Department of Communications and Networking

Inband Relaying in Long Term Evolution-Advanced Networks

Abdallah Bou Saleh

Aalto University

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Inband Relaying in Long Term Evolution-Advanced Networks

Abdallah Bou Saleh

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Abstract

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Abstract

The set of stringent requirements for 4G radio access networks has triggered the embodiment of new small low-power nodes, e.g. relay, Femto and Pico access nodes, as part of the network infrastructure. Various types of relay nodes are currently supported in IEEE 802.16m and 3GPP LTE-Advanced, e.g. inband Layer 2 or Layer 3 nodes and outband nodes, considering different functional capabilities and backhauling characteristics. In general, relay nodes are characterized by compact physical characteristics, low power consumption, a wireless backhaul link to the core network, and relaxed installation guidelines with respect to radiation and planning regulation. In specific, inband relay nodes, the matter of this study, are Layer 3 access nodes with time-multiplexed transmission and reception on their wireless backhaul and access links, which operate on the same frequency band. These characteristics impose serious challenges on one hand, but allow for significant improvements on the other hand.

In this context, the deployment flexibility of relay nodes simplifies the network planning procedure and reduces deployment costs. On the other hand, low power transmission and limited antenna capabilities result in small relay cell coverage areas which will lead to load imbalances. Besides, multiplexing backhaul and access communications on different subframes implies the need for suitable two-hop resource allocation and scheduling. Further challenges are attributed to increased interference levels compared to macrocell deployments, as well as the introduction of a new interference type known as relay-to-relay interference resulting from the misalignment of access and backhaul link dedicated subframes at different relay nodes.

The research towards this thesis has addressed these challenges within 3GPP LTE-Advanced context. A feasibility study of different relaying modes is provided and the performance of relay deployments is evaluated in different propagation environments. Thereafter, simple network planning techniques are proposed to alleviate the limitations of the inband backhaul link. Further, novel techniques are investigated to address resource allocation and scheduling, load balancing and interference coordination. The performance of proposed techniques along with the energy efficiency of relay nodes is evaluated. Results show in general significant gains and validate relaying as an efficient enhancement technology.

Keywords Inband relaying, network planning, resource allocation, interference coordination, load balancing, energy efficiency, performance evaluation, LTE-Advanced

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Preface

The research work towards this doctoral thesis has been carried out at the Department of Radio Systems at Nokia Solutions and Networks - NSN (formerly Nokia Siemens Networks), Munich, Germany, throughout Nov-2008 and Sept-2011 and at the Department of Communications and Networking (ComNet) at Aalto University School of Electrical Engineering (formerly known as Helsinki University of Technology), Espoo, Finland. This work was mainly funded by NSN.

This dissertation is the result of continuous guidance, support and encouragement of my advisor Dr. Simone Redana and supervisor Prof. Jyri Hämäläinen, to whom I express herein my sincere appreciation and gratitude. It was both a pleasure and a great experience working with them on this research. I would like to thank as well Bernhard Raaf for the insightful discussions and feedback he provided throughout the thesis work.

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My deepest gratitude goes to my family for their unconditional love and support at all times, which give me the strength to go through all challenges in life.

Munich, March 9, 2014,

Abdallah Bou Saleh

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I A. Bou Saleh, C. Hausl, R. Kötter. Outage Behavior of Bidirectional Half-Duplex Relaying Schemes. In *IEEE Information Theory Workshop ITW 2009*, Taormina, Italy, pp. 50-54, October 2009.

II A. Bou Saleh, T. Riihonen, S. Redana, J. Hämäläinen, R. Wichman, B. Raaf. Performance of Amplify-and-Forward and Decode-and-Forward Relays in LTE-Advanced. In *IEEE Vehicular Technology Conference VTC-Fall 2009*, Anchorage, USA, pp. 1-5, September 2009.

III A. Bou Saleh, S. Redana, J. Hämäläinen, B. Raaf. On the Coverage Extension and Capacity Enhancement of Inband Relay Deployments in LTE-Advanced Networks. *Journal of Electrical and Computer Engineering*, Volume 2010, Special Issue LTE/LTE-Advanced Cellular Communication Networks", Article ID 894846, pp. 1-12, Vol. 2010, May 2010.

IV A. Bou Saleh, Ö. Bulakci, J. Hämäläinen, S. Redana, B. Raaf. Analysis of the Impact of Site Planning on the Performance of Relay Deployments. *IEEE Transactions on Vehicular Technology*, pp. 3139 - 3150, Vol. 61, NO. 7, September 2012.

V A. Bou Saleh, Ö. Bulakci, Z. Ren, S. Redana, B. Raaf, J. Hämäläinen. Resource Sharing in Relay-enhanced 4G Networks. In *European Wireless Conference 2011 - Sustainable Wireless Technologies*, Vienna, Austria, pp. 1-8, April 2011.

VI A. Bou Saleh, Ö. Bulakci, S. Redana, J. Hämäläinen. On cell range extension in LTE-Advanced Type 1 inband relay networks. *Wireless Communications and Mobile Computing*, June 2013, DOI: 10.1002/wcm.2377.

VII Z. Ren, A. Bou Saleh, Ö. Bulakci, S. Redana, B. Raaf, J. Hämäläinen. Joint Interference Coordination and Relay Cell Expansion in LTE-Advanced Networks. In *IEEE Wireless Communications Networking Conference WCNC 2012*, Paris, France, pp. 2874-2878, April 2012.

VIII A. Bou Saleh, Ö. Bulakci, S. Redana, B. Raaf, J. Hämäläinen. A Divide-and-conquer Approach to Mitigate Relay-to-Relay Interference. In *IEEE Personal, Indoor and Mobile Radio Communications PIMRC 2011*, Toronto, Canada, pp. 1889-1893, September 2011.

IX A. Bou Saleh, Ö. Bulakci, S. Redana, B. Raaf, J. Hämäläinen. Impact of Relay-to-Relay Interference on the Performance of LTE-Advanced Relay Networks. In *17. VDE ITG workshop on Mobile Communications*, Osnabrück, Germany, pp. 1-6, May 2012.

X A. Bou Saleh, Ö. Bulakci, S. Redana, B. Raaf, J. Hämäläinen. Evaluating the Energy Efficiency of LTE-Advanced Relay and Picocell Deployments. In *IEEE Wireless Communications Networking Conference WCNC 2012*, Paris, France, pp. 2335-2340, April 2012.

Author's Contribution

Publication I: "Outage Behavior of Bidirectional Half-Duplex Relaying Schemes"

The author of this thesis is the main contributor to this work. The author of this thesis had the lead role in developing the concepts and derivations, generating simulation results and analyzing them, and planning and writing the entire paper. Simulations were carried out via a link-level MATLAB simulator developed by the author of this thesis.

Publication II: "Performance of Amplify-and-Forward and Decode-and-Forward Relays in LTE-Advanced"

The author of this thesis is the main contributor to this work. The idea and theoretical framework have been developed in cooperation among the authors of the paper. The author of this thesis carried out the simulations, did the analysis and has written the entire paper except Section II.A. The utilized simulation script has been developed by the author of this thesis.

Publication III: "On the Coverage Extension and Capacity Enhancement of Inband Relay Deployments in LTE-Advanced Networks"

The author of this thesis is the main contributor to this work. The author of this thesis had the lead role in developing the concept, generating simulation results and analyzing them, and planning and writing the entire paper. Simulations were carried out via a system-level MATLAB-based simulator developed by the author of this thesis.

Publication IV: "Analysis of the Impact of Site Planning on the Performance of Relay Deployments"

The author of this thesis is the main contributor to this work. The author of this thesis had the lead role in developing the concepts, generating simulation results and analyzing them, and planning and writing the entire paper. Simulations were carried out via a MATLAB script developed by the author of this thesis.

Publication V: "Resource Sharing in Relay-enhanced 4G Networks"

The author of this thesis is the main contributor to this work. The author of this thesis had the lead role in developing the concepts, generating simulation results and analyzing them, and planning and writing the entire paper. Simulations were carried out via a system-level MATLAB-based simulator developed by the author of this thesis.

Publication VI: "On cell range extension in LTE-Advanced Type 1 inband relay networks"

The author of this thesis is one of the lead contributors to this work. The author of this thesis had a main role in paper planning, and framework and concept development. Besides, the author of this thesis has solely contributed to generating simulation results and analysis on the downlink. Simulations on the downlink were carried out via a system-level MATLAB-based simulator developed by the author of this thesis. Further, the author of this thesis has driven the writing of this paper and wrote the whole downlink-related part of the paper.

Publication VII: "Joint Interference Coordination and Relay Cell Expansion in LTE-Advanced Networks"

The author of this thesis is one of the lead contributors to this work. The author of this thesis had main role in paper planning and concept development, and has contributed significantly to generating simulation results and analysis. Simulations were carried out via a system-level MATLAB-based simulator developed by the author of this thesis.

Publication VIII: "A Divide-and-conquer Approach to Mitigate Relay-to-Relay Interference"

The author of this thesis is the main contributor to this work. The author of this thesis had the lead role in developing the concepts, generating simulation results and analyzing them, and planning and writing the entire paper. Simulations were carried out via a system-level MATLAB-based simulator developed by the author of this thesis.

Publication IX: "Impact of Relay-to-Relay Interference on the Performance of LTE-Advanced Relay Networks"

The author of this thesis is the main contributor to this work. The author of this thesis had the lead role in developing the concepts, generating simulation results and analyzing them, and planning and writing the entire paper. Simulations were carried out via a system-level MATLAB-based simulator developed by the author of this thesis.

Publication X: "Evaluating the Energy Efficiency of LTE-Advanced Relay and Picocell Deployments"

The author of this thesis is one of the lead contributors to this work. The author of this thesis had a main role in paper planning and framework and concept development. Besides, the author of this thesis has solely contributed to generating simulation results and analysis on the downlink. Simulations on the downlink were carried out via a system-level MATLAB-based simulator developed by the author of this thesis. Further, the author of this thesis has driven the writing of this paper and wrote the whole downlink-related part of the paper.

List of Abbreviations and Symbols

Abbreviations

3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
ABS	Almost-Blank Subframe
AF	Amplify-and-Forward
APC	Area Power Consumption
ARS	Advanced Relay Station
ASIT	Achievable Sum Instantaneous Throughput
AUIT	Achievable UE Instantaneous Throughput
AUP	Access UE Proportional
BAF	Bursty Amplify-Forward
BPSK	Binary Phase Shift Keying
CA	Carrier Aggergation
CDF	Cumulative Distribution Function
CF	Compress-and-Forward
CoMP	Cooperative Multi-point Transmission and Reception
CRC	Cyclic Redundancy Check
CRE	Cell Range Extension

CS	Cell Selection
DA	Directional Antenna
DCA	Divide-and-Conquer Approach
DF	Decode-and-Forward
DL	Downlink
eICIC	enhanced Inter-cell Interference Coordination
eNB	enhanced Node B
FDD	Frequency Division Duplex
HARQ	Hybrid Automatic Repeat Request
HDTV	High Definition TV
ICIC	Inter-cell Interference Coordination
IEEE	Institute for Electrical and Electronics Engineering
IMT-Advanced	International Mobile Telecommunications-Advanced
ISD	Inter-site Distance
ITU-R	International Telecommunications Union-Radiocommunications Sector
JF	Jain Fairness Index
KPI	Key Performance Indicator
LI	Loop Interference
LOS	Line-of-Sight
LS	Location Selection
LTE	Long Term Evolution
MBSFN	Multi-Media Broadcast Single Frequency Network
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
MMF	Max-Min Fairness
NLOS	Non-Line-of-Sight

OAM	Operations, Administration and Maintenance
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
PDF	Probability Distribution Function
PF	Proportional Fair
PL	Pathloss
Prob	Probability
QoS	Quality of Service
RAT	Radio Access Technology
RN	Relay Node
RNTP	Relative Narrowband Transmit Power
R-PDCCH	Relay Physical Downlink Control Channel
R-PDSCH	Relay Physical Downlink Shared Channel
RR	Round Robin
RRM	Radio Resource Management
RSP	Relay Site Planning
RSRP	Reference Signal Received Power
RV	Random Variable
Rx	Receive
Sc1	Scenario 1
Sc2	Scenario 2
Sc3	Scenario 3
SC-FDMA	Single Carrier Frequency Division Multiple Access
SE	Spectral Efficiency
SINR	Signal-to-Interference-plus-Noise Ratio

SIR	Signal-to-Interference Ratio
SNR	Signal-to-Noise Ratio
STR	Simultaneous Transmit and Receive
TCO	Total Cost of Ownership
TP	Throughput
TPC	Throughput Power Consumption
TTI	Transmission Time Interval
TTR	Time-division Transmit and Receive
Tx	Transmit
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
Un	Interface between eNB and RN
Un subframe	Backhaul subframe
UTRAN	UMTS Terrestrial Radio Access Network
Uu	Interface between access node and UE
Uu subframe	regular subframe
WiMAX	Worldwide interoperability for Microwave Access

Symbols

A_{eff}	SINR efficiency factor
$a_{i,j}$	Fading coefficient between nodes i and j, where $i, j \in \{$eNB, RN, UE$\}$
B_{eff}	Bandwidth efficiency factor
BW	Bandwidth per PRB

$C(\gamma_{\text{i-j}})$	Capacity of the link i-j, where $i, j \in \{\text{eNB, RN, UE}\}$
d	Distance between the access point (eNB or RN) and the UE
$d_{m,i}$	Distance between m^{th} RN candidate location and i^{th} eNB
erf	Error function
E_1^{p2p}	Event where first condition on the achievable rate on a point-to-point communication link to achieve reliable communication
E_2^{p2p}	Event where second condition on the achievable rate on a point-to-point communication link to achieve reliable communication
$\bar{E}_{p2p}^{out}$	Complement of outage event on a point-to-point communication link
F	CDF
$F_a(R)$	CDF of the access link rate
$F_{m,i}(\Gamma)$	CDF of relay link SIR towards i^{th} cell of an RN at the m^{th} RN candidate location
$F_{\hat{m},i}(\Gamma)$	CDF of relay link SIR when applying LS RSP strategy
$F_{m,\hat{i}}(\Gamma)$	CDF of relay link SIR when applying CS RSP strategy
$F_{\hat{m},\hat{i}}(\Gamma)$	CDF of relay link SIR when applying LS and CS RSP strategies
$F_{e;m,i}(R)$	CDF of the end-to-end UE rate without applying RSP
$F_{r;m,i}(R)$	CDF of the relay link rate without applying RSP
$F_{e;\hat{m},i}(R)$	CDF of the end-to-end UE rate when applying LS RSP strategy
$F_{e;m,\hat{i}}(R)$	CDF of the end-to-end UE rate when applying CS RSP strategy
$F_{e;\hat{m},\hat{i}}(R)$	CDF of the end-to-end UE rate when applying LS and CS RSP strategies
ISD_0	Inter-site-distance between two eNBs in original macrocell-only deployment
ISD_{ext}	Extended inter-site-distance between two eNBs

$\mathrm{JF}_{\mathrm{eNB}}$	Jainś fairness index in a macrocell
$\mathrm{JF}_{\mathrm{RN}}$	Jainś fairness index in a RN cell
K	Number of candidate eNBs in RSP
K_{eNB}	Length of data block to be transmitted by eNB
K_{UE}	Length of data block to be transmitted by UE
L	Downlink path loss estimate including log-normal shadowing
$\lim$	Limit function
L_k	Path loss on access link to serving RN k
L_l	Path loss on access link to interfering RN l
LOS	Line-of-sight communication
M	Number of candidate RN locations in RSP
M_a	Total number of resources available on the access link
M_{eNB}	Number of eNB coded symbols to be transmitted in a transmission phase P1
m_i	Number of PRBs scheduled for RN i
M_r	Total number of PRBs available for the relay link in a macrocell
M_{UE}	Number of UE coded symbols to be transmitted in a transmission phase P2
N_{RN}	Number of relay nodes deployed in a macrocell
$NLOS$	Non-line-of-sight communication
P	Probability density function
P_N	Thermal noise power
P_{p2p}^{out}	Outage probability for a point-to-point communication scheme
P_{3P}^{out}	Outage probability for a three-phase communication scheme
$P_{\mathrm{Tx},i}$	Transmit power of macrocell i
PL	Downlink path loss [dB]

$Prob$	Probability
$P1$	Transmission phase 1
$P2$	Transmission phase 2
R	Rate per PRB
R_a	Achievable rate on the access link
R_i	Achieved rate per PRB of RN i on the relay link.
R_{ij}	Rate per PRB for a UE j served by RN i
R_e	End-to-end rate experienced by a UE served by RN k
R_r	Achievable rate on the relay link
$R_{\text{RN-eNB}}$	Exchange ratio of an RN to an eNB
RSRP_{eNB}	RSRP of an eNB at the UE
RSRP_{RN}	RSRP of an RN at the UE
S	Overhead scaling accounting for LTE DL overhead, e.g. control channel
SE	Spectral efficiency
SE_{DF}	End-to-end spectral efficiency of a decode-and-forward relaying scheme
SE_{max}	Maximum achievable spectral efficiency
$\text{TP}_{D,k}$	Throughput achieved by UE k on the direct link
TP_{ij}	End-to-end throughput achieved by UE j served by RN i
TP^a_{ij}	Throughput achieved by UE j on the access link to RN i
TP^r_{ij}	Throughput reserved for transmitting data on relay link directed to UE j served by RN i
$TP_{R,ij}$	Throughput achieved by UE j in RN cell i
U_D	Number of UEs in a macrocell served directly by an eNB
u_i	Number of UEs served by RN i
U_R	Number of UEs served by all RNs in a macrocell
X	eNB transmission power reduction parameter in CRE
Y	Biasing in handover and cell selection parameter in CRE
α	Constant term in Okumura-Hata path loss model

β	Path loss exponent
Γ	SINR on a link
Γ_{AF}	End-to-end SINR at UE in a two-hop amplify-and-forward relaying scheme
$\gamma_{\text{i-j}}$	Instantaneous link SNR
$\gamma_{m,i}$	Relay link SINR at the m^{th} RN candidate location in macrocell i
$\gamma_{\hat{m},i}$	Relay link SINR towards eNB i at the best RN location selected according to LS RSP strategy.
$\gamma_{m,\hat{i}}$	Relay link SINR at m^{th} RN candidate location towards best serving cell which is chosen according to CS RSP strategy.
$\Gamma_{m,i}$	Relay link SIR of an RN at m^{th} candidate location towards eNB serving macrocell i
Γ_{max}	Lowest SINR value at which SE_{max} is achieved
Γ_{min}	Minimum SINR level on the control channel, below which data detection is not possible
ϵ	Shadowing correlation coefficient
$\zeta_{m,i}$	Random variable modeling log-normal shadowing between an RN at m^{th} candidate location and eNB serving macrocell i
$\mu_{m,i}$	Mean of the Gaussian-distributed relay link SIR in RSP
ν	Standard deviation of the Gaussian-distributed relay link SIR in RSP
ρ	Average link SNR
ρ_{LI}	Loop interference SNR
σ	Standard deviation of the log-normal shadowing
$\sigma_{i,j}$	Square root of the inverse of the rate parameter of the exponential distribution of fading coefficients $a_{i,j}$
τ_a	Normalized portion of resources allocated for communicating on the access link

τ_r	Normalized portion of resources allocated for communicating on the relay link
$\tau_{r,k}$	Normalized portion of resources allocated for communicating on the relay link of RN k
υ	Mean SIR on the access link
Υ	Access link SINR
$\bar{\Upsilon}_k$	Mean SNR on the access link to serving RN
$\bar{\Upsilon}_l$	Mean SNR on the access link to interfering RN
∞	Infinity

1. Introduction

1.1 Motivation

The Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access Network (UTRAN) Long Term Evolution (LTE) has been designed as a revolutionized successor of Third Generation (3G) radio access technologies (RATs). Three fundamental technologies have shaped the LTE radio interface, namely, multi-carrier multiple access, multiple-antenna technology, and fully packet-switched radio interface design [1]. The first technology has been realized via Orthogonal Frequency-Division Multiple Access (OFDMA) in downlink (DL) and Single-Carrier Frequency Division Multiple Access (SC-FDMA) in uplink (UL). Such access schemes introduced the frequency domain as a new dimension of flexibility in system design. Along that, the multiple antenna technology enabled the exploitation of the spatial domain as yet another new design dimension, by making use of space-diversity and supporting techniques such as precoding, beamforming and spatial multiplexing. Similarly, the adoption of packet-switching along all the layers of the protocol stack and reducing the transmission time interval (TTI) to 1ms opened spacious rooms for cross-layer optimization.

Early standardized releases of LTE, i.e. Release 8 and Release 9, constituted a major step towards the International Mobile Telecommunications (IMT)-Advanced technologies of the International Telecommunication Union - Radiocommunications Sector (ITU-R). The IMT-Advanced RATs are expected to offer increased broadband capacity with high quality of service (QoS) for the Internet and next generation multimedia services, such as, high-definition TV (HDTV) content, video chat, mobile TV, and real-time gaming. Such advanced RATs are necessary to address the rapid-paced growth in data-based wireless access, high data rates demand and capacities required by the data-intensive services and applications dominating the market especially where smart phones and tablets are widely utilized.

The requirements set for the IMT-Advanced technologies are defined by ITU-R in a circular letter issued in March 2008 calling for candidate RATs [2]. In response to ITU-R circular letter, 3rd Generation Partnership Project (3GPP) made a formal submission in September 2009 proposing that LTE Release 10 and beyond would be evaluated as a candidate IMT-Advanced technology [3]. The proposed RAT, referred to as LTE-Advanced, promises to go beyond the IMT-Advanced requirements [4]. In technology evolution, LTE-Advanced defines the framework for further significant advancements to LTE Release 8 and Release 9. While LTE Release 8 supports peak data rates exceeding 300 Mbps in DL and 75 Mbps in UL, LTE-Advanced Release 10 is promising to offer up to 1 Gbps in DL and 500 Mbps in UL in low mobility environments. Extended carrier bandwidths up to 100 MHz will be supported in LTE-Advanced while the maximum bandwidth in Release 8 is limited to 20 MHz. Furthermore, increased spectral efficiency up to 30 bps/Hz in DL and 15 bps/Hz in UL, along with improved cell edge capacity, decreased user and control plane latencies and a more homogeneous user experience over the cell area are urged [4].

To address these stringent requirements, different technologies were investigated in the 3GPP study items on LTE-Advanced: Bandwidth extension through carrier aggregation (CA), relay node (RN) deployments, improved multiple-input multiple-output (MIMO) schemes, coordinated multi-point transmission and reception (CoMP), and local area optimization features such as femto cell deployments [5, 6]. Such technologies are the corner stone of LTE-Advanced RATs and promise to offer solutions to overtake the limitations of previous radio access networks. For example, the very high peak data rates cannot be achieved solely through enhancements of the spectral efficiency, e.g. via advanced MIMO techniques; a significant increase in transmission bandwidth is indispensable. Considering the scarcity of spectrum and unavailability of very wide contiguous spectrum, CA promises to be a valuable solution. Similarly, RN deployments are expected to provide the improved cell edge capacity and a more homogeneous user experience.

To recognize the need for RN deployments, it is important to note that for high carrier frequencies, e.g. around the 2.6 GHz carrier frequency where LTE-Advanced will mostly operate, radio propagation losses are more severe, especially at the cell edge, resulting in significant capacity and coverage problems. Such problems could be tackled by increasing the density of enhanced Node B (eNB), aka base stations, or equivalently by decreasing the cell coverage area. Such a solution is, however, unappealing for network operators, as it implies high extra costs, inferred from the linear proportionality of the infrastructure costs of a homogeneous wireless system to the number of eNBs deployed [7].

In this context, RN deployments offer a promising solution. Installing RNs results in lower operational expenditure (OPEX) of 30% and more [8] and faster network upgrade when operators aim to improve QoS [9]; the cost-efficiency of RNs is investigated in [10, 11]. Further, RNs promise to increase the network capacity [12, 13] and to better distribute resources in the cell, or alternatively, extend the cell coverage area [III] [12, 14, 15, 16].

Hence, relaying has been investigated as a potential technology in the first study item of LTE-Advanced Release 10. 3GPP study items evaluate the maturity of a technology to be incorporated in the standardization within moderate effort. The evaluation focuses as well on the performance enhancement resulting from adopting the technology and how much it can help achieve the requirements set by ITU-R for the RAT. Therefore, it was of great value to assess the viability of relaying within the LTE-Advanced framework, research and eventually propose novel practical solutions to the serious challenges posed when attempting to realize the technology in practice.

1.2 Relaying in Standardization

Multi-hop data communication with decode-and-forward (DF) relay functionality was first standardized in Institute for Electrical and Eletronics Engineering (IEEE) standard IEEE 802.16j mobile multi-hop Worldwide interoperability for Microwave Access (WiMAX) which is an amendment to the existing single-hop mobile WiMAX standard IEEE 802.16e [17]. The evolution of relay technologies within IEEE and 3GPP standardization bodies have been following since then similar paths in the successor IEEE 802.16m and LTE-Advanced specifications [18]. Both standards consider fixed DF RNs, aka Advanced Relay Station (ARS) in IEEE 802.16m terminology, mainly as a coverage enhancement technology improving the user experience over the network area, although capacity improvement capabilities are not, by any means, excluded. As well, both IEEE 802.16m and LTE-Advanced require maintaining the backwards compatibility with previous standard releases (IEEE 802.16e in WiMAX and Release 8 and Release 9 in LTE).

Such amendment to the conventional macrocell deployment is referred to as local area extension because it is foreseen that single-hop networks are still deployed to provide overlaying wide area access whereas RNs or ARSs complement the coverage and/or capacity requirement, where needed. Generally, relays are characterized by wireless backhaul connection, low power consumption and compact physical characteristics. The wireless backhaul link enables deployment flexibility and eliminates the high costs of a fixed backhaul. Furthermore, relays do not have strict installation guidelines with respect to radiation, visual disturbance and planning regulation. Thanks to such characteristics, RNs can be mounted on structures like lamp posts with power supply facilities, thus significantly reducing the site acquisition costs [8].

From a functionality perspective, relays are divided into Type 1 and Type 2 RNs in 3GPP terminology, whereas the corresponding classification in IEEE 802.16m is non-transparent and transparent ARSs. Type 1 RNs and non-transparent ARSs are Layer-3 access nodes which are considered as stand-alone eNBs; each has a physical cell ID of its own, transmits its own synchronization channels and reference and control signals, and supports functionalities such as scheduling, radio resource management (RRM) and hybrid automatic repeat request (HARQ). On the other hand, the latter type supports up to Layer-2 functionalities only. Type 1 RNs and non-transparent ARSs are expected to provide better coverage extension, whereas Type 2 RNs and transparent ARSs could be more favorable in providing capacity enhancements [19].

RNs and ARSs are further classified according to their resource utilization strategy on the backhaul and access links. The communication between the user equipment (UE) and its serving RN or ARS on the latter link is carried out on the Uu interface in LTE-Advanced or R1 interface in IEEE 8021.6m. Whereas, the wireless connection to the core network on the former link is carried out on the Un interface with an eNB in LTE-Advanced or on the R1 interface with an advanced BS in IEEE 802.16m; in this work the wireless backhaul link will be referred to as the relay link. In 3GPP specifications, Type 1 and Type 1b RNs are defined as inband RNs which utilize the same frequency band on both the access and relay links. For Type 1 RNs, both links are time-division multiplexed imposing hard limitations on resource utilization efficiency. On the other hand, Type 1b RNs are assumed to experience high signal isolation between the relay and access links, due to well-separated and well-isolated antenna structures, so that both links can be operated simultaneously. This is though rarely the case in outdoor deployments, but could be the case in e.g. underground train stations where the transceiver for the relay link is placed outdoor whereas the transceiver for the access link is located in the station underground. 3GPP also defines out-band relaying as Type 1a where exclusive resources are utilized on each link thus allowing simultaneous communications. This however may increase the deployment costs since a separate extra spectrum is needed. It is worth noting that similar classification is considered in IEEE 802.16m with time-division transmit and receive (TTR) and simultaneous transmit and receive (STR) modes [18].

1.3 Scope of the Thesis and Research Questions

The main objective of this thesis is to validate the viability of relaying technology as a candidate amendment to current RATs, and complement and enhance the current knowledge and techniques required to realize it in practical LTE-Advanced deployments. The research work in this thesis has been going side by side with the standardization of RNs in LTE-Advanced, starting with Release 10 study item up till the release freeze and further till Release 11 study item. Thus, the research herein has been as well contributed in part to 3GPP as technical reports supporting the advancement of relaying standardization.

Within this context, the scope of the thesis has been limited within the boundaries set gradually by the discussions and agreements about relaying within 3GPP standardization. The research work tries to adhere to the requirements, performance evaluation methodology, system model and scenarios defined by LTE-Advanced, practicality of the proposed solutions and backward-compatibility with earlier standardization releases. A big part of the research work specifically focuses on the performance of Type 1 inband RNs in DL as a coverage extension means. As the research work has been conducted within the LTE-Advanced framework, 3GPP terminologies will be used throughout the remaining part of the thesis report.

Throughout our research work towards this thesis, we address the following research questions:

1. Is relaying a viable enhancement technology for current RATs? What relaying modes would best fit 3GPP-defined technologies and what performance gains do relay nodes promise in different deployment environments?

2. How to alleviate the backhaul link limitation in inband relaying mode and what improvements will this bring to the end-to-end user performance?

3. How to best partition resources and schedule users and relay nodes in a 3GPP LTE based network?

4. How to best address load imbalance in relay-enhanced networks while ensuring simplicity and backward compatibility with 3GPP LTE Release 8 and Release 9 standards.

5. What is the impact of relay node deployment on inter-cell interference levels and how to best mitigate resulting network performance degradations?

6. How efficient are relay nodes in terms of energy consumption?

1.4 Contributions and Structure of the Thesis

The main contribution of the thesis is related to Type 1 inband relaying which was found to be a valid candidate to LTE-Advanced deployments, since it significantly improves the coverage performance and provide a more homogeneous ubiquitous user experience.

First, the research herein briefly investigates different relaying modes and corresponding communication schemes in terms of outage probability considering the utilization of network coding as a powerful means to improve spectral efficiency of relaying schemes. Then, proceeding in alignment with LTE-Advanced study item agreements, we prove that DF half-duplex RNs are well suited for deployment in LTE networks and promise to offer significant coverage extension or capacity gains in various propagation environments. Guidelines for network dimensioning are thus given and exchange ratios between traditional eNBs and Type 1 and Type 1b RNs are formulated in this context to enable better assessment of the cost efficiency of RNs to provide required capacity or coverage extension in different scenarios. In an attempt to alleviate the limitations of the backhaul link of Type 1 RNs and narrow the performance gap with respect to Type 1b RNs, simple, yet efficient, network planning techniques are then proposed and evaluated. Significant gains were shown which attributed to the adoption of site planning gains in the performance evaluation methodology of RNs in the 3GPP specification TR 36.814 [20].

After discussing on the mode of relaying to be adopted, its promised gains in different propagation environments and a suitable network planning methodology, the thesis work proposes practically viable solutions to solve problems of inband Type 1 relaying pertaining to resource allocation efficiency and scheduling, load imbalance and interference. Further, the energy efficiency of relay deployments utilizing proposed techniques to address these challenges is investigated in different scenarios. Thorough performance evaluations for the proposed and reference techniques are carried out within 3GPP LTE-Advanced Case 1 (urban scenario) and Case 3 (suburban scenario) context considering different deployments of RNs per macrocell. The utilized channel models, system model and simulation parameters adhere to 3GPP requirements and definitions. Thus, simulation results provided herein gives an indication of the performance in realistic scenarios.

The remainder of this thesis is organized as follows. Chapter 2 discusses on the relaying mode suitable for LTE deployments, whether RNs utilizing such a mode is justifiable in terms of coverage and capacity performance, and finally on how to efficiently plan a relay network deployment. Thereafter, Chapter 3 addresses radio resource management challenges in inband Type 1 RNs within the LTE-Advanced context presenting our contributions on solving issues related to resource allocation and scheduling, load imbalances, and interference. Further, the chapter highlights the energy efficiency of RN deployments. Finally, the thesis is concluded in Chapter 4.

1.5 Summary of Publications

The thesis is a summary of ten publications listed above and appended at the end of this manuscript. In what follows we briefly summarize the contribution of each paper.

Publication [I] provides an analytical comparison of different relaying modes and the corresponding communication schemes taking into consideration network coding as a promising enhancement to classical relaying techniques. Closed form expressions of the outage probability for different schemes are derived when assuming Gaussian distributed channel inputs, necessary conditions on achieving diversity for discrete channel inputs are as well given and practical coding schemes based on turbo codes are investigated. It is shown that for discrete channel inputs a proposed scheme allows a diversity gain for higher rates compared to a conventional bi-directional relaying scheme without network coding.

Publication [II] investigates the performance of full-duplex AF and half-duplex DF RNs as two candidate enhancement technologies in 3GPP LTE-Advanced study item. Performance evaluation considers AF RN loop back signal interference due to leakage of transmit signal to receive antenna and the ability of multiple DF RNs to transmit concurrently to multiple users on the access link. Results show that the concurrent transmissions improve the spectral efficiency provided by DF RNs over AF RNs one, thus qualifying DF mode as a suitable candidate for LTE-Advanced RNs.

Publication [III] investigate the feasibility of half-duplex Type 1 DF RN deployments in terms of system throughput and cell coverage area extension as compared to Type 1b RN and traditional homogeneous single-hop macrocells. Relay backhaul link overhead of Type 1 RNs is taken into consideration as a limiting factor. [III]extends the study comparing inband RNs to picocells in [12] to a comparison between Type 1 and Type 1b relay nodes in different propagation characteristics. As well, the effect of the relaying overhead on the system performance in inband RN deployments is studied therein. System level simulations show that Type 1 and Type 1b (similar to picocells) inband relay deployments offer low to very high gains depending on the deployment environment. As well, it is shown that the effect of the relaying overhead is minimal on coverage extension whereas it has more impact on system throughput.

Publication [IV] complements the studies [I-III] proposing simple techniques for planning relay network deployments to alleviate the limitations on throughput of the relaying backhaul overhead in in-band relaying. In this context, two approaches, namely, location selection and cell selection are analytically modeled and their impact on the quality of the relay link, end-to-end user rate, resource allocation on the two hops, upper bounds on planning gains, access link limitations and deployment of multiple RNs is studied. Results show significant gains on the link and end-to-end levels.

Publications [V] through [X] extend further on the previous contributions and focus on tackling radio resource management issues arising during network operation, specifically on the downlink of in-band Type 1 RNs within LTE-Advanced deployments.

Publication [V] investigates resource assignment and scheduling aiming specifically at satisfying two main requirements of LTE-Advanced, namely, better cell edge coverage and spectral efficiency and more homogeneous user experience in the network. The publication evaluates the performance of different schemes for resource sharing among RNs and prioritization techniques of RN UEs on the relay link coupled with the corresponding scheduling on the access link. A combination of resource sharing based on the number of RN UEs and relay link prioritization and scheduling achieving max-min fairness is proposed. A comprehensive system-level simulation campaign is carried out in 3GPP urban and suburban models considering 4 and 10 RNs per cell, which shows that the proposed scheme achieves high system fairness and significant throughput gains at the low and mid throughput regimes at no or negligible loss in cell throughput.

Publication [VI] explore further the issue of resource management focusing though on solving the problem of low resource utilization efficiency resulting from load imbalances in the network. In particular, two relay cell range extension techniques, introducing a bias to cell selection and handover thresholds along with reduction in eNB transmission power, are investigated. Resource assignment is jointly considered with relay cell range extension aiming at optimizing different key performance metrics pertaining to the network operator preferences. Further, the realization of cell range extension as part of network planning and offline optimizations is discussed. Results based on a similar simulation campaign as in [V] reveal that the investigated solution yields better resource utilization efficiency compared to the conventional scheme and thus achieves significant throughput gains.

Publications [VII, VIII, IX] address interference problems resulting from full frequency reuse in relay-enhanced networks. Publication [VII] proposes an interference coordination scheme to mitigate traditional inter-cell interference among RN cells and resulting interference from RN cells on macrocell UEs in their vicinity. The scheme is considered on top of the relay cell range expansion and resource assignment techniques presented in [V-VI] and jointly optimized to improve further the system performance. Neighboring RNs are configured with different scheduling patterns, such that UEs in neighboring macrocell or RN cells suffering from an aggressor RN's interference are scheduled on subframes with lowest probability that they will be interfered by the aggressor RN. Results confirm that the interference imposed by RNs can be reduced and that cell edge and cell average throughput gains are observed. It is worth noting though that traditional inter-cell interference is not the only interference model experienced in in-band relay deployments. Publications [VIII, IX] investigate a new interference model referred to as relay-to-relay interference which could occur due to misalignment of access and backhaul transmissions in neighboring RN cells. In [VIII] a divide-and-conquer approach is proposed to alleviate the impact of relay-to-relay interference, by exploiting the localized nature of the interference and hence avoids the need to perform a network-wide subframe configuration alignment. On the other hand, publication [IX] investigates simple subframe configuration alignment schemes to solve the problem in deployments considering directional antennas on the backhaul link of RNs. Both solutions prove to alleviate the problem and enhance the system performance in the corresponding targeted deployment scenario.

Finally, publication [X] evaluates the energy efficiency of RN deployments. Specifically, the work investigates the impact of deploying different numbers of small nodes on reducing area power consumption, or alternatively, on enhancing the throughput power consumption of access networks.

2. Towards Relay-enhanced Networks

Relaying was first used in wired communications in repeaters of long-distance telegraph circuits. Since then, many relaying modes and communication schemes have been studied [21, 22], specifically in the context of wireless communications.

2.1 Relaying Modes and Communication Schemes

Different relaying modes have been proposed in the literature in search for optimal performance. The main modes can be classified into AF, DF, compress-and-forward (CF), and mixed-forward schemes that combines DF and CF functionalities. The modes differ in terms of functionality, required relaying capabilities and knowledge, and complexity. In what follows, we briefly highlight some of the well known relaying modes:

- Amplify-and-forward - AF: The relay simply acts as an analog repeater, amplifying the noisy signal and then forwarding it to the destination terminal [23]. Note that the noise (including interference) will be also amplified. This scheme requires knowledge of the channel coefficients at the receiver to properly combine the two received signals from the relay and source. The amplify-and-forward scheme is however a simple strategy and was proved to achieve full diversity in certain relaying schemes [23, 24]; a system is considered to achieve full diversity gain, if it can tolerate the deep fading, i.e. outage, of one of its links. Several relaying strategies based on AF scheme have been proposed, such as the bursty amplify-forward (BAF) [25], where the relay transmits for only a fraction of its total allocated time. BAF scheme achieves better performance than classical AF in the low signal-to-noise ratio (SNR) regime.

- Decode-and-forward - DF: The relay in this scheme decodes the signal, re-encodes, and then forwards it to the destination [23]. DF schemes assumes that the full codebooks of the source are known at the relay [26]. The complexity of DF scheme is much higher than that for AF. Several strategies based on DF schemes have been considered in literature: A classical DF relay simply decodes and forwards the data without error checking. There are also DF strategies where the relay remains silent in case of decoding error (assuming the use of cyclic redundancy check (CRC) as error detection code), selective DF strategies where the relay transmits in case the SNR on the relay route is better than a specific threshold, incremental DF strategies where the relay transmits only in case extra information is still needed at the destination to decode the message, thus achieving high spectral efficiency especially at high SNR [27], and multipath DF strategy where multipath routing and DF functionalities are combined by using the rate splitting technique [23]. A comparison of some DF and AF schemes is presented in [28].

- Compress-and-forward - CF: In CF schemes, the relay samples, quantizes, compresses and then forwards the signal to the destination terminal; CF based relaying strategies require knowledge of the channel output distribution at the relay - a more relaxed requirement as compared to DF schemes which need the full codebooks [23, 26]. Different relaying schemes which process the signal but do not decode it before transmission, as in the case of CF scheme, are also proposed in the literature, namely, clean-and-forward approach [29] and denoise-and-forward approach [30]. Also, mixed schemes of CF and DF have been proposed. A comparison of DF, CF and mixed schemes is presented in [26]. The mixed scheme of [26] has a complexity in between CF and DF schemes and requires the knowledge of a codebook beside the channel output distribution.

The mentioned relaying modes may still need to different communication arrangements depending on the availability of side information at the receiver from the source and the time multiplexing scheme of the source, RN and destination transmissions. The latter can as well be shaped by the utilization of network coding. In this context, relaying can be classified into classical multi-hop relaying and cooperative relaying, where in the former the destination receives the message from RN only, as opposed to the latter where messages are received from RN and the source. Figure 2.1 illustrates (a) the traditional point-to-point communications and various examples of relaying schemes, namely (b) classical four-phase relaying, (c) classical cooperative four-phase relaying, and (d) cooperative three-phase relaying with network coding.

Classical relaying has been considered as an enhancement to traditional point-to-point communications in various works in literature [23]. Furthermore, cooperative communications in relay channels has promised still further gains, especially when network coding is utilized. Cooperative communications offers the possibility of achieving diversity gains as side information received directly from the source is made available at the receiver beside the signal received from the relay, i.e., the receiver receives two or more signals carrying the same or complementary information over different paths. It is important to note that such gains are not obtainable in classical relaying and point to point communications as only one signal is received from the relay at the destination. Thus, schemes (a) and (b) lag behind cooperative schemes (c) and (d). The performance of the different schemes can be evaluated by investigating the outage behavior and the achievable cooperative diversity gain [I].

In our contribution [I], we show that a diversity gain is achievable for the classical cooperative relaying (Figure 2.1 (c)) scheme and three-phase scheme (Figure 2.1 (d)) when assuming Gaussian channel inputs as opposed to the point-to-point communications (Figure 2.1 (a)) for example. Moreover, it is shown that for discrete channel inputs, e.g. Binary Phase Shift Keying (BPSK), the three-phase scheme allows a diversity gain for higher rates compared to classical cooperative relaying.

The first conclusion is seen by deriving the outage behavior and investigating the asymptotic behavior of a communication scheme when the SNR is very high. Specifically, if the outage probability decays inversely proportional to the average SNR on the channels, the system will not achieve diversity gain. However, if it decays inversely proportional to the square of average SNR, then the scheme achieves a diversity order of two, i.e. it can tolerate the deep fading of one of its links. To briefly highlight this, we illustrate in what follows the outage behavior and diversity gains for point-to-point traditional communications and the three-phase cooperative relaying with network coding scheme.

Let us assume that the eNB and the UE wish to communicate data blocks of lengths K_{eNB} and K_{UE}, respectively, over a wireless channel

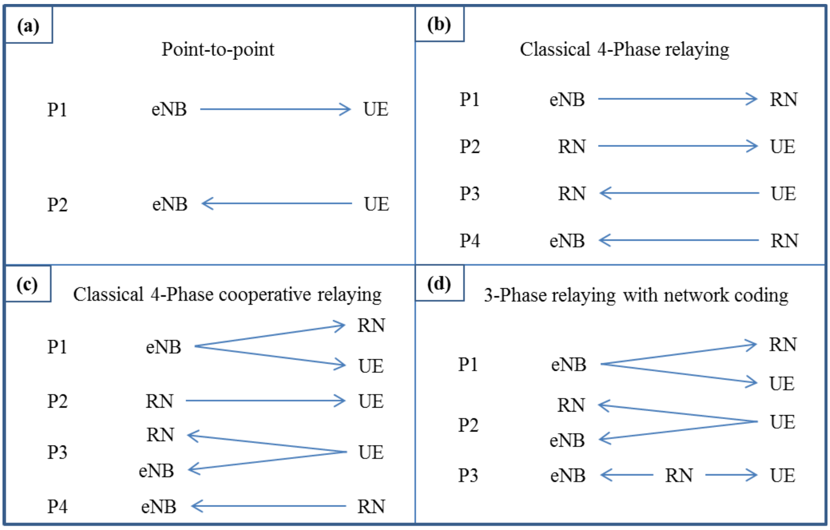

Figure 2.1. Communication Schemes: (a) Point-to-point Communication, (b) Classical 4-Phase relaying, (c) Classical 4-Phase cooperative relaying, and (d) 3-Phase cooperative relaying with network coding.

with noise, propagation pathloss and fading. The aforementioed schemes in Figure 2.1 are to be impacted by slow, flat Rayleigh fading. The fading coefficient is denoted by $a_{i,j}$, where $i, j \in \{\text{eNB, RN, UE}\}$ and channels are reciprocal, i.e. $a_{i,j} = a_{j,i}$. We assume as well that the coherence time of the channels is in the order of the total transmission time. Due to the Rayleigh fading assumption, coefficients $a_{i,j}$ are zero-mean, independent, circularly symmetric, complex Gaussian random variables (RVs), and $|a_{i,j}|^2$ is exponentially distributed with parameter $\sigma_{i,j}^{-2}$:

$$P_{|a_{i,j}|^2}(\upsilon) = \frac{1}{\sigma_{i,j}^2} \cdot \exp\left(-\frac{\upsilon}{\sigma_{i,j}^2}\right), \upsilon \geq 0. \tag{2.1}$$

Consider the point-to-point communication scheme of Figure 2.1 (a), where eNB and UE transmit M_{eNB} and M_{UE} coded symbols in total, in the first and second phases P1 and P2, respectively. To achieve reliable communications, the following conditions on the achievable rates on the links should hold:

$$E_1^{p2p}: \quad K_{\text{eNB}} \leq M_{\text{eNB}} \cdot C(\gamma_{\text{eNB-UE}}), \tag{2.2}$$

$$E_2^{p2p}: \quad K_{\text{UE}} \leq M_{\text{UE}} \cdot C(\gamma_{\text{UE-eNB}}), \tag{2.3}$$

where $\gamma_{\text{i-j}}$ is the instantaneous link SNR, $C(\gamma_{\text{i-j}})$ is the link capacity given by $C(\gamma) = \log_2(1 + |a_{ij}|^2 \cdot \rho) = \log_2(1 + \gamma_{ij})$, ρ is the average link SNR and E_1^{p2p} and E_2^{p2p} are defined as the events where conditions (2.2) and (2.3) hold respectively. We can then define the complement of an outage event as:

$$\bar{E}_{p2p}^{out} = E_1^{p2p} \cap E_2^{p2p}. \tag{2.4}$$

Knowing that

$$P(|a_{ij}|^2 \leq K) = 1 - \exp(-\frac{K}{\sigma_{ij}^2}), K \geq 0, \tag{2.5}$$

the outage probability for a point-to-point communication scheme can be formulated as:

$$\begin{aligned} P_{p2p}^{out} &= P(|\mathrm{a}_{\text{eNB-UE}}|^2 \leq \frac{2^{\max(\frac{K_{\text{eNB}}}{M_{\text{eNB}}}, \frac{K_{\text{UE}}}{M_{\text{UE}}})} - 1}{\rho}) \\ &= 1 - \exp(-\frac{2^{\max(\frac{K_{\text{eNB}}}{M_{\text{eNB}}}, \frac{K_{\text{UE}}}{M_{\text{UE}}})} - 1}{\rho\sigma_{\text{eNB-UE}}^2}). \end{aligned} \tag{2.6}$$

The asymptotic behavior of this scheme at high SNR is as follows:

$$\lim_{\rho \to +\infty} \rho \cdot P_{p2p}^{out} = \frac{2^{\max(\frac{K_{\text{eNB}}}{M_{\text{eNB}}}, \frac{K_{\text{UE}}}{M_{\text{UE}}})} - 1}{\sigma_{\text{eNB-UE}}^2}. \tag{2.7}$$

The $1/\rho$ behavior in (2.7) indicates that the point-to-point communication scheme does not offer diversity gains in high SNR regime. Similar conclusions hold for the classical 4-phase relaying scheme.

The derivation of the outage behavior of the 3-phase relaying scheme with network coding given in Figure 2.1 (d) is obtained similarly. For the asymptotic behavior, there holds [I]:

$$\lim_{\rho \to +\infty} \rho^2 \cdot P_{3P}^{out} = \frac{\sigma_{eNB-RN}^2 + \sigma_{UE-RN}^2}{\sigma_{eNB-RN}^2 \sigma_{UE-RN}^2 \sigma_{eNB-UE}^2} \cdot (2^{\frac{3}{2}\frac{K_{\text{eNB}}+K_{\text{UE}}}{M_{\text{eNB}}+M_{\text{UE}}}} - 1)^2, \tag{2.8}$$

Contrary to the traditional schemes, the $1/\rho^2$ behavior in (2.8) indicates that the three-phase scheme with network coding offers diversity gains in high SNR regime. Similar conclusion holds for the classical 4-phase cooperative relaying scheme when assuming Gaussian-distributed channel input. Such behavior is clearly illustrated in Figure 2.2, where the cooperative relaying schemes outperform the traditional scheme especially at high SNR region where performance is dominated by the ability of the scheme to achieve diversity. Network coding still offers for the 3-phase scheme noticeable gain over classical cooperative 4-phase scheme.

In contrast to the case of Gaussian-distributed channel input, however, the 4-phase cooperative relaying scheme may not achieve diversity gain when assuming coded BPSK channel input, as illustrated in Figure 2.3. For such practical coding scheme, diversity gain may be achieved if the utilized channel coding rate is lower than $1/2$ [I]. The upper limit on the channel coding rate is relaxed to $2/3$ for the 3-phase scheme [I].

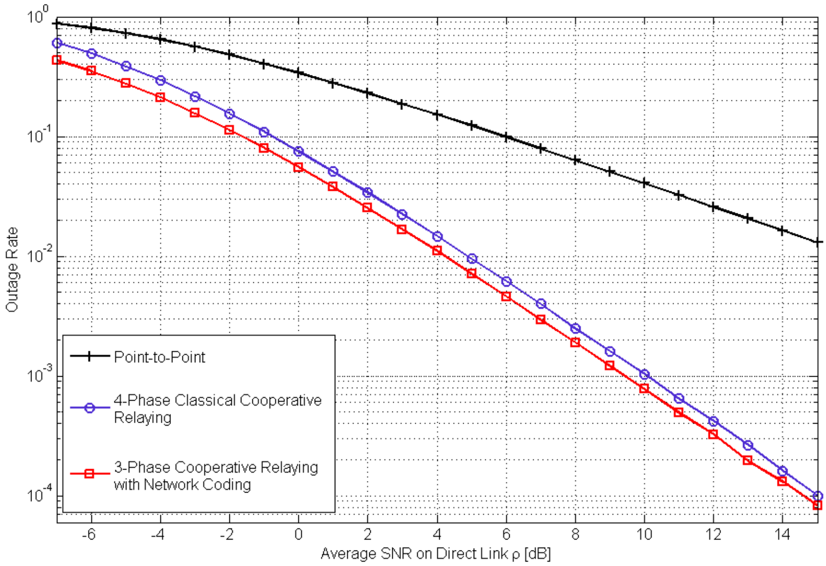

Figure 2.2. Outage behavior of point-to-point scheme, classical 4-phase cooperative relaying scheme and 3-phase cooperative relaying scheme with network coding when assuming Gaussian-distributed channel input.

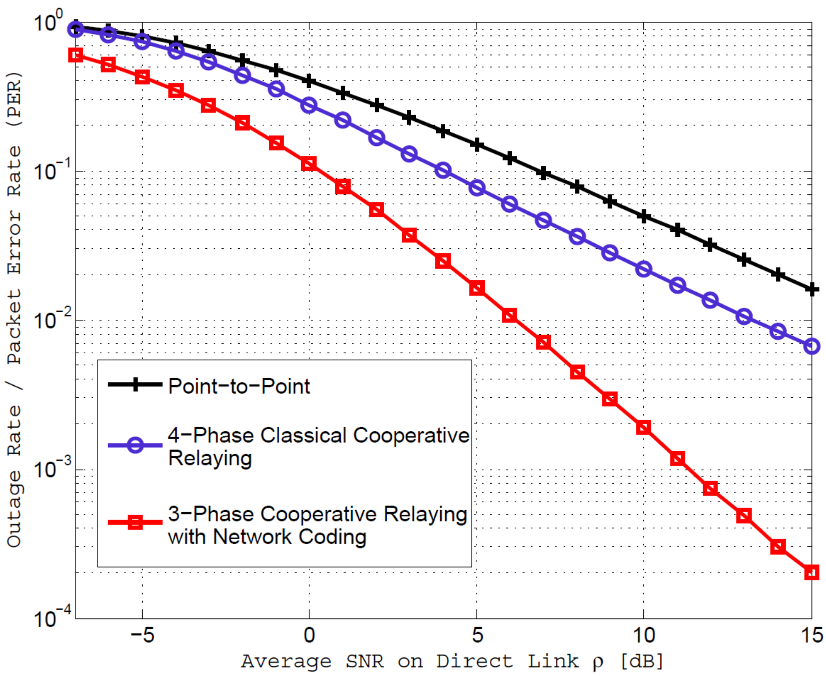

Figure 2.3. Outage behavior of point-to-point scheme, classical 4-phase cooperative relaying scheme and 3-phase cooperative relaying scheme with network coding when assuming BPSK channel input.

Though it has been proved that cooperative relaying, especially when considering network coding, clearly outperforms classical multi-hop relaying and by far point-to-point communication used in current RATs, only classical DF (4-phase) and AF relaying were proposed by 3GPP partners to be included in the study item on LTE-Advanced. Although, there was no justification by 3GPP members for excluding other relay modes, various reasons could be behind such choice. On one hand, cooperative relaying with network coding introduces significant complexity to standardization especially when addressing signaling and control channel issues and considering that it would require changes at the different layers of the protocol stack [22]. Second, considering that an RN and an eNB will be supporting two distinct cells, the eNB would be wasting resources transmitting the same information being forwarded by the RN to a UE, when it can serve another UE in its cell. Other reasons could be attributed to the data flow asymmetry of the uplink and downlink channels. Besides, AF RNs can be easily integrated into current networks, and DF relaying is mature enough and integrating it into current standards is relatively straightforward.

As the scope of the research towards this thesis is limited to realizing relaying in practice in alignment with 3GPP LTE-Advanced standardization, only classical DF and AF relaying have been investigated in the rest of the thesis.

2.2 Relaying Mode Selection in LTE-Advanced

Before introducing relays to LTE networks, it is important to decide on what type of RNs to deploy, or in other words, what relaying mode to adopt. Hence, a discussion on the role of classical two-hop AF and DF RNs has been conducted within the 3GPP study item on LTE-Advanced. In this context, our contribution [II] provides a preliminary analytic comparison between full-duplex AF and half-duplex DF relaying within the LTE-Advanced framework. Performance evaluation assumes AF RN loop back signal interference and concurrent DF RN transmissions on the access link with full frequency reuse in the network, i.e. frequency reuse factor of one.

While the introduction of DF RNs requires more standardization efforts and increases the system complexity, AF RNs, on the other hand, suffer from loop interference (LI) that refers to the leakage of transmit signal to receive antenna [31, 32]. Concurrent transmission and reception at the same frequency band due to the full-duplex operation of AF RNs requires two separated antennas. However, since a high physical isolation between the antennas cannot be always guaranteed (such arrangement is costly and usually feasible only in specific deployment scenarios, e.g. where outdoor-to-indoor isolation is possible), the signal being transmitted on the access link of the AF RN is overheard in the receiving antenna of the relay link. The strength of such interference depends significantly on the antenna isolation and is herein modeled by the loop interference SNR ρ_{LI}.

In [II], the impact of LI in AF RNs and concurrent transmission to multiple users in DF RNs are investigated considering simple scenarios where at most two hops are allowed. Such scenarios are interesting from a practical perspective in case of DF relaying where the system complexity is strongly related to the number of hops and in case of AF relaying where interference may start to ping pong between RNs on consecutive hops. Additionally, two-hop relaying induces acceptable communication delay.

Performance evaluation can be carried out in terms of the end-to-end spectral efficiency (SE) between an eNB and a UE. Therefore, SE of AF and DF RN deployments are to be modeled in terms of the respective SNRs on the relay and access links, ρ_{eNB-RN} and ρ_{RN-UE}, respectively. First, link-level SE is formulated as:

$$SE = B_{eff} \cdot \log_2(1 + A_{eff} \cdot \rho), \tag{2.9}$$

where the parameters $B_{eff} = 0.88$ and $A_{eff} = 1/1.25$ are, respectively, the bandwidth and SNR efficiency factors that are selected so that SE modeling fits with the set of LTE adaptive modulation and coding curves [33].

In AF relaying, the signal-to-interference-plus-noise ratio (SINR) at UEs connected to RN is obtained as follows. The total useful signal power is a combination of both the signal received directly from eNB and the two-hop signal which is amplified by RN. On the other hand, the total interference plus noise power contains the effect of the loop back signal, relayed noise and UE receiver noise. Extending the analysis in [34] by explicitly including the effect of LI, the end-to-end SINR Γ_{AF} at UE, which is used to estimate the system SE using (2.9), is found to be [II]

$$\Gamma_{AF} = \frac{\rho_{eNB-RN} \cdot \rho_{RN-UE} + \rho_{eNB-UE}\left(1 + \rho_{LI} + \rho_{eNB-RN}\right)}{\rho_{eNB-RN} + \left(1 + \rho_{RN-UE}\right)\left(1 + \rho_{LI}\right)}. \tag{2.10}$$

On the other hand, the end-to-end SE in DF RN deployments, assuming balanced relay and access links, can be formulated as [II]

$$SE_{DF} = \left(\frac{1}{SE_{eNB-RN}} + \frac{1}{N_{\mathrm{RN}} \cdot SE_{RN-UE}} \right)^{-1}, \qquad (2.11)$$

where N_{RN} is the number of DF RNs deployed in the macrocell. Herein, it was assumed that the eNB transmits exclusively to the N_{RN} RNs, which then transmit concurrently to their UEs.

Evaluating the performance of both deployments according to the above derivations and parameter settings given in [II], it is shown that the loop interference reduces the AF relaying efficiency, especially at high access link SNR. The performance of AF relaying decreases rapidly if strong loop interference is experienced. This may happen when e.g. AF relay antenna installation is not done properly or the transmit/receive antenna isolation is difficult to obtain, due to site or cost limitations. Further, it is shown that DF RNs are more attractive for cell edge deployments providing a better performance as compared to the direct link SE. On the other hand, AF RN deployments are more suitable near the middle of the cell. It is worth noting that in both deployments AF relaying performs better than DF relaying assuming single DF RN transmission. The conclusion however changes as concurrent transmissions take place. Figure 2.4 shows that DF RN deployments outperform AF RN deployments already with moderate number of concurrent transmissions when the number of RNs deployed per cell increases.

Considering that the focus of relaying in early releases of LTE-Advanced is on coverage enhancements around the cell edge and that 4 to 10 RNs are expected to be deployed per cell, DF RNs prove to be a more plausible solution than AF ones. In what follows, the study will hence focus on two-hop half-duplex DF relaying.

2.3 Relay Network Deployment Viability

Different environments exhibit different propagation characteristics which reflect on eNB and RN coverage areas rendering the network planning a rather challenging task. Small coverage areas may lead to high access node density and considerably high costs for operators. Hence, it is important to validate the RN deployments in different radio environments and give guidelines to the expected deployment costs. Due to increasing rate requirements, it is equally important to investigate the performance

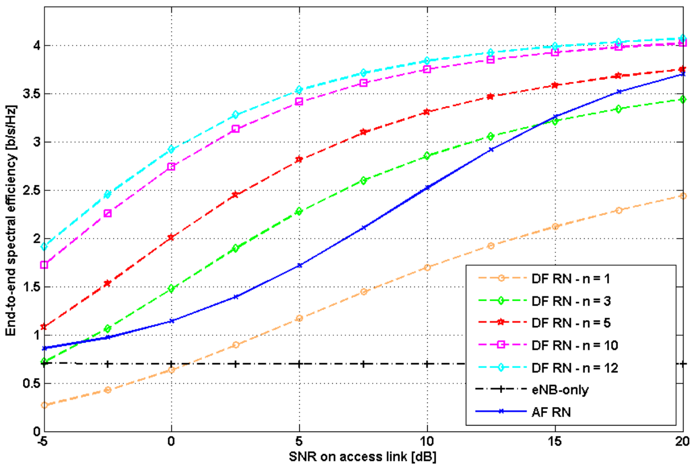

Figure 2.4. Performance of AF and DF RNs when considering loop interference and different number of concurrent DF RN transmissions. SE_{eNB-UE} is assumed to be 0.7 bit/s/Hz, relay link SNR is 16 dB better than that of the direct link partly due to outdoor deployment of RNs, and ρ_{LI} = -5 dB.

of RNs in terms of throughput in different propagation scenarios.

It was early acknowledged in 3GPP LTE-Advanced study item that the propagation modeling is of essential importance when designing and assessing different RN deployments. This fact was reflected in the 3GPP discussion on the distance dependent path loss model which was open for quite a long time during which the model was changed several times. The first proposed 3GPP model, given in [35], consists of only a non-line-of-sight (NLOS) component and is based on the NLOS ITU-R Urban Micro model [36]. The related scenario, which we refer to as Scenario 1 (Sc1), assumes that both UEs and RNs always experience NLOS propagation conditions to their donor eNB and thus, the so-called single slope model of the form

$$PL = 10\log_{10}(\alpha) + 10\cdot\beta\cdot\log_{10}(d)\,[dB] \quad (2.12)$$

is applied, where d is the distance between the access point (eNB or RN) and the UE. In single slope models like Okumura-Hata, the constant term α contains the impact of factors such as carrier frequency, and eNB and UE antenna heights, while the path loss exponent β does not usually depend on the terminal antenna height. The model in (2.12) is feasible for densely built areas when a UE is on the street level and the line-of-sight (LOS) probability is very small. Following this model, the RN-UE path loss model on the access link will exhibit aggressive attenuation compared to macrocells due to low RN antenna height.

The single slope model is pessimistic since it does not take into account the fact that being in LOS conditions is becoming more and more probable when cell sizes are getting smaller. This is especially true when UEs are connected to RNs. Hence, the assumption of considering exclusively a NLOS connection as in [35] might be valid only in very densely populated cities. In the 3GPP evaluation framework, users are assumed to be indoors and the channel model is applied where the path loss towards the building is determined before adding the penetration loss. In many scenarios, there is a LOS connection or at least a clearly dominant direction in the channel between the RN and the building where the UE is located. Therefore, the link suffers from smaller path loss than the channel that assumes propagation over rooftops as in [36].

To address the above-explained propagation characteristics, a probabilistic dual slope model was proposed in [37] for the RN access link. The model given in (2.13) is not a conventional dual slope model where a certain breakpoint distance is assumed; it considers the breakpoint through a probability and is based on measurements.

$$PL = Prob\left(LOS\right) \cdot PL\left(LOS\right) + Prob\left(NLOS\right) \cdot PL\left(NLOS\right), \qquad (2.13)$$

$$PL\left(LOS\right) = 10\log_{10}\left(\alpha_{LOS}\right) + 10 \cdot \beta_{LOS} \cdot \log_{10}\left(d\right), \qquad (2.14)$$

$$PL\left(NLOS\right) = 10\log_{10}\left(\alpha_{NLOS}\right) + 10 \cdot \beta_{NLOS} \cdot \log_{10}\left(d\right). \qquad (2.15)$$

The corresponding model, which we refer to as Scenario 2 (Sc2), assumes a mixed LOS/NLOS modeling of the RN access channel. The path loss on the access link is a weighted combination of two, LOS and NLOS, components, where the weighting factor decays as the UE-RN distance increases. The model in [37], however, does not consider environments, where users in a macrocell deployment may experience LOS propagation conditions with their donor eNB.

Finally, the 3GPP propagation Scenario 3 (Sc3), which is based on the model in [20], considers environments with better propagation conditions as compared to both models in Scenario 1 and Scenario 2, to both eNB and RN. This scenario applies probabilistic dual slope model on all three links and defines a LOS probability function versus the UE-eNB or UE-RN distance. The model thus accounts for the case where a UE is in LOS condition with their eNB or RN, and as well for cases where the UE might be round-the-corner and experience NLOS condition.

The scenarios reflect three possible propagation conditions where RNs may be deployed. As the performance of a network depends significantly on the propagation conditions, it is essential to validate the deployment of RNs in all mentioned environments and give guidelines to the deployment costs and prospective gains. Performance evaluation can be carried out in terms coverage extension and network capacity enhancements of RN deployments. For the latter case, average cell throughput and throughput cumulative distribution function (CDF) plots assuming a fixed coverage area, i.e. fixed inter-site distance (ISD) between eNBs, can be utilized to assess the gain of RN deployments. In the former case, results can be given in terms of an exchange ratio between the RNs and macrocell eNBs [III] [12, 13]. Exchange ratios indicate how many small nodes like RNs are needed to replace a conventional eNB, while still ensuring the required coverage in the network. In this context, we use the evaluation methodology of [13], where the cell coverage requirement is defined in terms of the 10%-ile throughput CDF level. The 10%-ile level reflects the performance of the worst UEs, which might go easily into outage.

Let us describe the applied comparison methodology in the following. Assume a predefined ISD_0 between macrocell eNBs and that RNs are deployed at the edge of each macrocell. Then, the deployed RNs will increase the system throughput with respect to the reference macrocell (eNB-only) deployment. Yet, if the system is scaled by increasing the ISD, then the cell edge throughput can be decreased until the new deployment admits the same 10%-ile throughput as that of the reference eNB-only deployment. In the above procedure, the number of deployed RNs per cell can be varied to obtain different extended ISD and RN density combinations that fulfill the coverage criterion (10%-ile throughput CDF level).

The different RN density and ISD combinations are referred to as ISO-performance deployments. The eNB-only deployment is referred to by the combination (0, ISD_0) and the different ISO-performance RN deployments are referred to by (N_{RN}, ISD_{ext}); recall that N_{RN} refers to the number of RNs deployed per macrocell. The ISO-performance deployments are used to define the trade-off between number of RNs deployed per macrocell to satisfy the given coverage criterion.

It is worth noting that although the ISO-equivalent deployments perform similarly in terms of coverage, they may result in different exchange ratios according to the relative extension in ISD achieved, $ISD_{\mathrm{ext}} - ISD_0$,

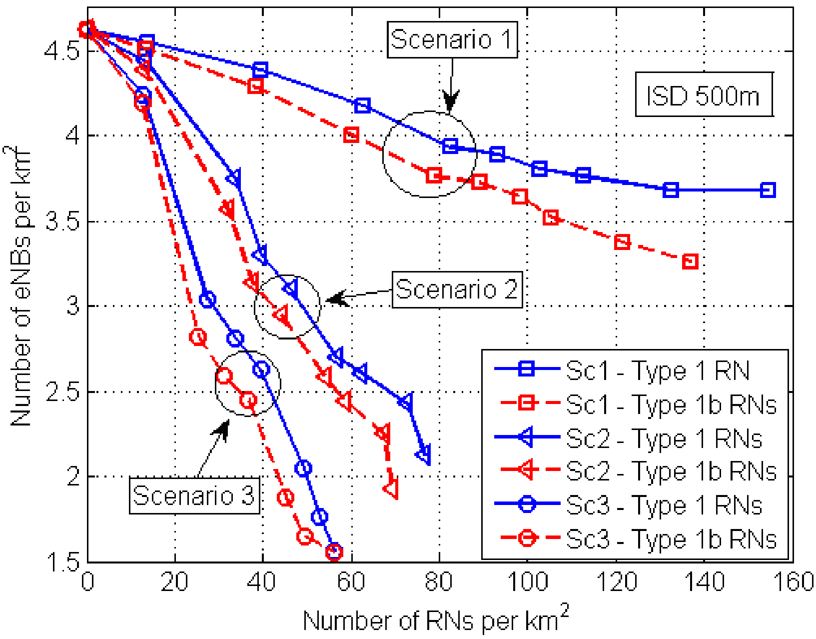

Figure 2.5. ISO-performance curves of urban Type 1 and Type 1b RN deployments considering various propagation environments. The curves imply the exchange ratio between RNs and eNBs when guaranteeing certain coverage requirement in the network.

with respect to the number of RNs deployed, N_{RN}. The exchange ratio $R_{\text{RN-eNB}}$ for a specific (N_{RN}, ISD_{ext}) combination can be modeled as [III]:

$$R_{\text{RN-eNB}} = \frac{3 \cdot N_{\text{RN}} \cdot (ISD_{ext}/ISD_0)^2}{1 - (ISD_{ext}/ISD_0)^2}. \tag{2.16}$$

After simulating several combinations (N_{RN}, ISD_{ext}), the so-called ISO-performance curve is obtained and the minimum exchange ratio can be computed. The solution can then be used to e.g. estimate the maximum costs of an RN site when the costs of macrocell sites are known. In Figure 2.5, ISO-performance curves are given for Type 1 and Type 1b RNs in an urban ($ISD_0 = 500m$) LTE-Advanced deployment considering the three investigated propagation environments. Recall that though both RN types are in-band RNs, the latter can operate in full-duplex mode due to enough isolation between the access link and relay link (see Section 1.2). Hence, the presented study illustrates as well the impact of the half-duplex in-band backhaul operation of Type 1 RNs, i.e. the impact of backhaul relaying overhead.

Two conclusions are clearly deductible from Figure 2.5. On one hand, the ISO-performance differences between Type 1 and Type 1b RNs are relatively small in all three scenarios, which means that in terms of coverage extension, the half-duplex operation mode in Type 1 RNs have limited impact on system performance. On the second hand, there is a significant difference between the ISO-performances of RN deployments in different propagation environments. The required numbers of RNs in ISO combinations of Scenario 3 are smaller than those in Scenario 2, which in turn is much more favorable for relaying than Scenario 1. The impact of propagation conditions is as well reflected in the number of RNs required to cover the cell edge in each of the scenarios [III]; whereas, 7 RNs are needed in the first scenario to cover one tier on the cell edge and provide coverage of roughly 20% of the macrocell area, 5 RNs in Scenario 2 and Scenario 3 almost double the coverage area.

The exchange ratios presented in Table 2.1 and calculated using (2.16) reflect the performances shown by the ISO plots of Figure 2.5 and values can be used to compare Type 1 and Type 1b RNs in terms of costs. Note that such cost can be used to compute the total cost of ownership (TCO), where the extra expenses incurred to insure enough antenna isolation on the access and relay links in Type 1b RN deployments should be taken into account. According to Table 2.1, in-band Type 1 RNs are appealing, cost-wise, if RN TCO is less than 1/120 times that of a macrocell eNB. In Scenario 2 and Scenario 3, the cost limitation diminishes significantly down to 1/30 and 1/18 times that of an eNB. Similarly, for Type 1b RNs, the exchange ratio falls from 1/86 in Scenario 1 to 1/26 and 1/15 in Scenario 2 and Scenario 3, respectively, indicating a higher cost efficiency.

It is worth noting that similar conclusions are obtained in suburban deployments (ISD 1732 m), where Type 1 and Type 1b RNs provide practically the same performance in terms of coverage extension showing that in-band relay link for Type 1 RN does not incur noticeable costs on resource utilization in coverage-oriented rural/suburban areas [III]. Type 1 relay deployments, as compared to Type 1b RN deployments, are hence well justified since they incur less costs than Type 1b RNs. The conclusions hold as well when comparing Type 1 RN and picocell deployments [12].

Investigating the capacity enhancement of RN deployments, we conclude that UEs connected to Type 1 RNs can in general experience better throughput than in eNB-only deployment but only Type 1b RNs clearly increase the number of UEs that admit extremely high throughput [III]. The conclusion is illustrated in Figure 2.6 that presents the achieved average cell throughput gains with respect to the eNB-only reference case.

Considered Scenario	Best Exchange Ratio	
	Type 1 RN	Type 1b RN
Scenario 1	1/120	1/93
Scenario 2	1/30	1/26
Scenario 3	1/18	1/15

Table 2.1. Exchange Ratios of Type 1 and Type 1b RNs in urban deployments considering different propagation environments.

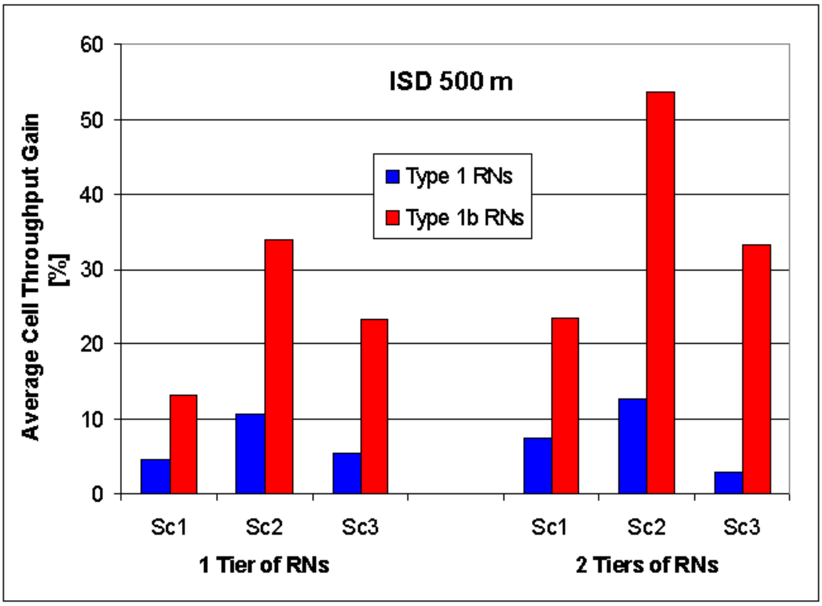

Figure 2.6. Average cell throughput gains (%) in urban Type 1 and Type 1b RN deployments with different propagation conditions. Macrocell eNB-only deployment is used as a reference.

We note that a 2-tier deployment can be used to increase the cell rate when employing Type 1b RNs but in case of Type 1 RNs the gain from the second tier is small. It is also worth noting that in the coverage investigations the large throughput performance difference between Type 1 and Type 1b RNs was not well visible in the coverage extension capabilities of RNs because the difference at the 10%-ile throughput level is small.

After comparing the performance of RNs in all three scenarios, we notice that relaying benefits can significantly differ, as was the case in the coverage extension study [III]. RN deployments in Scenario 2 show better performance than in Scenario 1: When LOS conditions are experienced on the access link, the performance of relay deployments is clearly enhanced whereas the eNB-only performance does not change. When comparing Scenario 2 and Scenario 3, it was found that RN deployments in the former scenario achieve higher relative gain in average cell throughput compared to the eNB-only deployment. This is due to the considerably high throughput levels of eNB-only deployments in Scenario 3 where the UEs close to the eNB experience a LOS connection and hence achieve much higher throughputs as compared to those in Scenario 2. Such UEs contribute significantly to the average cell throughput as compared to those on the cell edge.

In suburban deployments, results show that gains from RN deployments are similar in case of Type 1 and Type 1b RNs [III]. However, a significant difference in RN performance in the three propagation scenarios is observed. RN deployments perform remarkably better in Scenario 2 and Scenario 3 as compared to Scenario 1. Note that significant capacity improvements are achieved by RN deployments in all scenarios as compared to eNB-only deployments.

2.4 Relay Network Planning

In what preceded, we have discussed on what types of RNs and relaying modes are to be considered for LTE-Advanced, and investigated the impact of propagation characteristics of various environments on RN technology giving guidelines to RN density per cell and expected deployment costs. Herein, we proceed further to the network planning phase and investigate simple techniques which promise to significantly boost the RN deployment performance.

The performance evaluation of in-band Type 1 RNs in [III] highlighted the limitations of the relay link in terms of capacity enhancement capabilities of such RNs (see Figure 2.6). It was shown that there is a potential for significant extra throughput gain, if these limitations are relaxed. One approach to address such a problem is characterized by relay site planning (RSP) techniques which aims at enhancing the relay link, the bottle-neck in this case, enabling shifting more resources to the access link [IV].

Network planning tools are routinely used by operators to improve the system performance and to provide a satisfactory service with minimal deployment expenditure. In this context, the deployment flexibility of RNs can be exploited to enhance the system performance through simple RSP. Such flexibility stems in part from the wireless backhaul between RN and eNB, RN's compact physical characteristics and low power consumption, and relaxed installation guidelines with respect to radiation and planning

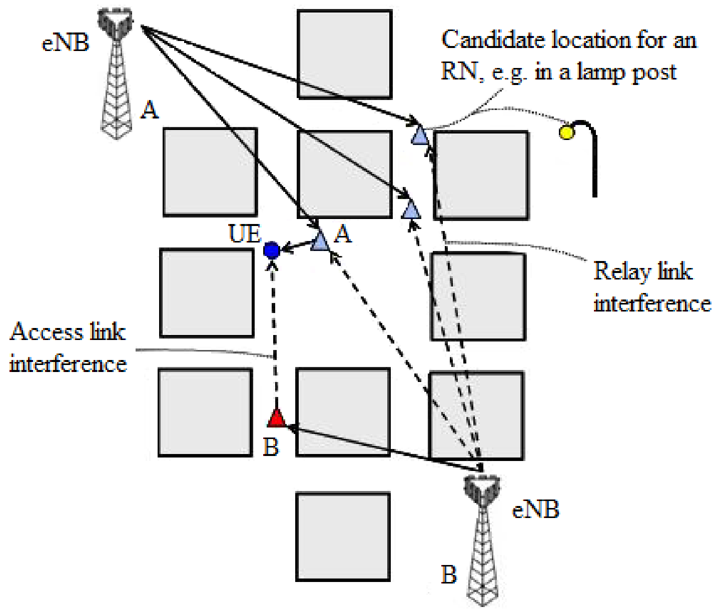

Figure 2.7. Exemplified single-interferer relay site planning model.

regulation. These characteristics allow RNs to be mounted on structures like lamp posts with power supply facilities, offering ample potential deployment sites.

Conventionally, an RN is deployed at a predefined location and it is forced to connect to the closest eNB. Yet, flexibility in choosing the location, referred to as location selection (LS), and to which donor eNB to connect, referred to as cell selection (CS), gives further degrees of freedom in deployment [IV]. Performing LS, random deployment of RNs is avoided and an RN location is chosen from a set of possible locations. As exemplified in Figure 2.7, LS takes into account the shadowing properties at the three different candidate RN locations and considers their links' qualities toward the serving donor eNB in order to optimize the relay link quality. Yet, in some potential RN locations, the shadowing toward the interfering eNB can be low which may make such locations not desirable. Considering CS then, RN can be served by a neighboring cell rather than the severely shadowed closest eNB. That is, for a specific location, the RN is set to connect to the eNB with the best received signal at the RN and not necessarily the closest.

In what follows, we build upon the concepts presented in [38] to deduce a simple model for the impact of RSP on the performance of RNs and present an analytical framework which explains and justifies RSP gains on the relay link and on the end-to-end UE rate. It is important to establish an understanding of how the qualities of both access and relay links will shape the end-to-end UE performance, and hence evaluate the user-experienced impact of the proposed RSP strategies.

The two investigated RSP strategies are modeled as follows.

Location Selection: In location planning it is assumed that there are M potential locations for RN deployment in cell i out of which we select the best location in terms of SINR. In each location, RN is assumed to be served by a predefined eNB solely. Then, the SINR in the selected location is of the form

$$\gamma_{\hat{m},i} = \max\{\gamma_{m,i} : m = 1, 2, ..., M\}, \tag{2.17}$$

where $\gamma_{m,i}$ is the SINR for the m^{th} location in the i^{th} cell.

It is worth noting that the location of the RN is to be decided on as part of the network planning phase. Operators usually perform coverage prediction simulations and carry out extensive drive tests, which could be used as input (long term average statistics) to identify the best location for an RN. LS is hence not considered to be performed on a short-term basis.

Cell Selection: For a specific RN location, the RN selects to connect to the best donor eNB out of K alternatives. That is, if cell selection is enabled, then SINR at the m^{th} RN candidate location is given by

$$\gamma_{m,\hat{i}} = \max\{\gamma_{m,i} : i = 1, 2, ..., K\}. \tag{2.18}$$

Herein, cell selection is assumed to happen according to long term average statistics rather than instant changes of the channel conditions which might lead to the ping-pong effect. The frequency of reselecting a new cell is hence low.

To evaluate the performance of both RSP techniques, let us assume a simple propagation model given as:

$$L = \alpha \cdot d^{\beta} \cdot 10^{\zeta/10}. \tag{2.19}$$

Parameters α and β are, respectively, a propagation constant and the path loss exponent, which together define the NLOS distance-dependent path loss given in (2.12). RV ζ models log-normal shadowing with standard deviation σ. Such model accounts for the fact that different locations with the same distance to the serving eNB may exhibit differences in average received signal levels, i.e. the average received signal level changes with location due to shadowing process caused by different numbers of various obstructing large objects [39, 40, 41]. It is further assumed that at the m^{th} RN location the shadow fading variables $\zeta_{m,i}$ and $\zeta_{m,j}$ with respect to the i^{th} and j^{th} eNBs are correlated according to the model of [42], whereas variables $\zeta_{m,i}$ and $\zeta_{n,i}$, corresponding to different RN locations, are practically uncorrelated for ISD of 50 m [43].

If we assume a dominant interferer model on the relay link, the SINR can be approximated by the signal-to-interference ratio (SIR). Then, the relay link SIR $\Gamma_{m,i}$ [dB] at location m and served by donor cell i can be modeled as a Gaussian-distributed RV with mean $\mu_{m,i}$ and standard deviation ν,

$$\begin{aligned}\mu_{m,i} &= 10 \cdot \log_{10}\left(\frac{P_{\text{Tx},i}}{P_{\text{Tx},j}}\right) + \beta \cdot 10 \cdot \log_{10}\left(\frac{d_{m,j}}{d_{m,i}}\right), \\ \nu^2 &= \text{Var}\left\{\Gamma_{m,i}\right\} = 2(1-\epsilon)\sigma^2,\end{aligned}$$

where $P_{\text{Tx},i}$ and $P_{\text{Tx},k}$ are the transmit powers of the serving and interfering eNBs, respectively, and ϵ is the correlation coefficient related to any pair of eNBs [42]. The CDF is of the form

$$F_{m,i}(\Gamma) = \frac{1}{2}\left[1 + \text{erf}\Big(\frac{\Gamma - \mu_m}{\nu\sqrt{2}}\Big)\right], \tag{2.20}$$

where erf refers to the error function.

If LS RSP strategy of (2.17) is carried out in cell i over M candidate locations, then the CDF of the SIR attains the form

$$F_{\hat{m},i}(\Gamma) = \prod_{m=1}^{M} F_{m,i}(\Gamma). \tag{2.21}$$

On the other hand, if CS is performed following (2.18), we have

$$\begin{aligned}\Gamma_{m,\hat{i}} &= \max\{\Gamma_{m,i}, \Gamma_{m,j}\} = \max\{\Gamma_{m,i}, -\Gamma_{m,i}\} \\ &= |\Gamma_{m,i}|,\ i \neq j.\end{aligned} \tag{2.22}$$

Hence, the probability distribution function (PDF) of $\Gamma_{m,\hat{i}}$ is defined by a folded normal distribution and the corresponding CDF is given by

$$F_{m,\hat{i}}(\Gamma) = \frac{1}{2}\Big[\text{erf}\Big(\frac{\Gamma + \mu_m}{\nu\sqrt{2}}\Big) + \text{erf}\Big(\frac{\Gamma - \mu_m}{\nu\sqrt{2}}\Big)\Big]. \tag{2.23}$$

If both LS and CS are applied in RSP, then the SIR CDF attains the form

$$F_{\hat{m},\hat{i}}(\Gamma) = \prod_{m=1}^{M} F_{m,\hat{i}}(\Gamma). \tag{2.24}$$

After modeling the SIR on the relay link for the different technique combinations, the impact of RSP can be illustrated as given in Figure 2.8 based on analytical formulations (2.20), (2.21), (2.23) and (2.24). When

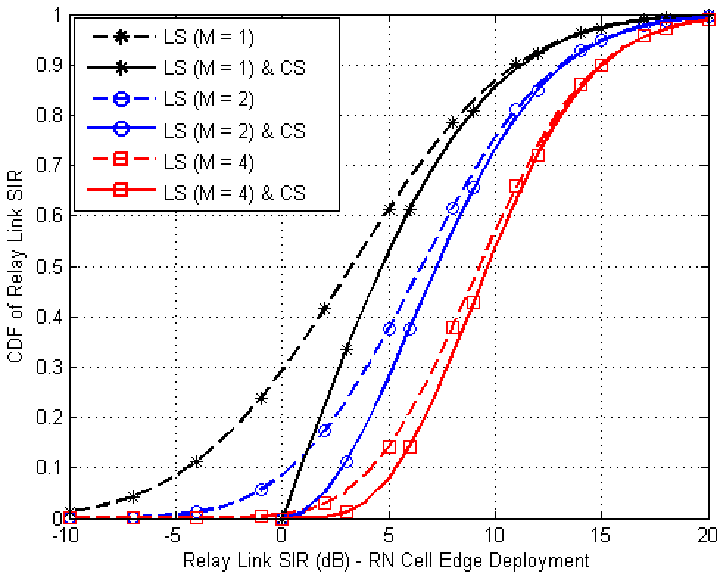

Figure 2.8. CDF of relay link SIR in RN cell-edge deployment. Dashed curves correspond to LS only and solid curves consider both LS and CS. Numbers of potential relay locations are $M = 1$ ($\star$), $M = 2$ ($\circ$) and $M = 4$ ($\Box$). The relative distances from the RN to the serving eNB and to the interfering eNB are, respectively, $0.9 \cdot \frac{ISD}{2}$ and $1.1 \cdot \frac{ISD}{2}$

using CS and LS on the relay link, a significant gain is achieved at the low percentiles of the SIR CDF, highlighting especially the impact of CS. Enabling CS on the relay link alleviates the effects of the severe shadowing toward the serving BS, which contributes to SIR on low CDF levels. However, as the number of candidate RN locations increases, the improvement in relay link quality from LS becomes more prominent, whereas that of CS becomes less significant because the probability of having a worse signal to the serving eNB than that to a nearby eNB decreases. As opposed to enabling CS alone, LS offers clear gains over all the SIR CDF levels. When utilizing both CS and LS with $M = 4$ candidate locations, gains of 11 dB and 6.5 dB are achieved at the 5%-ile and 50%-ile SIR CDF levels, respectively.

Considering such gains on the relay link, it is interesting to investigate the impact of RSP on the end-to-end UE performance. For that purpose, we first need to model the SINR on the access link. We adopt the single-interferer model of [44], where block Rayleigh fading conditions are assumed. The instantaneous channel coefficients are modeled as independent and identically distributed zero-mean complex Gaussian RVs and, thus, signal powers follow exponential distribution. The CDF of the access link SINR Υ is given, according to [44, A.7], as:

$$\begin{aligned} F(\Upsilon) &= 1 - \frac{\upsilon}{\upsilon + \Upsilon} e^{-\Upsilon/\bar{\Upsilon}_k}, \\ \upsilon &= \frac{\bar{\Upsilon}_k}{\bar{\Upsilon}_l} = \frac{E\left\{P_{\text{Tx},k}/L_k\right\}}{E\left\{P_{\text{Tx},l}/L_l\right\}}, \\ \bar{\Upsilon}_k &= E\left\{\frac{P_{\text{Tx},k}}{P_N L_k}\right\}, \bar{\Upsilon}_l = E\left\{\frac{P_{\text{Tx},l}}{P_N L_l}\right\}, \end{aligned} \tag{2.25}$$

where $P_{\text{Tx},k}$ and $P_{\text{Tx},l}$ are the transmit powers of the serving and interfering RNs, respectively, L_k and L_l are the corresponding respective path losses, and P_N is the thermal noise power. Furthermore, $\bar{\Upsilon}_k$ and $\bar{\Upsilon}_l$ are the mean SNRs which depend on the user distance and the shadowing to the serving and interfering RNs, respectively, and υ defines the mean SIR on the access link.

Let us assume that resources allocated for the relay link and access link communication constitute τ_r and τ_a of the total available resources, respectively, where resource normalization is given as $\tau_r + \tau_a = 1$. Further, let us consider N_{RN} RNs per cell, where RN k is to be scheduled on a portion $\tau_{r,k}$ of the total available resources on the relay link, and $\sum_{k=1}^{N_{\text{RN}}} \tau_{r,k} = \tau_r$. Hence, the end-to-end rate experienced by a single UE served by RN k can be defined as the minimum of the user rate achieved on the relay and access links:

$$R_e = \min\left(\frac{\tau_{r,k}}{\tau_{r,k} + \tau_a} \cdot R_r, \frac{\tau_a}{\tau_{r,k} + \tau_a} \cdot R_a\right), \tag{2.26}$$

where rates on the relay and access links are scaled by the portion of resources allocated to each, and R_r and R_a are the achievable rates on the relay and access links, respectively, defined similar to SE in (2.9) and they are independent RVs. Thus, the CDF of the end-to-end rate for the case where neither LS nor CS is applied is then formulated as

$$\begin{aligned} F_{e;m,i}(R) = {} & F_{r;m,i}\left(\frac{(\tau_{r,k} + \tau_a)R}{\tau_{r,k}}\right) + F_a\left(\frac{(\tau_{r,k} + \tau_a)R}{\tau_a}\right) \\ & - F_{r;m,i}\left(\frac{(\tau_{r,k} + \tau_a)R}{\tau_{r,k}}\right) \cdot F_a\left(\frac{(\tau_{r,k} + \tau_a)R}{\tau_a}\right). \end{aligned} \tag{2.27}$$

The rate distributions $F_{e;\hat{m},i}$ and $F_{e;m,\hat{i}}$ when performing LS and CS, respectively, and the rate distribution $F_{e;\hat{m},\hat{i}}$ considering both RSP techniques are formulated using (2.21), (2.23) and (2.24).

Following the above modeling, Figure 2.9 shows the CDF of the optimal end-to-end UE rate (upper bound) when assuming a dynamic resource allocation which achieves the equilibrium on both access and relay links at any instance. Similar conclusions as for the relay link SIR distributions

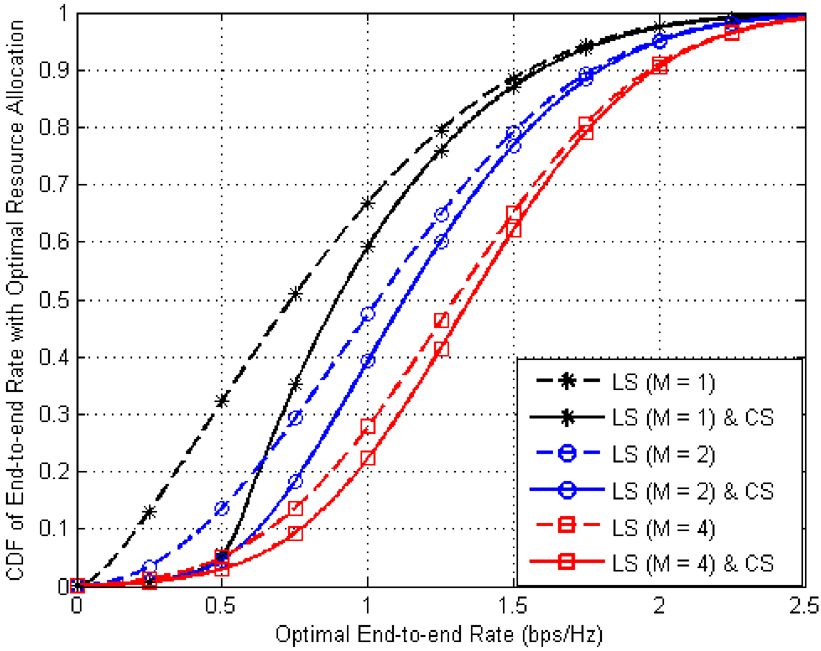

Figure 2.9. End-to-end rate distribution considering optimal resource allocation on access and relay links. Dashed curves correspond to LS only, whereas solid curves consider also CS. Numbers of potential relay locations are $M = 1$ ($\star$), $M = 2$ ($\circ$) and $M = 4$ ($\square$). RN is positioned at the macrocell edge. The mean access link SNR toward the serving RN and the access link SIR are, respectively, $(\bar{\Upsilon}_k)_{dB}$ = 20 dB and $(\upsilon)_{dB}$ = 20 dB.

are noticed, where significant gains are achieved as a result of RSP techniques. Gains up to around 365% and 85% are achievable on the 5%ile and 50%-ile CDF levels, respectively. Note that the former level reflects the cell coverage, whereas, the latter indicates the median UE rates. Such gains are achieved as a result of enhancing the relay link and hence moving resources to the access link.

It is worth noting that the impact of RSP has been investigated in standardization [45, 46], and was eventually modeled as an improvement to the relay link channel in 3GPP evaluation guidelines [20]. The given modeling therein will be used throughout the rest of this thesis.

3. Radio Resource Management in Relay-deployments

In-band Type 1 RNs are characterized by compact physical characteristics, low power consumption and time-multiplexed transmission and reception on the relay and access links. Though the former two characteristics are partly responsible for RN deployment flexibility enabling simple RSP techniques which provide significant gains [IV], they, as well, result in small RN cell coverage within the overlaying macrocell, which may lead to load imbalances. Additionally, the realization of relay and access communications on the same frequency band implies the need for a balance in resource partitioning among the different links which compete for resources at the eNB and proper two-hop resource allocation. Further challenges in relay deployments are attributed to increased interference levels in the network compared to homogeneous deployments, as well as the introduction of a new interference type known as RN-to-RN interference. The latter is due to the misalignment of reception and transmission on the access and relay links of different RNs. In this section, we address the mentioned radio resource management challenges and study the performance of proposed simple practical solutions which adhere to the LTE-Advanced framework.

3.1 System Model and Simulation Environment

Herein, we introduce the system and simulation parameters which will be used to evaluate the proposed RRM techniques. Unless otherwise stated, the parameters apply for Sections 3.2 through 3.5.

The simulated network is represented by a regular hexagonal cellular layout with 19 tri-sectored sites, i.e. 57 cells in total. RNs are regularly deployed at the sector borders. Urban (3GPP Case 1) and suburban (3GPP Case 3) scenarios with ISD of 500 m and 1732 m, respectively, are consid-

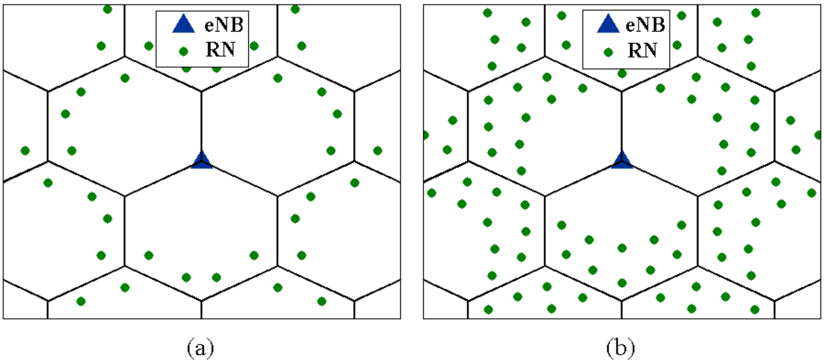

Figure 3.1. RN deployments where (a) 4 RNs and (b)10 RNs are deployed at the macrocell edge.

ered [20]. For each scenario, deployments with 4 (1 tier of RNs) and 10 RNs (2 tiers of RNs) per cell are investigated, see Figure 3.1. Simulation parameters follow the latest parameter settings agreed in 3GPP [20] and are summarized in Table 3.1.

Indoor users are assumed, where 25 uniformly distributed UEs are dropped per sector and the full buffer traffic model is applied. In total, 250 user drops are simulated using a system level semi-static simulator, where results are collected from the inner most sector only, to ensure proper modeling of interference (two tiers of tri-sector sites). Note that a frequency reuse factor of one (full frequency reuse) is considered among the RNs and macrocells in the network.

$$R = S \cdot BW \cdot B_{eff} \cdot \log_2 (1 + A_{eff} \cdot \Gamma) \,. \tag{3.1}$$

A resource-fair round robin (RR) scheduler is utilized at the eNB to schedule macro-UEs on the direct link. All available resources in a cell are assumed to be used, and hence a pessimistic interference modeling is considered. The SINR to link throughput mapping is carried out by the approximation given in (3.1), where the bandwidth and SINR efficiencies of Table 3.1 are utilized to adapt the mapping to LTE specifications, taking the LTE modulation and coding scheme (MCS) into consideration [33]. Further, a minimum SINR level Γ_{min} is used on the control channel, below which data detection is not possible, i.e. the achievable rate is zero. In (3.1), BW is the bandwidth per PRB, SE_{max} is the maximum SE depending on the highest MCS for a given Γ_{max} and S is the overhead scaling accounting for LTE DL overhead. Note that the rate per PRB R is assumed to be the same for all of the PRBs assigned to a UE given that fast fading is not considered and a full buffer model is assumed.

In the considered two-hop relay based deployment, each UE is either served directly by an eNB or indirectly via an RN. Cell selection and handover decisions are performed based on periodic measurements of the reference signal received power (RSRP) from different access nodes at the UE in DL. A UE is then served by the access node having the highest RSRP.

Two antenna sets are considered for RNs. Directional antennas are as well assumed at the RNs for backhaul transmission, while Omni-directional antennas are assumed for the access link transmission.

3.1.1 Channel Models

Relay site planning is assumed as modeled in [20]. In this context, the relay link quality improvement is modeled by increased LOS probability and lower pathloss towards the donor eNB when experiencing NLOS propagation conditions. Log-normal shadow fading is as well modeled and applied for NLOS propagation conditions only, while fast fading is not simulated. Channel models for 3GPP urban and suburban scenarios are given in Table 3.2; see Section 2.3 for model description.

3.1.2 Frame Structure in FDD LTE Networks

An LTE radio frame duration is 10 ms and it comprises 10 subframes. We consider frequency division duplex (FDD) mode, where the UL and DL are each allocated exclusive 10 MHz transmission bandwidth. As full frequency reuse is expected among the RN cells and macrocells in LTE-Advanced, macro-UEs and relay-UEs are served on the same resources by eNBs and RNs, respectively. When considering the resource allocation strategy defined for in-band Type 1 RNs in [20], relay and access link transmissions are time-division multiplexed. This is depicted in Figure 3.2 where, as exemplified, two subframes are reserved for DL relay link transmissions and thus data transmission gaps are experienced on the access link. The transmission gaps, where UEs should not expect any data transmission, but the reference and control signals, are realized by configuring Multi-Media Broadcast over Single Frequency Network (MBSFN) subframes. The use of MBSFN subframe structure allows backwards compatibility; LTE Release 8 UEs, after reading the control channel and reference signals in the first OFDM symbols, would know that

Parameter	Value
System Parameters	
Carrier Frequency	2 GHz
Bandwidth BW	180 KHz
Number of PRBs	50
Highest MCS	64-QAM, R = 9/10
Penetration Loss	20 dB
SINR Efficiency A_{eff}	0.8
Bandwidth Efficiency B_{eff}	0.88
Overhead Scaling S	0.75
Thermal Noise PSD	-174 dBm/Hz
SINR Lower Bound Γ_{min}	-7 dB
eNB Parameters	
Transmit Power	46 dBm
Elevation Gain	14 dBi
Noise Figure	5 dB
Antenna Configuration	Tx-2, Rx-2
Antenna Pattern	$A(\theta)$ = -min [12$(\theta/\theta_{3dB})^2, A_m$], θ_{3dB} = 70^o, A_m = 25 dB
UE Parameters	
Noise Figure	9 dB
Antenna Configuration	Tx-1, Rx-2
Antenna Pattern	Omni-directional
RN Parameters	
Transmit Power	30 dBm
Noise Figure	5 dB
Antenna Configuration	Tx-2, Rx-2
RN-eNB Elevation Gain	7 dBi
RN-UE Elevation Gain	5 dBi
Access Link Antenna Pattern	Omni-directional
Relay Link Antenna Pattern	$A(\theta)$ = -min [12$(\theta/\theta_{3dB})^2, A_m$], θ_{3dB} = 70^o, A_m = 20 dB

Table 3.1. Simulation Parameters.

Distance	d [Km]
Direct Link (eNB - UE)	
PL(LOS) = 103.4 + 24.2 $\log_{10}(d)$ PL(NLOS) = 131.1 + 42.8 $\log_{10}(d)$ Urban Model - ISD 500 m Prob(LOS) = $\min(0.018/d,1)(1-\exp(-d/0.063))+\exp(-d/0.063)$ Suburban Model - ISD 1732 m Prob (LOS) = $\exp(-(d-0.01)/0.2)$	
Access Link (RN - UE)	
PL(LOS) = 103.8 + 20.9 $\log_{10}(d)$ PL(NLOS) = 145.4 + 37.5 $\log_{10}(d)$ Urban Model - ISD 500 m Prob(LOS) = 0.5 - $\min(0.5,5\exp(-0.156/d))$ + $\min(0.5,5\exp(-d/0.03))$ Suburban Model - ISD 1732 m Prob (LOS) = 0.5 - $\min(0.5,3\exp(-0.3/d))$ + $\min(0.5,3\exp(-d/0.095))$	
Relay Link (eNB - RN)	
β	5, towards donor eNB 0, towards interfering eNBs
α	3, towards donor eNB 1, towards interfering eNBs
PL(LOS) = 100.7 + 23.5 $\log_{10}(d)$ PL(NLOS) = 125.2 + 36.3 $\log_{10}(d) - \beta$ Urban Model - ISD 500 m Prob(LOS) = 1 - $(1-(\min(0.018/d,1)(1-\exp(-d/0.072)) + \exp(-d/0.072)))^{\alpha}$ Suburban Model - ISD 1732 m Prob (LOS) = 1 - $(1-\exp(-(d-0.01)/0.23))^{\alpha}$	
Log-normal Shadowing	
Standard Deviation σ	8 dB on the direct link 10 dB on the access link 6 dB on the relay link
Decorrelation Distance	50 m
Correlation Factor	0.5 between sites 1 between cells of same site

Table 3.2. Utilized Channel Models in Urban and Suburban Scenarios.

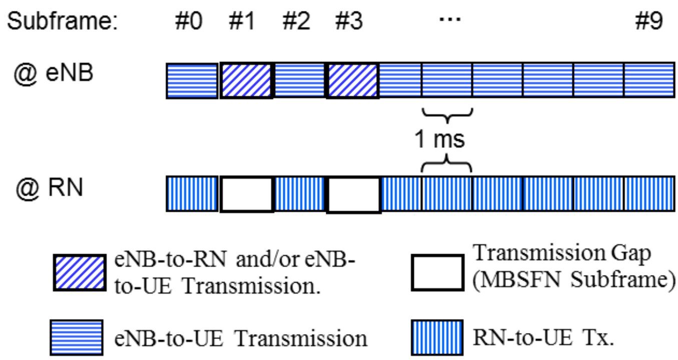

Figure 3.2. FDD DL LTE-Advanced frame structure considering Type 1 RNs.

no data should be expected in the following symbols which can therefore be used by the RNs to exclusively communicate with the eNB. In addition, the set of MBSFN subframes is semi-statically assigned, where a maximum of 6 subframes can be configured out of the subframes 1, 2, 3, 6, 7, and 8 (other sub-frames contain indispensable synchronization and broadcast channels) [47]. It is to be noted that both macro-UEs and RNs can be co-scheduled on such subframes.

To support resource scheduling on the subframes allocated to the relay link, a new physical control channel, Relay-Physical Downlink Control Channel (R-PDCCH), is defined in LTE-Advanced. R-PDCCH carries scheduling grants for RNs on the Relay-Physical Downlink Shared Channel (R-PDSCH).

3.1.3 Performance Evaluation Criteria

Performance evaluation is carried out in terms of the 5%-ile throughput CDF level, 50%-ile throughput CDF level and the average cell throughput. It is worth noting that the former reflects the cell edge performance which implies the cell coverage, whereas the 50%-ile CDF level reflects the median performance of UEs in the system. This is especially important measure when identifying cases where few UEs with very high TP significantly increase the average UE throughput.

In our work, we focus on techniques to improve the low throughput regime, i.e. 5%-ile throughput CDF level, to achieve a more homogeneous user experience over the cell area and thus a high level of fairness in the system.

Jain's fairness index (JF) is used herein as a criterion to evaluate the system fairness. The index value one indicates full fairness where all UEs achieve the same throughput. Equations (3.2) and (3.3) model JF within the RN cells and macrocell (including relay-UEs and macro-UEs), respectively. Therein, N_{RN} is the number of RNs deployed in macrocell m, U_D is the number of UEs in the macrocell served directly by the eNB, U_R is the number of UEs served by all RNs in the macrocell, u_i is the number of UEs served by RN i, $TP_{R,ij}$ is the throughput achieved by UE j in RN cell i, and $\mathrm{TP}_{D,k}$ is the throughput achieved by UE k on the direct link.

$$\mathrm{JF}_{\mathrm{RN}} = \frac{\left(\sum_{i=1}^{N_{\mathrm{RN}}} \sum_{j=1}^{u_i} \mathrm{TP}_{R,ij}\right)^2}{U_R \sum_{i=1}^{N_{\mathrm{RN}}} \sum_{j=1}^{u_i} \mathrm{TP}_{R,ij}^2}. \tag{3.2}$$

$$\mathrm{JF}_{\mathrm{eNB}} = \frac{\left(\sum_{i=1}^{N_{\mathrm{RN}}} \sum_{j=1}^{u_i} \mathrm{TP}_{R,ij} + \sum_{k=1}^{U_D} \mathrm{TP}_{D,k}\right)^2}{(U_R + U_D)\left(\sum_{i=1}^{N_{\mathrm{RN}}} \sum_{j=1}^{u_i} \mathrm{TP}_{R,ij}^2 + \sum_{k=1}^{U_D} \mathrm{TP}_{D,k}^2\right)}. \tag{3.3}$$

3.2 Resource Sharing and Scheduling

Type 1 RNs support a relaying mode where the relay link transmission is time-division multiplexed with the access link transmission on different subframes, whereas macro users share the same resources with the RNs at the eNB. Therefore, system performance depends strongly on how good is the competition for resources at the eNB managed. Hence, it is important to investigate the resource sharing among and within the links.

In [48], time-division and frequency-division multiplexing of relay and access link transmissions were investigated in order to maximize throughput and/or fairness. Moreover, an RR scheduler was utilized on each link to allocate resources for UEs and RNs. However, optimizing either criterion should not only consider the subframe allocation for access and relay links; it should as well jointly consider, along the access/relay link resource split, proper corresponding techniques for scheduling on the different links and prioritization of relay-UEs on the relay link since it is usually the bottleneck.

The split of resources among the access and relay links was also addressed in different 3GPP technical contributions [49, 50, 51], where a fair split of resources among relay-UEs and macro-UEs was achieved by allocating resources to the relay link proportional to the ratio of the number of relay-UEs to the total number of users in the cell. Besides, independent proportional fair (PF) schedulers were utilized on each link. However, knowing that the relay link experiences better propagation conditions as compared to the direct link, and that relay-UEs experience abundance of resources in the RN cells, then, such an approach favors relay-UEs over the eNB-served macro-UEs in terms of throughput. Another approach was followed in [52, 53], where a resource sharing on the relay link according to the buffer state at the RNs was investigated along with PF scheduling on the links and the resource split at the eNB was optimized. The considered technique benefits more the relay-UEs with a better access channel quality; the method as such does not focus on achieving strict fairness among RN UEs although the PF scheduler at the RNs still guarantees a certain level of fairness.

In [V], we target a more homogeneous performance of UEs in the RN cells - a requirement of LTE-Advanced, and at the same time we consider a proper choice of resource split between macro-UEs and RNs in order to guarantee a good performance at the low and mid throughput regime. We adopt the model of [52] and investigate a resource sharing algorithm on the relay link jointly with a prioritization technique of the relay-UEs data flows at the eNB. The considered resource sharing algorithm on the relay link allocates resources to RNs based on the ratio of the number of UEs served by an RN to the total number of relay-UEs in the cell. Besides, the prioritization technique on the relay link along with the corresponding scheduling on the access link guarantees max-min fairness.

3.2.1 Resource Splitting between RNs and UEs

In a heterogeneous system where RNs and macro-UEs share the same resources (see Figure 3.2), the system performance is reflected by a balance between the three links, namely, direct, relay and access links. In particular, the relay link experiences better channel conditions than the direct link and the resources available per UE are abundant on the access link while a high competition on resources between the RNs and macro-UEs is experienced at the donor eNB. Thus, allocating a high number of subframes exclusively to the relay link will yield a gain on the high throughput regime, whereas the direct link will starve and deteriorate the performance at the low throughput regime. Hence, to target a better performance for low-rate users, a balance need to be achieved between the direct and relay links taking into consideration that extreme allocation of resources on either side would push the users to a bad throughput regime.

When the target is a homogeneous UE performance in the network and

Deployment Scenario	Number of MBSFN Subframes
3GPP Urban Scenario - 4 RNs per cell	2
3GPP Urban Scenario - 10 RNs per cell	4
3GPP Suburban Scenario - 4 RNs per cell	4
3GPP Suburban Scenario - 10 RNs per cell	6

Table 3.3. Optimum MBSFN subframe (equivalently, number of RN-exclusive subframes at eNB) configuration assuming no co-scheduling of RNs and macro-UEs at the eNB.

good average throughput, the subframe allocation given in Table 3.3 is proved to provide the required performance [V]. For simplicity, we have assumed that a subframe at the eNB is exclusively allocated to either RNs or macro-UEs.

3.2.2 Resource Sharing among RNs

Assuming the LTE frame structure in Section 3.1.2 (see Figure 3.2) and RN-exclusive relay link subframe configuration of Section 3.2.1, the next step is to investigate the resource allocation to the different RNs on the relay link, i.e. RN scheduling at the eNB. In this context, different scheduling techniques could be utilized, such as resource-fair RR scheduling or variations of PF scheduling. Whereas the former schedules the RNs on the same number of resources irrespective of their QoS requirements or channel quality, the latter takes into consideration the channel quality and tries to enhance the throughput over time making use of multi-user diversity.

Knowing that the RN is not the end user, pure PF scheduling on the relay link at the eNB will not be a suitable solution as it does not consider the users channel qualities and hence requirements from the RN on the second hop. Therefore, it is worth considering a variation of PF which takes into account the total UE throughput requirement from an RN which in turn reflects the channel quality of each UE served by the RN. In our contribution [V], we investigate such scheme, referred to as the Achievable Sum Instantaneous Throughput (ASIT). ASIT allocates resources to RNs according to the proportion of the sum instantaneous throughput achievable on the access links of an RN to the total achievable sum instantaneous access throughputs of all RNs in the cell. The number of resources m_i scheduled for an RN i in ASIT is given as:

$$m_i = \frac{\sum_{j=1}^{u_i} R_{ij}/u_i}{\sum_{i=1}^{N_{\mathrm{RN}}} \sum_{j=1}^{u_i} R_{ij}/u_i} M_r, \tag{3.4}$$

where R_{ij} is the rate per PRB given as in (3.1) for a UE j served by RN i, u_i is the number of UEs served by RN i, and M_r is the total number of PRBs available for the relay link. This scheme requires the knowledge of the instantaneous throughput of each RN at the eNB, which is neither standardized nor practically favorable.

A more feasible approach which depends solely on standardized available information at the eNB is the Access UE Proportional (AUP) scheduling. The resource shares in AUP scheme are defined according to the ratio of the number of UEs attached to an RN i, u_i, to the total number of relay-UEs U_R. Thus, the number of resources allocated to an RN is given as:

$$m_i = \frac{u_i}{U_R} M_r. \tag{3.5}$$

Note that in this manner, AUP is achieving resource fairness for all UEs by viewing the RN as transparent entity on the two-hop communication.

3.2.3 Data Flow at eNB

After investigating techqniques for RN resource allocation, it is important to study how much data is to flow for each UE, i.e. UE data flow prioritization on the relay link. We consider two types of user data flow prioritization schemes, one which depends on the achievable UE instantaneous throughput on the access link (AUIT), implicitly depending on channel quality, and one which achieves max-min fairness (MMF). In AUIT scheme, a UE j connected to RN i is expected to achieve the following end-to-end throughput TP_{ij}:

$$\mathrm{TP}_{ij} = \min\left(\frac{M_a}{u_i} R_{ij}, \frac{R_{ij}}{\sum_{k=1}^{u_i} R_{ik}} m_i R_i\right), \tag{3.6}$$

where m_i is calculated according to the resource allocation scheme on the relay link at the eNB, and M_a is the total number of resources available on the access link.

On the other hand, user data flow prioritization in an MMF scheme is achieved as follows:

1. Initialize for every UE j in RN cell i the access link throughput $\mathrm{TP}^a_{ij} = \frac{M_a R_{ij}}{u_i}$.

2. Sort the UEs in an ascending order of TP^a_{ij}.

3. Iterate over all UEs, $j = 1...u_i$, in RN cell i

   (a) calculate the UE throughput on the relay link $\mathrm{TP}^r_{ij} = \frac{m_i R_i}{u_i} + \frac{\sum_{k=1}^{j-1} \frac{m_i R_i - M_a R_{ik}}{u_i}}{u_i-(j-1)}$, where R_i is the achieved rate per PRB of RN i on the relay link. $\mathrm{TP}^r_{ij} = \frac{m_i R_i}{u_i} + \frac{\sum_{k=1}^{j-1} \frac{m_i R_i - M_a R_{ik}}{u_i}}{u_i-(j-1)}$, where R_i is the achieved rate per PRB of RN i on the relay link.

   (b) if $\mathrm{TP}^a_{ij} \leq \mathrm{TP}^r_{ij}$, then set the end-to-end throughput TP_{ij} to TP^a_{ij} for UEs $j = j...u_i$ and exit the iteration loop.

   (c) Otherwise, set TP_{ij} to TP^r_{ij} and continue the iteration loop.

3.2.4 Performance Evaluation

Considering the MBSFN/RN-exclusive subframe configuration according to Table 3.3, we evaluate the performance of the aforementioned resource allocation strategies and prioritization techniques according to the system and simulation models given in Section 3.1. It is worth noting that these techniques will only impact the performance of relay-UEs and thus no effect will be imposed on macro-UEs.

In what follows, we define the reference model to utilize ASIT-based scheduling of RNs at the eNB and AUIT-based UE prioritization and scheduling on the access link. We refer to the proposed scheme, where AUP scheduling at the eNB along with MMF prioritization and access link scheduling are utilized, as the hop-optimization model. Herein, we aim at enhancing the low percentile throughput and the fairness in the system aiming at a ubiquitous homogeneous user experience in the network. Note that RR scheduler is used in eNB-only deployment scenarios.

Figure 3.3 presents the end-to-end UE throughput CDF for 4 RNs and 10 RNs per sector deployments in 3GPP Case 1 scenario with an ISD of 500 m. Results show, in both deployments, a clear gain at the low and mid throughput regimes brought by the hop-optimization model over the reference model.

The gains in end-to-end user throughput at the mid to low rate regimes are realized, however, at the expense of a negligible loss in the cell average throughput of about 1%. This is mainly due to the fact that RNs

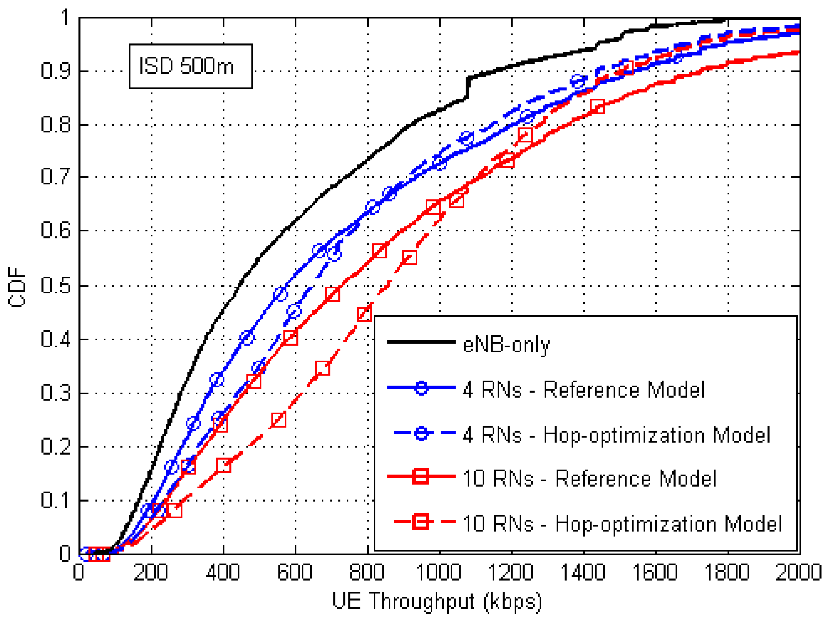

Figure 3.3. CDF of UE throughput in 4-RN and 10-RN deployments in ISD 500 m urban scenario.

experience similar channel qualities to the eNB and hence exchanging resources among them on the access link will not lead to a high loss in relay link throughput. Beside that, the extra throughput achieved at the relay link of an RN is mostly translated to access link gain as the latter is not the bottleneck to the system performance.

The throughput gains at the low and mid throughput regimes as a result of the hop-optimization model yield as well higher fairness. As depicted in Figure 3.4, the deployment of 10 RNs per sector (ISD 500 m) may even result in a deterioration of the system fairness as is the case for the reference model. Figure 3.4 presents the CDF of Jain's fairness index for relay-UEs and for the UEs in the whole system. It is clear that the hop-optimization model results in a much better fairness in the RN cell, which in turn leads to better system fairness. It is worth noting that more pronounce gains are obtained in the suburban scenario with ISD 1732 m [V].

3.3 Relay Cell Range Extension

In Section 3.2.1, we have seen that the relay link is actually the bottleneck for the system performance considering that it competes with the

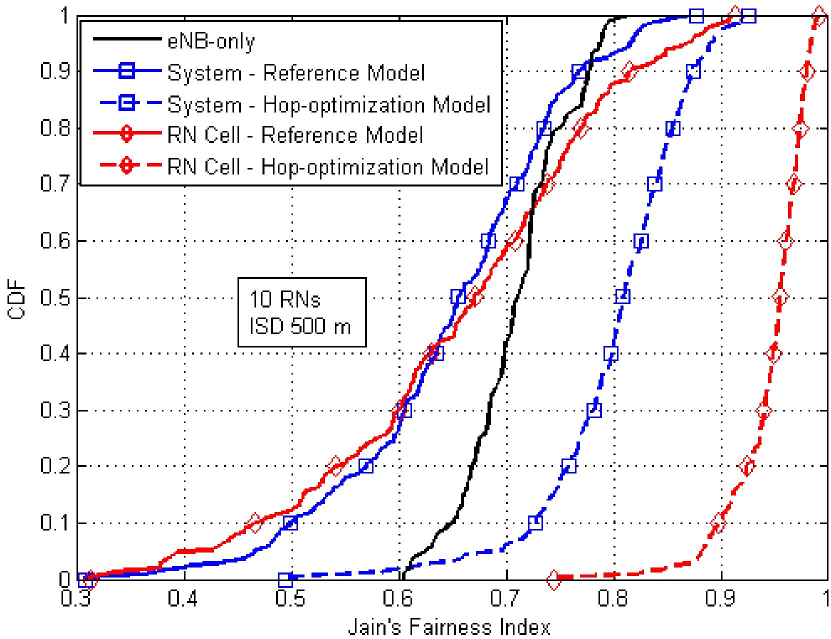

Figure 3.4. CDF of Jain Fairness Index reflecting the fairnes in the RN cells and the system as a whole for 10-RN deployment, ISD 500 m urban scenario.

macro-UEs for resources available at the eNB. Accordingly, we end up with abundance of resources on the access link of the RNs which are not utilized, whereas the eNB is overloaded. This problem is a direct implication of the low transmission power and limited antenna capabilities of RNs which implies small coverage areas and hence low load.

A practical solution for the problem of resource utilization inefficiency in RN deployments is given by relay cell range extension (CRE). CRE can be realized by introducing a bias to cell selection and handover decisions [54] along with a reduction in eNB transmit power [55][VI]. CRE results in an extension of the RN cells, thus, achieving a better load balance in the network.

CRE techniques has been as well investigated for picocell deployments in [56, 57, 58, 59] showing significant gains. It is worth noting, however, that picocells are differentiated from in-band RNs by a fixed backhaul link, assumingly satisfying the capacity requirements on the access link without adding any load on eNB. On the other hand, Type 1 relay deployments are characterized by the wireless in-band relay link, where RNs and macro-UEs compete for the same resources at eNB. For instance, handing over a UE from an eNB to a Type 1 RN cell requires that the eNB still allocates additional resources on the relay backhaul link of the

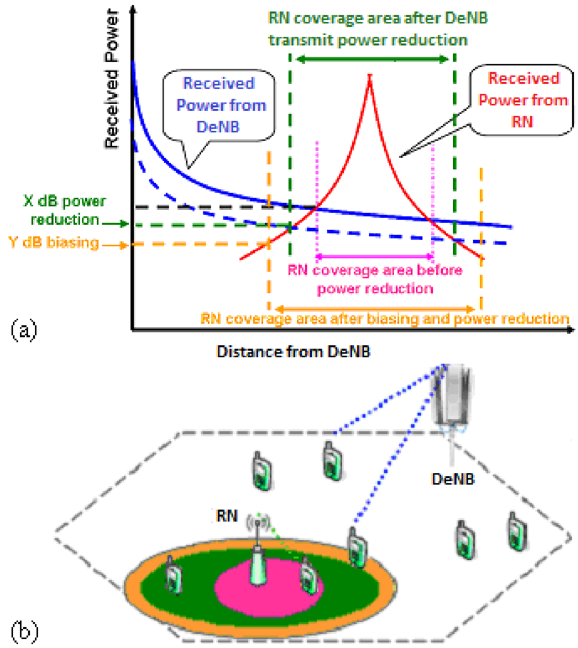

Figure 3.5. Relay CRE via power reduction and biasing: Received power (a) and extended coverage (b).

RN to serve the UE on the two-hop connection.

To better illustrate the CRE concept, let us model a reduction of eNB transmission power by X dB and biasing by Y dB. Considering that the RSRP changes proportional to the transmit power of the access nodes, the RSRP of an eNB after power reduction received at the UE can be modeled as: $\text{RSRP}_{\text{eNB}}^{\text{ext}} = \text{RSRP}_{\text{eNB}} - X$. On the other hand, after adding a bias to the RN cell selection and handover procedure, the cell selection can be formulated as: $\arg\max\{\text{RSRP}_{\text{eNB}}^{\text{ext}}, \text{RSRP}_{\text{RN}}+Y\}$. The concept is illustrated in Figure 3.5.

Considering that both, power reduction and biasing, have the same impact on cell selection and handover procedure, they can be modeled as a common effective biasing, which is the sum of both values. The coverage extension for different effective biasing values is given in Figure 3.6. A moderate extension value of 6dB results in an extra 15% of the total macrocell coverage in urban scenarios being served by RNs. On the other hand, in suburban scenarios, coverage extension is limited to an extra 5% of the total macrocell area being served by RNs afer CRE.

Such behavior is explained by the different characteristics of the propagation models in both scenarios. It is worth noting that deploying 10 RNs per sector instead of 4 RNs does not increase the RN coverage area pro-

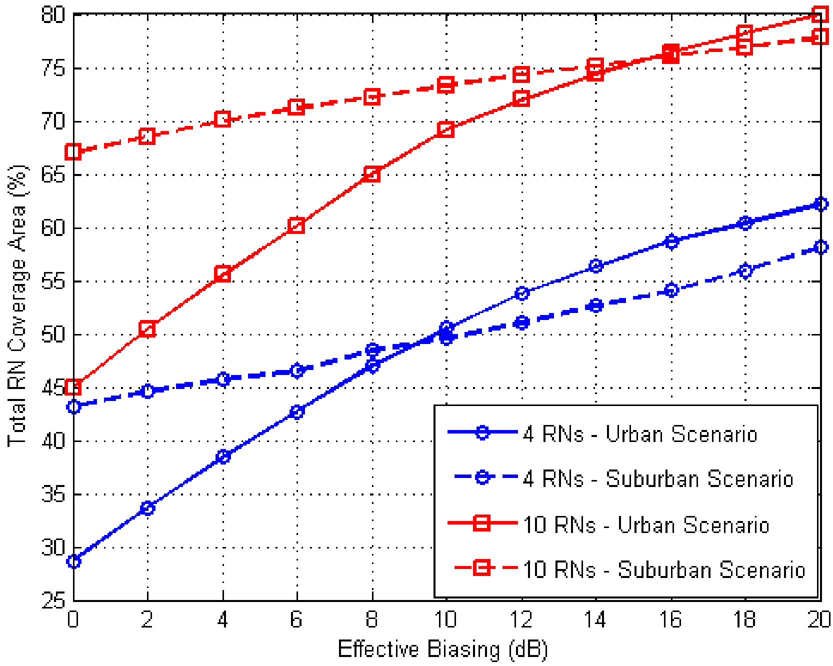

Figure 3.6. Extension of RN cells coverage area as percentage of total macrocell area in terms of effective biasing in urban and suburban scenarios.

portionally. This is due to the overlap in extended RN cells and relatively lower increase in the total RN coverage since the second tier of RNs is deployed closer to the eNB; each tier consists of 5 RNs (see Figure 3.1).

In what follows, we illustrate the impact of CRE on the performance of RN deployments.

3.3.1 CRE Performance Evaluation

Though both CRE techniques are expected to bring throughput gains due to better load distribution, the impact on SINR is different. The SINR distribution is degraded when biasing cell selection and handover thresholds. Handing over cell-edge macro-UEs to RNs results directly in degradation in SINR values and leads to outage for biasing values as of 7 dB. Such behavior is a result of embracing UEs into the RN cell, while they suffer from eNB interference that is stronger than that of the signal from their own serving RN cell; cell selection has been forced against the experienced radio signal conditions.

On the other hand, eNB transmission power reduction translates into lower interference levels on relay-UEs, whereas RNs still transmit at the same power level. Further, UEs joining the RN cell were cell-edge UEs

Key Performance Indicator	Bias [dB]	Power Reduction [dB]	Number of MBSFN Subframes
5%-ile TP Level	1	10	3
50%-ile TP Level	0	8	4
Average TP	7	10	4

Table 3.4. CRE settings configuration achieving optimum performance for different key performance indicators in 3GPP urban scenario with 4-RN deployment.

with SINR around the 0 dB level, and hence lowering the interference on them and handing them over to an RN with good signal will significantly improve their experienced SINR levels. In an urban scenario, which is typically interference limited, macro-UEs are not affected by power reduction. However, in a coverage-limited suburban scenario, SINR degradation is experienced by cell-edge macro-UEs.

Hence, effective CRE should adapt power reduction parameter X and biasing parameter Y according to the propagation conditions and deployment scenario. Yet another influential parameter in CRE is the resource allocation at the eNB and RN. Allocated resources are to conform with the extended range and load of RN cells. Combinations of the parameters will lead to different performance at the 5%-ile, 50%-ile, and mean throughput. Therefore, a desired performance can be achieved by properly setting X, Y and the number of RN-exclusive MBSFN subframes to maximize the key performance indicator (KPI) reflecting the requirements of a network operator.

Table 3.4 presents the CRE settings optimizing the 5%-ile, 50%-ile, and mean throughput in a 4-RN urban deployment [VI]. First of all, compared to the optimum configuration in Table 3.3, it is seen that CRE require different subframe configuration at the eNB, mainly shifting more resources to the relay link as the RN cell load increases. For example, if we aim at optimizing the cell edge UE performane by focusing on the 5%-ile UE throughput as the performance criterion, a very large eNB power reduction and a mere 1 dB bias are to be used. This is due to the fact that the considered urban scenario is interference limited; as discussed beforehand, biasing degrades the SINR of cell edge UEs due to increased interference levels, whereas eNB power reduction improves their experienced SINR levels since interference is reduced. On the other hand, in order to enhance the average UE throughput, focus is to be put on increasing the high throughput regime UEs. This is achieved for $X + Y = 17$dB

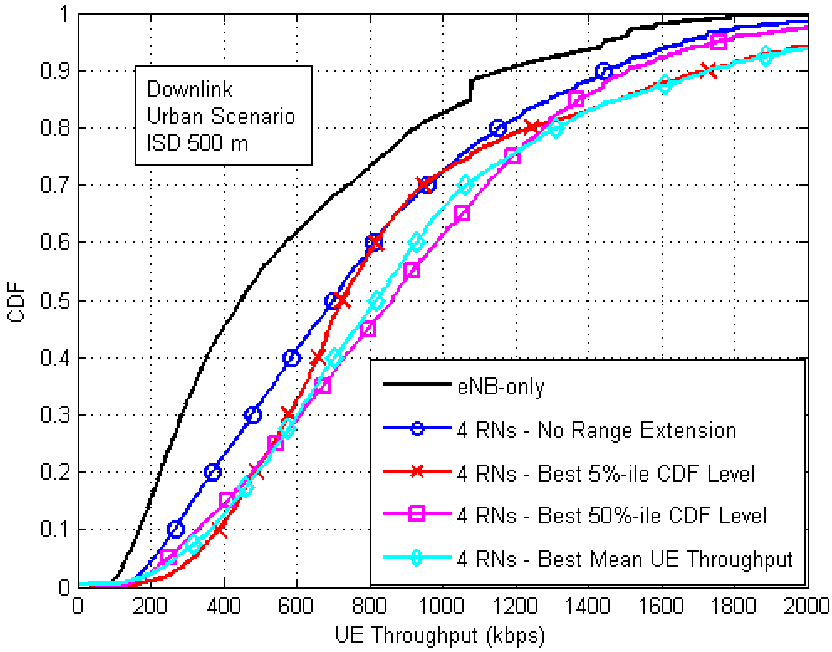

Figure 3.7. UE throughput distribution considering different KPIs as optimization criterion in DL of 4-RN urban scenarios.

and allocating one more subframe for relay link communication.

The corresponding throughput performance is illustrated in the throughput CDFs given in Figure 3.7. In contrast to the SINR behavior, a clear gain in UE throughput is experienced. Similar CRE behavior is as well experienced in 10-RN deployments in urban scenarios (see Figure 3.8 (a)), whereas the gains in suburban scenarios are moderate (see Figure 3.8 (b)) [VI].

In a nutshell, deploying RNs and extending their coverage relaxes further the competition for resources at the eNB thus boosting the performance of macro-UEs. As well, the power reduction reduces the interference in the system and combined with biasing in some cases, it provides abundance of resources for UEs which can then overcome any deterioration in SINR. However, it is worth noting that in some cases, large CRE, e.g. case of maximizing average UE throughput, can cause notable degradation in the 5%-ile throughput due to very high interference on the RN cell edges, where UEs are forced by CRE into the RN cells, though their experienced radio conditions are bad. For some UEs, the loss in SINR cannot be compensated by scheduling more resources and might in some cases even lead to radio link failures. In this context, inter-cell interference coordination (ICIC), when jointly considered with CRE, might be

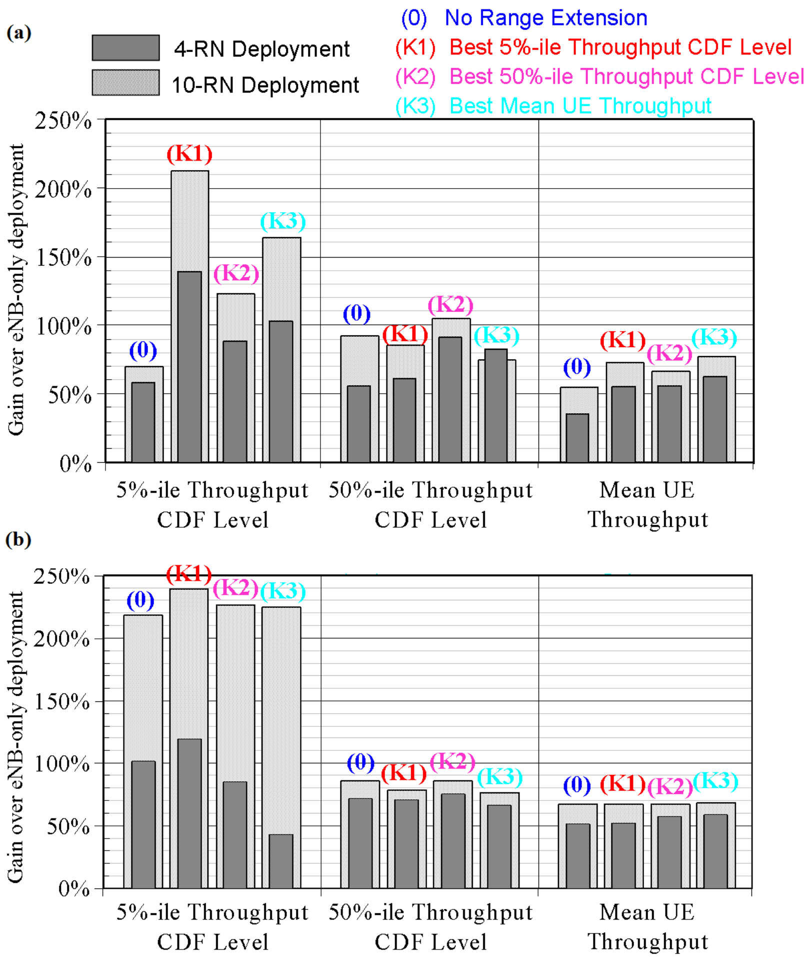

Figure 3.8. Achieved DL gains of RN deployments with/without CRE in 4-RN and 10-RN deployments: (a) urban scenario and (b) suburban scenario. K1 illustrates the CRE gain when optimizing the cell edge performance, i.e. 5% throughput CDF level. Similarly, K2 and K3 optimize the 50%-ile level and average UE throughput, respectively.

helpful in certain deployment scenarios to overcome such problem and relax the range extension. In the following subsection, we elaborate on that.

3.3.2 Interference Coordination and Cell Range Extension

ICIC techniques within the LTE framework, Release 8 and Release 9, are limited to the frequency and power domains. Frequency planning, by means of allocating exclusive subbands to neighboring access nodes (hard or static frequency reuse), seems to be the most straight forward method to avoid co-channel interference. Another well-known approach is the fractional frequency reuse, where a part of the spectrum is fully reused among access nodes whereas the other part is assigned via an exclusive hard frequency reuse approach. The main advantage of such approach is the very high SINR levels where UEs are not interfered by neighboring cell, however, the loss in throughput due to inefficient utilization of resources made them unfavourable for LTE. Finally, soft frequency reuse utilizes the whole spectrum at all access nodes though with a non-uniform power spectrum allowing to limit the interference on certain parts of the spectrum by each access node. ICIC techniques promise moderate to low gains, though they are mostly inefficient in highly loaded cells scenario.

In LTE-Advanced, a new degree of freedom was introduced allowing ICIC techniques to utilize time-domain resource coordination, labeling such schemes as enhanced ICIC (eICIC). The extension is seen as a complement to range extension in heterogeneous networks. eICIC techniques promise to relax the range expansion by significantly lowering the eNB interference on UEs moved to the small cells (RNs or picocells) upon range expansion. For that reason, almost-blank subframes (ABS) are used at the eNB; ABSs are configured in 40 ms patterns to align with the uplink HARQ round trip times [1]. The result of utilizing ABSs lead to a tricky tradeoff between decreasing number of available resources at eNB compared to better SINRs for UEs connected in the small cells and chance for further range expansion which offloads the macrocell. Whereas, good results are expected for hot-spot scenarios considering Picocells, gains might easily vanish or even losses might be experienced in a coverage-enhancement scenario, where the distribution of UEs is homogeneous.

Different works in literature have touched on static frequency planning [60, 61] and adaptive frequency planning [62] to mention a few. There have been also various dynamic ICIC schemes for RN networks with full frequency reuse, e.g. [63, 64]. However, most of the work on ICIC/eICIC and CRE has been conducted assuming picocell deployments [59, 65, 66, 67, 68, 57, 69], where high gains were shown.

However, the main difference between picocells and RNs is that the handovered UEs due to CRE are still to be indirectly served via the eNB. This imposes a notable load on the eNB as compared to the picocell scenario. Further the access link cannot be fully utilized due to the relay link limitation and hence less resources are usable on the access link of an RN as compared to a picocell. Main issue still is that such limitations might not allow enough offloading for the eNB to compensate the loss of resources.

The considered scenario herein is an example of such scenarios; we assume homogeneous UE drops in a network and full buffer traffic model.

Hence, in our contribution [VII], we focus on the interference from RNs to other RNs or macrocells. Relay deployments add to the macrocells underlying small cells which reuse the same set of resources with the macrocells. On one hand, with cell edge deployments, the impact of traditional inter-cell interference between macrocells will be relaxed due to relaying deployment where macrocell UEs are mostly away from macrocell edges. On the other hand, new cell edges and hence interference is experienced by introducing RNs.

The main idea in [VII] is to overcome the interference from RNs by using time-domain interference coordination based on the observation that the access link of an RN is usually underloaded. The unutilized resources on the access link are packed into subframes, where the RN will not generate notable interference on other access nodes; this eases the coordination since alignment is done on subframe-level in time-domain rather than PRBs. Depending on the number of unutilized subframes and their location within a radio frame, different subframe patterns are created. In this context, scheduling on the access link with different subframe prioritizations patterns at neighboring RNs is expected to enhance the performance of cell edge UEs. The critically interfered cell-edge UEs served by the neighboring cells of an aggressor RN, i.e. RN interfering reception of serving cell at UE, are to be scheduled on non-utilized subframes of the interfering RN. Similarly, the eNB schedules its UEs on resources where they experience lowest interference from RNs. The subframe patterns, i.e. combination of unutilized subframes, can be modified on the fly to account for multi-user diversity (though not fully utilized) ; information can be relayed to neighboring RNs and eNBs directly using the Relative Narrowband Transmit Power (RNTP) message [1] or through a central entity.

Results show clear SINR improvement in urban deployments, where RN interference was mainly limiting the UE SINR after reducing the eNB interference by means of eNB power reduction CRE. When aiming at optimizing the 5%-ile throughput in urban depployments, the proposed interference coordination scheme provides extra 10% (in 4-RN deployment) and 35% (in 10-RN deployment) throughput gain when using eNB-only deployment as a reference scheme. In suburban deployments marginal gains are observed, namely 1% gain in 4-RN deployment and 7% gain in the 10-RN deployment, are observed at the 5%-ile throughput on top of CRE gains over macrocell deployments.

It is worth noting that relay-UEs, whose throughput is limited by the relay link, do not benefit from interference coordination. However, the scheme improves the access link SINR and reduces the number of resources required on the access link, consequently reducing the interference imposed on the macro-UEs. Cell-edge relay-UEs, for which the number of scheduled PRBs on the access link is the bottleneck, will benefit though. In addition, simulations in suburban models show marginal gains in the 4-RN deployment, since it is not the co-channel interference but the received power levels which limit the system performance in suburban scenarios.

3.3.3 Practical Realization Considerations

The 3GPP LTE specifications impose limitations on the optimization of CRE. Specifically, the cell selection and handover parameters (power reduction and biasing parameter values) and the number of configured MBSFN subframes, need to be aligned in DL and UL, such that a UE is connected to the same access node (eNB or RN) both in UL and DL and the same subframe configuration is utilized. As optimum CRE settings might be different for DL and UL, either of them shall be prioritized in terms of performance or a tradeoff is needed; in both cases, this will influence the choice of CRE settings [VI].

Another practical limitation comes from the complexity pertaining to choosing the optimal CRE parameter configurations. Assuming power reductions up to 10 dB, biasing up to 7 dB, and up to 6 backhaul subframes with granularity of 1 unit for each parameter, a comprehensive brute-force approach to performance optimization would require 528 network trial runs in DL. This may prove too time consuming and costly to network operators. In this context, optimization algorithms such as Taguchi's method can be used to automate the CRE settings optimization and reduce significantly the network trial runs required during network planning or offline optimization [70, 71]. Taguchi's method uses nearly orthogonal arrays to select a reduced set of parameter combinations from the full search space to be tested from the full search space. The number of selected combinations determines the number of network trials being carried out and evaluated against a performance measure. Using all the trials' results, a candidate solution is found and the process is repeated till a desired criterion is fulfilled. Performing CRE utilizing Taguchi's method, it is noticed that the required network runs can be kept below 10% of the network runs needed in the exhaustive search approach [VI]; trial network runs can be still significantly reduced by aiming at gains close to the optimum rather than targeting optimum performance.

3.4 Relay-to-Relay Interference

Due to time-division multiplexing of relay link and access links for inband relaying (see Section 3.1.2), a new interference type known as RN-to-RN interference, aka access-to-backhaul interference, may occur in DL of relay-enhanced deployments. RN-to-RN interference is experienced when an RN transmits on its access link and interferes the backhaul reception on the relay link of another RN. RN-to-RN interference can occur due to asynchronous operation in FDD systems, which results in partial overlapping between the reception and transmission on relay and access links. Another main reason for such interference is the misalignment in scheduling relay link transmissions at different eNBs, or consequently misaligned configuration of MBSFN subframes at RNs; this is the case as eNBs adapt the subframe configuration according to network variations, e.g. cell loads or traffic. In this context, an RN-to-RN interference free system is a one where perfect inter-node synchronization is achieved and a system-wide MBSFN subframe configuration is applied.

As opposed to traditional inter-cell interference where the serving cells usually admits the best signal quality at the receiver, RN-to-RN interferene might be several folds stronger than the received serving cell signal power level due to the small RN cell coverage area and thus the relatively close-by deployment of RNs; e.g. 70 m inter-RN distance is typical in different deployments [III]. Hence, there is an urge to investigate the impact of RN-to-RN interference within LTE-Advanced, especially since RN-to-RN interference has not been adequately addressed in 3GPP standardization or scientific community in general. In 3GPP technical contributions [72] and [73], the impact of RN-to-RN interference was briefly analyzed. Yet, current works on relaying deal with RN-to-RN interference on a network-scale assuming tight synchronization among different access nodes and a system-wide subframe configuration alignment. However, this does not allow optimizations e.g. according to the cell loads and traffic variations in a network.

In our contributions [VIII, IX], we address the problem by aligning the subframe configuration at different network levels to avoid RN-to-RN interference. In [IX], the problem is investigated in scenarios assuming different degrees of inter-eNB coordination resulting in different subframe alignment capabilities among the eNBs, e.g. intra-cell alignment where all RNs in one macrocell have the same subframe configuration as opposed to intra-site alignment where the same configuration is utilized for all RNs in the 3-sector site. Results show that RN-to-RN interference can have moderate to severe impact on the system performance of RN deployments. Furthermore, it has also been shown that intra-cell subframe configuration alignment and use of directional antennas (DAs) at the RN for the relay link can relax the impact of interference. Yet, such an approach remains short from solving the problem, especially when considering a large number of RNs per cell and unavailability of DAs due to cost constraints [VIII].

The characteristics of RN-to-RN interference imply that an optimum solution should consider the locality of such problem and approach it accordingly; RN-to-RN interference is a local problem which originates from RNs deployed in the close vicinity of each other and is thus confined to a relatively small area considering the signal power degradation due to propagation. That is, interference is confined to cases where RN pairs admit low signal attenuation between them, e.g., either due to short distance or LOS propagation conditions. Thus, there is no need to coordinate and align subframe configuration for all RNs in the network or within a macrocell as this might introduce unnecessary rigidity in the system. Rather, a localized solution where RN-to-RN interference is divided into many small local problems and then handled accordingly seems to be a promising approach [VIII]. The goal is two-folded: high flexibility to adapt to network variations, and mitigating RN-to-RN interference in the area where it is a problem.

In this manner, a divide-and conquer approach (DCA) was proposed in [VIII], which requires inter-eNB coordination and partial subframe configuration alignment. DCA follows a centralized approach where a proposed Operations, Administration and Maintenance (OAM) interference management entity decides on the subframe configuration of each RN in the network based on interference measurements from the different eNBs. In particular, DCA proposes a two-step solution, namely grouping of RNs in exclusive groups according to interference measurements, possi-

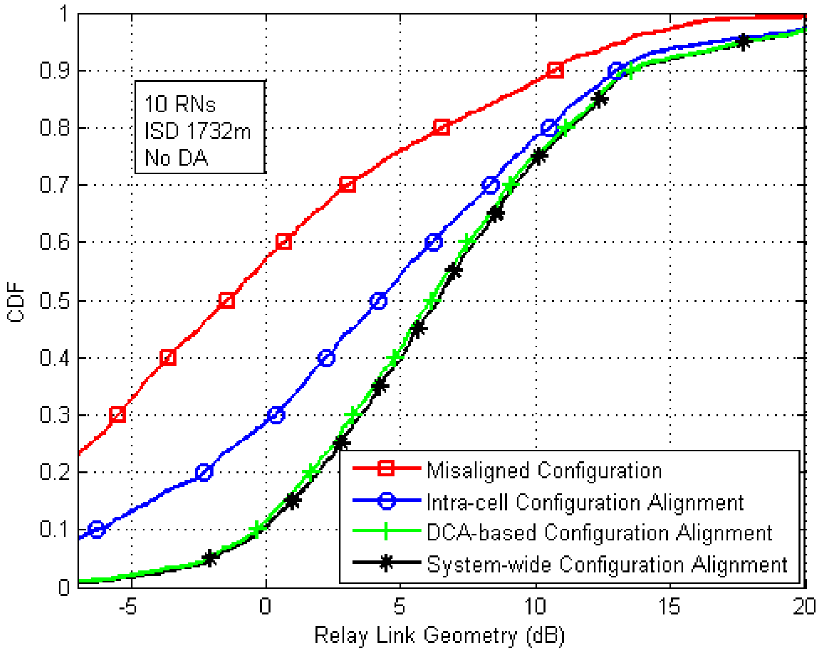

Figure 3.9. Distribution of the relay link geometry for different subframe configuration alignment strategies in 10-RN suburban scenario. Relay link geometry is defined as the wideband SINR level when assuming 1x1 Tx-Rx antenna configuration.

bly with RNs belonging to different cells, and then aligning the subframe configurations within each group. The size of the group could be either limited or made flexible according to the interference conditions in the network. In the former case, flexibility in subframe configuration comes at the cost of lower SINR performance on the relay link due to higher RN-to-RN interference. Note that DCA creates some level of overhead and increases the system complexity.

Figure 3.9 illustrates the impact of RN-to-RN interference in a 3GPP suburban scenario where 10 RNs are deployed per macrocell and omni-directional antennas are utilized at the RNs on both access and relay links. Performance is studied in terms of the relay link geometry, which is the wideband SINR level when assuming 1x1 Tx-Rx antenna configuration at the RNs and eNBs. The system-wide configuration alignment and completely disaligned configuration are taken as refereces for the two extremes of RN-to-RN interference, i.e. no interference at all and worst-case scenario interference. It is seen that interference in the worst case can severely hurt the SINR on the backhaul link with more than 5 dB SINR degradation against the best case on most of the CDF levels. Align-

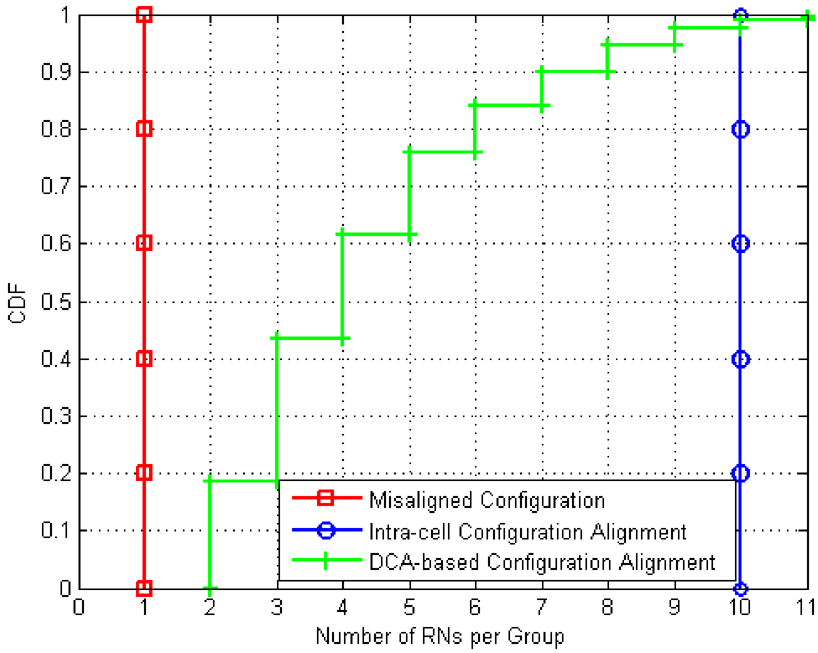

Figure 3.10. Distribution of the number of RNs whose subframe configuration is aligned to avoid RN-to-RN interference in 10-RN suburban scenario. System-wide configuration alignment (not shown in Figure) requires that all RNs in the network have the same configuration and is thus not shown herein as it scales with the network size.

ing the subframe configuration within the macrocell, i.e. intra-cell alignment, significantly relaxes the impact of interference, though it falls short from providing close to optimum results. Since such scheme does not require inter-eNB coordination, the interference from RNs outside the same macrocell is very high thus reducing the efficiency of interference mitigation. Finally, it is seen from Figure 3.9 that DCA can almost completely mitigate the impact of RN-to-RN interference providing SINRs with less than 0.5 dB degradation from the ideal system-wide configuration alignment. This is achieved by aligning the subframe configuration within relevant RN groups. The distribution of the number of RNs grouped together is given in Figure 3.10; DCA aligns the configuration for a small number of RNs, which, though, are not necessarily in the same macrocell.

It is worth noting that the impact of RN-to-RN interference is more pronounced in such a deployment scenario due to the high number of deployed RNs, better propagation conditions and unavailability of DAs at RNs. Intra-cell subframe configuration alignment can provide excellent mitigation capabilities if DAs are used and low number of RNs are deployed in the cell [IX].

3.5 Energy Efficiency of Relay Deployments

In what preceded we have investigated the capacity and coverage enhancements brought by relay-enhanced networks and addressed different challenges arising therein. In this section, we present our investigation [X] on energy efficiency of RNs, which is another decisive factor in adopting the relay technology.

Energy efficient networks are important for extending the battery life of a UE, reducing the operation costs of a network operator, enhancing corporate image of operators and vendors alike, and providing a lower total energy consumption which reflects in a lower CO_2 footprint and negative impact on environment.

The evolution of RANs is ultimately leading to unavoidable increase in energy consumption. Yet efficient networks can significantly limit such increase and still provide the required performance. Energy efficiency can be evaluated in terms of the area power consumption (APC) required to achieve a certain coverage criterion and in terms of the throughput power consumption (TPC) in a predefined coverage area [74].

TPC studies the energy efficiency from a bit-per-power unit perspective, which is a viable metric when aiming at evaluating the gain in capacity brought by RN deployments. On the other hand, APC evaluates whether the coverage increase brought by RN deployments is justified in terms of the power consumption increase. APC assesses the power consumption of a network relative to its coverage area and is measured in kilowatt per square kilometer. In this context, we normalize the energy consumed by the coverage area assuming a fixed coverage criterion, e.g. 10%-ile UE throughput CDF level; whereas for TPC, the coverage area itself is fixed. APC will thus be evaluated following the coverage extension methodology presented in Section 2.3. This is especially interesting since the deployment prioritization of RN networks in LTE-Advanced early releases aims at coverage enhancement and extension capabilities of RNs.

For this evaluation, we adopt the power models presented in [75]. Therein, the power consumption of different access nodes is modeled as the sum of the static and dynamic power consumptions. Static power is the power consumed to keep the access node on. The static power depends on factors such as the minimum transmit power (related to e.g. control signalling), power amplifier efficiency, static signal processing overhead, and cooling loss. On the other hand, the dynamic power consumption depends on factors such as power amplifier efficiency, dynamic signal processing per link, number of active links (cell load), and dynamic transmit power per link.

The model in [75] considers a traditional base station without dynamic power saving mechanisms and hence the power model is described by the static part only. In contrast to macrocell power consumption model, due to smaller coverage and thus more dynamic variation of the number of served UEs, the power model for RNs consists of both a static and a dynamic part. In our study [X], the power model is a modified form of that of a micro base station given in [75]. Specifically, we take into consideration the rate of an RN being on (when there is at least one UE in the cell), number of configured MBSFN subframes where no transmission takes place, and the access activity factor, i.e. transmission on only part of the access link resource blocks.

The energy efficiency of RN deployments is illustrated in Figure 3.11 and Figure 3.12. Figure 3.11 shows the APC for urban RN deployments. Though introducing RNs increase the power consumption in the network, the coverage extension they offer is achieved at a lower unit power per unit area cost, thus increasing significantly the energy efficiency of such

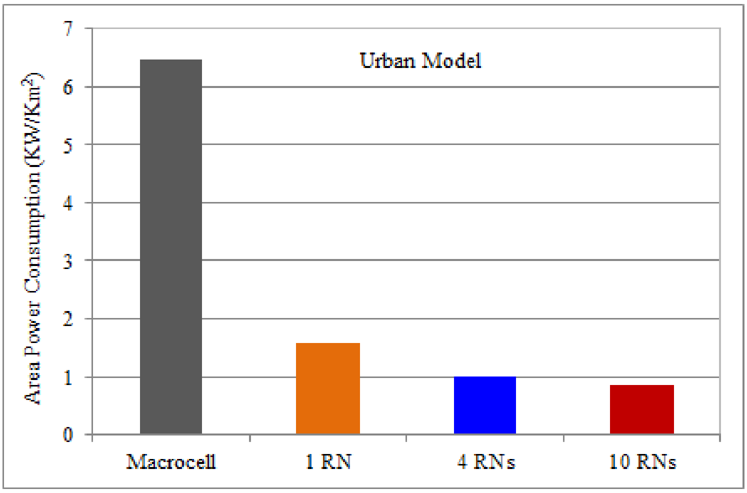

Figure 3.11. Area Power Consumption of RN deployments in 3GPP urban scenarios.

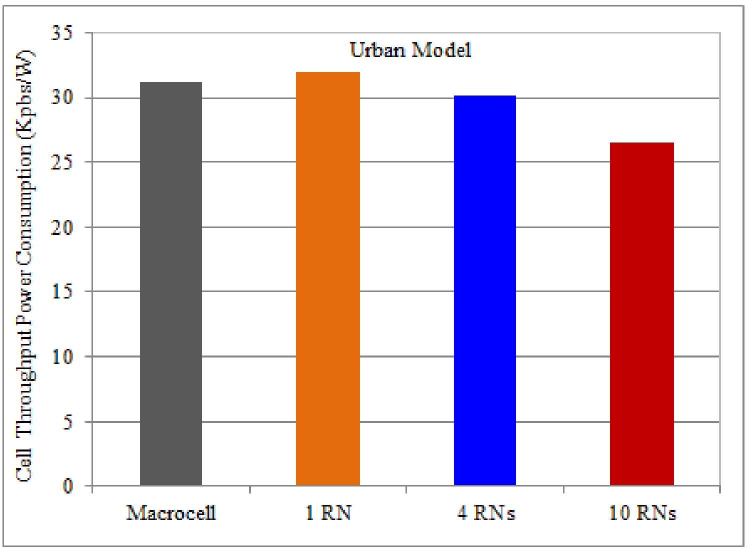

Figure 3.12. Throughput Power Consumption of RN deployments in 3GPP urban scenarios.

networks. It is worth noting that such gain is as well attributed to the fact that the urban scenario is interference-limited. On the other hand, APC savings in the suburban model are moderate since RNs do not enable notable ISD extensions considering the power consumption overhead they add to the network [X].

Figure 3.12 illustrates that the RN deployments achieve low efficiency improvements and even low losses for some deployments. This is mainly due to two reasons. First, the deployment prioritization aims at improving the cell edge performance and not the capacity of a hot-spot scenario and hence the capacity improvement is somehow limited. This includes the scheduling scheme applied herein, where we assumed a max-min fair scheduler which aims at improving the throughput of bad users at the expense of lower throughput for cell center UEs. The second reason is that RNs are limited by the backhaul link being the bottleneck on the two-hop communication. Similar performance is seen in suburban scenarios [X].

It is worth noting that the above results highlight the ¨raw¨ energy efficiency of RN deployments in comparison to macrocell deployments. In this context, different studies aiming at enhancing the UE energy consumption, e.g. [76, 77, 78], or the energy consumption of access nodes, whether macrocells or micro base stations, e.g. [79, 80, 81], are still valid and corresponding benefits can be harnessed in both network types.

4. Conclusions

In-band relaying has been investigated in a study item of 3GPP LTE-Advanced and later standardized as a promising cost-efficient approach to alleviate propagation losses at high carrier frequencies especially at cell edges and to achieve a more homogeneous user performance in the network. The research towards this thesis has gone side by side with the standardization efforts aiming to validate the viability of relaying as an enhancement technology to current RATs and solve problems arising when realizing the relaying technology in practice. The work herein has addressed different problems within the context of LTE-Advanced.

First, the feasibility of different relaying modes have been studied and the performance of relay node deployments have been evaluated in terms of coverage and capacity enhancements in different propagation environments. Among the proposed 3GPP relaying types, half-duplex DF in-band relaying was proven to provide better performance than full-duplex AF relaying. In specific, it has been shown that Type 1 DF RNs provide clear capacity and/or coverage improvements in some scenarios, though the performance significantly depends on the propagation conditions on the access link and the probability of being in LOS conditions. Further, it was shown that the overhead of in-band relaying is low in coverage enhancement scenarios, though the impact is significant on capacity. In this context, simple RN network planning techniques were proposed which significantly boost the SINR on the backhaul relay link and hence the experienced end-to-end user throughput.

Second, radio resource management challenges related to resource allocation and scheduling, load balancing and interference coordination in relay deployments were addressed. It was shown that throughput fairness can be significantly improved in the network by properly splitting resources between the RNs and UEs at the eNB and utilizing max-min fairness to prioritize UEs on the relay link and schedule them on the access link of RNs. Thereafter, the resource utilization efficiency in the network was improved by extending the RN cell ranges which proved to be an important load balancing feature providing large gains at different throughput regimes. The combination of ICIC and CRE was as well investigated showing that ICIC can slightly relax CRE limitations leading to moderate gains. Another interference type referred to as RN-to-RN interference arising from misalignment of access and backhaul transmissions of in-band RNs was then investigated. It was shown that local alignment of subframe configuration can mitigate RN-to-RN interference in different scenarios. Finally, the energy efficiency of in-band RNs was analyzed showing yet another advantage of RN deployments as energy-efficient coverage-enhancers.

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Errata

Publications V, VII, VII, IX, and X

- The expression of LOS probability for the relay link channel model in the suburban scenario ("ISD 1732m - Suburban Model"), given in the *Simulation Parameters* table, should be corrected as follows: $Prob(LOS) = 1 - (1 - exp(-(R - 0.01)/0.23))^{\alpha}$. The equation in the published papers includes a typo where the 0.23 factor in the denominator is mistakenly given as 1.15. Note though that the right parameter value is used in simulations and hence presented results and conclusions remain valid.

Publication II

- A typo occured in the abstract of the publication, where the terminology '3G' in the sentence *'In this paper, we consider the performance of full duplex Amplify-and-Forward (AF) and half duplex Decode–and-Forward (DF) Relay Nodes (RNs) from 3G LTE-Advanced perspective.*' should have been '3GPP'.

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The stringent requirements of 4G access networks have triggered the embodiment of low-power relay nodes as part of the network infrastructure. Various types of relays are supported in IEEE 802.16m and LTE-Advanced considering different capabilities and backhauling characteristics. The matter of this study is the Layer 3 relay node whose wireless backhaul link and access link to the user operate on the same frequency band. Challenges pertaining to realizing such technology within LTE-Advanced context are addressed herein. A feasibility study of different relaying modes is provided and the performance of relay deployments is evaluated in different propagation environments. Further, novel techniques are proposed to alleviate the backhaul link limitation and to address resource allocation, load balancing and interference coordination in such multi-hop heterogeneous deployments. The significant system performance improvement achieved along with the energy efficiency of relay nodes proves that relaying is a viable enhancement technology.

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