

MASTERING 5G NETWORKS

THE DEFINITIVE GUIDE FOR
ENGINEERS AND TELECOM PROFESSIONALS

A Complete Immersion into SA and NSA Architecture

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MASTERING 5G NETWORKS

From Telecom Basics to Implementation Details, Dimensioning, and the Future of 5G

Abstract:

This book is the most comprehensive technical reference on 5G Standalone (SA) and Non-Standalone (NSA) networks. With a detailed approach spanning from the fundamentals of telecommunications to advanced implementations of network slicing and edge computing, this work is essential for engineers, network architects, and students seeking to master the technical details of 5G architectures.

Highlights:

- ✓ 5GC and EPC Architecture
- ✓ Step-by-Step SA and NSA Implementation
- ✓ Network Slicing and MEC
- ✓ Millimeter Waves and Massive MIMO
- ✓ Real Use Cases and Performance Metrics

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PREFACE

We are witnessing one of the most significant transformations in the history of telecommunications. 5G does not merely represent an incremental evolution in data speed; it is a complete revolution that redefines the role of mobile networks in our society. This technology enables an entirely new ecosystem of applications and services, ranging from tactile internet to smart factories, autonomous vehicles, and remote surgeries.

This book was born from the clear need for comprehensive and technical material that explains not only the fundamental concepts of 5G but also delves into the two crucial deployment architectures: **Standalone (SA)** and **Non-Standalone (NSA)**. While most available materials treat these concepts superficially, our mission here is to provide complete technical immersion, meticulously detailing the components, protocols, signaling flows, and use cases of each architecture.

The target audience includes telecommunications engineers, engineering students, IT professionals, network architects, and any technology enthusiast who wants to truly understand the technical

intricacies of 5G networks. Our goal is that, by the end of this work, the reader possesses not only theoretical knowledge but also robust practical understanding sufficient to actively participate in 5G network deployment, optimization, and operation projects.

Happy reading and welcome to the next frontier of mobile communications!

Ibiapina/CE, October 28, 2025

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CHAPTER 1: FUNDAMENTALS OF MOBILE TELECOMMUNICATIONS

1.1. Introduction to Wireless Communication

Wireless communication represents one of the fundamental pillars of the modern connected society. At its core, it is the transmission of information through space using electromagnetic waves, eliminating the need for physical conductors or cables. This form of communication has revolutionized how we relate, work, and access information.

Basic Propagation Principles:

Radio waves propagate in free space following well-established physical principles. The transmitter converts electrical signals into electromagnetic waves through an antenna, while the receiver performs the inverse process. Between these two points, various physical phenomena affect propagation:

- **Reflection:** Occurs when the wave encounters a surface large relative to its wavelength (buildings, mountains).

- **Diffraction:** Allows waves to bend around obstacles due to scattering.
- **Scattering:** Occurs when the wave encounters irregular surfaces.
- **Attenuation:** Gradual reduction of signal intensity with distance.

Understanding these phenomena is crucial for efficient mobile network planning, as they directly determine coverage quality, system capacity, and the end-user experience.

1.2. The Electromagnetic Spectrum

The electromagnetic spectrum comprises the entire range of electromagnetic radiation, from the lowest frequencies (radio waves) to the highest (gamma rays). For mobile telecommunications, we primarily work with the Radio Frequency (RF) portion of the spectrum.

Fundamental Characteristics:

- **Frequency (f):** Number of complete cycles per second, measured in Hertz (Hz).
- **Wavelength (λ):** Distance between two corresponding points on consecutive waves.

- **Fundamental Relationship:** $c = f \times \lambda$, where c is the speed of light (3×10^8 m/s).

Frequency Bands in Mobile Telecommunications:

Sub-6 GHz Bands:

- **600-900 MHz:** Excellent propagation, ideal for rural coverage and building interiors.
- **1.8-2.5 GHz:** Balance between coverage and capacity, widely used in 4G.
- **3.3-4.2 GHz:** Primary bands for 5G Sub-6, offering a good balance.

mmWave Bands (Millimeter Waves):

- **24-29 GHz:** Ka band, high capacity but shorter range.
- **37-40 GHz:** Additional Ka band.
- **64-71 GHz:** V band, extremely high capacity.

Spectrum Management:

Spectrum is a finite and scarce resource, strictly regulated by government agencies (ANATEL in Brazil, FCC in the US). Operators acquire licenses through auctions to operate in specific bands,

ensuring no interference between different services.

1.3. Key Concepts: Modulation and Multiplexing

Modulation Techniques:

Modulation is the process of impressing information onto a high-frequency carrier wave. The main techniques include:

- **AM (Amplitude Modulation):** Varies the carrier's amplitude.
- **FM (Frequency Modulation):** Varies the carrier's frequency.
- **PM (Phase Modulation):** Varies the carrier's phase.
- **QAM (Quadrature Amplitude Modulation):** Combines amplitude and phase variations.

Evolution to 5G:

5G primarily uses **256-QAM** and **1024-QAM**, allowing more bits per symbol to be transmitted, significantly increasing spectral efficiency.

Multiple Access and Multiplexing Techniques:

- **FDMA (Frequency Division Multiple Access):** Divides the spectrum into frequency channels.
- **TDMA (Time Division Multiple Access):** Divides time into slots.
- **CDMA (Code Division Multiple Access):** Uses codes to separate users.
- **OFDMA (Orthogonal Frequency Division Multiple Access):** Used in 4G/5G, divides the spectrum into multiple orthogonal subcarriers.

OFDMA in 5G:

5G uses OFDMA with subcarrier spacings of 15, 30, 60, 120, or 240 kHz, compared to the fixed 15 kHz of 4G. This flexibility allows network optimization for different scenarios.

1.4. The Evolution of Mobile Generations

1G - First Generation (1980s):

- Analog technology.
- Voice services only.
- Low security and quality.
- Systems: AMPS, TACS, NMT.

2G - Second Generation (1990s):

- Transition to digital.
- Voice and SMS.
- Introduction of encryption.
- Systems: GSM, CDMA.

3G - Third Generation (2000s):

- Focus on mobile data.
- Mobile internet and video calls.
- Speeds up to 2 Mbps.
- Systems: UMTS, CDMA2000.

4G - Fourth Generation (2010s):

- All-IP architecture.
- Low latency (<50ms).
- Speeds up to 1 Gbps.
- System: LTE/LTE-Advanced.

5G - Fifth Generation (2020s):

- Massive Internet of Things.
- Ultra-low latency (<1ms).

- Multi-Gbps speeds.
 - Native Network Slicing.
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CHAPTER 2: THE 4G LTE ARCHITECTURE

2.1. Overview of the EPC Architecture

The Evolved Packet System (EPS) architecture that comprises 4G LTE represents a paradigmatic shift from previous mobile network generations. The EPS consists of two main domains: the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and the Evolved Packet Core (EPC). This architecture was conceived from its origin as a fully IP-based network, eliminating the circuit and packet domain duality that existed in previous generations.

The EPC introduces a flat and simplified architecture that significantly reduces data transmission latency and improves service delivery efficiency. Unlike previous hierarchical architectures, the EPC allows direct routing between network elements, minimizing potential congestion points. This architecture was designed to support seamless handovers between different

access technologies, including mobility between LTE, Wi-Fi, and legacy 3GPP networks.

A fundamental characteristic of the EPC is the clear separation between the control plane and the user plane. The control plane is responsible for signaling, mobility management, and session establishment, while the user plane handles exclusively the forwarding of user data traffic. This separation allows independent scalability of each plane and facilitates the implementation of specific optimizations for each traffic type.

The EPC also introduces the concept of mobility anchors, allowing user mobility to be managed without affecting data session continuity. This is particularly important for latency-sensitive applications and for ensuring quality of service during transitions between cells or even between different access technologies.

2.2. Main Components of the EPC

MME (Mobility Management Entity)

The MME is the central element of the control plane in the EPC, responsible for all functions related to user mobility and session management.

As the brain of the control network, the MME

processes user attach and detach procedures, authentication and authorization, bearer activation and deactivation, and manages tracking area lists.

One of the MME's critical functions is the selection of the Serving Gateway (S-GW) and Packet Data Network Gateway (P-GW) during the initial attach procedure. The MME is also responsible for mobility control in connected states, including orchestrating handovers between LTE cells and inter-technology handovers to 3G or 2G networks. It maintains context information for each connected user, including identifiers, security parameters, and mobility state.

The MME interfaces with the HSS via the S6a interface to retrieve subscriber authentication and profile information, and with the eNodeB via the S1-MME interface for signaling transport. In networks with high user density, multiple MMEs can be organized into an MME pool to provide redundancy and scalable capacity.

S-GW (Serving Gateway)

The Serving Gateway acts as the local anchor point for user plane mobility, routing and forwarding data packets between the eNodeB and the P-GW. Each user connected to the network is associated

with a single S-GW at a given time, which remains as a fixed point during intra-LTE movements, ensuring data session continuity.

The S-GW performs critical traffic replication functions for legal interception, collects usage information for accounting and consumption reporting, and applies charging policies based on connection time or data volume. During inter-eNodeB handovers, the S-GW serves as a local anchor point, redirecting the data path from the source eNodeB to the target eNodeB.

The S-GW also maintains context information about established bearers, including QoS parameters and traffic statistics. In optimized architectures, the S-GW can be collocated with the P-GW in a single physical element to reduce latency and complexity.

P-GW (Packet Data Network Gateway)

The Packet Data Network Gateway is the exit point for data traffic to external packet networks, including the internet and corporate IP services.

The P-GW functions as the anchor point for mobility between 3GPP and non-3GPP systems, allowing transparent transitions between LTE and technologies like Wi-Fi.

Among its main functions are IP address allocation for user devices, application of access control policies based on subscriber profile, and QoS policy enforcement through traffic classification and packet marking. The P-GW also implements advanced charging functionalities, including real-time metering for prepaid services and generation of detailed usage records for billing.

The P-GW interfaces with the Policy and Charging Rules Function (PCRF) via the Gx interface to receive real-time policy and charging rules, allowing granular control over services accessed by users. In roaming scenarios, the P-GW in the visited network (VPLMN) or home network (HPLMN) determines appropriate traffic routing.

HSS (Home Subscriber Server)

The Home Subscriber Server is the central database storing all permanent subscriber information, including identification details, security parameters, service information, and registration status. The HSS maintains the relationships between user identifiers, phone numbers, and the MMEs to which users are currently registered.

The HSS authentication functions are fundamental to network security, generating authentication vectors based on the AKMA (Authentication and Key Agreement) algorithm and validating user credentials during the attach procedure. The HSS also stores subscriber service profiles, including activated supplementary services, access restrictions, and roaming preferences.

To support scalability in large networks, the HSS can be implemented in federated configurations, where multiple instances share user load while maintaining data consistency through synchronization mechanisms.

PCRF (Policy and Charging Rules Function)

The PCRF is the brain for policy and charging decisions in the network, determining in real time how services should be treated in terms of quality of service and billing. Based on subscriber profile information, type of service being accessed, and network conditions, the PCRF generates dynamic rules sent to the P-GW for enforcement.

The PCRF supports differentiated service monetization through the application of charging policies based on content, access time, or volume of data consumed. It also enables the

implementation of QoS-guaranteed services, such as Voice over LTE (VoLTE) and video streaming, through the allocation of dedicated bearers with specific quality of service characteristics.

2.3. The Radio Access Network: eNodeB

The eNodeB (Evolved Node B) represents a significant evolution compared to the NodeBs of previous generations, consolidating functions that were distributed among multiple elements in the 3G architecture. In LTE, the eNodeB incorporates the functions of the NodeB and the RNC (Radio Network Controller), resulting in a flatter architecture with lower latency and greater operational efficiency.

Each eNodeB is responsible for all radio transmission and reception functions in one or more cells, including modulation/demodulation, coding/decoding, and signal processing. The eNodeB implements sophisticated resource scheduling algorithms in the time and frequency domains, dynamically allocating radio resources among active users based on QoS criteria, channel conditions, and service requirements.

Radio Resource Management (RRM) functions include power control, admission control, handover management, and load balancing between cells. The eNodeB makes autonomous decisions about handovers between cells under its control, coordinating with neighboring eNodeBs via the X2 interface to execute seamless handovers without data loss.

The eNodeB is also responsible for implementing HARQ (Hybrid Automatic Repeat Request) mechanisms at the physical level, ensuring reliable transmission over the radio interface, and for encrypting the user plane over the air interface to ensure data confidentiality.

2.4. The Signaling Protocol: Diameter

The Diameter protocol was selected as the primary signaling protocol for the EPC, replacing SS7 and SIGTRAN used in previous generations. Diameter is an application protocol that operates over TCP or SCTP, providing message delivery reliability and robust fault management mechanisms.

In the EPC context, Diameter is used on several critical interfaces. The S6a interface between MME and HSS uses Diameter for authentication,

authorization, and subscriber profile retrieval. The Gx interface between P-GW and PCRF employs Diameter for the provision of policy and charging rules. The Gy interface between P-GW and Online Charging System (OCS) uses Diameter for real-time credit authorization for prepaid users.

The Diameter protocol offers significant advantages in terms of security, supporting message authentication and transport encryption via TLS. Its extensible nature allows the addition of new commands and attributes to support future functionalities without requiring fundamental protocol changes.

The Diameter architecture includes elements like agents, relays, and proxies that allow intelligent message routing in complex and distributed networks. In large-scale deployments, Diameter Edge Agents (DEA) are used to interconnect roaming domains and manage security in interconnections between operators.

2.5. Limitations of 4G LTE

Despite its significant advances, the 4G LTE architecture presents several limitations that became apparent with the evolution of mobile