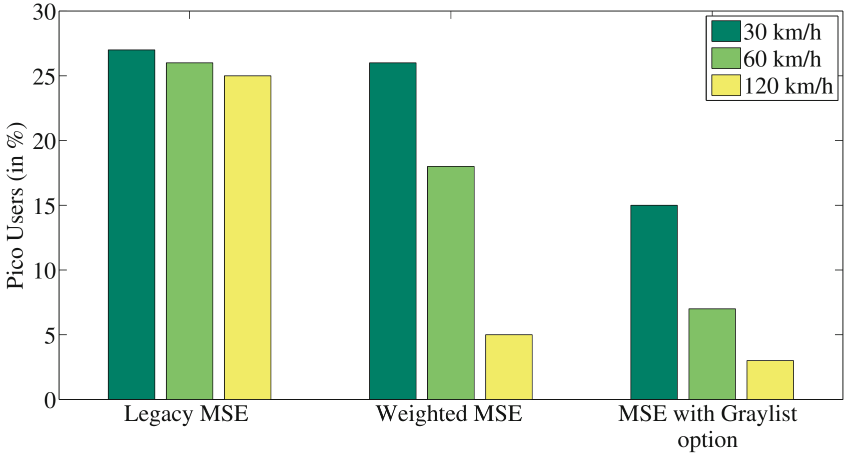


**Fig. 5.11** Percentage of pico-users for legacy MSE, weighted MSE using GrayList option, and MSE with GrayList option (adapted from [18])

## 5.5 Trajectory-Based MSE Scheme

The issue of inconsistent MSE is addressed by giving consideration to the UE trajectory in the MSE. The trajectory-based MSE procedure introduces new mobility event which gives consideration to the UE trajectory by defining a threshold for the RSRP measured by the UE from the serving macro-eNB. Whenever the RSRP measurement crosses the given threshold, it is considered to be a 'threshold crossing event' and these events are subsequently used in the MSE procedure. The procedure for threshold update and counting threshold crossing events is as follows: UE sets the initial value of threshold as $RSRP_{high}$ if the measured RSRP from the serving eNB is less than $RSRP_{high}$, else it sets the threshold value as $RSRP_{low}$. The updates happen as follows: When the configured threshold is $RSRP_{high}$ and UE's measured RSRP becomes greater than the threshold, the threshold crossing event counter is incremented by one and the threshold is updated to $RSRP_{low}$. Similarly, when the configured threshold is $RSRP_{low}$, the threshold crossing event counter is incremented by one when the measured RSRP becomes less than the threshold, and consequently, the threshold is updated to $RSRP_{high}$.

Figure 5.12 illustrates the trajectory-based MSE procedure. Here, two RSRP thresholds are depicted—$RSRP_{high}$ and $RSRP_{low}$, one for UE moving toward the serving eNB (increasing RSRP trend) and other for UE moving away from the eNB (decreasing RSRP trend), respectively. The initial value for threshold in the figure is set as $RSRP_{high}$. Hence, when the measured RSRP becomes greater than the threshold at point P1, it is recognized as a threshold crossing event. After P1, the threshold is re-configured as $RSRP_{low}$; hence, P2, P3, and P4 are not considered as threshold crossing events. Measured RSRP becomes less than $RSRP_{low}$ at P5 which leads to

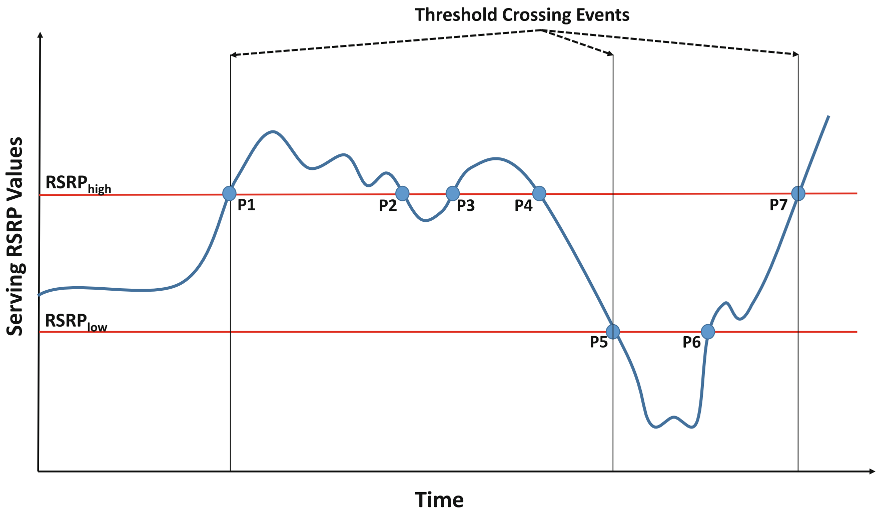


**Fig. 5.12** Threshold crossing event for varying RSRP values with time. ©2016 IEEE. Reprinted, with permission, from IEEE Wireless Communications and Networking Conference (WCNC), 2016 (DOI: 10.1109/WCNC.2016.7564960)

a threshold crossing event after which the threshold is updated to $RSRP_{high}$. Similarly, the third threshold crossing event occurs at P7. The rationale behind two RSRP thresholds instead of a single threshold is to mitigate the effects of fading which may otherwise increase the count of threshold crossing events significantly, leading to overestimation of UE's mobility state.

The threshold values are determined such that the mean of the two thresholds is the 50th percentile of the RSRP distribution in the network. It is to ensure the occurrence of sufficient number of threshold crossing events. By extensive simulations with inter-eNB distance of 500 m, the 50th percentile of the RSRP distribution is found to be $-101$ dBm. The difference between $RSRP_{high}$ and $RSRP_{low}$ is set as 6 dBm considering the effects of fading. Hence, the values of $RSRP_{high}$ and $RSRP_{low}$ are configured as $-98$ and $-104$ dBm, respectively.

Figure 5.13 gives the flowchart representation of the trajectory-based MSE procedure. In this procedure, the number of mobility events, i.e., both HO events and threshold crossing events, are counted during the counting period $t_{eval}$. The HO events include only successful HO events (as in 3GPP legacy MSE procedure) for trajectory-based MSE scheme.

Each mobility event is assigned a distinct weight based on the HO type or threshold crossing event. At the advent of counting period, variable *Count* is initialized to zero. On the occurrence of each mobility event within the counting period, *Count* is incremented appropriately by the weight assigned to that mobility event. At the expiry of counting period, the variable *Count* represents the weighted sum of the mobility events that occurred in the counting period. The weighted sum obtained is then compared with NCC_h and NCC_l to estimate the mobility state. $w_{mm}$, $w_{mp}$,

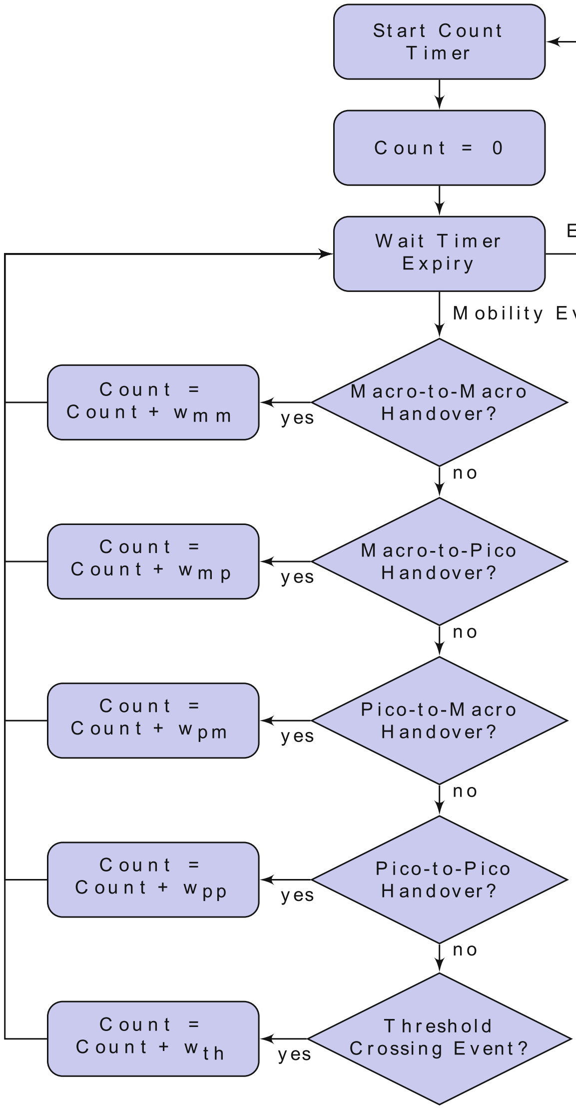


**Fig. 5.13** Flowchart: trajectory-based MSE procedure. ©2016 IEEE. Reprinted, with permission, from IEEE Wireless Communications and Networking Conference (WCNC), 2016 (DOI: 10.1109/WCNC.2016.7564960)

**Table 5.2** Weight assignment for mobility events

| Mobility event | Weight assignment | | |
|---|---|---|---|
| | Weighted MSE [18] | Trajectory MSE [19] | ETMSE [19] |
| Macro-to-macro | 1 | 0.5 | 0.35 |
| Threshold cross event | N.A. | 0.5 | 0.45 |
| Macro-to-pico | 0.45 | 0.15 | 0.15 |
| Pico-to-macro | 0.25 | 0.15 | 0.15 |
| Pico-to-pico | 0.1 | 0.1 | 0.1 |

$w_{pp}$, $w_{pm}$ in the flowchart represent the weights assigned to each type of HO event and $w_{th}$ represents the weight for threshold crossing event.

The weight assignment to mobility events is done as follows: The weight for macro-to-macro HO is determined by performing extensive simulations and validating with the MSE distribution of users, as done in the weight-based MSE scheme. Likewise, the weight for threshold crossing event is determined as given in Table 5.2.

The presence of small cells in the network increases the number of mobility events, and therefore, the weight assigned to a HO event should decrease with decreasing size of the cells involved in the HO process to stabilize the MSE. Note that this aspect has not been considered in the weight-based MSE scheme. Thus, the following weight formulation is applied in the trajectory-based MSE scheme for a HO event involving small cells,

$$w_{HO} = \frac{{Range_{macro}}^2}{Range_{serv} * Range_{target}} \tag{5.2}$$

where $Range_{macro}$, $Range_{serv}$, and $Range_{target}$ indicate the signal transmission range of the macro, serving and target eNBs in terms of distance. With 250 and 40 m as the transmission range of macro- and pico-eNB, the weights determined for macro-to-pico, pico-to-macro, and pico-to-pico HO are 0.15, 0.15, and 0.1, respectively.

With this formulation, the weight for macro-to-macro HO event comes out to be 1. However, this is not feasible because in addition to the weights of HO event, there is nonzero weight assignment for threshold crossing event. Therefore, in this case, the overestimation of UEs mobility state is likely to happen. To prevent this, it is to be ensured that the weights for macro-to-macro HO and threshold crossing event remain less than 1. Therefore, the weights are determined by performing simulations for different weight combinations and validating with the corresponding MSE distribution. The resulting weights are shown in Table 5.2.

Table 5.3 gives the simulation parameters for the analysis of MSE procedures. The performance of the MSE procedure is evaluated based on the following criteria.

1. UE with speed 30 km/h is considered to be in normal mobility state
2. UE with speed 60 km/h is considered to be in medium mobility state
3. UE with speed 120 km/h is considered to be in high mobility state.

**Table 5.3** Simulation parameters

| Parameter | Value |
|---|---|
| Number of users/iteration | 1 |
| Simulation iterations | 12 |
| Total simulation time | 36,00,000 ms (1 h) |
| User speed | 30,60,120 km/h |
| eNB Tx power | Macro: 43 dBm, pico: 27 dBm |
| Macro inter-site distance | 500 m |
| Pico-eNB deployment | Hotspot deployment—2 pico-eNBs/macro sector |
| A3_offset | 1 dB |
| Time to trigger | 480 ms |
| $T_{eval}$, NCC-h, NCC-l | 30 s, 2, 4 |
| TTT scaling factors | sf-medium: 1/2, sf-high: 1/4 |
| $RSRP_{thresh}$, $RSRP_{hyst}$ | −98, 6 dB |

### 5.5.1 Evaluation and Results

Following metrics are used to analyze the mobility performance of the UE,

1. *MSE state distribution*: The distribution of UE's mobility state is defined as the probability of a UE being estimated to be in a particular mobility state.
2. *HOF rate*: HOF rate is defined as the ratio of number HOFs to the count of HO attempts (HO success + HOF).
3. *Average time of stay* (*ToS*): Time of stay in an eNB is the duration for which UE is associated with a particular eNB before switching association due to either HO or RLF.

Figure 5.14 shows the distribution of MSE for weighted MSE and trajectory-based MSE schemes for the macro-only network. The MSE distribution is represented by using histogram plots for three UE speeds—30, 60, 120 km/h. Note that for 30 km/h speed, the trajectory-based MSE and weighted MSE schemes produce similar MSE distribution. However for the case of 120 km/h speed, the trajectory-based MSE outperforms the estimation accuracy of weighted MSE as the proportion of time the UE is designated as HIGH mobility state in enhanced MSE is ∼20% higher than for the weighted MSE scheme. This means that a UE can potentially avoid 20% HO events to the pico-eNB for the trajectory-based MSE scheme compared to the weighted scheme, if UE implements the strategy of avoiding HO of high-speed users to small cells.

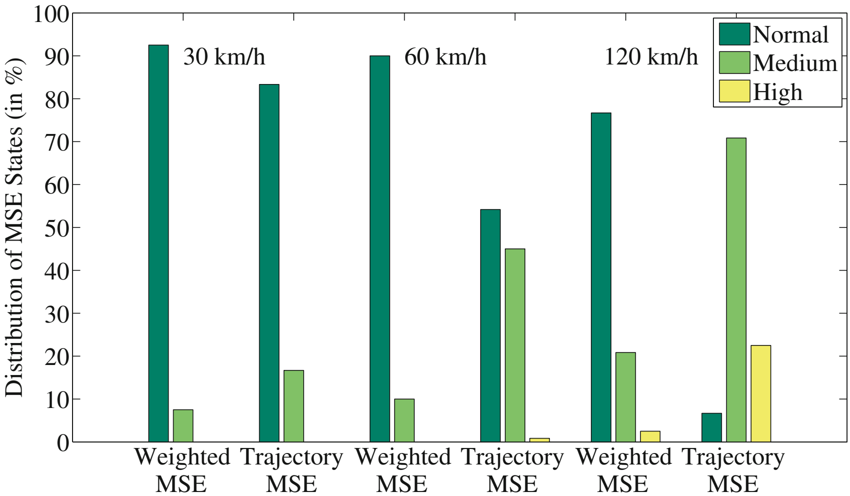


**Fig. 5.14** MSE state distribution for weighted and trajectory-based MSE schemes for macro-only deployment scenario. ©2016 IEEE. Reprinted, with permission, from IEEE Wireless Communications and Networking Conference (WCNC), 2016 (DOI: 10.1109/WCNC.2016.7564960)

## 5.6 Enhanced Trajectory-Based MSE Scheme

In the enhanced trajectory-based MSE (ETMSE) scheme, the aspects of both enhanced MSE as well as trajectory-based MSE schemes are combined. Thus, the count of HO failures is also given consideration in the mobility state estimation, as done in enhanced MSE scheme. In addition, consideration is given to the threshold crossing events that UE undergoes, as done in the trajectory-based MSE scheme. The assigned weight for a HOF event is same as that of a HO success event in the same scenario. To mitigate the likelihood of overestimation by HOF consideration, smaller weights are used for macro-to-macro and threshold crossing events compared to those used in the trajectory-based MSE, i.e., less than 0.5. The weights for the corresponding events are determined in the same way as described for trajectory-based MSE. The weight assignment is shown in Table 5.2.

Next, we compare the simulation results obtained for the trajectory-based MSE and enhanced trajectory-based MSE with those of the weighted scheme. Figures 5.15, 5.16, and 5.17 depict the MSE distribution for the HetNet with 2 pico-eNBs per macro-sector. It is observed that enhanced trajectory-based MSE scheme produces the most accurate results for the case of 120 km/h speed wherein 55% of instances the UE is estimated as HIGH mobility state compared to trajectory-based MSE scheme (24%) and weighted MSE (0.8%). Since the probability of detecting a UE in its original mobility state (normal for 30 km/h, medium for 60 km/h, and high for 120 km/h) is high for the enhanced trajectory-based scheme, it gives accurate estimation results followed by the trajectory-based scheme and then the weighted

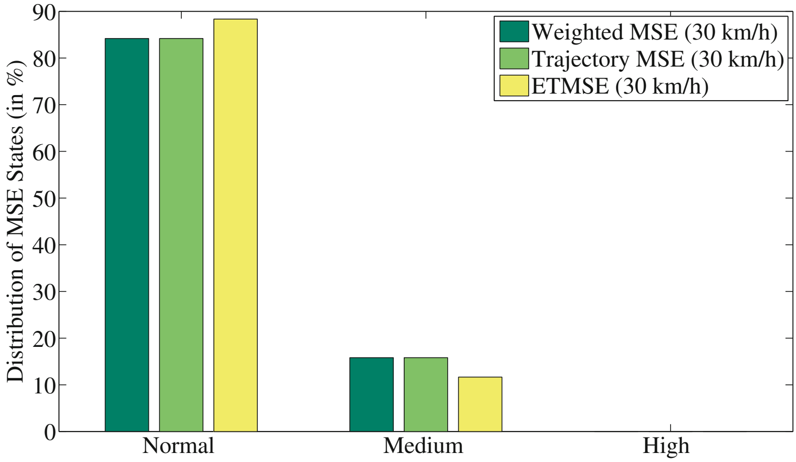


**Fig. 5.15** MSE state distribution for weighted, trajectory-based, and enhanced trajectory-based MSE schemes for deployment scenario: 2 pico-eNB/macro-sector and speed 30 km/h. ©2016 IEEE. Reprinted, with permission, from IEEE Wireless Communications and Networking Conference (WCNC), 2016 (DOI: 10.1109/WCNC.2016.7564960)

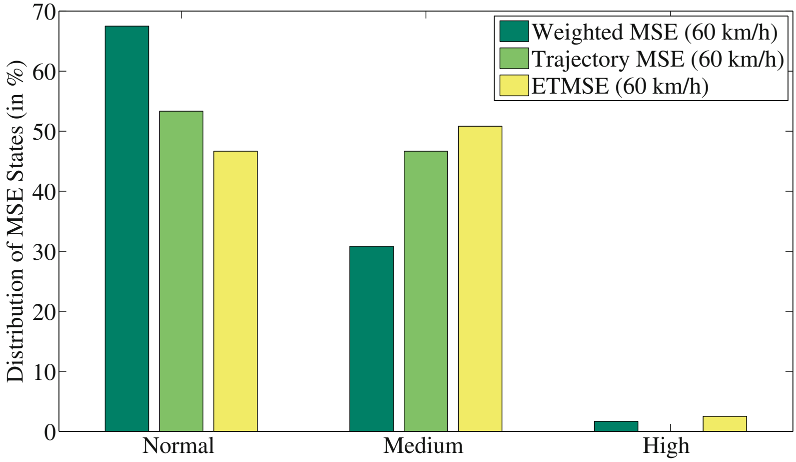


**Fig. 5.16** MSE state distribution for weighted, trajectory-based, and enhanced trajectory-based MSE schemes for deployment scenario: 2 pico-eNB/macro-sector and speed 60 km/h. ©2016 IEEE. Reprinted, with permission, from IEEE Wireless Communications and Networking Conference (WCNC), 2016 (DOI: 10.1109/WCNC.2016.7564960)

MSE. This is attributed to the fact that since HOF rate is very high for high-speed users compared to the low-speed users, adding HOF events to MSE procedure further helps in differentiating the given MSE states.

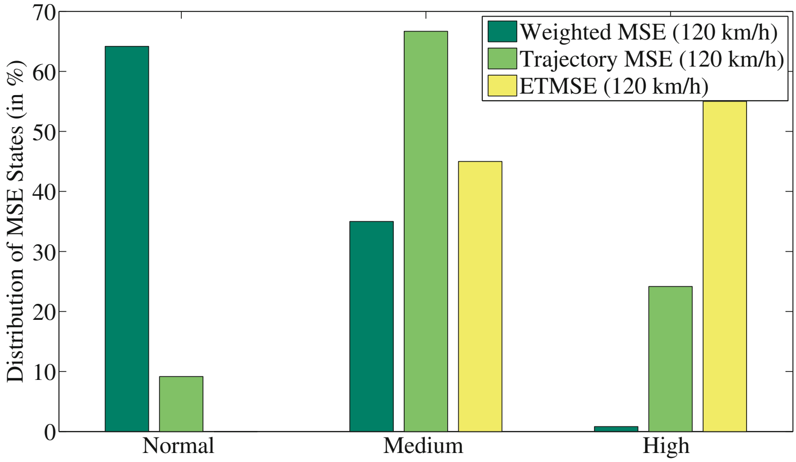


**Fig. 5.17** MSE state distribution for weighted, trajectory-based and enhanced trajectory-based MSE schemes for deployment scenario: 2 pico-eNB/macro-sector and speed 120 km/h. ©2016 IEEE. Reprinted, with permission, from IEEE Wireless Communications and Networking Conference (WCNC), 2016 (DOI: 10.1109/WCNC.2016.7564960)

The impact of MSE distribution on the HO performance can be observed by determining the effective value of TTT for the UE. If we consider the case shown in Fig. 5.17, the average value of TTT for the case of 120 km/h speed of the UE and using enhanced trajectory-based MSE scheme can be computed to

$$\begin{aligned} TTT_{combined} &= 0.00 * 480 + 0.45 * 240 + 0.55 * 120 \\ &= 174 \text{ ms} \end{aligned} \tag{5.3}$$

Here, the distribution of normal, medium, and high states is 0, 45, and 55% and corresponding values of TTT are 480, 240, and 120 ms, respectively. Similarly, the average value of TTT for the case of trajectory-based MSE and weighted MSE is given by,

$$\begin{aligned} TTT_{trajectory} &= 0.09 * 480 + 0.67 * 240 + 0.24 * 120 \\ &= 233 \text{ ms} \end{aligned} \tag{5.4}$$

$$\begin{aligned} TTT_{weighted} &= 0.64 * 480 + 0.35 * 240 + 0.01 * 120 \\ &= 392 \text{ ms} \end{aligned} \tag{5.5}$$

As evident from the above results, there is a delay of 159 and 218 ms in handover completion for weighted MSE compared to trajectory-based MSE and enhanced trajectory-based MSE, respectively. This implies that a user with speed 120 km/h will traverse an extra distance of 5 m (120 km/h * 160 ms) and 8 m (120 km/h * 220 ms) before triggering the HO process for weighted MSE scheme in comparison with trajectory-based MSE and enhanced trajectory-based MSE schemes. In the context of HetNets, where pico-eNBs with radius ∼40 m are deployed, this may result in increased call drop rate, in particular for pico-to-macro HO events. It may happen because UE will continue to remain associated with pico-eNB for longer duration even when the received signal power from the serving pico-eNB has reduced significantly. Moreover, the strong interference from the macro-eNB will reduce the SINR experienced by UE, resulting in call drop before the completion of HO process.

Figures 5.18, 5.19, and 5.20 depict the impact of MSE state distribution on the HOF rate for HetNet deployment with 2 pico-cells per macro-sector. The figure shows the HOF rate for different HO types when using the three MSE schemes. We observe that with higher MSE accuracy, the HOF rate for each type of HO decreases for high-speed users, with overall HOF rate decreasing from 61% (weighted MSE) to 49% (enhanced trajectory-based MSE). As evident, no significant change is observed in the HOF rate for the 30 km/h speed.

Figure 5.21 shows the comparison of average ToS values in macro- and pico-cells for the three schemes for the case of 120 km/h speed. Since HOF rate is much lower for Enhanced Trajectory based MSE scheme compared to weighted MSE scheme, significant improvement is observed in the average ToS at macro- and pico-cells. There is an increase of 287% (4.6–13.2 s) for average ToS in pico-cells when

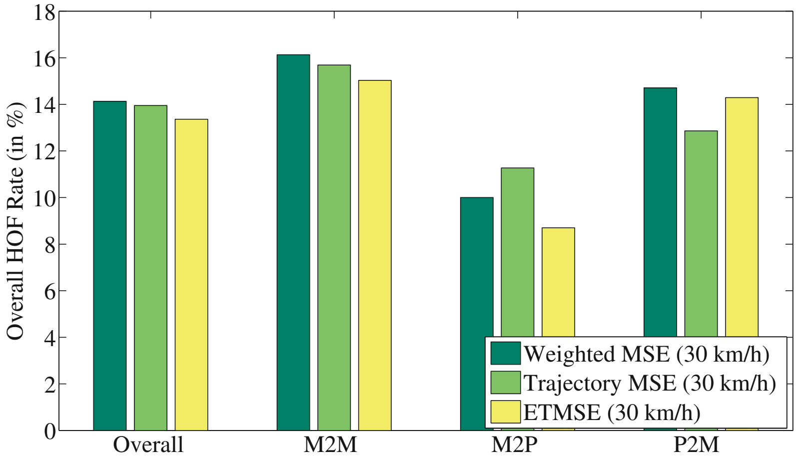


**Fig. 5.18** HOF rate for weighted, trajectory-based, and enhanced trajectory-based MSE schemes for deployment scenario: 2 pico-eNB/macro sector and speed 30 km/h. ©2016 IEEE. Reprinted, with permission, from IEEE Wireless Communications and Networking Conference (WCNC), 2016 (DOI: 10.1109/WCNC.2016.7564960)

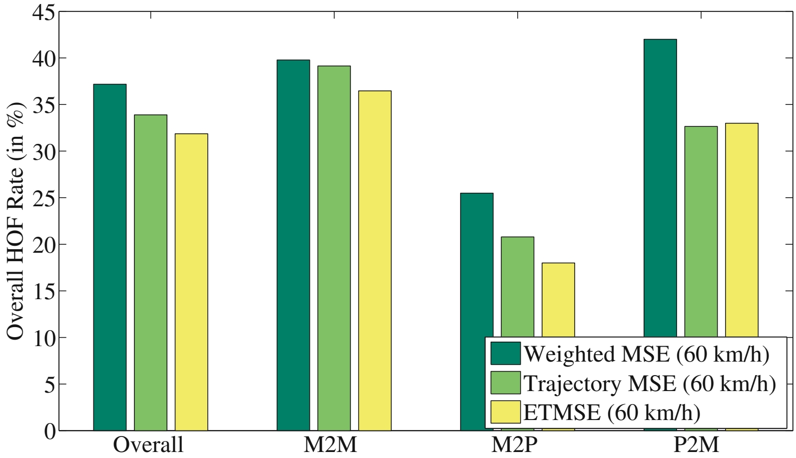


**Fig. 5.19** HOF rate for weighted, trajectory-based, and enhanced trajectory-based MSE schemes for deployment scenario: 2 pico-eNB/macro-sector and speed 60 km/h. ©2016 IEEE. Reprinted, with permission, from IEEE Wireless Communications and Networking Conference (WCNC), 2016 (DOI: 10.1109/WCNC.2016.7564960)

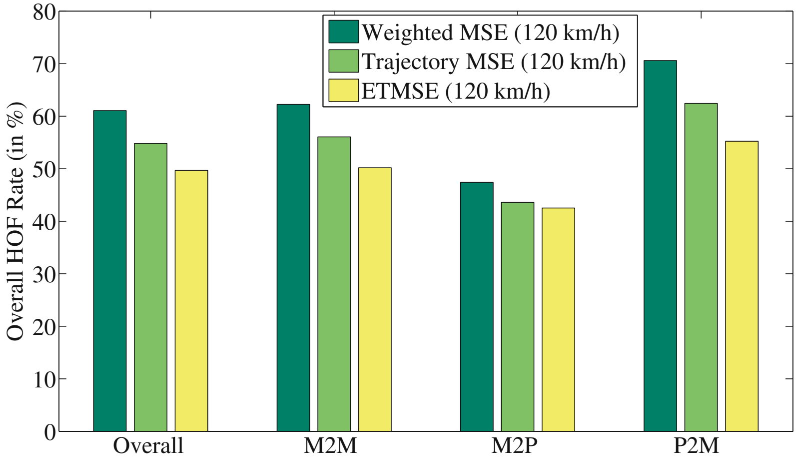


**Fig. 5.20** HOF rate for weighted, trajectory-based and enhanced trajectory-based MSE scheme for deployment scenario: 2 pico-eNB/macro-sector and speed 120 km/h. ©2016 IEEE. Reprinted, with permission, from IEEE Wireless Communications and Networking Conference (WCNC), 2016 (DOI: 10.1109/WCNC.2016.7564960)

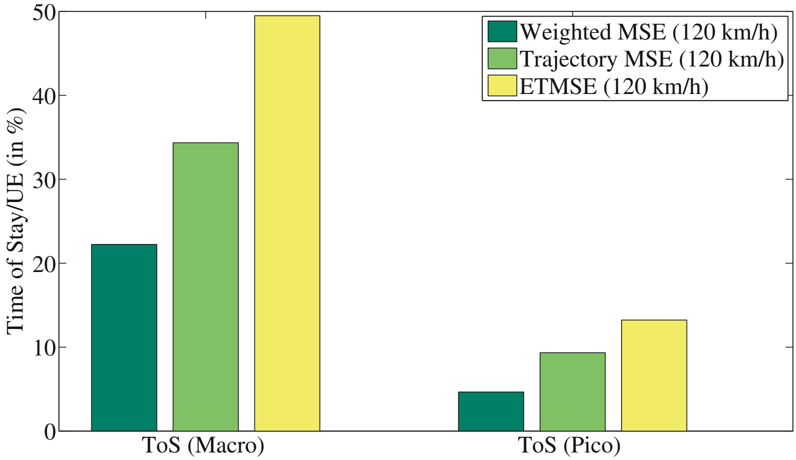


**Fig. 5.21** Average time of stay comparison for trajectory-based MSE, enhanced trajectory-based MSE, and weighted MSE schemes for UE's speed of 120 km/h for deployment scenario: 2 pico-eNB/macro-sector. ©2016 IEEE. Reprinted, with permission, from IEEE Wireless Communications and Networking Conference (WCNC), 2016 (DOI: 10.1109/WCNC.2016.7564960)

switching from weighted MSE scheme to enhanced trajectory-based MSE scheme while the corresponding increase in macro-ToS is 223% (22.2–49.5 s) from weighted MSE to enhanced trajectory-based scheme. The improvement in ToS results in reduced signaling overhead due to HO and also efficient battery conservation.

## 5.7 Conclusions

This chapter focuses on the need for enhancements in 3GPP legacy MSE scheme. To improve HO performance, UE needs to accurately estimate its mobility state to decide whether to speed up or slow down the HO process. The performance of the enhanced MSE scheme has been analyzed which reduces the average number of State 2 HO failures by about 15.4% compared to that of 3GPP legacy MSE scheme.

The significance of avoiding high-speed UEs to handover of pico-cells, while ensuring such handovers to meet the requirement of continuous coverage, has been analyzed in the Weighted MSE scheme available in the literature. We have also realized that the MSE procedure specified by 3GPP does not give consideration to the dependencies of MSE on the user movement trajectory. Trajectory based MSE scheme addresses this issue by including new mobility events based on RSRP threshold criteria in the MSE procedure. Different weights are assigned to different types of mobility events as done in the weighted MSE scheme. The trajectory-based MSE scheme has shown improved estimation compared to the schemes discussed in other works for varied deployments of HetNets. Further, enhanced trajectory-based

MSE scheme which gives consideration to UE trajectory as well as HOF count in the MSE computation has given even better mobility performance for users in co-channel deployment of HetNets.

**Bibliographic Notes**

The 3GPP legacy MSE procedure is described in [10]. Handover performance metrics like Time of Stay (ToS) are defined in [4]. The mechanism of handover avoidance to improve mobility performance is given in [14]. Our work on enhanced MSE scheme in Sect. 5.3 first appeared in [28]. The weighted MSE procedure in Sect. 5.4 is from [18]. The inconsistency in mobility state estimation due to different mobility paths followed by UE is described in [26]. Our work on trajectory-based MSE and enhanced trajectory-based MSE schemes in Sects. 5.5 and 5.6 first appeared in [19].

Reviewing the available literature, authors in [37] propose a simplistic approach for mobility state estimation in HetNet scenario, where handovers are counted according to the cell type and the absolute weights of one or zero. Handovers are counted only when source and target cells belong to different macro-cell coverages. However, in case of large macro-cell coverage, ignoring the handovers within macro-cell coverage might be misleading, resulting in inaccurate mobility state estimation. Also, there is no consideration given to the UEs with varying speed. Authors in [34] propose a mobility-based interference coordination scheme to improve the mobility performance. The procedure discussed in [26] uses the observed range of received signal power in a 3GPP cell to estimate the distance traveled by the UE, and thereby, determines its mobility state. One approach [25] emphasizes on TTT scaling based on Signal-to-Interference-plus-Noise Ratio (SINR) experienced from the serving cell. Other proposals such as dual simultaneous filtering and Doppler estimation are also available in the literature [35]. Authors have proposed two network-based algorithms in [23] to improve the accuracy of mobility state estimation based on the Sounding Reference Signal (SRS) measurements at eNB. The authors claim that the proposed algorithm can be implemented at UE as well by considering RSRP instead of SRS measurements. The techniques exploit the speed-dependent time variations of slow fading in the SRS measurements using spectral analysis method and time-based spectrum spreading method, respectively.

In an interesting work [24], authors have extended our works [19, 28] by giving consideration to randomized network topology and nonlinear UE trajectory. They have modeled the erratic UE trajectory as linear trajectory with enlarged equivalent cell radius indicated by stretch parameter. However, there is an overhead of this additional metric of stretch parameter which is required to be exchanged between eNBs.

# Chapter 6
# Optimization of Mobility-Related Parameters

In this chapter, we analyze the impact of various parameters on handover performance in HetNets. First, we examine the role of handover offsets to improve offloading while ensuring that overall handover performance is not adversely impacted. Second, we investigate the role of thresholds in the mobility state estimation in HetNets.

The primary consideration in mobility management is to reduce the occurrence of handover failures and ping pong events. To achieve this, two parameters are specified in 3GPP LTE standard: hysteresis and A3-offset. We recall from Chap. 2 that the purpose of A3 event is to trigger the reporting of measurements performed by a UE from neighboring cells to the serving eNB. The entry condition for event is that the RSRP/RSRQ of a neighboring cell becomes higher than that of the serving cell by an amount equal to A3-offset, i.e.,

$$M_n - Hyst > M_s + O_{A3} \tag{6.1}$$

where, $M_n$ and $M_s$ are the measurements (RSRP or RSRQ) from neighboring and serving cell, respectively, $Hyst$ is hysteresis (in dB) and $O_{A3}$ is A3-offset (in dB). Note that $Hyst$ is a nonnegative quantity and can take any value less than A3-offset, while A3-offset can take either positive or negative value.

The purpose of hysteresis is to avoid unnecessary handovers (leading to ping pong) by ensuring that A3 event gets triggered only when the RSRP/RSRQ from the target cell is sufficiently higher than that of the serving cell. Thus, handovers triggered due to short-term signal fluctuations on account of fading can be avoided. A3-offset enables the serving eNB to control the initiation of measurement reporting from the UE. When a positive value of A3-offset is used, it ensures that target cell quality is good. Thus, a positive A3-offset delays the triggering of A3 event until a strong neighbor cell is found. On the contrary, negative A3-offset triggers A3 event earlier and thus, advances the HO process. This may be required to achieve load-based handover when the serving cell is overloaded even though link quality from the serving cell may be better than that of the neighbor cells. Thus, an appropriate



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value of A3-offset needs to be selected, based on the deployment requirements to ensure that the objective of handover is achieved. It must be noted that eNB can set different values of these two parameters for different UEs in the cell.

In general, because of the power imbalance between macrocells and small cells, the likelihood of a UE associating with a small cell located away from the cell edge is quite small. Hence, offsets play an important role in offloading. In such a scenario, a positive A3-offset will delay the measurement reporting to the serving eNB. As a result, a UE may be deep inside the coverage of the target small cell by the time A3 condition is satisfied. This would result in short time of stay (ToS), which is not desirable. Therefore, to ensure that the time of stay of an offloaded UE in small cell is sufficiently long, negative A3-offset may need to be applied, so as justify the handover-related signaling overhead and maximize the offloading gain. However, negative offset may lead to premature handover, leading to radio link failure.

To achieve small cell offload while ensuring long ToS in small cell, *Cell-Specific Offsets* (CSO) can be used such that event A3 is triggered when the following condition is satisfied

$$M_n - Hyst + O_{CSn} > M_s + O_{A3} \tag{6.2}$$

where $O_{CSn}$ represents the cell-specific offset of target cell. It is chosen to be a positive value (greater than A3-offset) for small cells to increase the offload via cell range expansion as described in Chap. 4. In general, its value may be different for different type of cells. Four types of cell-specific offsets can be used in the HetNet case: macro to macro, macro to pico, pico to macro, and pico to pico.

Another important handover parameter is the Time-to-Trigger (TTT), which denotes the time over which the specified event condition must be satisfied before a measurement report is sent by the UE to its serving eNB. For example, if the A3 event is configured, then the A3 condition must be satisfied for all the measurements that are performed in T3 duration, and only at the end of T3, measurement report can be sent to the serving eNB. A small value of T3 will result in speeding up the handover process but at the same time, it may result in unnecessary handovers due to temporary signal fluctuations. Large values of T3 may help avoid such unnecessary handovers but also result in delayed handovers, increasing the chances of handover failures. Thus, the choice of T3 has a significant impact on handover performance. This is particularly true in HetNets where cell sizes are not uniform and hence, the handover region (defined in Sect. 5.2) size depends on source and target cells.

## 6.1 Impact of Offsets and TTT

In this section, the impact of A3 and cell-specific offsets as well as TTT on handover performance is illustrated. The simulations have been performed using MATLAB-based simulator for mobility modeling in HetNets. The simulation methodology is described in Chap. 3.

Next, we present the simulation results to illustrate the impact of A3-offset, cell-specific offsets, and time to trigger (TTT) on handover performance.

### *6.1.1 Simulation Results*

The results and analysis in this section, are based on the system model and mobility scenario described in Chap. 3. The set of parameters for radio configuration, radio link monitoring, and handover measurements has been chosen according to the 3GPP HetNet mobility evaluation methodology.

The objective of A3-offset is to advance or delay the A3 event triggering to ensure that the received signal power from the selected target eNB is good enough. In the present set of simulations, impact of A3-offset on HO performance is analyzed considering the following set of values $\{-2, 0, 1, 2, 3\}$ dB for A3-offset and UE speed is considered fixed at 60 km/h.

Increased A3-offset adversely impacts the HOF performance is shown in Fig. 6.1a. This scenario considers cell-specific offsets for macro-to-pico (M2P) and pico-to-macro (P2M) cases to be 2 dB and macro-to-macro (M2M) offset to be 0 dB. Based on the previous discussion, trigger for A3 event gets delayed due to positive A3-offset and hence, HO gets delayed. This increases the chance of HO failure due to deteriorating quality of received power from the serving cell. However, the response to positive A3-offset changes after a target cell is identified. As shown in Fig. 6.1b, State-3 HO failures reduce with the increase in A3-offset. The reason behind this behavior is that positive A3-offset enables selection of a target node which is significantly stronger compared to that of the serving node. We observe a small increase in RLF when A3 $=$ 3 dB, which happens because the effective A3-offset becomes positive, i.e., A3-CSO (P2M) becomes 1 dB (using Eq. (6.2)). This delays A3 event triggering compared to other values of A3-offset, resulting in increased chance of State-3 HOFs because signal from the serving cell is likely to become weak by the time HO process is initiated.

Negative A3-offset results in early trigger of A3 event, which is likely to increase the probability of macro-to-pico HO and pico-to-macro HO, eventually resulting in high ping pong rate as shown in Fig. 6.2a. Hence, the time of stay (Fig. 6.2b) in picocell is the shortest when $O_{A3} = -2$ dB. When the value of A3-offset is positive but small, it reduces ping pongs without significantly affecting offload opportunity. Therefore, ToS in macrocell decreases, while ToS in picocell increases. On the contrary, when A3-offset is positive but large, it reduces the effect of M2P offset, thus reducing offload opportunity and therefore ToS in macrocell increases while ToS in picocell decreases.

To analyze the impact of cell-specific offsets in HO management and offloading, we consider 0, 1, and 2 dB as the values of M2P offset and 1 dB as A3-offset value. The M2P offset biases association to picos and hence, increases offloading opportunities. This is clearly depicted in Fig. 6.3a, which shows the number of successful macro-to-pico HOs for different offset values. Figure 6.3b gives the time of stay comparison and

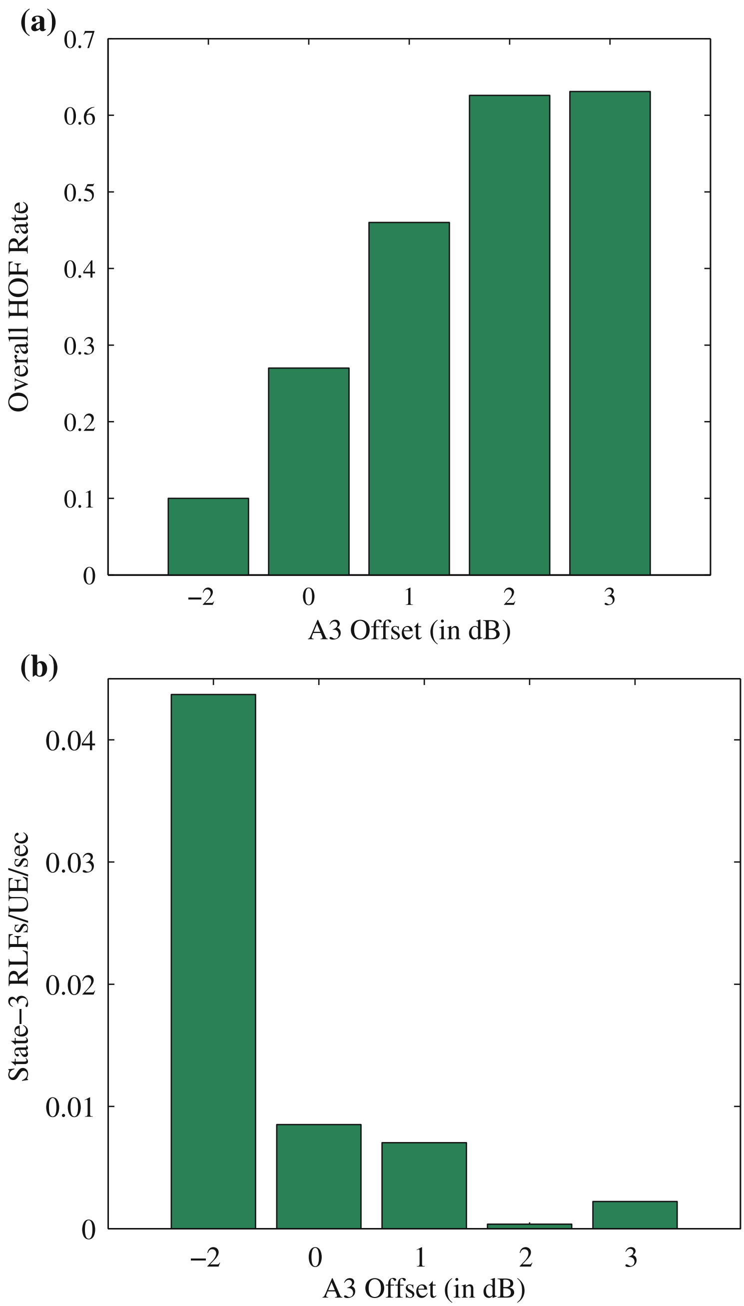


**Fig. 6.1** Impact of A3-offset on **a** HO failures and **b** state-3 RLFs. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084910)

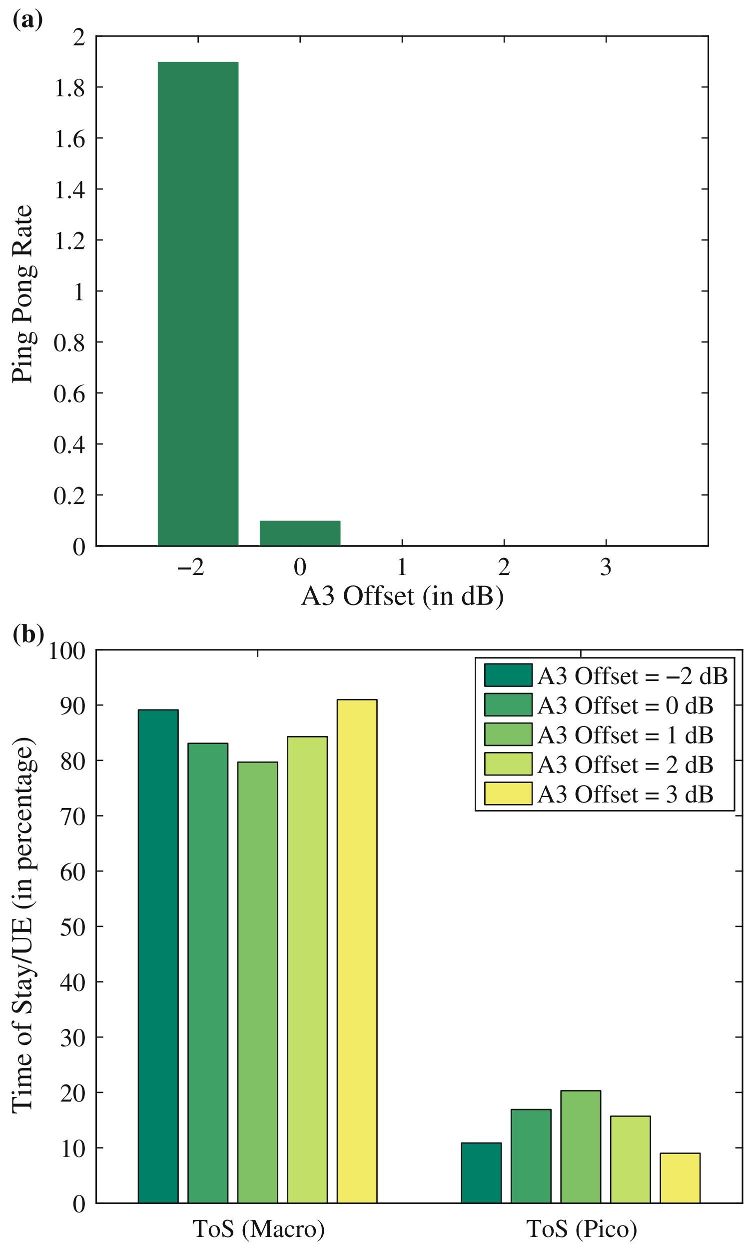


**Fig. 6.2** Impact of A3-offset on **a** ping-pong rate and **b** time-of-stay. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084910)

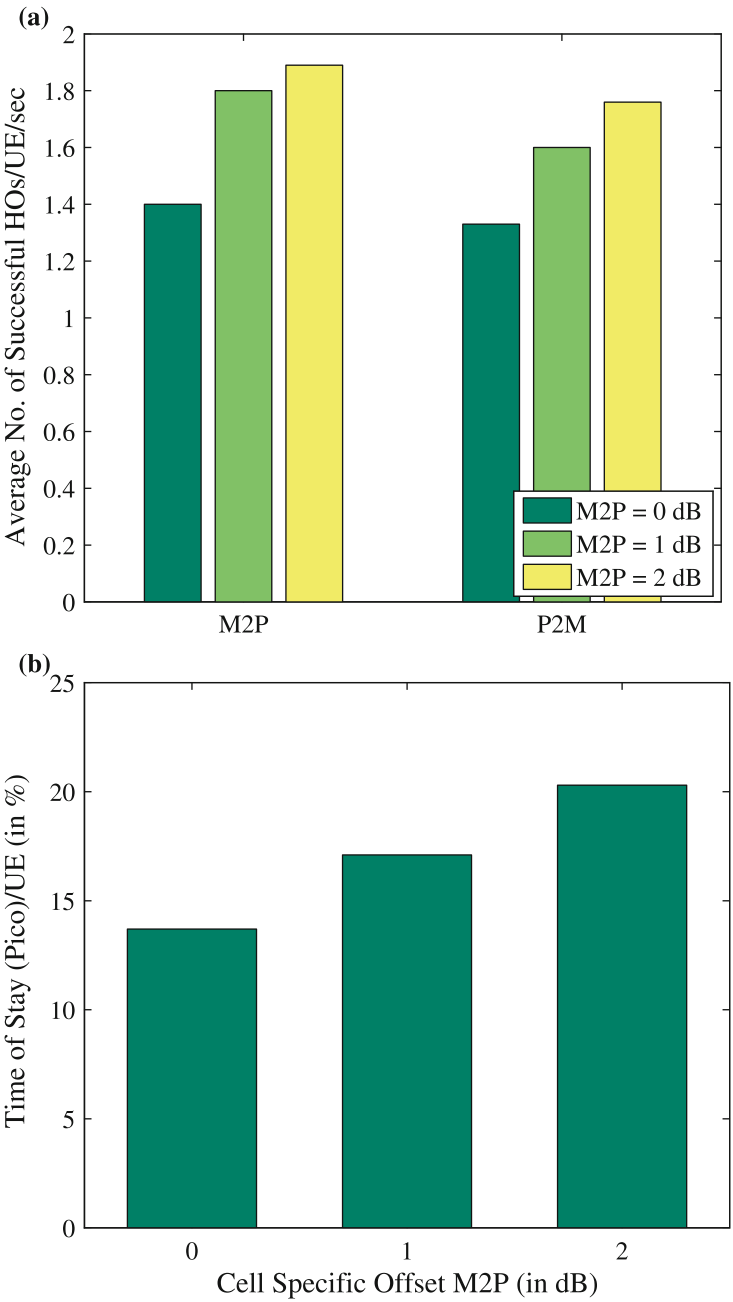


**Fig. 6.3** Impact of macro to pico-offset on **a** successful HOs and **b** time-of-stay. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084910)

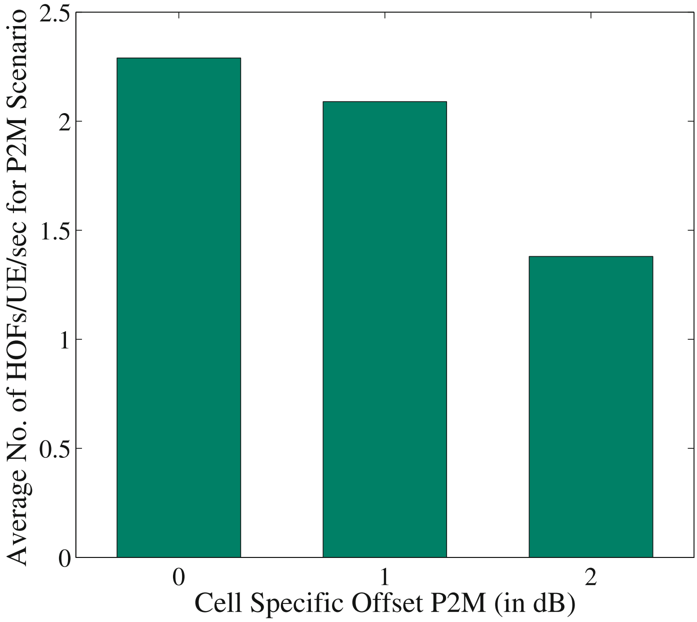


**Fig. 6.4** Impact of pico to macro offset on HO failures. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084910)

shows that as macro-to-pico offset increases, ToS in picocell increases. Thus, M2P offset positively impacts the offloading opportunity by ensuring increased handovers to small cells and as a consequence, longer Time of Stay.

The primary intention of picocell to macrocell-specific offset is to reduce pico-to-macro HO failures. When P2M offset is not considered, UE is required to be sufficiently away from the serving pico-eNB, in order to meet A3 event condition. This results in UE facing strong interference from macro, which adversely impacts the SINR experienced by UE. This may result in HO failures due to radio link failure. Figure 6.4 shows that the average number of pico-to-macro HOFs/UE/second decreases as pico-to-macro offset increases. Note that one fallout of this will be reduction in small cell ToS because of early handover to macro. We consider 0, 1 and 2 dB as pico-to-macro offset values for these simulations.

Another interesting observation can be made by analyzing the time of stay in picocell, based on the variations in pico-to-macro offset (Fig. 6.5b). When the number of successful macro-to-pico HOs remains almost same, while there is an increase in the number of successful pico-to-macro HOs (Fig. 6.5a), an increase in the number of *successful sojourns* inside pico is observed. Note that successful sojourn implies a macro-to-pico HO followed by a pico-to-macro HO. This is indicated in Fig. 6.5b where increasing pico-to-macro offset results in increased ToS in picocell.

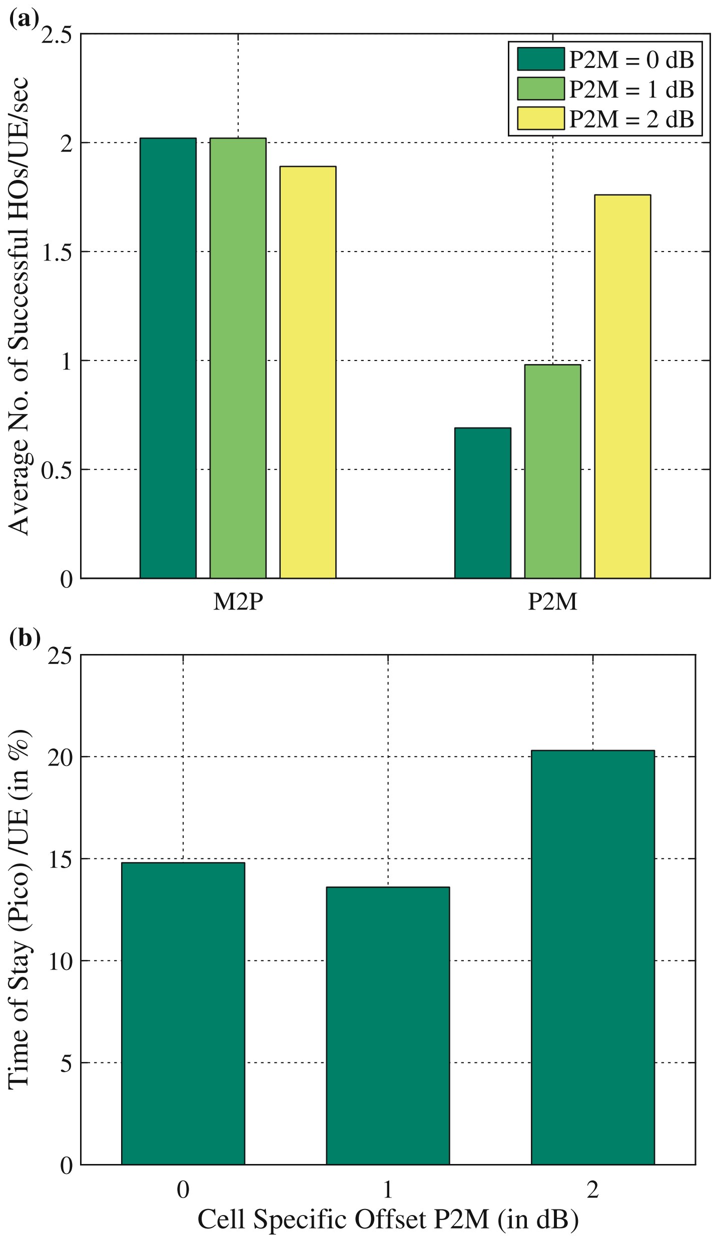


**Fig. 6.5** Impact of pico to macro offset on **a** successful HOs and **b** pico time-of-stay. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084910)

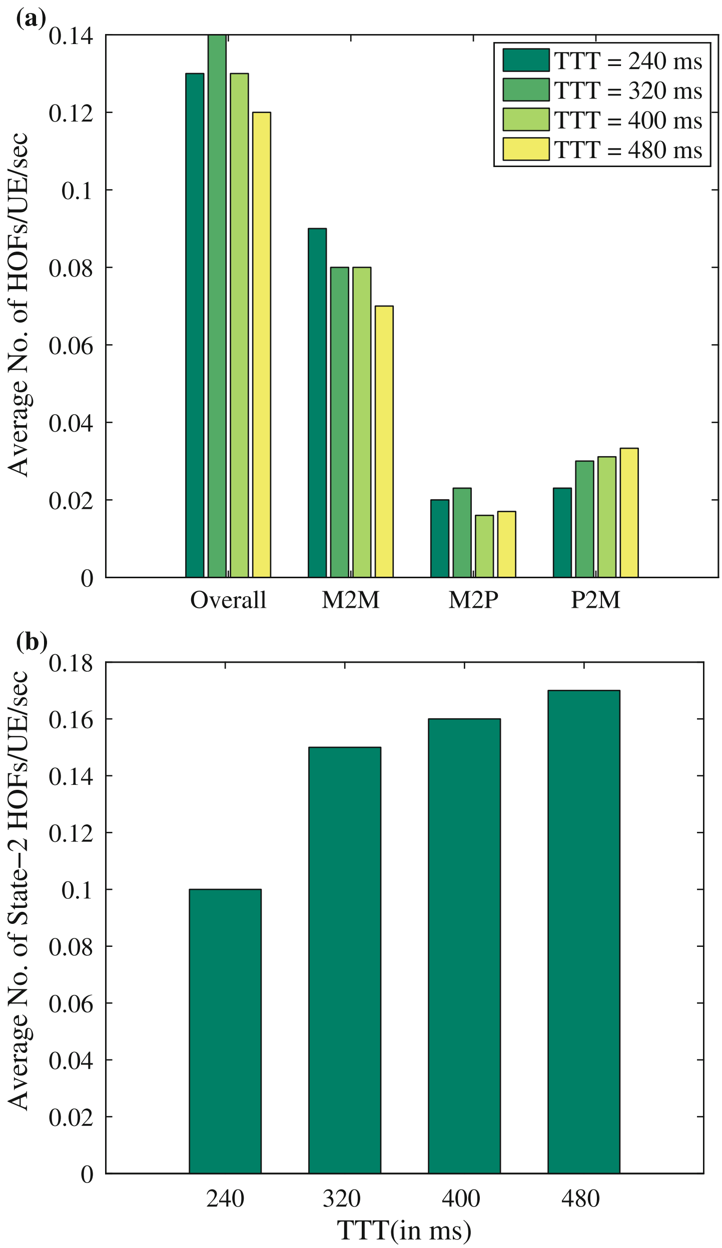


**Fig. 6.6** Impact of TTT on **a** HO failure and **b** state-2 HOF. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084910)

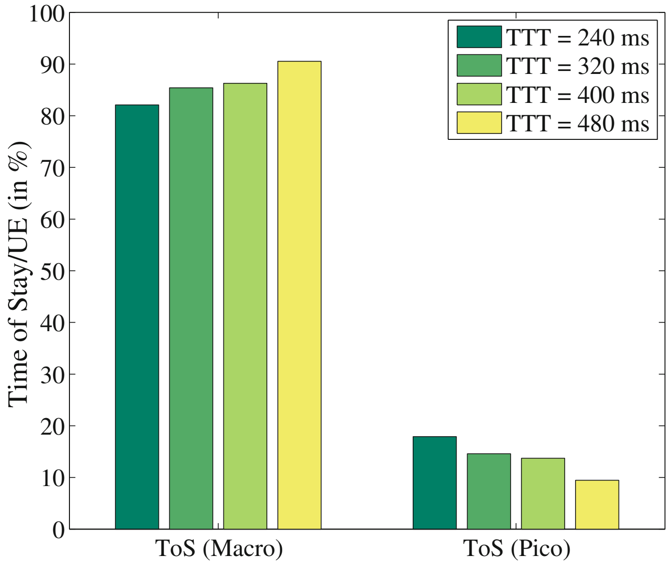


**Fig. 6.7** Impact of TTT on time-of-stay. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084910)

From Fig. 6.6a, we observe that longer TTT reduces the probability of unnecessary HOs, thereby reducing the number of macro-to-macro HO failures. On the contrary, longer TTT delays pico-to-macro handover, resulting in increased probability of HOF, in particular State-2 HOF (Fig. 6.6b). RLF is the reason behind these State-2 HOFs in different HO scenarios.

With increase in TTT, we can observe two things from Fig. 6.7 with regard to ToS. First, reduced macro-to-macro HOFs results in increased time of stay in macrocell. With macro-eNB as the serving node, UE remains connected to the serving cell for longer time before HO is triggered, i.e., size of the HO region becomes larger. Second observation is about the reduction in the time of stay in picocell because pico-to-macro failures increase with increase in TTT and only successful HOs are taken into account for ToS calculation.

Speed of UE also plays a significant role in determining the value for TTT because faster HO processing (i.e., smaller TTT) is required for high-speed UEs, while for low/medium speed UEs, we only need to ensure that TTT duration is sufficient enough to mitigate the fading-related variations in measurement. The HOF rate comparison is shown in Fig. 6.8 for users considering three different speeds {30, 60, 120} km/h and TTT is considered fixed at 480 ms. One general observation is that high-speed users experience higher HOF rate. We note that macro-to-pico and pico-to-macro HOs are more sensitive to speed changes, due to the HO region being relatively smaller. Thus, speed-dependent TTT is essential to reduce the HOF rate. This requires estimation of UE's mobility state for appropriate scaling of TTT.

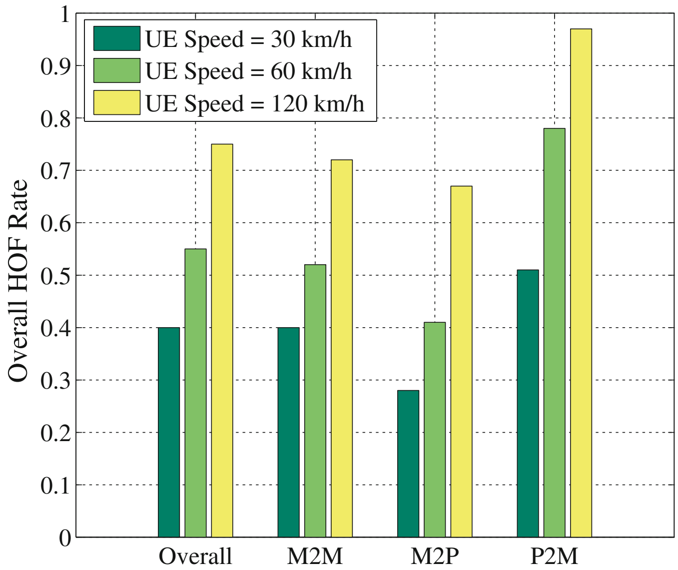


**Fig. 6.8** Impact of different UE speeds on HOF rate when TTT = 480 ms. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084910)

## 6.2 Impact of MSE Thresholds

MSE thresholds $N\_L$ and $N\_H$ (signaled by eNB to UE) are configurable parameters used in mobility state estimation, as discussed in Chap. 1. The HO count in every MSE interval is compared with these thresholds to determine one of the three mobility states for a UE. The handOver performance is investigated for three sets of MSE thresholds:

1. $N\_L = 2$, $N\_H = 4$ denoted by $\{2, 4\}$
2. $N\_L = 3$, $N\_H = 6$ denoted by $\{3, 6\}$
3. $N\_L = 4$, $N\_H = 8$ denoted by $\{4, 8\}$

Let TTT be 480 ms for this analysis.

Figure 6.9a compares the distribution of MSE states for all three sets of MSE threshold. Note that the actual UE speed is 60 km/h, which can be considered as medium mobility state (which is the actual state of UE). We observe that with increase in thresholds, MSE distribution shifts toward medium mobility state because the probability of HO count in MSE interval exceeding high-state threshold is lower. We also observe that with threshold increasing from $\{3, 6\}$ to $\{4, 8\}$, the percentage of time UE is considered to be in normal/medium mobility state increases from 21 to 57%. However, this is only 2% when threshold is the lowest, i.e., $\{2, 4\}$. For threshold

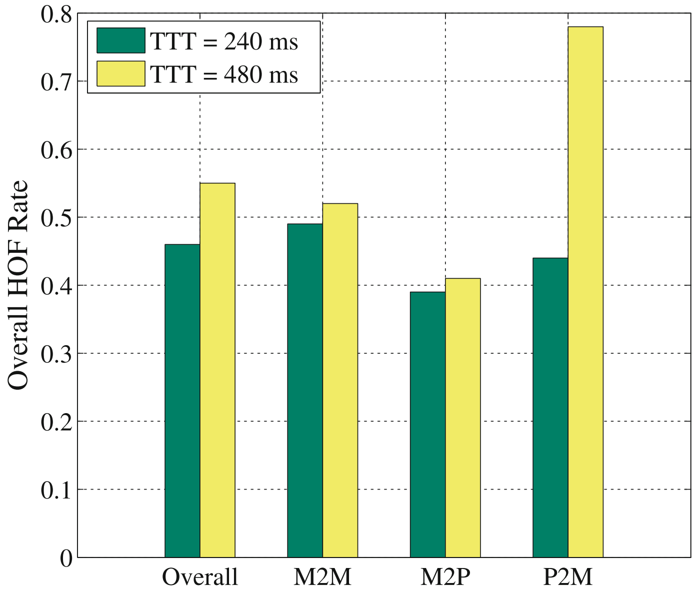


**Fig. 6.9** Impact of TTT on HOF rate (UE speed = 60 km/h)

{4, 8}, UE is considered to be in medium mobility state most of the time. This implies that TTT is mostly down scaled to 240 ms. We know that, HOF Rate is lower for TTT = 240 compared to TTT = 480 ms as observed in Fig. 6.2. For thresholds {2, 4} and {3, 6}, lower TTT values are used because UE is estimated to be in high mobility state most of the times. Therefore, lower HOF rate is achieved with MSE thresholds {3, 6} and {4, 8}, as can be seen in Fig. 6.10b.

In light of the above discussion, it is clear that higher MSE thresholds result in maintaining higher TTT value for longer time. This reflects in increased ToS in macrocell and corresponding reduction in picoToS (Fig. 6.11a). Ping pong performance comparison is given in Fig. 6.11b. Lower MSE thresholds drive TTT to be scaled down. Lower TTT value implies that fewer measurements are considered for HO decision, which may not be sufficient to alleviate the fluctuations in measurement due to fading. As a consequence, the ping pong rate increases for lower thresholds. This indicates a trade-off between reducing HOFs and ping pongs which is clearly observed with the variations in TTT.

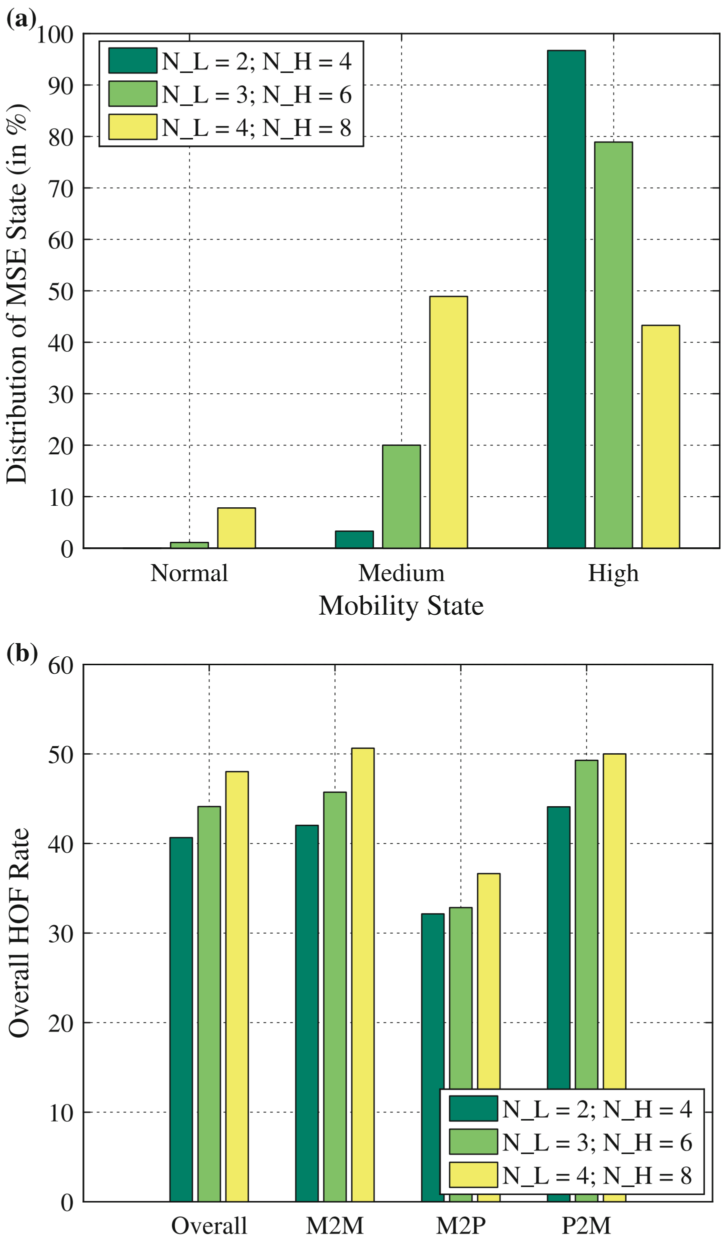


**Fig. 6.10** Impact of MSE thresholds on: **a** count of mobility states and **b** HO failure rate. © 2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084911)

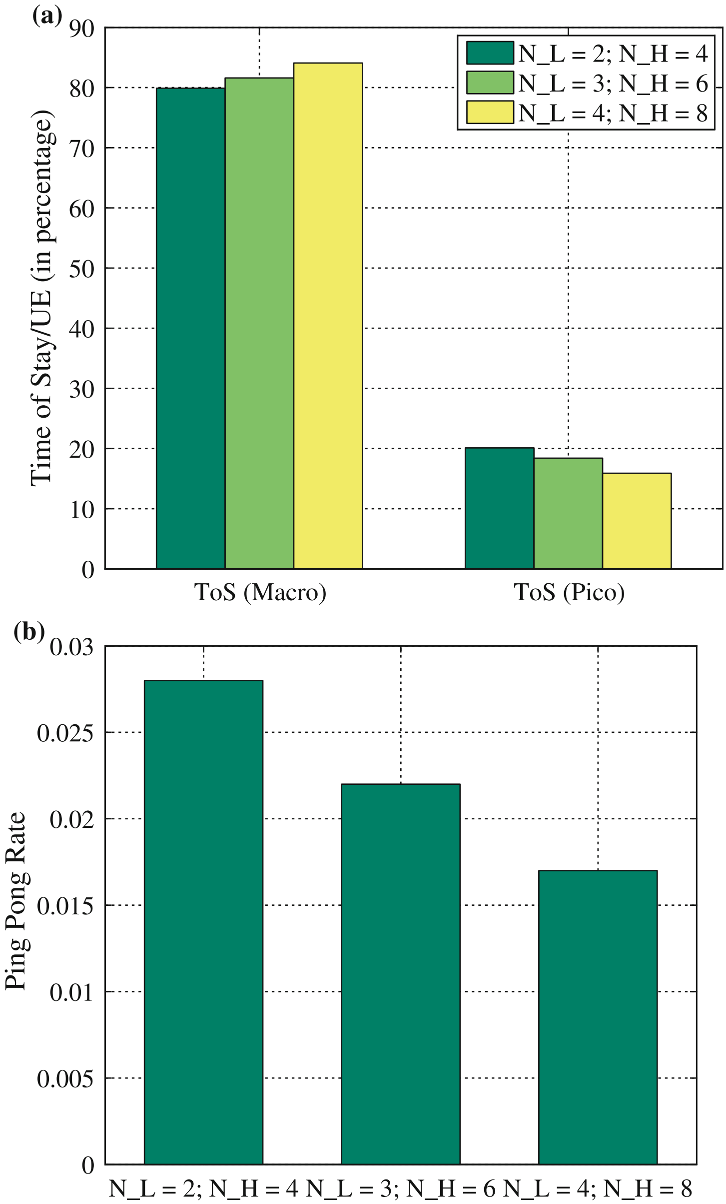


**Fig. 6.11** Impact of MSE thresholds on: **a** ToS and **b** ping pong rate. ©2015 IEEE. Reprinted, with permission, from IEEE Twenty First National Conference on Communications (NCC), 2015 (DOI: 10.1109/NCC.2015.7084911)

## 6.3 Summary

In this chapter, we have analyzed the impact of various parameters like offsets and TTT on handover performance. The choice of configurable parameters used in mobility management can affect the network performance significantly, as being investigated by 3GPP LTE standard. We have analyzed the role of A3-offset to control (delay or advance) the measurement reporting to eNB and its impact on HO performance. We have illustrated the use of cell-specific offsets to enhance offloading and its effects on other HO performance metrics. Further, the inter-dependence between UE speed and choice of TTT parameter has been investigated. Results show that the choice of TTT is critical because lower value of TTT reduces HOF, but increases ping pongs. The detailed analysis given in this chapter provides an insight that mobility performance can be optimized by appropriate selection of HO-related parameters.

We have also investigated the impact of MSE thresholds on mobility performance in LTE HetNet. The choice of configurable mobility parameters can affect the network performance significantly, as being investigated by the 3GPP LTE standard. The investigation shows the impact of MSE thresholds on HO performance, which can help to choose appropriate thresholds to improve the estimation of UE's mobility state.

**Bibliographic Notes**

Mobility management related parameters such as hysteresis and A3-offset are specified in 3GPP LTE standard [21]. The concept of cell range expansion is from [33]. Our analysis on the impact of parameters, such as A3 and cell-specific offsets, and TTT on handover performance first appeared in [29]. 3GPP specified HetNet mobility evaluation methodology is provided in [4].

Authors in [32] propose a handover optimization algorithm by dynamically adjusting the handover margin, giving consideration to UE speed and handover types. It uses enhanced MSE strategy to improve the accuracy of UEs mobility state estimation and proposes to adapt TTT and handover margin according to the type of handover. However, the proposed system model does not consider pico-to-pico handovers and the handover parameter adaptation is limited to the case when handover failures exceeds a given threshold. There is an interesting work in [31], where authors propose a unified self-organized mechanism to attain handover optimization along with load balancing. They propose modification of the handover parameters using Fuzzy logic and Reinforcement Learning to attain joint handover optimization and load balancing without impacting the connection quality of the connected users.

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