## Heterogeneous Cellular Networks

This detailed, up-to-date introduction to heterogeneous cellular networking presents its characteristic features, the technology underpinning it, and the issues surrounding its use.

Comprehensive and in-depth coverage of core topics catalog the most advanced, innovative technologies used in designing and deploying heterogenous cellular networks, including system-level simulation and evaluation, self-organization, range expansion, cooperative relaying, network MIMO, network coding, and cognitive radio. Practical design considerations and engineering tradeoffs are also discussed in detail, including handover management, energy efficiency, and interference management techniques.

A range of real-world case studies, provided by industrial partners, illustrate the latest trends in heterogenous cellular network development. Written by leading figures from industry and academia, this is an invaluable resource for all researchers and practitioners working in the field of mobile communications.

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# Heterogeneous Cellular Networks

## Theory, Simulation and Deployment

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**To those who have enlightened our lives
with love and knowledge**

# Contents

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# Forewords

## Gordon Mansfield

### Small Cell Forum

My name is Gordon Mansfield, and I currently serve as the elected chairman of the Small Cell Forum. The Forum is an industry body that promotes and drives the wide-scale adoption of small cell technologies to improve coverage, capacity and services delivered by mobile networks. I have many years of experience in the space, having previously served on the Femto Forum board from 2008–2010 and having led a tier one operators small cell effort since 2007. I consider it a great honor to be asked to write the foreword for this very informative book on small cells and heterogeneous networks. The authors are all highly respected researchers in academia and in industry, who have spent years working on the topics covered.

In recent years, small cells have become a very big topic when discussing mobile Internet and the tremendous data growth experienced over the past five years by operators around the globe. When we look at the recent history of data growth, some operators have experienced a 20,000 percent growth in data from 2007–2011. Combine that with the incredible forecast coming from all parts of the industry suggesting 10X and higher growth over the next four to five years, and it becomes clear that new ways to serve this data growth are necessary. We cannot continue to rely on new spectrum and advances in the air interface alone to sustain these types of data growth.

To be clear, small cells are not really new. They have been around for some time to provide capacity within limited amounts of spectrum. However, the solutions that were available up until a few years ago were limited in their functionality and, due to the massive growth in data, expensive to deploy on the scale required today. The high-power base stations in the macro network remain very important to maintain broad umbrella coverage, but, as demand in concentrated areas continue to rise, we will need not only traditional picocells and microcells that exist today but new innovative small cell solutions that allow for densification of networks in a cost-effective and aesthetically appealing way. These will range from femtocells, which have become a mature technology in the past couple of years, to new flavors of picocells and relays that are not yet productized in large numbers. Of course, to tie all of this together, we need software functionality to enable true heterogeneous networks and self-organizing network (SON) capabilities to manage the large increase in nodes within the mobile network of tomorrow.

The authors of this book effectively and insightfully break down the important factors of heterogeneous cellular networks and cover the various types of nodes that may be used. They lay a good technical foundation, and address several of the challenging areas that require focus for heterogeneous cellular networks to become a widespread success. They give the mobile operator several pieces of information that can be useful in helping them decide the best way to evolve their network, from the homogeneous network of today to the heterogeneous network of tomorrow.

As the topic of small cells and heterogeneous networks is at the forefront of many mobile operators' decision-making today, I am happy to see a book like this, which not only lays the foundation, but also provides many details on things that should be considered.

Gordon Mansfield
Chairman, Small Cell Forum

## Alan Stidwell

### Orange Labs, France Telecom

My name is Alan Stidwell, and I am Senior Technical Specialist within Wireless Technology Evolution at Orange Labs, France Telecom. My main role is to assess the performance benefits coming from future radio access technology evolutions (from two years +), to develop mid/long-term radio access network strategies, and to support work on radio access networks in 3GPP.

Until recently, most mobile network operators have been very focused on delivering customer performance needs mainly through macrocellular based deployments. This strategy is starting to be tested by the rapid increase in traffic volumes experienced during the last two to three years, which is expected to continue, and which are causing operators to deliver additional capacity at an accelerated rate compared to previous years. Additional capacity can be delivered by adding new technologies in additional spectrum on existing macrocell sites. This applies even for the early LTE deployments, primarily because this is the most cost-effective way to achieve coverage for a new technology whilst at the same time adding considerable capacity. Such deployments also bring big initial improvements in user experience because the early adopters will have the benefits of a largely unloaded network, thus amplifying the perceived performance compared to legacy 3G networks. However, it takes time for users to migrate their devices to LTE and in the meantime the traffic is still growing on the existing 3G network, which calls for a different strategy in order to avoid disappointing users on the legacy network. A primary way to achieve this additional capacity on legacy networks is through deployment of small cells, using legacy technologies that are in widespread use in existing devices. Furthermore, if the traffic predictions are correct, then it will not take too long before early LTE macrocell networks also become overloaded with a corresponding drop in user experience. Spectrum is also a finite and expensive resource, and therefore a continuing expansion of capacity in the macrocell domain alone may not be compatible with future capacity needs. In addition, macrocells are not necessarily the most cost- or energy-efficient way to deliver additional capacity in areas where there are predominantly non-uniformly distributed (or clustered) users. The need to maintain a reasonable user experience with this expected ongoing growth in traffic, whilst at the same time respecting the limits on spectrum, is therefore stimulating the whole industry to develop small cell solutions for both the new and legacy technologies.

These changes are happening very fast, and there is very little published on small cells and HetNets so far. This book is therefore very timely, and the way it comprehensively deals with all the relevant topics will appeal to many colleagues in all areas of the mobile industry who wish to get up to speed on this very important and fast-evolving technological change in network topology. Even experts and people with some prior knowledge in the field should find value in it, since it pulls together in one place a lot of valuable information and reference material.

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# Preface

Driven by a new generation of wireless user equipments and the proliferation of bandwidth-intensive applications, mobile data traffic and network load are increasing in unexpected ways, and are straining current cellular networks to a breaking point. In this context, heterogeneous cellular networks, which are characterized by a large number of network nodes with different transmit power levels and radio frequency coverage areas, including macrocells, remote radio heads, microcells, picocells, femtocells and relay nodes, have attracted much momentum in the wireless industry and research community, and have also gained the attention of standardization bodies such as the *3rd Generation Partnership Project* (3GPP) LTE/LTE-Advanced and the *Institute of Electrical and Electronics Engineers* (IEEE) Mobile *Worldwide Interoperability for Microwave Access* (WiMAX).

The impending worldwide deployments of heterogeneous cellular networks bring about not only opportunities but also challenges. Major technical challenges include the co-existence of various neighboring and/or overlapping cells, intercell interference and mobility management, backhaul provisioning, and self-organization that is crucial for efficient roll-outs of user-deployed low-power nodes. These challenges need to be addressed urgently to make the best out of heterogeneous cellular networks. This asks for a thorough revisit of contemporary wireless network technologies, such as network architecture and protocol designs, spectrum allocation strategies, call management mechanisms, etc. There is also an urgent need in the wireless industry, academia and even end-users to better understand the technical details and performance gains that heterogeneous cellular networks would make possible.

*Heterogeneous Cellular Networks – Theory, Simulation and Deployment* provides a complete and thorough exposition of heterogeneous cellular networks, with a delicate balance between theory and practice. It contains cutting-edge tutorials on the technical and theoretical foundations upon which heterogeneous cellular networks are built, while also providing high-level overviews of standardization activities that are informative to readers of all backgrounds. The book is written by researchers currently leading the investigations on heterogeneous cellular networks, covering a wide spectrum of topics such as simulation and evaluation models, advanced radio resource management, self-organization, mobility and handover issues, cooperative communications, network *multiple-input multiple-output* (MIMO) techniques, network coding, cognitive radio, energy efficiency, etc.

The book is organized into 14 chapters. Chapter 1 provides the background information necessary for understanding the theoretical and technical foundations of heterogeneous cellular networks, as well as discussions of technical challenges in deploying heterogeneous cellular networks, and serves as a summary of the rest of the book.

Chapter 2 describes the process of building a radio propagation model, and provides a detailed review of different radio propagation modeling techniques, including empirical models, deterministic models, semi-deterministic models and hybrid models. The tradeoff between radio channel modeling accuracy and complexity is discussed. Moreover, this chapter identifies the need and requirements for new radio propagation modeling tools that are able to operate in heterogeneous cellular network scenarios, which may involve both indoor and outdoor environments.

In Chapter 3, we look into important issues in system-level simulations for heterogeneous cellular networks. We review different kinds of system-level simulation, and compare dynamic system-level simulations with static ones. Intricate modeling issues, such as wrap-around, shadowing, multi-path fading, antenna patterns, diversity combining and signal quality modeling, are discussed. Traffic and mobility modeling is also described. Simulation setups for heterogeneous cellular networks from the perspective of 3GPP are illustrated, taking into account features of heterogeneous cellular network nodes and channel modeling, and covering macro-pico, macro-femto and macro-relay scenarios.

Access control enables flexible installation and operation of low-power nodes for different deployment scenarios. Chapter 4 provides an in-depth description of access control in heterogeneous cellular networks from the perspectives of the core network, radio access network and user equipments. The benefits and tradeoff of different access control mechanisms are analyzed through numerical simulations using various performance metrics, such as the percentage of offloaded user equipments, as well as cell-average and cell-edge data throughputs. Moreover, the access control enhancements standardized during LTE Releases 8, 9 and 10 are discussed.

In Chapter 5, we first provide an overview of stochastic models where the locations of network nodes can be modeled following a *Poisson point process* (PPP) or a hardcore point process. Then, motivated by the accuracy and tractability of PPP network models, we present a stochastic-geometry-based two-tier network framework, and study the effects of spectrum allocation and different access schemes on the link reliability of each tier of a heterogeneous cellular network and on the network area spectral efficiency. We investigate both disjoint and joint subchannel allocation, where the two tiers are assigned disjoint sets of subchannels or share the whole spectrum, respectively. Moreover, we quantify the enhancement in a user equipment's link reliability when it can hand over from the macrocell to the closest femtocell, and analyze the resulting benefits to the network throughput. The proposed framework also allows us to generalize the results to multi-tier heterogeneous cellular networks.

*Self-organizing networks* (SONs) provide means to facilitate network and service management, while supporting radio network robustness and optimized coverage and capacity. SON functionalities are commonly divided into self-configuration, self-optimization and self-healing. These are especially important to heterogeneous cellular networks due to the increasing number of nodes that need to be managed. Self-configuration enables smooth introduction of low-power nodes into an existing macrocell deployment. Continuous self-optimization and self-healing ensure that the low-power nodes are able to provide the intended capacity without requiring significant human management and monitoring efforts. In Chapter 6, we provide relevant insights about SON for heterogeneous cellular networks, with a main focus on 3GPP LTE, and discuss key performance monitoring aspects. Different deployment options are described in relation to the 3GPP management architecture. The associated 3GPP SON feature requirements and signaling support are also described together with 3GPP specification references.

Chapter 7 reviews intercell interference problems and interference management techniques for heterogeneous cellular networks. Some simulation results are used to demonstrate the downlink/uplink coverage imbalance issues in heterogeneous deployments. Range expansion of small cells, cell-selection methods and intercell interference coordination techniques are discussed, including mechanisms recently proposed in the 3GPP LTE. The dedicated focus is on frequency-domain, power-based and time-domain interference management. Moreover, performance assessments and comparisons are provided through system-level simulations, indicating some design guidelines for dynamic interference management.

Interference management becomes even more challenging if there are restrictions in access mechanisms and internode signaling, for example in femtocells. Chapter 8 looks into uncoordinated femtocell deployments, and self-organizing femtocell networks are discussed, from the perspectives of the Small Cell Forum. With less strict backhaul requirements as compared with other heterogeneous cellular network nodes, femtocell backhaul time synchronization becomes especially critical and is paid special attention. Moreover, power-based, antenna-based and frequency-domain techniques for interference mitigation in uncoordinated femtocells are reviewed in detail.

Chapter 9 provides an overview of mobility robustness, handover management and *mobility load balancing* (MLB) in LTE/LTE-Advanced systems, and develops *mobility robustness optimization* (MRO) algorithms under both *Radio Resource Control* (RRC) connected and idle modes. Under the RRC connected mode, we introduce the hard handover procedure in LTE and the MRO use case, and propose an MRO scheme to assign different handover hysteresis values for user equipment traveling at different velocities. Under the RRC idle mode, we introduce cell selection/reselection procedures, and propose a negotiation mechanism to solve the *cell-specific reference symbol* (CRS) parameter mismatch between neighboring cells and the mismatch between CRS and handover parameters. Specifically for heterogeneous cellular networks, we identify the technical challenges in mobility management, evaluate the mobility performance under 3GPP Release 10 enhanced *intercell interference coordination* (ICIC) features, and propose a mobility-based ICIC scheme.

In Chapter 10, we first review and analyze the performance of *amplify-and-forward* (AF) relay, *demodulate-and-forward* (DMF) relay and *decode-and-forward* (DCF) relay, and propose a link adaptation scheme for the DMF relay. Then, the 3GPP LTE-Advanced relay system architectures in heterogeneous cellular networks are introduced. In order to fully explore the capacity of cooperative relaying, the emerging *estimate-and-forward* (EF) relay and joint network-channel coding are presented together with a new link adaptation scheme.

Network MIMO, also known as *multi-cell processing* (MCP) or *coordinated multi-point* (CoMP), combines MIMO and cooperation techniques to provide new means to manage interference more intelligently, while increasing the spectral efficiency. In Chapter 11, we first analyze the problems with existing *single-cell processing* (SCP), review different types of MCP and introduce application scenarios of MCP for heterogeneous cellular networks. Afterwards, we demonstrate how MCP together with MIMO transmit beamforming techniques and power control can mitigate *intercarrier interference* (ICI) to achieve a better tradeoff between system throughput and user fairness in heterogeneous cellular networks. Practical implementation issues such as backhaul requirements, base station clustering and *channel state information* (CSI) acquisition are discussed, and future research directions are outlined.

Network coding is a technique that smartly controls the interference from different source nodes to improve the overall network performance. Overlaying network coding techniques upon existing cellular networks provides a simple and economical way to tremendously enhance the network performance without too many hardware replacements. In Chapter 12, we first explain the fundamentals of network coding and its state-of-the-art developments. Then, we give coding-gain upper bounds with and without practical geometry considerations, as well as illustrative examples to show the performance gains and effectiveness of applying simple network coding solution to heterogeneous cellular networks. Following that, we analyze the efficiency and reliability performance of network coding using a two-way relay-aided X network. Finally, we introduce a low-complexity and distributed coding solution construction method that is ideal for heterogeneous cellular networks.

*Dynamic spectrum access* (DSA) or *cognitive radio* (CR) has the potential to provide significant benefits and simple solutions to overcome many of the challenges faced by heterogeneous cellular networks. Chapter 13 presents a detailed overview of the functionalities and techniques associated with DSA/CR technologies, including methods to acquire spectrum awareness, select the appropriate frequency of operation and share spectrum opportunities in a non-interfering manner, and explores the potential application of DSA/CR concepts and techniques in heterogeneous cellular networks. Several practical scenarios are explored. Various implementation alternatives along with the corresponding pros and cons are discussed. Related cross-layer issues and design tradeoffs are investigated. Finally, recent standardization efforts aimed at developing new systems based on DSA/CR principles and including DSA/CR capabilities in existing standards are reviewed.

Making cellular networks green would have a tangible positive impact on reducing the carbon footprint of *information communication technology* (ICT), and achieve a long-term profitability for mobile service operators. Chapter 14 focuses on heterogeneous cellular network architectures and their potential to deliver improved performance at reduced energy and cost consumption levels. In particular, the chapter examines the fundamental tradeoffs between performance and energy consumption, recently proposed heterogeneous cellular network architectures, dynamic base station designs, advanced transmission schemes, hardware improvements, and cross-layer integration solutions. We also present a comprehensive survey of latest green techniques for homogeneous and heterogeneous cellular networks with discussions of their merits and demerits. Moreover, recent research projects for green cellular networks are reviewed, and a taxonomy of green metrics is summarized.

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# Acronyms

| | |
|---|---|
| 3GPP | 3rd Generation Partnership Project |
| 4G | fourth generation |
| ABS | almost blank subframe |
| AF | amplify-and-forward |
| AM | acknowledged mode |
| AMC | adaptive modulation and coding |
| ANR | Automatic Neighbor Relation |
| AoA | angle of arrival |
| AoD | angle of departure |
| AP | access point |
| APP | a posteriori probability |
| ARCF | automatic radio configuration data handling function |
| ARQ | Automatic Repeat reQuest |
| AWGN | additive white Gaussian noise |
| BCJR | Bahl–Cocke–Jelinek–Raviv |
| BER | bit error rate |
| BLER | block error rate |
| BPSK | binary phase-shift keying |
| BS | base station |
| BSP | binary space partitioning |
| CA | closed access |
| CAPEX | capital expenditure |
| CAS | cluster angular spread |
| CCC | common control channel |
| CCO | coverage and capacity optimization |
| CDF | cumulative distribution function |
| CDMA | code division multiple-access |
| CDS | cluster delay spread |
| CFL | Courant–Friedrichs–Lewy |
| CIO | cell individual offset |
| CIR | channel impulse response |
| CM | configuration management |
| CN | core network |

| | |
|---|---|
| CoMP | coordinated multi-point |
| CPC | cognitive pilot channel |
| CPE | customer premises equipment |
| CQI | channel quality indicator |
| CR | cognitive radio |
| CRC | cyclic redundancy check |
| CRE | cell range expansion |
| C-RNTI | cell radio network temporary identifier |
| CRS | cell-specific reference symbol |
| CSCC | common spectrum coordination channel |
| CSG | closed subscriber group |
| CSG ID | CSG identity |
| CSI | channel state information |
| CSIR | receiver-side channel state information |
| CSO | cell selection offset |
| CTS | Clear-to-Send |
| DAB | Digital Audio Broadcasting |
| DAS | distributed antenna system |
| DCF | decode-and-forward |
| DCH | dedicated channel |
| DCM | directional channel model |
| DECT | Digital Enhanced Cordless Telecommunications |
| DeNB | donor eNB |
| DFS | Dynamic Frequency Selection |
| DHCP | Dynamic Host Configuration Protocol |
| DL | downlink |
| DM | domain manager |
| DMC | dense multi-path componens |
| DMF | demodulate-and-forward |
| DNS | Domain Name System |
| DMT | diversity and multiplexing tradeoff |
| DoA | direction-of-arrival |
| DoD | direction-of-departure |
| DPC | dirty-paper coding |
| D-QDCR | Distributed QoS-based Dynamic Channel Reservation |
| DS | downstream |
| DSA | dynamic spectrum access |
| DSL | digital subscriber line |
| DSP | digital signal processor |
| DVB | Digital Video Broadcasting |
| E2E | end-to-end |
| ECGI | Evolved Cell Global Identifier |
| EESM | exponential effective SINR mapping |
| EF | estimate-and-forward |

| | |
|---|---|
| EGC | equal gain combining |
| EM | element manager |
| eNB | evolved NodeB |
| EoA | elevation of arrival |
| EoD | elevation of departure |
| EPC | Evolved Packet Core |
| EPS | Evolved Packet System |
| E-RAB | E-UTRAN radio access bearer |
| ESF | even subframe |
| ETSI | European Telecommunications Standards Institute |
| E-UTRA | Evolved UTRA |
| E-UTRAN | Evolved UTRAN |
| FAP | femtocell access point |
| FCC | Federal Communications Commission |
| FCFS | first come first served |
| FCI | failure cell ID |
| FD | frequency domain |
| FDD | frequency division duplexing |
| FDTD | finite-difference time domain |
| FER | frame error rate |
| FGW | femto gateway |
| FIFO | first in first out |
| FM | fault management |
| FPGA | field-programmable gate array |
| FTP | File Transfer Protocol |
| FUE | femtocell user equipment |
| GERAN | GSM EDGE Radio Access Network |
| GNSS | global navigation satellite system |
| GPS | Global Positioning System |
| GSCM | geometry-based stochastic channel models |
| GSM | Global System for Mobile Communications |
| GTD | geometry theory of diffraction |
| GTP | GPRS Tunnel Protocol |
| HA | hybrid access |
| HARQ | hybrid automatic repeat request |
| HCN | heterogeneous cellular network |
| HDTV | high-definition television |
| HeNB | Home evolved NodeB |
| HGW | home gateway |
| HII | high-interference indicator |
| HMS | HNB/HeNB management system |
| HNB | Home NodeB |
| HO | handover |
| HOF | handover failure |

| | |
|---|---|
| HOM | handover hysteresis margin |
| HRD | horizontal reflection diffraction |
| HSDPA | High Speed Downlink Packet Access |
| HSPA | High Speed Packet Access |
| HUE | home user equipment |
| IC | interference cancellation |
| ICI | intercarrier interference |
| ICIC | intercell interference coordination |
| ICT | information communication technology |
| ID | identifier |
| IEEE | Institute of Electrical and Electronics Engineers |
| IETF | Internet Engineering Task Force |
| IIR | infinite impulse response |
| IMEI-TAC | International Mobile Equipment Identity Type Allocation Code |
| IMT | International Mobile Telecommunications |
| InH | indoor hotspot |
| IP | Internet Protocol |
| IRC | interference rejection combining |
| ISD | intersite distance |
| ITU | International Telecommunication Union |
| JFI | Jain’s fairness index |
| KPI | key performance indicator |
| L1 | layer one |
| L2 | layer two |
| L3 | layer three |
| LLR | log-likelihood ratio |
| LMDS | Local Multipoint Distribution Service |
| LMMSE | linear minimum mean square error |
| LOS | line of sight |
| LPN | low-power node |
| LR | likelihood ratio |
| LSP | large-scale parameter |
| LTE | Long Term Evolution |
| LTE/SAE | Long Term Evolution/System Architecture Evolution |
| LUT | lookup table |
| MAC | medium access control |
| MBS | macrocell base station |
| MCC | mobile country code |
| MCM | multi-carrier modulation |
| MCP | multi-cell processing |
| MCS | modulation and coding scheme |
| MDT | minimization of drive tests |
| MIB | Master Information Block |
| MIESM | mutual information effective SINR mapping |

| | |
|---|---|
| MIMO | multiple-input multiple-output |
| MISO | multiple input single output |
| ML | maximum likelihood |
| MLB | mobility load balancing |
| MME | Mobility Management Entity |
| MMSE | minimum mean square error |
| MNC | mobile network code |
| MPC | multi-path components |
| MR | measurement report |
| MRC | maximal ratio combining |
| MR-FDPF | multi-resolution frequency-domain ParFlow |
| MRO | mobility robustness optimization |
| MUE | macrocell user equipment |
| NAS | non-access stratum |
| NAV | Network Allocation Vector |
| NB | NodeB |
| NE | network element |
| NGMN | Next Generation Mobile Networks |
| NLOS | non-line-of-sight |
| NM | network management |
| NMS | network management system |
| NRT | neighbor relation table |
| NTP | Network Time Protocol |
| OA | open access |
| OAM | operation, administration, and maintenance |
| OCXO | oven controlled oscillator |
| OFDM | orthogonal frequency division multiplexing |
| OFDMA | orthogonal frequency division multiple access |
| OI | overload indicator |
| OPEX | operational expenditure |
| OSF | odd subframe |
| OSI | Open Systems Interconnection |
| P2MP | point to multi-point |
| P2P | point to point |
| PBCH | primary broadcast channel |
| PCI | physical layer cell identity |
| PDCP | Packet Data Convergence Protocol |
| PDF | probability density function |
| PDSCH | physical downlink shared channel |
| PeNB | pico evolved NodeB |
| PGW | Packet Data Network Gateway |
| PH | power headroom |
| PHY | physical |
| PLMN | public land mobile network |

| | |
|---|---|
| PML | perfectly matched layer |
| PPP | Poisson point process |
| PRB | physical resource block |
| PSC | primary scrambling code |
| PSS | primary synchronization signal |
| PTP | Precision Time Protocol |
| PUE | picocell user equipment |
| QAM | quadrature amplitude modulation |
| QCI | QoS class identifier |
| QoS | quality of service |
| QPSK | quadrature phase-shift keying |
| RAB | Radio Access Bearer |
| RACH | random access channel |
| RAN | radio access network |
| RAT | radio access technology |
| RAXN | relay-aided X network |
| RB | resource block |
| RCI | re-establish cell ID |
| RE | range expansion |
| REB | range expansion bias |
| RF | radio frequency |
| RFC | Request for Comments |
| RIM | RAN information management |
| RLC | Radio Link Control |
| RLF | radio link failure |
| RMSE | root mean square error |
| RN | relay node |
| RNC | Radio Network Controller |
| RNL | radio network layer |
| RNS | Radio Network Subsystem |
| RNTP | relative narrowband transmit power |
| RPSF | reduced-power subframe |
| RRC | Radio Resource Control |
| RRH | remote radio head |
| RRM | radio resource management |
| RS | reference signal symbol |
| RSC | Recursive Systematic Convolutional |
| RS-CS | resource-specific cell selection |
| RSQ | reference signal quality |
| RSRP | reference signal received power |
| RSRQ | reference signal received quality |
| RSS | reference signal strength |
| RSSI | reference signal strength indicator |
| RTS | Request-to-Send |

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|---|---|
| S1AP | S1 Application Protocol |
| S1-MME | S1 for the control plane |
| S1-U | S1 for the user plane |
| SAE | System Architecture Evolution |
| SAEGW | System Architecture Evolution Gateway |
| SAS | spectrum allocation server |
| SBS | super base station |
| SCC | Standards Coordinating Committee |
| SCM | spatial channel model |
| SCP | single-cell processing |
| SCTP | Stream Control Transmission Protocol |
| SDMA | space-division multiple access |
| SDR | software defined radio |
| SE | spectral efficiency |
| SEF | soft symbol estimation and forward |
| SFBC | space frequency block coding |
| SGW | Serving Gateway |
| SI | system information |
| SIB | system information block |
| SIB1 | System Information Block Type 1 |
| SIB4 | System Information Block Type 4 |
| SIC | successive interference cancellation |
| SIM | subscriber identity module |
| SIMO | single input multiple output |
| SLA | service level agreement |
| SN | serial number |
| SNTP | Simple Network Time Protocol |
| SINR | signal to interference plus noise ratio |
| SIR | signal to interference ratio |
| SISO | single-input single-output |
| SLAC | stochastic local area channel |
| SLNR | signal to leakage interference and noise ratio |
| SNR | signal to noise ratio |
| SOCP | second-order cone programming |
| SON | self-organizing network |
| SoT | saving of transmissions |
| SPS | spectrum policy server |
| SSMA | spread spectrum multiple access |
| SSS | secondary synchronization signal |
| STBC | space-time block coding |
| TA | timing advance |
| TAC | tracking area code |
| TAI | tracking area identity |
| TCE | Trace Collection Entity |

| | |
|---|---|
| TCoSH | Triggering Condition of Self-Healing |
| TCP | Transmission Control Protocol |
| TCXO | temperature controlled oscillator |
| TDD | time division duplexing |
| TDM | time division multiplexing |
| TDMA | time division multiple access |
| TEID | tunnel endpoint identifier |
| TNL | transport network layer |
| TPC | Transmit Power Control |
| TR | transition region |
| TSG | Technical Specification Group |
| TTT | time-to-trigger |
| TU | Typical Urban |
| TV | television |
| TWXN | two-way exchange network |
| UE | user equipment |
| UL | uplink |
| UMa | urban macrocell |
| UMTS | Universal Mobile Telecommunication System |
| US | upstream |
| UTD | uniform theory of diffraction |
| UTRA | UMTS Terrestrial Radio Access |
| UTRAN | UMTS Terrestrial Radio Access Network |
| UWB | ultra-wide band |
| VD | vertical diffraction |
| VeNB | virtual eNB |
| VoIP | voice over IP |
| VR | visibility region |
| WCDMA | wideband code division multiple access |
| WG | working group |
| WiFi | Wireless Fidelity |
| WiMAX | Worldwide Interoperability for Microwave Access |
| WNC | wireless network coding |
| WLAN | wireless local area network |
| WRAN | wireless regional area network |
| X2AP | X2 Application Protocol |