COMPLETE MOBILE NETWORK ENGINEERING

2G-3G-4G-5G OPTIMIZING MOBILE NETWORKS

MASTERING 5G NETWORKS

CELLULAR NETWORK DEPLOYMENT

ERICSSON | HUAWEI | NOKIA

Wagner R Bomfim

Preface

Mobile network engineering has never been as strategic as it is today. In an increasingly connected world, where user experience directly defines the success or failure of an operator, network optimization has evolved from a purely technical activity into a critical driver of competitiveness, operational efficiency, and innovation.

This book was born from that reality. It was not conceived as just another theoretical manual, but as a practical, in-depth, and field-oriented guide, built upon years of real-world experience in mobile networks, addressing complex challenges, critical environments, and high-demand technical scenarios.

Throughout the following chapters, the reader is guided on a complete journey through mobile network engineering and optimization, covering everything from essential fundamentals to advanced techniques applied to GSM, WCDMA, LTE, and 5G networks, including both NSA and SA architectures. Every concept presented is directly connected to real operational practice, with a strong focus on measurable results, network stability, and continuous improvement of the end-user experience.

One of the key differentiators of this work is its multi-vendor approach, offering deep and practical coverage of Ericsson, Nokia, and Huawei ecosystems. Rather than treating optimization in a generic way, the book presents real configuration paths, parameters, commands, tools, and methodologies specific to each vendor, accurately reflecting what professionals encounter in day-to-day network operations.

Beyond current technologies, the book also looks ahead. Topics such as SON, Massive MIMO, 5G Standalone, artificial intelligence, machine learning, automation, and cloud-based optimization are addressed not as distant concepts, but as integral parts of modern optimization processes. The content bridges pure engineering, data-driven analysis, and strategic business vision, preparing the reader for both present and future challenges in the telecommunications industry.

This book is intended for RF engineers, optimization specialists, experienced technicians, network managers, telecommunications students, and consultants who seek not only to understand how a mobile network works, but how to extract maximum performance from it in a consistent, scalable, and sustainable way.

More than teaching how to make the network work, this book has a clear purpose: to teach how to make the network excellent, every day, in every scenario, under all conditions.

May this book serve not only as a source of knowledge, but as a practical reference, a working tool, and a catalyst for professional growth.

MASTER THE ART AND SCIENCE OF MOBILE NETWORK OPTIMIZATION

In an increasingly connected world, where mobile network quality has become a decisive factor for the success of operators and the satisfaction of millions of users, this book presents itself as the most complete and up-to-date reference on mobile network optimization.

WHAT YOU WILL FIND IN THIS WORK:

- **Proven Methodologies**: Step-by-step processes for systematic optimization and measurable results.
- **Multi-technology**: Detailed approaches for GSM, WCDMA, LTE, and 5G (NSA & SA).
- **Specialized Tools**: Advanced use of TEMS, Nemo, XCAL, Probe, and PHU.
- **Real Cases**: Detailed studies of complex problems and their solutions.
- **Vendor-Specific Optimization**: Specific configurations for Ericsson, Nokia, and Huawei.
- **Future Trends**: AI/ML, SON, Cloud, and Augmented Reality applied to optimization.

WHO THIS BOOK IS FOR:

- **RF and Optimization Engineers** seeking to deepen technical knowledge.
- **Mobile Network Managers** who need strategic vision and business metrics.
- **Telecommunications Students** looking for solid fundamentals and practical applications.
- **Operator Professionals** who desire operational excellence and competitive advantage.
- **Technical Consultants** who need a comprehensive and up-to-date reference.

WORK DIFFERENTIATORS:

- **Practical Approach**: Technical concepts explained through real-world applications.
- **Complete Update**: Coverage of the latest 5G SA and Massive MIMO technologies.
- **Multi-tool Integration**: Integration between different collection and analysis systems.

- **Strategic Vision**: Alignment between pure technique and business objectives.
- **Accessible Language**: Complex technical explanations presented clearly.

ABOUT THE APPROACH:

This book transcends the traditional technical manual, presenting optimization as a continuous and strategic process that connects the network infrastructure to the end-user experience. Through field-validated methodologies and real success cases, the reader is guided from the fundamentals to the most advanced techniques, always focusing on operational excellence and value creation.

"It's not just about making the network work, but about making it excellent - every day, for every user, under all conditions."

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CHAPTER 1: INTRODUCTION TO MOBILE NETWORK OPTIMIZATION

1.1 What is Optimization and Why is it Important?

Mobile network optimization is a continuous and systematic technical process that aims to extract the maximum possible performance from the existing network infrastructure. Imagine the mobile network as a complex road system: optimization would be the work of traffic engineers who adjust traffic lights, create exclusive lanes, improve signage, and optimize traffic flows to ensure traffic flows as smoothly as possible, avoiding congestion and ensuring everyone reaches their destination quickly and safely.

In concrete technical terms, optimization involves:

- **Fine-tuning of radio parameters**: Modifying antenna transmission power, adjusting tilt angles, optimizing handovers (transfers between cells), and calibrating hundreds of other parameters that control how radio signals behave in the environment.

- **Continuous performance analysis**: Constantly monitoring hundreds of technical indicators that show the "health" of the network, identifying problems before they become critical.
- **Correction of specific problems**: Resolving issues such as dropped calls in certain locations, slow internet at specific times, areas with inadequate coverage, or interference between neighboring cells.
- **Improvement of operational efficiency**: Ensuring that network resources (radio spectrum, processing capacity, energy) are used as efficiently as possible, allowing more users to be served with the same infrastructure.

The importance of optimization manifests at several levels:

- **End-User Experience**: When you make a call and it drops inexplicably, or when the internet becomes extremely slow in a certain location, or when videos constantly buffer - all these are problems that good optimization can solve. Satisfied users tend to stay with the operator and recommend its services.
- **Operational and Economic Efficiency**: Operators that optimize their networks well can serve more users with

the same infrastructure, delaying investments in new antennas and equipment. A well-optimized network consumes less energy, requires less maintenance, and operates more predictably.

- **Competitive Advantage**: In saturated telecommunications markets, where all operators offer similar prices, network quality often becomes the decisive factor in consumer choice. A well-optimized network can be the difference between gaining or losing customers.
- **Preparation for Future Services**: Proper optimization creates the solid foundation needed to support emerging services such as Internet of Things (IoT), connected cars, augmented reality, and telemedicine, which require extremely reliable performance.

1.2 The Optimization Lifecycle: Drive Tests, KPIs, Adjustments, and Monitoring

The optimization process follows a continuous and iterative cycle, consisting of interconnected phases that constantly repeat. This cycle ensures that the network is continuously improved and adapted to changes in the environment and usage patterns.

Drive Tests are data collections performed by specially equipped vehicles that follow pre-defined routes. These vehicles function as mobile laboratories, carrying:

- **Professional scanners**: Specialized devices that measure all radio signals present in the area, regardless of whether they are connected to the operator's network or competitors'. They provide a complete view of the radio environment.
- **Test phones**: Devices that simulate the behavior of real users, making calls, sending messages, browsing the internet, and using applications, while collecting detailed data about the experience.
- **High-precision GPS systems**: Which correlate exactly each measurement with its geographical location, allowing the creation of precise coverage and quality maps.
- **Computers with specialized software**: That collect, process, and analyze data in real time, allowing engineers to identify problems during the test itself.

KPIs (Key Performance Indicators) are the "grades" or "thermometers" of the network. They objectively quantify performance in different aspects:

- **Drop Call Rate**: Percentage of calls that are involuntarily interrupted before their normal completion. In well-optimized networks, this value should be less than 1%.
- **Call Setup Success Rate**: Percentage of call attempts that are successfully completed. Values above 99% are considered excellent.
- **Accessibility**: The ability of users to connect to the network when needed, measured through indicators such as RRC Success Rate and E-RAB Success Rate.
- **Throughput**: Data transfer speed, both in download (direction from network to user) and upload (direction from user to network).
- **Latency**: The time it takes for a data packet to go from one point to another in the network. Crucial for real-time applications like online games and video conferences.

Adjustments are the technical interventions performed on the network to correct problems or improve performance:

- **RF (Radio Frequency) Adjustments**: Involve physical or configuration modifications to antennas - changing angles (tilt), direction (azimuth), height, or transmission power.
- **Parameter adjustments**: Modification of software settings that control the intelligent behavior of the network - criteria for handover, power control algorithms, admission control policies.
- **Coverage optimization**: Correction of areas with weak or non-existent signal through antenna reorientation, power adjustment, or installation of complementary equipment.

Monitoring is the continuous and systematic observation of network performance:

- **OSS (Operational Support Systems)**: Platforms that collect data from all network elements 24 hours a day, 7 days a week.
- **Advanced analysis tools**: That process the collected data, identify patterns, detect anomalies, and generate

alerts when problems are detected or when performance falls below established limits.

- **Automatic reports**: That show trends over time, compare performance between different areas or periods, and provide insights for decision making.

1.3 Technology Overview: 4G (LTE) and 5G (NSA & SA)

Mobile networks have evolved through technological generations, each bringing significant advances in capacity, speed, and capabilities. Understanding these technologies is fundamental for effective optimization.

4G (LTE - Long Term Evolution) represents the fourth generation of mobile networks, bringing revolutionary advances:

- **Fully IP-based architecture**: Unlike previous generations that had separate infrastructures for voice and data, LTE uses only IP (Internet Protocol) networks for all services. This simplifies the architecture and reduces costs.

- **Significantly improved performance**: Offers latencies in the range of 20-40 milliseconds (compared to 100-200ms of 3G) and theoretical speeds of up to 300 Mbps download. In practice, users typically experience 10-50 Mbps.
- **Advanced radio access technologies**: Uses OFDMA (Orthogonal Frequency Division Multiple Access) for downlink, which is more efficient at handling multipath propagation (signal reflections), and SC-FDMA for uplink, which is more efficient in terms of device battery consumption.
- **MIMO (Multiple Input Multiple Output)**: Uses multiple antennas at both the base station and devices to improve capacity and reliability through spatial diversity.
- **Voice over LTE (VoLTE)**: Transmits voice calls as data packets over the 4G network, offering superior voice quality and faster call setup times.

5G (NSA & SA) represents the fifth generation, bringing not only incremental improvements but radically new capabilities:

- **NSA (Non-Standalone)**: A transition architecture that uses the existing 4G network as a base for control functions and adds 5G capabilities for increased data capacity. Imagine a car with a 4G engine that gets a 5G turbo - the base is old, but the performance is improved.
- **SA (Standalone)**: An independent and complete 5G architecture, with a dedicated core network and all functions implemented natively in 5G. It's like having a completely new car, designed from the start to be 5G.
- **Fundamental advantages of 5G**:
    - **Ultra-low latency**: Less than 10 milliseconds, enabling critical real-time applications like remote surgery and autonomous vehicle control.
    - **Extreme bandwidth**: Up to 10 Gbps under ideal conditions, supporting 8K video streaming and virtual reality.
    - **Massive IoT**: Support for up to 1 million devices per square kilometer, enabling smart cities with sensors everywhere.
    - **Extreme reliability**: 99.999% availability for critical applications.

- **5G enabling technologies**:
    - **Massive MIMO**: Arrays with tens or hundreds of antenna elements that form precise directional beams.
    - **Beamforming**: Dynamic focusing of the signal directly to each user, improving efficiency.
    - **Network Slicing**: Creation of virtual networks dedicated to different types of services with specific requirements.
    - **Edge Computing**: Data processing closer to users, reducing latency.

Optimization in 5G introduces new challenges and opportunities, such as dynamic beam management, coordination between different frequency bands (sub-6 GHz and mmWave), and guaranteeing quality of service in network slices dedicated to specific applications.

CHAPTER 2: THE STEP-BY-STEP OPTIMIZATION PROCESS

2.1 Phase 1: Definition of Objectives and Goals (Key KPIs)

The first phase of the optimization process is crucial because it establishes what will be measured, how it will be measured, and what the desired results are. Without clear and measurable objectives, optimization becomes a random exercise without a defined direction.

Key KPIs (Key Performance Indicators) are quantifiable metrics that reflect critical aspects of network performance. They function like measurement instruments in a laboratory - each reveals something specific about the "health" of the network:

- **Accessibility**: Measures the ability of users to obtain service when needed. Includes:
    - **RRC Success Rate**: Success rate in establishing the initial connection between the device and the network. Values above 99.5% are considered excellent.
    - **E-RAB Success Rate**: Success rate in establishing the data bearers that carry the actual traffic. A typical target is above 99.0%.
- **Retention**: Evaluates the network's ability to maintain services once established. Comprises:

- **Drop Call Rate (DCR)**: Percentage of calls that are involuntarily interrupted after successful establishment. In optimized networks, it should be less than 1.0%.
- **E-RAB Drop Rate**: Drop rate of data connections. Values below 0.8% are considered good.

- **Mobility**: Measures the efficiency with which the network manages user movement between cells. Includes:
  - **Handover Success Rate (Intra-LTE)**: Success in transfers between cells of the same LTE technology. Should exceed 98%.
  - **Handover Success Rate (Inter-RAT)**: Success in transfers between different technologies (e.g., LTE to 3G). A typical target is above 96%.
- **Throughput and Quality of Service**:
  - **Downlink Average Throughput**: Average download speed experienced by users. Values above 25 Mbps are considered good.

    - **Uplink Average Throughput**: Average upload speed. A typical target is above 8 Mbps.
    - **Cell Edge Performance (5th Percentile)**: Performance of users in the worst coverage situation (usually at the cell edge). Should be at least 2 Mbps download and 1 Mbps upload.

Establishment of SMART Goals:
Optimization goals should be Specific, Measurable, Achievable, Relevant, and Time-bound. For example: "Reduce the drop call rate in the central area from 2.5% to 1.0% within 4 weeks".

2.2 Phase 2: Data Collection (Drive Tests, Scanners, OSS Measurements)

Data collection is the "field investigation" phase where concrete facts about network performance are collected through multiple complementary methodologies.

Detailed Drive Tests involve vehicles equipped with specialized instrumentation that follow carefully planned routes:

- **Measurement equipment**: Includes professional scanners (like R&S TSME6), multiple test phones from different manufacturers, high-precision GPS, and computers with specialized software.

- **Collected metrics**:
  - **RF Parameters**: RSRP (Reference Signal Received Power), RSRQ (Reference Signal Received Quality), SINR (Signal to Interference plus Noise Ratio), PCI (Physical Cell ID), Timing Advance.
  - **Service Performance**: Download and upload throughput, round-trip latency, voice quality (MOS - Mean Opinion Score).
  - **Network Behavior**: Call Success Rate, Drop Call Rate, BLER (Block Error Rate), handover performance.
- **Route planning**: Routes should be representative of real usage patterns, covering different environments (dense urban, suburban, rural, highways) and different traffic conditions.

Professional Scanners are specialized devices that offer unique capabilities:

- **Independent measurements**: Capture all signals present in the environment, not only from the operator being tested but also from competitors.
- **Interference analysis**: Identify sources of interference that degrade signal quality.
- **Complete spectrum view**: Show all visible cells, even those to which they are not connected.

OSS (Operational Support Systems) Measurements provide the macro view of the network:

- **Data from all users**: Collect performance information from all users connected to the network, 24 hours a day.
- **Aggregated statistics**: Offer statistically significant data about the behavior of the network as a whole.
- **Pattern identification**: Reveal problems that affect many users simultaneously or that occur in specific temporal patterns.

Measurement Reports (MR) are reports sent by the users' own devices:

- **Statistical sampling**: Provide a representative view of the entire coverage area.

- **Quality metrics**: Include RSRP, RSRQ, PHR (Power Headroom Report) that show the real conditions experienced by users.
- **Interference analysis**: Allow identification of interference problems based on UE measurements.

2.3 Phase 3: Data Analysis and Problem Identification

This phase transforms raw data into actionable insights through deep technical analysis and correlation of multiple information sources.

Coverage Analysis focuses on the availability and quality of the radio signal:

- **RSRP Maps**: Identify coverage "holes" (areas where the signal is weak or non-existent). Values below -110 dBm usually indicate serious coverage problems.
- **SINR Analysis**: Reveal interference problems (when the signal is strong but the quality is poor). SINR below 0 dB indicates severe interference.
- **Overlap Analysis**: Detect areas with excessive overlapping cells, which can cause interference and unnecessary handovers.

Capacity Analysis examines how network resources are used:

- **PRB Utilization**: Shows the percentage of Physical Resource Blocks being used. Values consistently above 80-90% indicate congestion.
- **Congestion analysis**: Identifies cells with excess connected users or excessive traffic.
- **Throughput vs Utilization Correlation**: Reveals whether low speeds are related to high resource usage or other factors.

Mobility Analysis investigates the efficiency of transfers between cells:

- **Handover Performance per Relation**: Analyzes handover success between specific pairs of cells.
- **Ping-pong Analysis**: Identifies excessive handovers between the same cells, which wastes resources and can cause drops.
- **Too Late/Too Early Handovers**: Detects handovers that occur too late (causing radio link failure) or too early (causing interference).

Root Cause Analysis is the deep investigation to find the fundamental cause of problems:

- **5 Whys Methodology**: Asks "why" repeatedly until reaching the root cause.
- **Ishikawa Diagrams (Fishbone)**: Systematically map all possible causes of a problem.
- **Correlation analysis**: Identifies relationships between different variables (e.g., throughput drop when number of users increases).

2.4 Phase 4: Formulation and Implementation of Corrective Actions

With problems identified and their causes understood, this phase involves planning and executing specific solutions.

RF (Radio Frequency) Adjustments are interventions in the physical domain of the radio signal:

- **Mechanical Tilt**: Physical change of the vertical inclination of the antenna. Increasing the tilt reduces range but improves nearby coverage; decreasing the tilt increases range but can cause interference.

- **Azimuth**: Modification of the horizontal direction of the antenna. Used to redirect coverage to specific areas.
- **Antenna Height**: Adjustment of height relative to the ground. Higher antennas cover larger areas but can cause more interference.
- **Transmission Power**: Increase or reduction of signal power. More power improves coverage but increases interference; less power reduces interference but worsens coverage.

Parameter Adjustments are modifications to software settings that control the intelligent behavior of the network:

- **Handover Parameters**: Adjustment of a3Offset, hysteresis, timeToTrigger to optimize when and how transfers between cells occur.
- **Power Control**: Configuration of algorithms that control the transmission power of UEs to maximize quality and minimize interference.
- **Admission Control**: Definition of criteria for accepting or rejecting new users in the cell when resources are limited.

Feature Optimization involves activation, deactivation, or adjustment of advanced functionalities:

- **Carrier Aggregation**: Combination of multiple carriers to increase available speed.
- **MIMO**: Configuration of multiple antennas to improve capacity and reliability.
- **SON Features**: Use of Self-Organizing Networks functions for automation of optimizations.

2.5 Phase 5: Verification and Consolidation of Results

The final phase ensures that the implemented changes actually produced the desired results without introducing new problems.

Validation Methodology involves the systematic confirmation of improvements:

- **Identical tests**: Exact repetition of the same tests performed before the optimizations, using the same routes, same equipment, and same conditions.
- **Observation period**: Continuous monitoring for at least 48-72 hours to ensure that improvements are stable and not temporary.

- **Comparative statistical analysis**: Rigorous statistical comparison of "before" and "after" results to confirm that improvements are significant.

Success Criteria define when an optimization can be considered successful:

- **Improvement in target KPIs**: The specific indicators that were the focus of the optimization must show clear and significant improvement.
- **Absence of degradation**: No other critical KPI should have worsened as a result of the changes.
- **Proven stability**: Improvements must remain consistent over time, not just being a temporary effect.

Documentation and Lessons Learned capture the knowledge generated during the process:

- **Detailed technical report**: Documents the methodology used, data collected, analyses performed, changes implemented, and results obtained.
- **Lessons learned**: Identifies what worked well, what didn't work, and what insights can be applied in future projects.

- **Knowledge base update**: Incorporates the findings and best practices identified in the optimization process.

This complete cycle ensures that optimization is a continuous improvement process, where each iteration builds on the knowledge generated in previous ones, leading to a progressively better and more efficient network.

CHAPTER 3: TECHNICAL CONCEPTS FOR OPTIMIZATION

3.1 Fundamental Radio Parameters: RSRP, RSRQ, SINR

To understand and optimize mobile networks, it is essential to master three fundamental parameters that describe the quality of the radio signal. These parameters are like the vital signs of a network - they indicate the basic health of the connection between the user's device and the base station.

RSRP (Reference Signal Received Power) is the measure of the received power of the reference signals transmitted by the base station. Think of it as measuring the volume of a conversation - the louder, the better you hear. Technically, RSRP represents the average received power of a single reference signal carrier, measured in dBm (decibels relative to 1 milliwatt).

- **Excellent**: Above -85 dBm - strong signal, typical of locations very close to the antenna or with direct line of sight.
- **Good**: Between -85 dBm and -95 dBm - adequate signal for all services, including high-quality video streaming.
- **Fair**: Between -95 dBm and -105 dBm - sufficient signal for voice calls and basic internet use, but may have problems with services that require more bandwidth.
- **Poor**: Between -105 dBm and -115 dBm - weak signal, only for voice calls and text messages, with high probability of drops.
- **Very Poor**: Below -115 dBm - on the verge of coverage loss, unstable or unavailable services.

RSRQ (Reference Signal Received Quality) is the quality of the reference signal, considering both the received power and interference. If RSRP is like measuring volume, RSRQ is like measuring clarity - you can have high volume, but if there is a lot of noise, you still won't understand the message. RSRQ is calculated as the ratio between RSRP and the total received power (RSSI), measured in dB.

- **Excellent**: Better than -9 dB - superior quality, ideal for sensitive services like video conferencing.
- **Good**: Between -9 dB and -12 dB - good quality, supports video streaming and interactive applications.
- **Fair**: Between -12 dB and -15 dB - acceptable quality for web browsing and voice calls.
- **Poor**: Between -15 dB and -18 dB - degraded quality, may cause interruptions in data services.
- **Very Poor**: Worse than -18 dB - very poor quality, unstable services.

SINR (Signal to Interference plus Noise Ratio) is the ratio between the power of the desired signal and the sum of interference plus noise. This is perhaps the most important parameter for data performance, as it directly determines which modulation and coding scheme can be used, which in turn determines the maximum possible speed.

- **SINR > 20 dB**: Excellent conditions - allows the use of 256QAM modulation and high-efficiency coding, resulting in the maximum possible throughput.
- **SINR 13-20 dB**: Good conditions - supports 64QAM modulation with good efficiency, providing high speed.
- **SINR 0-13 dB**: Fair conditions - uses 16QAM or QPSK modulation, with moderate to low speeds.
- **SINR < 0 dB**: Poor conditions - noise and interference are greater than the desired signal, resulting in low speed and high error rate.

The relationship between these parameters is crucial: good RSRP with poor RSRQ/SINR indicates interference, while poor RSRP with good SINR suggests that the cell is well isolated, but too distant.

3.2 Handover (Mobility) and its Parameters

Handover (or transfer) is the process of passing a call or data session from one cell to another while the user moves. It's like passing the baton in a relay race - it needs to be done at the right time, in the right place, and smoothly so as not to drop the baton.

Measurement Events in LTE are conditions that trigger measurement reports from the UE to the network:

Event A3 (Neighbor becomes offset better than serving) is the main mechanism for intra-frequency handover. The mathematical condition is:

$Mn + Ofn + Ocn - Hys > Ms + Ofs + Ocs + Off$

Where:

- Mn: RSRP of the neighbor cell
- Ms: RSRP of the serving cell
- Ofn: Frequency offset of the neighbor
- Ocn: Cell individual offset of the neighbor
- Ofs: Frequency offset of the serving
- Ocs: Cell individual offset of the serving
- Hys: Hysteresis of event A3
- Off: Offset of event A3

Timing Parameters control when and how handovers occur:

- **timeToTrigger**: The time the handover condition must persist before being triggered. Typical values range from 0 ms (immediately) to 5120 ms (more than 5 seconds). A value too low causes unnecessary handovers due to temporary fluctuations; a value too high causes late handovers and possible drops.

- **hysteresis**: A safety margin added to prevent oscillations. Typical values from 0.5 dB to 3.0 dB. More hysteresis makes the handover more stable, but less sensitive.

- **a3Offset**: Defines how much better the neighbor cell needs to be to trigger the handover. Values from -15 dB to +15 dB. Positive offset makes the handover occur earlier; negative offset later.

Common Handover Problems:

- **Handover Too Early**: Occurs when the user still has a good connection with the serving cell, but is transferred prematurely. Causes interference and possible drop if the new cell is not stable.

- **Handover Too Late**: Occurs when the user has already lost the connection with the serving cell before the handover is initiated. Results in Radio Link Failure and call drop.

- **Ping-Pong Handover**: Fast and repetitive transfers between the same two cells, wasting network resources and degrading the user experience.

3.3 Load and Interference Management

Load and interference management is like air traffic control - it needs to coordinate multiple "flights" (connections) sharing the same space (spectrum) without colliding or interfering with each other.

Load Indicators monitor the utilization of network resources:

- **PRB Utilization**: Measures the percentage of Physical Resource Blocks being used. PRBs are the fundamental blocks of time and frequency allocated to users.
  - Low utilization (< 30%): Idle resources, possibly misconfiguration or low demand.
  - Moderate utilization (30-70%): Ideal operation, with margin for traffic peaks.
  - High utilization (70-90%): Network near capacity, requires careful monitoring.
  - Congestion (> 90%): Users experience low speed and high latency.

- **RRC Connected Users**: Number of users simultaneously connected to the cell. Each technology has maximum limits based on its processing capacity.
- **DL/UL Throughput**: Aggregate transmission rate in download and upload. Shows how much data is being transported by the cell.

Load Balancing Techniques:

- **MLB (Mobility Load Balancing)**: Automatically adjusts handover parameters to move users from congested cells to less utilized cells. Works like a traffic detour - when a road is congested, cars are redirected to alternative routes.
- **CCO (Coverage and Capacity Optimization)**: Adjusts the electrical tilt of antennas to optimize coverage and capacity simultaneously. Tilting the antenna more reduces the covered area but increases capacity in the nearby area; tilting less increases the covered area but reduces capacity per user.

Interference Control:

- **ICIC (Inter-Cell Interference Coordination)**: Coordinates resource allocation between neighboring cells to minimize interference. It's like coordinating construction schedules on neighboring roads to not cause simultaneous congestion.

- **Power Control**: Dynamically adjusts the transmission power of UEs to use only the necessary power, minimizing interference for other users.

3.4 Antenna Optimization: Azimuth, Mechanical Tilt, and Electrical Tilt

Antenna optimization is like adjusting spotlights in a stadium - each adjustment changes who is illuminated and with what intensity.

Azimuth is the horizontal direction of the antenna's main lobe, measured in degrees from true North:

- **Required accuracy**: ±5 degrees. A deviation of 10 degrees in an antenna 1 km away can displace the point of maximum coverage by more than 170 meters.
- **Typical applications**:
    - 0° (North): Common in north sectors of sites
    - 120° (Southeast): Southeast sectors
    - 240° (Southwest): Southwest sectors