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UPLINK RESOURCE ALLOCATION IN RELAY ENHANCED LTE-ADVANCED CELLULAR NETWORKS

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In parallel to HSPA evolution, 3GPP has adopted the Long Term Evolution track to fulfill the performance targets of 4G cellular networks. Multi-hop networks consisting of fixed decode and forward relays nodes are proposed to relax the capacity and coverage limitations encountered by traditional macro base station deployments. The relays are designed to operate on the in-band spectrum and support self-backhauling of user data. This thesis work provides an insight into the impact of uplink resource allocation in delivering improved user experience in relay enhanced cellular networks.

Radio resource allocation and power control play a crucial role in the performance of wireless communication systems. System level simulations reveal that reuse 1 based relay enhanced cells operate in an interference limited scenario. Therefore, a resource allocation scheme based on user grouping is investigated to coordinate and mitigate the negative effect of interference. It is shown that the proposed methodology is spectrally efficient and delivers improved system performance.

In addition to improving system performance, relaying is seen to be beneficial in significantly reducing battery consumption in devices. This is highly appealing since the next generation cellular networks are targeted towards higher bit rates and extended periods of mobile data usage. This work provides specific insights into the performance limiting criteria of the envisaged multi-hop system and, furthermore, is expected to contribute towards 3GPP's standardization of the relaying study item.

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Espoo. April 2, 2009

Anzil Abdul Rasheed

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Preface

This thesis work is undertaken for fulfillment of the requisites of the Master's Degree Program in Communications Engineering at Helsinki University of Technology, Finland. The task was performed at the research premises of Nokia Siemens Networks, Munich, Germany.

The literature is structured as follows:

- Section 1 states the motivation towards choosing the research topic - *Uplink Resource Allocation in Relay Enhanced LTE-Advanced Cellular Networks.*

- Section 2 introduces the concepts associated with the *Long Term Evolution* (LTE) technology.

- Section 3 discusses the principles of relaying in cellular networks and the advantages as well as challenges to successful relay deployment.

- Section 4 provides a background of the resource allocation metrics in LTE along with a literature review of single-hop and multi-hop resource allocation.

- Section 5 gives an overview of the system level simulator developed in this work. It mentions the most important system parameters adopted in the simulations.

- Section 6 proposes different resource allocation schemes and explains their impact on system behavior.

- Section 7 compares the proposed resource allocation schemes and highlights the merits of the best performing methodology. It further extends the particular scheme to provide the performance results in the multi-hop setting.

- Section 8 mentions the conclusions from this study and the potential for future work along the same lines.

List of Acronyms

1G	*First Generation*
2G	*Second Generation*
3G	*Third Generation*
3GPP	*Third Generation Partnership Project*
4G	*Fourth Generation*
ACLR	*Adjacent Channel Leakage Ratio*
AF	*Amplify and Forward*
AMC	*Adaptive Modulation and Coding*
AMPS	*Advanced Mobile Phone Service*
AWGN	*Additive White Gaussian Noise*
BCCH	*Broadcast Control Channel*
BCH	*Broadcast Channel*
BER	*Bit Error Rate*
CAPEX	*Capital Expenditure*
CDF	*Cumulative Distribution Function*
CDMA	*Code Division Multiple Access*
CDS	*Channel Dependent Scheduling*
CEPT	*Conference of Postal and Telecommunications Administrations*
CN	*Core Network*
CP	*Cyclic Prefix*
CRC	*Cyclic Redundancy Check*
CSI	*Channel State Information*
DCA	*Dynamic Channel Allocation*
DCCH	*Dedicated Control Channel*
DF	*Decode and Forward*
DFT	*Discrete Fourier Transform*
DL	*Downlink*
DL-SCH	*Downlink Shared Channel*
DRX	*Discontinuous Reception*
DSL	*Digital Subscriber Line*
DTCH	*Dedicated Traffic Channel*
E2E	*End-to-End*
EIRP	*Effective Isotropically Radiated Power*
eNB	*Enhanced Node-B*
EPC	*Evolved Packet Core*
ETSI	*European Telecommunications Standards Institute*
FDD	*Frequency Division Duplex*
FDMA	*Frequency Division Multiple Access*
FFFR	*Flexible Fractional Frequency Reuse*
FFT	*Fast Fourier Transform*
FH	*Frequency Hopping*
FPC	*Fractional Power Control*
FR/R1	*Full Reuse - Reuse 1*

FR/R3	*Full Reuse - Reuse 3*
GANSS	*Galileo and Additional Navigational Satellite System*
GPRS	*General Packet Radio Service*
GPS	*Global Positioning System*
GR/R1	*Grouped Reuse - Reuse 1*
GR/R3	*Grouped Reuse - Reuse 3*
GSM	*Global System for Mobile Telephony*
HARQ	*Hybrid Automatic Repeat Request*
HeNB	*Home Enhanced Node-B*
HLR	*Home Location Register*
HSPA	*High Speed Packet Access*
HSS	*Home Subscriber Server*
ICI	*Inter-Cell Interference*
IDFT	*Inverse Discrete Fourier Transform*
IFFT	*Inverse Fast Fourier Transform*
IoT	*Interference over Thermal*
IP	*Internet Protocol*
IR/R1	*Isolated Reuse - Reuse 1*
IR/R3	*Isolated Reuse - Reuse 3*
ISD	*Inter-Site Distance*
ISI	*Inter-Symbol Interference*
ITU	*International Telecommunications Union*
ITU-R	*International Telecommunications Union - Radiocommunications*
LOS	*Line-of-Sight*
LTE	*Long Term Evolution*
LTE-A	*Long Term Evolution - Advanced*
MAC	*Medium Access Control*
MBMS	*Multimedia Broadcast/Multicast Service*
MCCH	*Multicast Control Channel*
MCH	*Multicast Channel*
MCS	*Modulation and Coding Scheme*
MIMO	*Multiple-Input Multiple-Output*
MTCH	*Multicast Traffic Channel*
MUD	*Multi-User Detection*
NLOS	*Non-Line-of-Sight*
NMT	*Nordic Mobile Telephony*
OFDM	*Orthogonal Frequency Division Modulation*
OFDMA	*Orthogonal Frequency Division Multiple Access*
OLPC	*Open Loop Power Control*
OPEX	*Operational Expenditure*
PAPR	*Peak to Average Power Ratio*
PC	*Power Control*
PCCH	*Paging Control Channel*
PCH	*Paging Channel*
PDCP	*Packet Data Convergence Protocol*

PHY	*Physical Layer*
PRB	*Physical Resource Block*
PSD	*Power Spectral Density*
QAM	*Quadrature Amplitude Modulation*
QoS	*Quality of Service*
RA	*Resource Allocation*
RAN	*Radio Access Network*
RAP	*Radio Access Point*
REC	*Relay Enhanced Cell*
RLC	*Radio Link Control*
RN	*Relay Node*
RR	*Round Robin*
RRM	*Radio Resource Management*
SAE	*System Architecture Evolution*
SC-FDMA	*Single Carrier Frequency Division Multiple Access*
SDMA	*Spatial Division Multiple Access*
SGSN	*Serving Gateway Support Node*
SINR	*Signal to Interference plus Noise Ratio*
SON	*Self Organizing Network*
TCH	*Transport Channels*
TDD	*Time Division Duplex*
TDMA	*Time Division Multiple Access*
TFS	*Transport Format Set*
TIA	*Telecommunications Industry Association*
TS	*Time Slots*
TTI	*Transmission Time Interval*
UE	*User Equipment*
UL	*Uplink*
UL-SCH	*Uplink Shared Channel*
UMTS	*Universal Mobile Telecommunications System*
WCDMA	*Wideband Code Division Multiple Access*
WiMAX	*Worldwide Inter-operability for Microwave Access*
WLAN	*Wireless Local Area Network*

List of Figures

1   Motivation

The *Third Generation Partnership Project* (3GPP) evolution track includes the LTE air interface specifications in Release 8's 36-series specification branch. 3GPP has approved the functional freeze of Release 8 specifications in December 2008. Quite many interesting features such as the repeater, *Home Enhanced Node-B* (HeNB), *Self Organizing Network* (SON), 3GPP-*Wireless Local Area Network* (WLAN) inter-working, *Galileo and Additional Navigational Satellite System* (GANSS) and the public warning system have been introduced. Release 8 standardization teams will now focus on fine tuning the standard to ensure optimal performance.

Long Term Evolution - Advanced (LTE-A) compliant networks are termed as the *Fourth Generation* (4G) cellular systems since they target fulfillment of the 4G requirements specified by the *International Telecommunications Union - Radiocommunications* (ITU-R). The standardization of LTE-A is expected to be included in 3GPP Release 10 specifications. The LTE-A work group proposes novel enhancements such as the *Relay Node* (RN), *Multiple-Input Multiple-Output* (MIMO), flexible spectrum usage, cognitive radio and automatic as well as autonomous network configuration. In this thesis work, the proposed relaying study item is of prime interest. Release 10's RN aims to overcome some of the drawbacks of release 8's HeNB architecture (even though HeNB and RN have different deployment goals). A HeNB requires wired backhaul to tunnel data to the core network which introduces problems for security and charging. Also, since these devices are of plug-and-play type, their uncoordinated deployment leads to complications with respect to access control.

In cellular communications, the success of an envisioned feature is greatly dependent on the *User Equipment's* (UE's) response to the enhancement. Since the *Uplink* (UL) transmission requires the UE to perform within strict device constraints and yet satisfy system performance targets, conducting research on the *Relay Enhanced Cell* (REC) UL seemed interesting. Also, compared to LTE *Downlink* (DL), the UL appeared to be less investigated thereby providing this work with greater scope to contribute to standardization/system design. The major impact (besides protocol changes) of RN deployment in LTE-A systems is the intermediate (Relay) link between the UE and an *Enhanced Node-B* (eNB). Since RNs are designed to transmit on the in-band spectrum, the impact of interference on system performance needs to be analyzed. Also, the influence of the relay link with respect to resource share raised interest. The scenario of the REC deployed to work on the same transmission bandwidth as in a single-hop network, while improving the user experience is especially challenging due to the lack of well-designed resource allocation and interference mitigation schemes.

The coupling of the principles of relaying with resource allocation put forth a worthwhile problem to investigate and solve. The recently standardized LTE system parameters provide a great opportunity to study REC performance closer to true LTE deployment. Therefore, the availability of critical system parameters, coupled with the lack of deep insight into the performance of REC UL, provided the motivation to investigate and reveal the finer details of the envisioned network.

2 Long Term Evolution

2.1 Historical Background

The evolution of radio communications from the first experiments by Guglielmo Marconi in the 1980s to today's advanced mobile telephony is one of the most critical technological advancements of the last century. In 1981, the first international mobile communication system, namely the *Nordic Mobile Telephony* (NMT) system, was introduced in the Nordic countries. At the same time, the analog *Advanced Mobile Phone Service* (AMPS) was introduced in North America. These devices were bulky and power-hungry and, therefore, were often mounted on vehicles. These systems supported voice as well as some supplementary services and are known as the *First Generation* (1G) communication systems.

With the advent of digital communications during the 1980s, the interest in developing a successor to the analog communication system materialized and provided the foundation towards the evolution of the *Second Generation* (2G) mobile communication systems. In Europe, the *Conference of Postal and Telecommunications Administrations* (CEPT) initiated the *Global System for Mobile Telephony* (GSM) project to develop a pan-European mobile telephony system. In 1989, the work on GSM continued within the newly formed *European Telecommunications Standards Institute* (ETSI). In the United States of America, the *Telecommunications Industry Association* (TIA) proposed the IS-54 standard which later evolved into IS-95 in 1993. GSM is based on a combination of Time-Frequency Division Multiple Access (TDMA/FDMA) and the IS series is based on *Code Division Multiple Access* (CDMA).

In the later half of the 1990s, *General Packet Radio Service* (GPRS) was introduced into GSM and other cellular technologies followed up with a similar enhancement and evolved the 2G system to 2.5G. The success of the Japanese based NTT DOCOMO's proprietary wireless data service, known as *iMode*, provided the clear indication of the potential of high speed connectivity services. In the 1980s, in order to realize higher data rates, the *International Telecommunications Union* (ITU) initiated the *Universal Mobile Telecommunications System* (UMTS) which is referred to as the *Third Generation* (3G) mobile communications systems. 3G systems are based on *Wideband CDMA* (WCDMA). With increasing desire for faster connectivity and efficiency, development of evolved 3G systems like *High Speed Packet Access* (HSPA) gained momentum and are referred to as 3.5G systems. Since 1998, the 3GPP which was formed by the standards developing organizations from all over the world has been responsible for the well coordinated development of mobile telecommunications standards.

LTE is the latest standardization track initiated by 3GPP in parallel to HSPA in order to realize the performance goals of the 4G communication systems.

Figure 1 illustrates the evolution of 3GPP standards. Each frozen/completed standard is known as a *Release*. An important feature/enhancement of each release is mentioned.
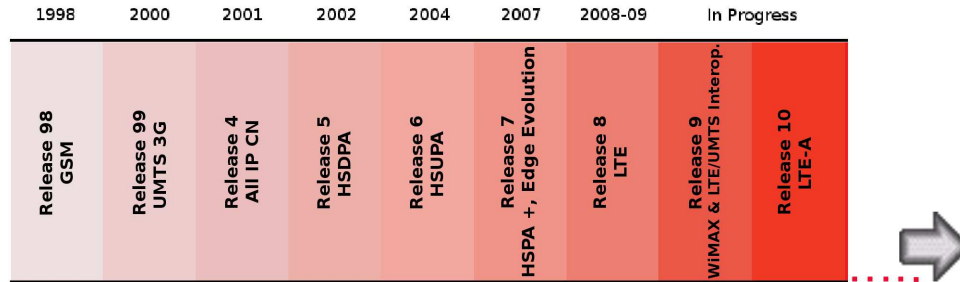
Figure 1: Evolution of 3GPP Standards

2.2 Design Targets

The radio access and core network architectures are the corner stones of every mobile communication technology. With increasing performance demands, communication systems have constantly evolved. Every modification in the communication system's design poses deployment and compatibility issues. Also, it was reasoned that a new radio access technology is required to meet the performance goals of the next generation communication systems. With these considerations in mind, 3GPP rolled out the LTE track. As the name suggests, LTE is considered as a long term answer to overcoming the performance constraints of present day mobile radio access technologies. The design targets of the LTE system are as follows [4]:

- **Performance**
  LTE systems target high spectral efficiency of 2.5 bps/Hz in the UL and 5 bps/Hz in the DL. For a 20 MHz spectrum allocation, this corresponds to 50 $Mbps$ and 100 $Mbps$ data rates in the UL and DL respectively. Both *Frequency Division Duplex* (FDD) and *Time Division Duplex* (TDD) modes are supported. The best system performance is obtained at $0 - 15\ km/h$ speeds. The LTE system is designed to support user mobility rates as high as 350 km/h. In noise limited scenarios, the system should satisfy the given performance metrics of throughput, spectral efficiency and mobility requirements for a 5 km cell radius. Acceptable degradations in system performance have been defined for cases such as high mobility and larger cell radius. LTE supports enhanced *Multimedia Broadcast/Multicast Service* (MBMS) with the possibility to initiate simultaneous voice calls and MBMS. In MBMS, MB and MS imply the support for generic multimedia services such as television broadcast and

multicast based interactive services respectively. The LTE framework aims to provide services with reduced latency. The latency requirements are split between the control-plane and user-plane. The control-plane latency refers to the delay in transition from different non-active states to an active state. The user-plane latency refers to the delay in transmitting an *Internet Protocol* (IP) packet from the terminal to the *Radio Access Network* (RAN) edge node or vice-versa.

- **Spectrum Allocation**
  LTE systems are designed to be deployable in the IMT-2000 frequency band. Therefore, the system should co-exist with the legacy GSM and UMTS networks and support inter-system handovers. Also, LTE systems can be deployed in both paired and unpaired spectrum allocations, i.e. the system should support both FDD and TDD. LTE systems support bandwidth scalability and can operate in any of the LTE specific allocations of 1.25, 1.6, 2.5, 5, 10, 15 and 20 MHz. The support for bandwidth scalability permits the deployment of LTE systems in the existing 2G/3G spectrum and assists in easier migration towards higher spectrum allocations. 3GPP release 8 defines 14 and 8 frequency bands for FDD and TDD respectively. A LTE enabled device's frequency band support is release independent which means that the first release of LTE need not support operation on all the defined bands.

- **Architecture**
  LTE RAN is an all IP based architecture with support for conversational and real-time traffic. Compared to WCDMA/HSPA, the LTE network consists of a fewer number of network elements/interfaces. The migration from hierarchical to flat network architecture envisaged in LTE reduces network signaling and jitter. LTE base stations known as eNB provide the all-in-one radio access interface between the UE and the *Core Network* (CN). A single applications domain serving customers across multiple networks and devices promotes the convergence of technologies and networks.

- **Cost**
  LTE supports SON capability. This intelligent mechanism collects live network data and collectively diagnoses a number of issues and fixes them in an optimal way. Thus, LTE networks reduce an operator's network planning and maintenance costs.

- **Security**
  A multi-layer multi-vendor security paradigm is designed for LTE since security challenges are significant in IP networks. Strict user/operator authentication, authorization and auditing, secure data storage, configuration integrity, secure network management and unsolicited traffic protection are viewed as the major targets of LTE network security.

2.3   Radio Access

The earlier generations of cellular communication systems have used single carrier modulation schemes. LTE on the other hand adopted the *Orthogonal Frequency Division Modulation* (OFDM). The reasoning for the change in approach is discussed in the following paragraphs.

In a conventional single carrier system, symbol duration decreases as the data rate increases. As a result of multipath propagation, these systems are vulnerable to *Inter-Symbol Interference* (ISI) while transmitting at high data rates. In the frequency domain, each multipath results in a specific phase shift. When the multipath signals are combined at the receiver, the signal passband can undergo either constructive or destructive interference. Therefore, the composite received signal is distorted by frequency selective fading. On the other hand, OFDM based communication systems do not rely on increased symbol rates in order to achieve higher data rates. Thus, with OFDM transmission, ISI is unaffected by data rate. ODFM systems employ parallel transmission over multiple narrow subcarriers. Additionally, each OFDM subcarrier uses a guard interval to effectively eliminate ISI. In LTE, the guard interval is known as the *Cyclic Prefix* (CP). The CP also assists in mitigating *Inter-Carrier Interference* (ICI) by preventing the spilling over of symbols among the closely placed subcarriers. LTE's CP duration is determined by the anticipated degree of delay spread during the transmission. The standardized value of 4.69 μs enables the system to cope with path variations of up to 1.4 kms. The CP is discarded during receiver side processing. Thus, OFDM is more robust to multipath effects.

OFDM systems experience reduced interference due to the transmission over orthogonal subcarriers. Therefore, the problem of intra-cell non-orthogonality is mitigated. Compared to WCDMA based systems, OFDM packs more data bits into the same spectrum. As a result, the spectral efficiency of LTE is much higher than the legacy cellular technologies. Increased spectral efficiency combined with operational benefits of an all-IP network reduces the cost per bit.

Conventional single carrier systems compensate for channel distortion via time domain equalization. As data rates increase, the complexity of traversal filter implementation increases due to the need for faster sampling clocks. Also, as the bandwidth and the number of multipath increases, the number of equalizer taps needs to scale up to provide efficient communication. The support for frequency domain equalization which fits well within the OFDM transceiver architecture enables the design of less complex terminals.

2.3.1   Interface Architecture

Similar to WCDMA/HSPA systems, LTE protocols are designed upon a layered architecture. LTE radio access architecture consists of a single node - the eNB. Data that needs to be transmitted emerges in the form of IP packets. The incoming IP packets are processed by multiple protocol entities such as [8]:

- *Packet Data Convergence Protocol* (PDCP) performs IP header compression to reduce the number of bits transmitted over the radio interface. The PDCP is also responsible for ciphering and integrity protection of the transmitted data. There is one PDCP entity per radio bearer configured for a UE.

- *Radio Link Control* (RLC) performs segmentation/concatenation, transmission format handling and in-sequence delivery to higher layers. The RLC offers services to the PDCP in the form of *radio bearers*. There is one RLC entity per radio bearer configured for a UE.

- *Medium Access Control* (MAC) handles the *Hybrid Automatic Repeat Request* (HARQ) for retransmissions and performs UL as well as DL scheduling. The scheduling functionality is located in the eNB, with one MAC entity per cell for both the UL and DL. The HARQ protocol is present in both the transmitting and receiving end of the MAC entity. The MAC offers services to the RLC in the form of *logical channels*.

- *Physical Layer* (PHY) performs coding/decoding, modulation/demodulation multi-antenna mapping and other typical physical layer functions. The PHY offers services to the MAC layer in the form of *Transport Channels* (TCH).

Figure 2 illustrates the LTE radio interface protocol architecture. In principle, the protocol architecture in the UL is very similar to the DL with variations in MAC and PHY layer functionalities like *Transport Format Set* (TFS) selection and multi-antenna transmission respectively.

As already mentioned, the MAC offers services to the RLC in the form of logical channels. A logical channel is differentiated based on the type of information it carries; namely *control channels* and *traffic channels*. Compared to WCDMA/HSPA systems, LTE incorporates a reduced number of logical channels and are defined as follows:

- *Broadcast Control Channel* (BCCH) transmits system information from the eNB to all the UEs in a cell. The UEs decode the BCH to learn the network configuration.

- *Paging Control Channel* (PCCH) tracks UEs by paging them.
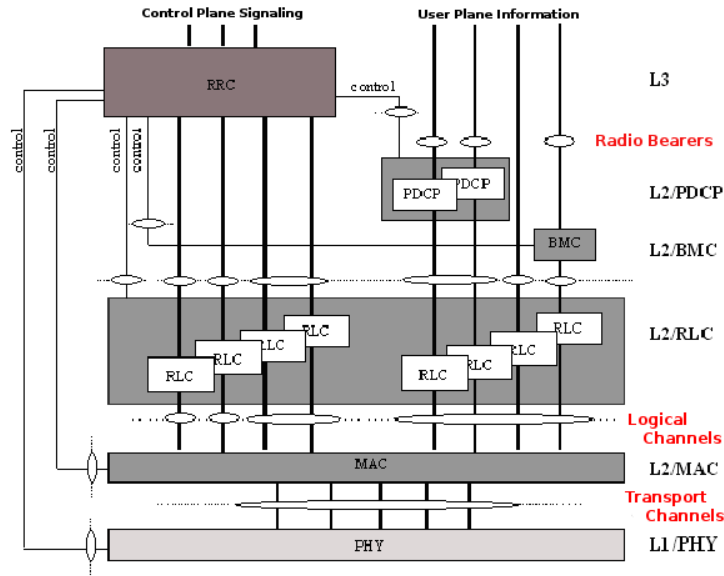
Figure 2: LTE Radio Interface Protocol Architecture

- *Dedicated Control Channel* (DCCH) transmits control information to/from a UE. The DCCH configures procedures such as handovers.

- *Dedicated Traffic Channel* (DTCH) transmits data to/from a UE. The DTCH is used for all UL and non-MBMS DL data.

- *Multicast Traffic Channel* (MTCH) transmits the DL MBMS data.

- *Multicast Control Channel* (MCCH) transmits control information required for the reception of MTCH.

The MAC layer uses services from the PHY layer with the aid of TCH. A transport channel is defined by the method and the characteristic information carried by it. The *Transport Format Set* (TFS) defines the transport block's characteristics such as its size, modulation scheme, rate allocation and antenna mapping. The set of TCH incorporated by LTE are as follows:

- *Broadcast Channel* (BCH) transmits BCCH specific information.

- *Paging Channel* (PCH) transmits PCCH specific information. The PCH supports *Discontinuous Reception* (DRX) to enable the UE to save battery power by listening to the PCH only at specific intervals.

- *Downlink Shared Channel* (DL-SCH) transmits DL data. It supports features such as dynamic rate adaptation, *Channel Dependent Scheduling* (CDS), HARQ and spatial multiplexing.

- *Multicast Channel* (MCH) transmits MBMS specific information.

- *Uplink Shared Channel* (UL-SCH) is the uplink counterpart of the DL-SCH.

Figure 3 illustrates the mapping of logical channels into transport channels in LTE systems.
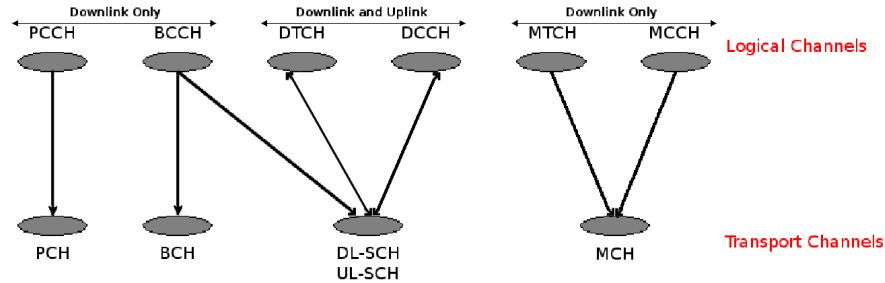
Figure 3: Mapping of Logical Channels into Transport Channels

2.3.2 Frame Structure

Figure 4 illustrates the high-level time domain structure of LTE transmission with each radio frame of length $T_{frame} = 10\ ms$ consisting of ten equally sized subframes of length $T_{subframe} = 1\ ms$ [25]. Each subframe is further divided into two slots of length $T_{slot} = 0.5\ ms$. Each slot consists of either 6 or 7 OFDM symbols depending on the length (normal or extended) of the CP. Each subcarrier has a bandwidth $\Delta f = 15\ kHz$. 3GPP has standardized the value of Δf to facilitate the simpler design of WCDMA/HSPA/LTE multi-mode terminals. The total number of subcarriers depends on the overall transmission bandwidth. A *Physical Resource Block* (PRB) consists of 12 consecutive subcarriers within the duration of one slot. Thus, the bandwidth of a PRB is $180\ kHz$. A PRB is the most basic element of resource allocation assigned by the eNB scheduler. This degree of granularity in resource allocation allows two-dimension based time-frequency domain smart scheduling thereby enhancing system utility [18].
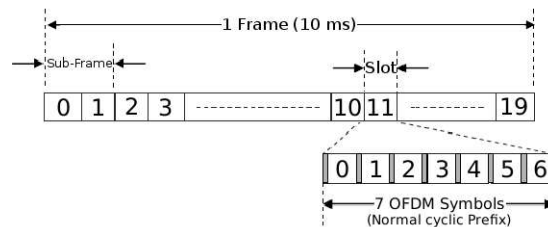
Figure 4: LTE Frame Structure

2.3.3   Transmission Scheme

The transmission scheme determines the link level system performance. Since LTE is like its predecessors, a multi-user cellular technology, the transmission scheme is well designed to support statistical multiplexing of users. A distinct design feature of LTE is that the UL and DL use slightly different signal generation techniques in order to align closer to the performance targets.

LTE transmission is based on Fourier (and inverse Fourier) transform operations [8]. The signal is generated at a sampling rate of $\Delta f * N_{fft}$ where N_{fft} is the *Fast Fourier Transform* (FFT) size defined for the overall transmission bandwidth. In order to assist the coherent demodulation at the receiver, reference symbols are inserted at specific positions in the OFDM time-frequency grid of each PRB. Similar to WCDMA/HSPA systems, LTE utilizes block wise transmission of data symbols. *Cyclic Redundancy Check* (CRC), channel coding, HARQ, bit-level scrambling, data modulation and resource block mapping are all performed on each of the transport blocks. The CRC assists in error detection and in the functioning of the HARQ protocol. Turbo coding is the channel coding scheme. Bit-level scrambling is done in order to allow the receiver to exploit the processing gain from channel coding. The data modulation transforms the scrambled bits into symbols which are then mapped to the corresponding constellation points of the modulation scheme. An additional function of antenna mapping may be used to realize MIMO transmissions. Resource block mapping maps the symbols to be transmitted on each antenna to the set of resource blocks assigned by the MAC scheduler. At the receiver side, all the transmitter side operations are neutralized by performing reverse operations. Figure 5 illustrates the block diagram of an OFDMA based eNB transmitter and UE receiver. LTE's OFDMA based transmission introduces the term *Bandwidth Expansion Factor* which denotes the number of parallel UE transmissions over the overall transmission bandwidth. The transmitted signal waveform is

$$S = F^* * T * D \tag{1}$$

where

- F^* is the *Inverse Fast Fourier Transform* (IFFT) upon the modulated Data Symbols D.

- T is the subcarrier mapping matrix.

The signal waveform S is transmitted over a channel where each subcarrier k experiences a frequency selective channel response H_k. The received signal waveform after FFT processing is

$$R = H * T * D + Noise \tag{2}$$

The OFDMA scheme is accomplished by parallel modulation of narrow subcarriers. The transmission in the time domain resembles a sum of parallel random signals.

This phenomenon leads to high *Peak to Average Power Ratio* (PAPR) and requires the power amplifier to operate over a large dynamic range. Operating a device with high PAPR requires an expensive power amplifier and relatively higher power consumption. Since, at the eNB, these two factors are not of prime concern, OFDMA is adopted due to the advantages of mitigated frequency selective fading and simpler receiver design.

In the UL, the battery life of the UE is one of the prime performance concerns. Therefore, the high PAPR OFDMA was not adopted by 3GPP. An alternative technique, namely *Single Carrier Frequency Division Multiple Access* (SC-FDMA), is standardized as the UL multiple access scheme. SC-FDMA is basically a *Discrete Fourier Transform* (DFT) spread OFDM transmission [21]. The DFT spreading prior to subcarrier mapping spreads the symbol sequence over all subcarriers so that each subcarrier carries information over the entire symbol sequence. The *Inverse Discrete Fourier Transform* (IDFT) operation at the receiver removes the DFT pre-coding and transforms the signal into the time domain. The DFT pre-coding at the transmitter transforms the signal into a single carrier like waveform. This reduces the PAPR and thus greatly benefits power constrained UEs at the cell-edge. In other words, SC-FDMA improves cell coverage along with reduced power consumption [16]. SC-FDMA transmission can be implemented in a localized or distributed manner. In localized SC-FDMA, each UE is allocated a contiguous set of subcarriers. On the other hand, in distributed SC-FDMA, UEs are allocated resources in a distributed manner. The term *Chip Repetition Factor* denotes the spacing among the PRBs allocated to the same UE [14]. After transmitter side processing, a set of contiguous non-overlapping comb-shaped frequency spectrum is realized with a user specific phase. Distributed SC-FDMA can exploit frequency diversity but increases the complexity with regard to channel estimation. Since pilot signals now need to detect more subcarriers, the accuracy of channel estimation is reduced. Therefore, localized SC-FDMA is adopted by 3GPP for UL transmission. Frequency diversity is derived on the same scheme with the aid of CDS and *Frequency Hopping* (FH). Figure 5 illustrates the block diagram of a SC-FDMA based UE transmitter and eNB receiver.

The block diagram in Figure 5 shows the significant degree of functional commonality in signal generation between the UL and DL multiple access schemes in LTE.

2.4   System Architecture

LTE *System Architecture Evolution* (SAE) follows the WCDMA/HSPA system by splitting the architecture between the RAN and the CN. The functionalities of the LTE RAN can be summarized from the functions of each of the protocol layers described earlier. The CN functions include charging, subscriber management, mo-
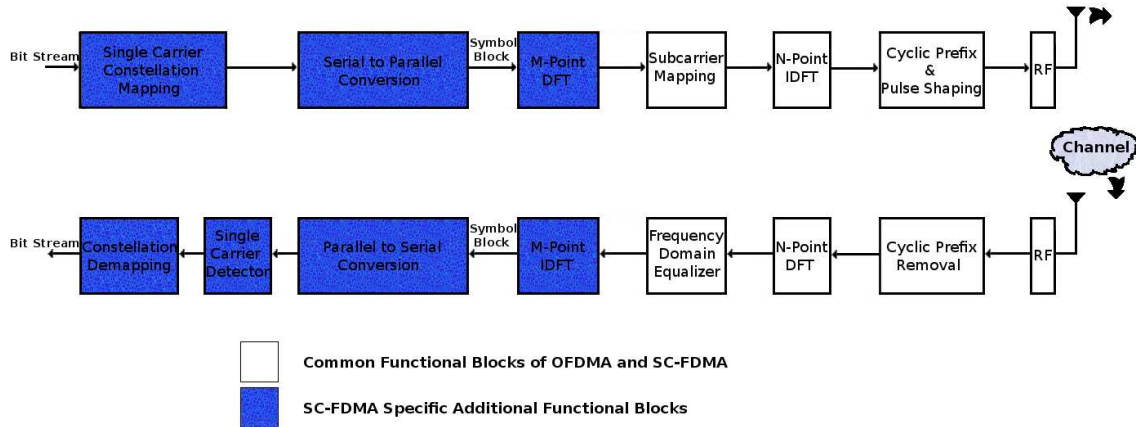
Figure 5: OFDMA and SC-FDMA Transmitter-Receiver Block Diagram

bility management, *Quality of Service* (QoS) handling, policy control and network inter-connectivity/inter-working.

The eNB is connected to the CN via the *S1* interface. The *X2* interface interconnects the neighbor cell eNBs. The X2 interface supports active-mode mobility and multi-cell *Radio Resource Management* (RRM) functions. LTE does not support soft handover. Therefore, a UE is always under the control of its serving eNB only. In order to support MBMS, different cells are synchronized with the aid of a *Global Positioning System* (GPS).

The LTE SAE is also known as the *Evolved Packet Core* (EPC). The *Home Subscriber Server* (HSS) is similar to the *Home Location Register* (HLR) in GSM/WCDMA systems. The EPC and HSS are connected via the *S6* interface. The EPC connects to the Internet via the *SGi* interface.

LTE SAE supports the inter-system LTE-WCDMA/HSPA handovers through the *S3* interface which connects the EPC with the *Serving Gateway Support Node* (SGSN).

3 Relaying in Cellular Networks

3.1 Relaying Background

The next generation of cellular systems are envisioned to support very high data rates over reasonably large coverage areas. The current spectrum allocation indicates that these future networks would operate in the beyond 2 GHz carrier frequency thereby making the radio propagation more vulnerable to the fading phenomenon. The target data rates for these networks is of the order of twice that of currently deployed evolved 3G networks. In order to support such high data rates, the bit rate over the air interface needs to be increased. This implies that for a constant transmit power, when the bit rate increases, bit energy (correspondingly symbol energy) reduces. This degrades the reliability of the communication channel thereby challenging the fulfillment of the system's target QoS.

The next generation cellular networks are being heavily researched for all possible performance improvements like never before. An option to improve the user experience is to increase the eNB density. The cost of deploying additional eNBs, however, makes business sense to the operator only if revenues increase proportionally. This means that either the number of subscriptions increase or the existing subscribers use the enhanced network capacity. Firstly, the option of increasing the number of subscriptions does not seem feasible for the very reason that these advanced networks would be introduced in the developed nations. In developed nations, cellular penetration is saturated to an extent where it is almost impossible to sign up more subscribers. Secondly, the option of existing subscribers using the increased network capacity would mean that users start using more content rich or real-time applications through their wireless devices. This would need the pricing of the service to be competitive with currently deployed, and proven, connectivity options such as *Digital Subscriber Line* (DSL), WLAN and fixed *Worldwide Inter-operability for Microwave Access* (WiMAX). Due to the high costs incurred in deploying new networks, it is very unlikely that network operators can provide low priced subscriptions at the network roll-out phase. Therefore, to improve QoS, increasing eNB density is not attractive from an operator's point of view. Advanced antenna based transmission such as smart antennas, MIMO and multi-hop communications are promising options to satisfy performance targets of the next generation wireless networks. Therefore, today these topics are of immense research interest in the communications space.

The focus point of this thesis work is 3GPP's relaying study item which would be incorporated into the LTE-A standards. It is believed that concepts such as relaying would contribute to the fulfillment of ITU-R's 4G performance goals.

3.2   Relaying Fundamentals

Historically, multi-hop networking has been associated with wireline long distance and wireless long distance as well as wide area communications. Technically, the devices were signal repeaters. In wireless networks, multi-hop transmissions are mainly associated with ad-hoc and peer to peer communications. In a conventional cellular network, the source and destination (eNB and UE or vice-versa) communicate directly with each other. In such a scenario, a UE located far from the eNB experiences low signal strength due to the high path loss in its transmission. Cellular systems hypothetically have a hexagonal (in reality distorted circular) coverage region where the area increases with distance from the eNB. This means that a greater part of the cell experiences worse radio conditions. To counteract this effect, transmit powers could be increased, leading to power constrained transmissions since a UE's transmit power is limited to its maximum *Effective Isotropically Radiated Power* (EIRP). Also, since wireless networks reuse spectrum, an increase in transmit power increases interference among the regions where the spectrum is reused. These added challenges create further complications in reaching target transmission rates envisioned in the next generation of cellular networks. As already mentioned, a possible solution to improve the network performance, especially with regard to cell-edge UEs, is to integrate fixed RNs into the existing macro eNB networks. The RN can be considered as an intermediate access point between the eNB and UE. Figure 6 illustrates the transformation from a conventional single-hop to a relay enhanced multi-hop cellular network.
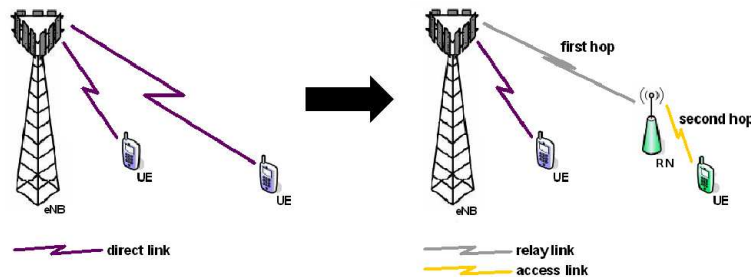
Figure 6: Cellular Network Topology Transition from Single-Hop to Multi-Hop

A distinction between pico/femto nodes deployed with existing cellular networks and RNs is that a RN has a wireless backhaul making it an all-wireless access point. *Decode and Forward* (DF) type RNs are of research interest in future networks and, therefore, the well examined *Amplify and Forward* (AF) type RNs are not discussed [26]. A DF relay is different from an AF relay in the sense that a DF relay only regenerates and retransmits the informative/useful part of the received signal. A DF relay operates like a digital repeater with an intelligent variable gain. It allows smart retransmissions of the received signal and can take advantage of adaptive transmission techniques such as variable *Modulation and Coding Schemes* (MCS) on different hops. Furthermore, RNs can implement interference avoidance/mitigation

schemes. The RNs can be mobile (like in mobile ad-hoc networks) or stationary. Stationary/fixed RNs are of interest in this work since they align better to LTE-A's deployment goals. Therefore, fixed RNs can be deployed at locations wherever the eNB alone cannot satisfy performance targets due to coverage or capacity constraints [20] [27]. So, potential RN deployment regions are at coverage holes, hot spots and cell-edges. In this work, the focus is on the improvement of cell-edge performance and, therefore, RNs are assumed to be deployed at such locations. Also, considering the results in [13], which states that the incremental throughput gains are significant for up to two-hop links and for the simplicity of analysis, this work considers a multi-hop network deployment with a maximum of two hops per connection.

3.3   Anticipated Advantages of Relaying

The RNs are interesting to network operators because they assist in simpler as well as cost-effective network upgrades. Since they are layer-2 devices, they do not require to support higher layer functionalities. RNs unlike eNB are relatively small sized, therefore they do not require exclusive site acquisition for their installation. The wireless backhaul cuts costs incurred on data tunneling. Also, they do not have strict installation guidelines with respect to radiation, visual disturbance and planning regulation. So, placing RNs in locations of need involves lower *Capital/Operational Expenditure* (CAPEX/OPEX) and enables faster network upgrade when operators aim to improve QoS [10] [22]. The physical characteristics and low power requirements of RNs makes them easily mountable on structures like lamp posts which are generally well positioned/elevated with power supply facility to feed the RN transceiver. These flexible features of RNs promote network enhancement with the capability towards adaptive traffic capacity engineering. Therefore, the performance limiting criteria of cell-edge UEs, such as power constrained transmission and ICI between macro cells, can now be reduced with RNs. The introduction of RNs is expected to improve fairness to UEs in the cell with lower side-effects due to their positioning with respect to the serving eNB.

The wireless backhaul (known as the *Relay Link*) forwards the RN-UE transmission (known as the *Access Link*) to the eNB. The *Cumulative Distribution Function* (CDF) plot of the UL *Signal to Interference plus Noise Ratio* (SINR) at the cell-edge in Figure 7 illustrates the improvement in the UE's link quality with relay deployment. This is significant in the sense that RNs assist in realizing a more uniform UE performance along the cell radius, thereby also improving cell capacity. Since UEs are generally power constrained, RN deployment brings in improved UE battery life as UEs now employ lower powered transmission. Since the cell-edge UE's transmit power is lowered, ICI originating from cell-edge UE transmissions is also reduced.

Figure 7 illustrates the improvement in SINR at the cell-edge. The baseline case is the eNB-only network and RNs are deployed at the cell-edge of the existing single-

hop setting. A significant improvement in SINR is observed for major parts of the cell-edge. A reduction in SINR in the 10%-ile region corresponds to those UEs in the handover region between an eNB and a RN. This effect will be reduced with improved multi-hop network deployment parameters.
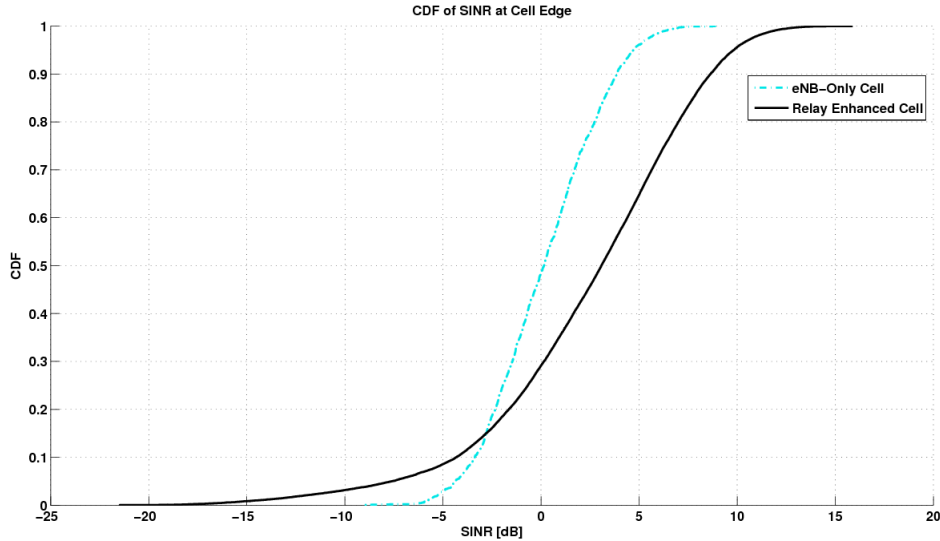
Figure 7: SINR Improvement at Cell-Edge with Relaying

3.4   Challenges to Successful Relay Deployment

In a single-hop network, the cell-edge UEs encounter significant radio wave propagation losses due to their distant positioning from the eNB. With RN deployment, these cell-edge UEs will be served by a closer access point - the RN. In terms of radio conditions, the reduced propagation loss of cell-edge UEs in a REC provides them with similar leverage as cell-center UEs. In the RN architecture and protocol design, it is stressed that the UE treats the RN just like another eNB. This would mean that no extra mode or reconfiguration is required and the UE design remains unaffected by the newly introduced network hardware. Hand-held device manufacturers would appreciate that the UE remains as simple as possible so that additional costs on hardware and software are minimal. Also, from a user perspective, a UE connected to a RN should not operate differently than a UE connected to an eNB. In other words, the system design should abstract the complexity of the underlying network from the real world.

In general, similar to eNBs, RNs can be configured to operate in TD, FD or hybrid TD-FD multiplexed mode. *Spatial Division Multiple Access* (SDMA) and CDMA are other possible multiple access options. Since RNs form an intermediate interface between the eNB and UEs, the RN listens to RN-specific control/broadcast information transmitted by the eNB. In principle, the introduction of RNs could

result in additional transceivers at the eNB since the eNB should communicate simultaneously with the UE and the RN. Also, MAC and RRM modules at the eNB may need to be upgraded to successfully support and coordinate the multi-hop transmission.

In order to achieve significant gains in system performance, the network's transition from single-hop to multi-hop introduces the relay link which adds a new dimension to system design. For example, radio resources being a scarce and expensive component needs to be dimensioned judicially. With RNs, the methodologies for resource allocation and interference mitigation gets more complex. The relay link could be a bottleneck if the system is dimensioned without considering the side-effects of this new link. Also, RNs introduce intermediate packet processing which accounts for additional delays. This is detrimental for interactive or real time applications and the implementation should take care of mitigating these effects. Post RN deployment, the *Radio Access Point* (RAP) selection criteria should be well defined by considering the advantages and feasibility of each of the possible criteria. The possible criteria for a UE to select its RAP could be on the basis of DL received power, SINR and throughput. In terms of deployment acceptance of LTE-A RECs, the system requires to exhibit performance gains by overcoming the above mentioned challenges.

The inefficiencies and challenges introduced by relaying in LTE-A needs to be compensated for by proposing a multi-hop system design which would realize an improved performance over the single-hop deployment.

4 Resource Allocation in LTE

4.1 Resource Allocation Background

The shared wireless channel makes it necessary to have a well-defined transmit mechanism so that network utility is maximized and user fairness criteria are met. The next generation networks like LTE are designed to support services which have a discrete demand for resources, such as video, that requires a certain frame rate. LTE's air interface - OFDM is an improved transmission scheme with high spectral efficiency and robust performance over heavily impaired communication channels. OFDM has been successful in WLAN, HiperLAN as well as the IEEE 802.11 series and it is foreseen to be a major force in the success of LTE.

The goal of RRM is to devise mechanisms to improve system stability and performance by reducing interference, improving user perceived QoS, increasing spectral efficiency and maximizing network operator revenue. The scarcity and expensiveness of radio resources coupled with the challenging propagation conditions endured to meet the performance targets makes RRM a key module. For a UE to start communicating, it needs an eNB to connect to, battery power and a carrier/timeslot to transmit. In other words, RAP selection, *Power Control* (PC) and *Resource Allocation* (RA) are key players in LTE RRM. PC in wideband systems like UMTS is used to mitigate the *near-far effect*. In narrow band systems like LTE, since intracell interference is theoretically zero, PC is beneficial to compensate for path loss, shadowing and ICI. The primary focus of this work is to investigate the RA aspect in LTE-A RECs. Therefore, PC and RAP selection are considered as supporting metrics which integrate together to form a robust RRM scheme.

4.2 Resource Allocation Fundamentals

Multi-User Detection (MUD) in wireless communication systems aims to maximize system performance. UL and DL transmission can be implemented by either FDD or TDD. Unlike FDD, TDD does not require *Channel State Information* (CSI) due to channel reciprocity in either direction. In TDD, the transmission demands temporal orthogonality between the UL and DL. This requires synchronization between neighboring cells. Also, additional guard bands are needed to account for propagation delays due to the duplex switching pattern. Since LTE networks are designed upon a packet based protocol architecture, minimal latency is a major goal. The availability of an exclusive spectrum for the UL and DL further favors the adoption of FDD as the primary duplexing scheme in LTE systems (even though TDD is also being studied by 3GPP). As a result, FDD-based LTE RA schemes are investigated in this work.

The primary goal of RA is to maximize the system throughput for a given power budget and target *Bit Error Rate* (BER) as well as to minimize the transmit power for a target system throughput and BER. LTE's distinguishable feature over its predecessors is that the system architecture promotes flexible RA in both frequency and time domains. The basic allocatable resource unit is one subcarrier on a time-frequency grid.

The transmission over a large number of parallel, flat-faded and orthogonally overlapping subcarriers reduces ISI. LTE may, therefore, operate as a reuse 1 network with high spectral efficiency. However, it still needs to combat inter-carrier interference from subcarriers used in neighboring cells. The interference perceived in an UMTS system and LTE system is different to an extent. This is primarily because UMTS uses wideband transmission opposed to LTE's narrow band transmission scheme. In UMTS, the entire transmission bandwidth is shared between UEs by using orthogonal codes in each cell. Due to the imperfect orthogonality of the codes, UEs in the same cell cause intra-cell interference. In addition to this, ICI exists because every UE in the neighbor cell is a candidate interferer. With such a large number of interferers, the perceived interference averages out and takes the form of a nearly flat *Additive White Gaussian Noise* (AWGN) like spectrum. On the other hand, LTE allocates a particular subcarrier to only one UE in a cell resulting in, theoretically, zero intra-cell interference. In such an allocation scheme, only ICI exists and exactly one UE in the neighboring cell is a candidate interferer. As a result, there is reduced interference in LTE. Additionally, since each of the interferers have different transmission profiles such as path loss, shadowing and fast fading, the perceived interference fluctuates and is no more like AWGN.

Therefore, interference modeling with the aid of RA is an investigative aspect in the LTE system. The goal of interference modeling is to coordinate transmissions in a proactive and/or reactive manner such that it degrades the system performance to the least possible extent.

4.3 State of the Art in Resource Allocation

4.3.1 Resource Allocation Metrics in LTE

Figure 8 illustrates the different resource allocation metrics that are feasible in OFDMA based LTE systems [15]. Option A denotes the simplest and most widely used allocation scheme of a reuse 1 network which implies that a UE can transmit on any of the subcarriers provisioned by the network operator. This scheme does not require much network planning but has a drawback in a sense that a UE at the cell-edge can sometimes cause high interference on transmissions in neighboring cells. Option G is an improvement over A where a feedback on CSI is available and the UE can exploit the channel with a water-filling approach and gain from

MUD. In the following schemes, only a part of the resources are allocated to each cell. Option B denotes the case of static allocation of resources similar to frequency planning at network deployment phase. A modification of option B results in dynamic allocation schemes. Broadly, the dynamic allocation can be exploited with FH or *Dynamic Channel Allocation* (DCA). FH can be either slow (option C) or fast (option D). The difference between the two schemes is significant when only a few subcarriers are allocated to each cell and slow FH is applied. This results in insufficient averaging of interference since the UE may not hop within the transmission interval. In such a scenario, fast FH performs better in averaging out the system effects. Slow FH is beneficial to create frequency diversity from almost stationary channels [5] [11]. DCA introduces flexible RA and improves resource utilization. DCA can be performed with a centralized (option E) or distributed (option F) controller. Centralized DCA requires coordination between network devices to maximize performance by considering current system statistics. The coordination requires additional tracking and signaling of information between the network nodes at a regular time scale. This is considered as an overhead with centralized DCA even though the mechanism aims to maximize system utility. Distributed DCA derives system information from inherently available metrics such as CSI and UE measurements. This mechanism works on a unique (network-wide) channel allocation rule but gives the freedom to each network node to decide its transmissions based on its independent view. Due to this merit, distributed DCA is preferred over centralized DCA.
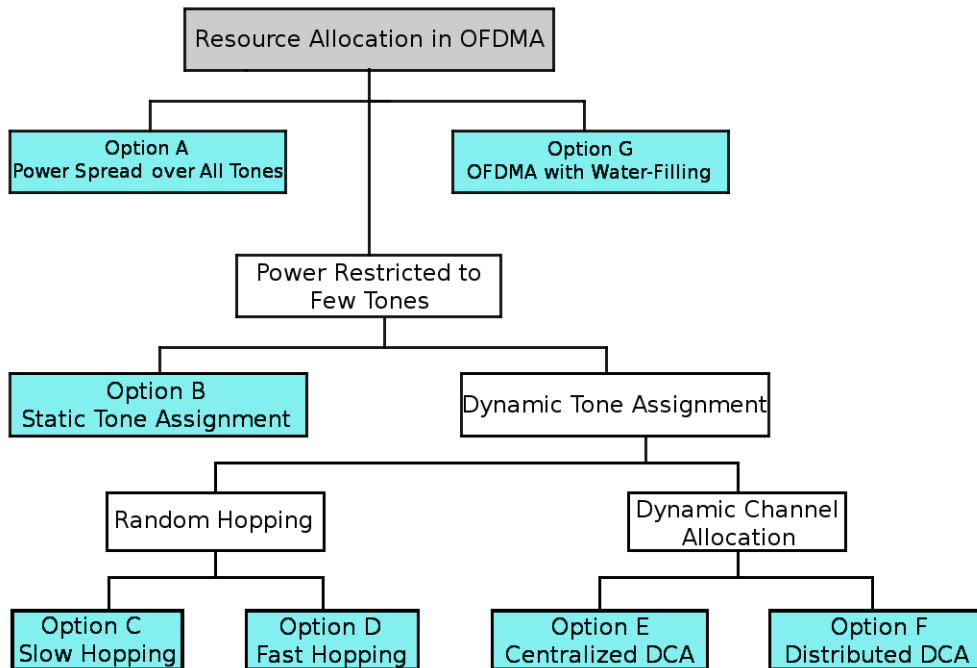
Figure 8: Possible Resource Allocation Metrics in LTE

In this work, in order to categorize UEs based on their geometry (i.e. positioning) in the sector, a UE could be referred to being in *good geometry* or *poor geometry*.

4.3.2 Single-Hop Resource Allocation - Literature Review

As discussed in Section 4.2; In LTE systems, the ICI across subcarriers is non-white since the orthogonal subcarrier based transmission introduces fewer interfering samples. The perceived non-white interference is also affected by resource allocation in neighboring cells [12]. The interference on a subcarrier varies randomly based on the re-allocation of the particular subcarrier in the neighboring cell. This randomly fluctuating ICI poses a challenge to LTE RRM especially with respect to features such as channel-aware RA and link adaptation techniques like *Adaptive Modulation and Coding* (AMC). In wideband systems, fading was the main random component that needed to be tracked to achieve optimal scheduling and AMC performance. LTE introduces the additional requirement for ICI awareness to exploit the gains from MUD and accurate MCS selection. To mitigate this fluctuation, two strategies are proposed namely, user grouping based RA and power compensation based RA. With user grouping, the UEs are grouped based on their strongest interfering eNB. The UEs interfering the maximum to a common eNB are grouped together. This is similar to user geometry based grouping since interference depends on the position of the interferer. The user grouping threshold metric decides the group to which a UE belongs. Setting a higher threshold improves MUD gain but randomizes ICI and vice-versa. So, the threshold is set in a way to balance MUD gain and ICI fluctuation. With power compensation, the ICI is managed by adjusting the UE transmit power. Thus, the fluctuation in ICI perceived by a UE is averaged out. User grouping implemented on top of power compensation is useful since the user grouping first reduces ICI fluctuation and the power compensation further fine tunes the performance. Figure 9 illustrates the discussed system behavior.
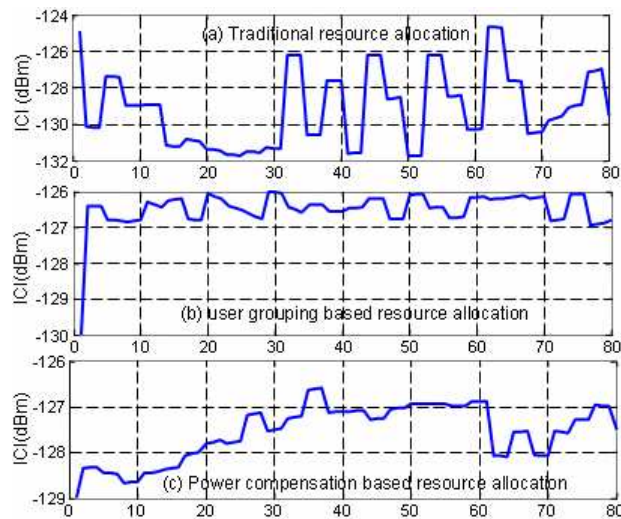

Figure 9: Effect of Resource Allocation on Inter-Cell Interference Fluctuation [12]

In [24], a *Flexible Fractional Frequency Reuse* (FFFR) is analyzed with a subcarrier reuse scheme. Therefore, with FFFR the network does not employ a reuse 1 resource allocation. The allocated group of subcarriers for a cell is further logically sub-divided. The subsets within a cell are allocated to UEs in chronological order. The creation of subsets of resources within a cell allows an ordered/flexible allocation. The flexibility is in terms of the subcarrier borrowing among cells. A subcarrier within a cell is borrowable by overloaded cells in the reverse chronological order of subsets. The flexible subset allocation scheme, therefore, improves allocation efficiency. An additional criterion of power allocation can be applied on the borrowed subcarriers such that the borrower uses them with lower transmit power. The lower transmit power on borrowed subcarriers reduces their chances of creating interference in cells where they are reused (allocated/borrowed). A mechanism to reduce the transmit power on borrowed subcarriers is to allocate them to good geometry UEs. Since these UEs would be close to the eNB, they cause lower additional ICI. If the UE does not meet its throughout target with reduced power, the UE can borrow additional resources for transmission and again employ low power transmission on them without causing much ICI. Since good geometry UEs are not power limited, this approach is exploitable by them. In addition, a power allocation scheme could also try to reduce the transmit powers of the good geometry UEs by using its own (unborrowed) subcarriers. The availability of CSI of potentially borrowable subcarriers assists in selecting a subcarrier with good radio quality. With this, a similar effect of reduced ICI is achieved. To conclude, in addition to reuse, ICI mitigation is further improvable among shared resources by proper subcarrier selection and power control.

4.3.3 Towards Multi-Hop Resource Allocation

Resource allocation in single-hop cellular networks is quite a mature topic. The different strategies assign resources in the UL and DL among homogeneous network nodes. Multi-hop networks are confronted by the challenge of resource allocation among dissimilar transmission links. For example; In UL, the access link and direct link transmit to different end points. Additionally, the links are modeled on different channels. The addition of the relay link into the system introduces further complications. It is important that the access link and the relay link are dimensioned in conjunction so that the targeted end-to-end throughput of the UE connected a RN is met. To summarize, in addition to the other multi-hop related overheads, the varied performance of each link due to different source-destination system parameters and channel models pose an interesting challenge to resource allocation in multi-hop cellular networking.

4.3.4 Multi-Hop Resource Allocation - Literature Review

In [9], the concept of soft reuse on a Manhattan grid like RN deployment is introduced. The work highlights the losses of the hard reuse scheme with respect

to system capacity because each RAP is offered a reduced number of resources for transmission. Therefore, a soft reuse is proposed such that each RAP gets all the resources thereby maintaining a reuse 1 system with the added constraint of power masks. The power masks are applied in the time/frequency domain to control ICI. The idea is to have orthogonal resources at the cell-edge so that high power resources can be used without much ICI. The remaining spectrum is used in the inner regions of the cell with low power. The low powered transmission coupled with the high path loss to the interferer makes this a spectrally efficient resource allocation scheme. Further enhancement to this idea is introduced by the fact that each RN has variable traffic loads, therefore an adaptive power mask is proposed. A highly loaded cell can borrow resources from its lowly loaded neighbors by selecting the borrowable resource with the highest power gain. This guarantees that the best exploitable unused resources are reallocated to a highly loaded RN. This adaptive power mask based soft reuse scheme requires additional control information to propagate within the network to inform the neighbor cell's load, power mask information etc. The algorithm claims to be extendable to be integrated to a REC and provide similar performance gains.

In [17], another reuse partitioning based resource partitioning framework is proposed. The work analyzes the DL but provides useful insight into issues/ideas that could be exploited in the UL. LTE's time-frequency domain scheduling is performed to improve the system capacity in RECs. Along with the reuse 1 network, in each cell every subchannel is allocated to only one of the three links to avoid intra-cell interference. The RN is considered to work in half-duplex mode. Therefore, the RN's reception from the eNB and transmission to the UE is established by TDD. In the time domain, the RN is in reception mode first and transmission mode next. The eNB is in transmission mode to both the UE as well as the RN first and only to the UE next. Based on this basic TD rule, the proposed scheme is developed and explained across two *Time Slots* (TS). Three adjacent cells constitute a virtual cluster. In addition to efficient resource utilization with reuse 1, ICI is mitigated with coordinated scheduling. The UEs in a cell fall into one of the three groups - i, j and k ordered in the decreasing order of signal quality when the UE is connected to an eNB. Logically, group k will be served by RNs since it experiences worst performance when connected to the eNB. The UEs of groups i (i.e. UE_i) and j (i.e. UE_j) will be served by the eNB. In TS1, the eNB transmits to the RNs and the UE_i. In TS2, the eNB transmits to the UE_j and the RN transmits to the UE_k. Since the UE_k are at the cell-edge, the transmission is coordinated in the frequency domain such that the cluster has orthogonal resources among this group. The remaining resources are allocated to UE_j. Figure 10 illustrates the proposed interference coordination scheme.

Since the relay link is for data forwarding, it is dimensioned to have the same capacity as the access link. The transmit powers of RNs are varied with respect to the eNB. The effect of RN positioning along with RN power is compared to
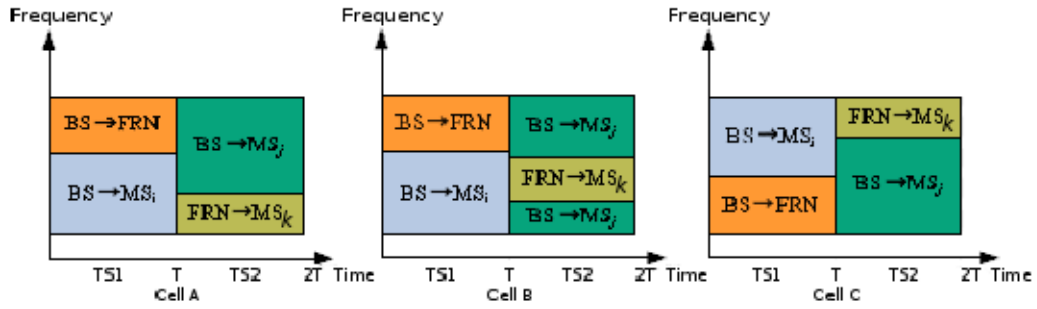
Figure 10: Time-Frequency Resource Partitioning [17]

obtain the optimal power settings for RNs at different distances from the eNB. The resource partitioning scheme aims to maximize system capacity with TD-FD resource allocation and RN position-based optimal power allocation.

5 System Level Simulator

Compared to UMTS, the LTE network architecture is more robust by providing improved deployment flexibility. The flat network architecture permits greater feasibility of uncoordinated network deployment.

The primary aim of the investigation is to study the impact of relaying on the existing macro base station deployment and ascertain the gains while migrating towards the REC model. With the thought of deploying RNs, certain automatic questions crop up in terms of their positioning, power allocation, resource allocation and UE performance. This work investigates the REC system behavior and aims to throw some light on the advantages and challenges of integrating RNs into macro eNB deployments.

5.1 Simulator Overview

To get a realistic view of system characteristics, a system level simulator was developed. In order to have sufficient inter-cell effects, 19 tri-sectored hexagonal cells were considered, providing two tiers of interferers around the sector of interest. Each sector is assumed to have the same UE density. The UEs are then dropped randomly within each sector. To simplify the analysis, a UE dropped within a sector's coverage area is considered to camp on to an access point in that sector only. In other words, a UE is never considered to be in handover state. In order to get a unperturbed view of the system, shadow fading and fast fading are not considered in the simulations. These fading effects provide a more realistic setting, but since the investigations begin from a nascent stage, understanding the system without any side-effects took priority. The RAP selection by a UE is based on the downlink received power. So, the UE camps to the access point from which it receives the best power profile. The power received by a UE in the DL is the difference between the transmit power of the RAP and the *net loss* of the transmission link. Net loss refers to the difference between the distance dependent path loss and the device gains (elevation and diversity gains). Once the UE camps onto an access point, a *Round Robin* (RR) scheduler provides the UL access grants. The RR scheduler is aimed towards simple and fair UE scheduling. More sophisticated schedulers better exploit the time-frequency domain characteristic of LTE scheduling. But, since the focus point of this work is not on the packet scheduler, the RR scheduling is adopted. The UEs are then scheduled and this setup forms the basis of the uplink study.

The random drops of UEs are performed over many iterations to provide the required number of samples that could generalize the system behavior. The statistics of the central sector of the 19 tri-sectored layout is analyzed. Interference and thermal noise spectral density are taken into account while calculating the SINR. The throughput is computed with the modified Shannon formula which considers

the *bandwidth efficiency* and *SINR efficiency* of the transmission scheme [19]. The bandwidth efficiency factor accounts for the reduction in effective bandwidth due to the *Adjacent Channel Leakage Ratio* (ACLR), practical filter implementation issues and signaling overheads. The SINR efficiency factor accounts for the reduction in performance due to limited code block length. The modulation scheme of 64 *Quadrature Amplitude Modulation* (QAM) is assumed to be used thereby limiting the maximum spectral efficiency to 6 *bps/Hz*. The SINR and throughput statistics are calculated up to the granularity of a single resource block.

The simulations are performed in an interference limited scenario. This is referred to as the *3GPP Case 1* propagation scenario where the *Inter-Site Distance* (ISD) is 500 *m* and system bandwidth (uni-directional) is 10 *MHz* [6]. On the other hand, the *3GPP Case 3* refers to a coverage limited scenario where the ISD is 1732 *m*.

5.2 Antenna Pattern

The antenna pattern defines the sensitivity of the antenna as a function of direction. The eNB antenna pattern is defined as follows [6]:

$$A(\theta) = -\ min\ \left[12 \left(\frac{\theta}{\theta_{3dB}} \right)^2, A_m \right] \tag{3}$$

where

- θ_{3dB} is the 3 *dB beamwidth* of the antenna's main lobe.

$$\theta_{3dB} = 70\,°$$

- A_m is the antenna's *front-to-back ratio*.

$$A_m = 25dB$$

The RN antenna is omni-directional [6] which implies that it has equal sensitivity across all angles. The antenna pattern of the eNB in the sector of interest can be observed in the color plot in Figure 12.

5.3 Channel Models

The wireless channel performs under one of the most hostile and dynamic propagation conditions. A channel model mathematically defines the propagation scenario. Channel models are derived by investigating the behavior of the transmitted wave under the influence of the propagation environment. Proposing logically correct channel models requires exhaustive study of the theoretical, physical and statistical

influences that affect the radio wave propagation. Channel models are the cornerstone of successful system design because the system behavior reflects upon how the propagation is modeled. An accurate channel model is one which exhibits coherent system performance in simulation as well as in real-life deployment.

3GPP work groups discuss proposals from different research companies/institutes and assess them in order to provide the standards with more accurate channel models. The channel models used in this work are taken from 3GPP's technical archives and are defined as follows:

- Direct link [3]

$$Path\ loss = 128.1 + 37.6\ log_{10}R \tag{4}$$

- Access link [6]

$$Path\ loss = 140.7 + 36.7\ log_{10}R \tag{5}$$

- Relay link [6]

$$Path\ loss = 124.5 + 37.6\ log_{10}R \tag{6}$$

Note:

- All the above formulae are defined for 2 GHz carrier frequency.

- R is the distance in km.

- Direct link and access link will experience an additional 20 dB penetration loss.

- Relay link is not influenced by penetration loss (In the simulations, RNs are aimed towards outdoor deployment [6]).

5.4   Relay Node Positioning

In this work, the RN deployment aims to increase the performance of UEs experiencing poor radio conditions. Since these UEs are generally located at the cell-edge, the RNs are located at such positions. Figure 11 illustrates the improvement in UE received power with the deployment of RN at the cell-edge for the 3GPP case 1 propagation scenario. Since the UE's RAP selection is based on DL received power, the distance from the eNB where the UE selects the RN is visible. All device parameters like transmit powers, elevation gains, diversity gains are considered in the received power calculation and the values can be referred from the appendix (Section 8).

Figure 12 illustrates the positioning and coverage boundaries of RNs with the combination of the adopted channel models and device parameters. The color plot also highlights the variation in received power along the sector radius.
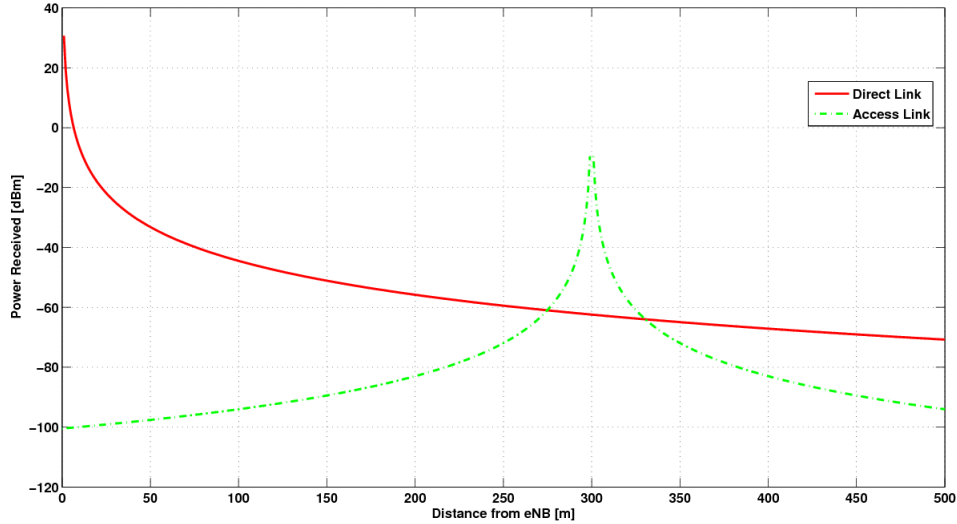
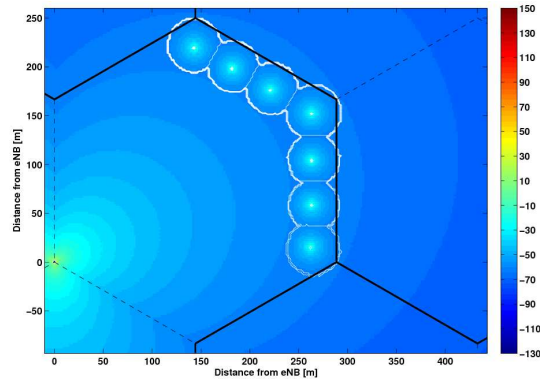Figure 11: Distance from eNB vs Downlink Power Received

Figure 12: RN Positioning in a REC

5.5   Power Control

Generally, transmissions are powered such that they can achieve the goals of successful communication. Transmit power is an important metric in wireless communications. Due to the shared nature of the wireless channel, a well formulated transmit power scheme is needed so that the simultaneous transmissions by UEs do not interfere much with each other. Also, since UEs are battery powered devices, power is a limiting factor to their performance as well as talk time. In such a case, the basic approach would be to use just enough power to communicate and thereby conserve the battery. Therefore, PC in cellular communications is designed along these fundamental principles.

The LTE air interface is realized with a set of numerous narrow-band subcarriers among which a subset of them are allocated to a UE. This kind of transmission scheme involves spreading the transmit power over the allocated subcarriers. So, the

concept of *Power Spectral Density* (PSD) is introduced which defines the transmit power per subcarrier. 3GPP has proposed the following power control formula for LTE UL as follows [2]:

$$P = min \ \{P_{max}, \ P_o + 10 \ log_{10}M + \alpha \ L + \Delta_{mcs} + f(\Delta_i)\} \tag{7}$$

where

- P_{max} is the maximum UE transmit power.

- P_o is the minimum transmit PSD.

- M is the number of subcarriers allocated to the UE in the *Transmission Time Interval* (TTI).

- α is the path loss compensation factor.

- L is the net loss in transmission power.

- Δ_{mcs} is the MCS specific correction term.

- $f(\Delta_i)$ is the term that permits either accumulated or absolute corrections.

The parameter P_{max} is dependent on the UE power class. P_o and α are cell specific values decoded by the UE from the broadcast information. Δ_{mcs} and Δ_i are the UE specific values signaled by the UL access grant.

The simulations consider *Open Loop Power Control* (OLPC) terms only since fast channel fluctuations due to fading are not realized by the simulator. As a result, Δ_{mcs} and $f(\Delta_i)$ are neglected while controlling the transmit power. Therefore, the PC formula in (7) simplifies as follows:

$$P = min \ \{P_{max}, \ P_o + 10 \ log_{10}M + \alpha \ L\} \tag{8}$$

In the simulations,

- $P_{max} = 23 \ dBm$ [6].

- P_o is set such that 30% of UEs transmit at P_{max}. This setting is believed to be optimal from an operator's point of view. Also, in terms of *Interference over Thermal* (IoT) specific analysis, the 30% UEs at P_{max} provides a good trade-off between system throughput and cell-edge performance.

- α is set according to the analysis done in the following part of this section.

In the 3GPP PC formula defined by (7), the parameter α takes values between 0 and 1 implying that it defines the fraction of path loss that that would be compensated by the PC mechanism. Precisely, $\alpha = 0$ implies no path loss compensation (i.e. No PC) while $\alpha = 1.0$ implies full path loss compensation. An $\alpha = 1.0$ is the traditional PC strategy used in pre-LTE systems. The flexibility in compensating for a fraction of the path loss is introduced into the LTE PC formula to control the scaling of the transmit powers of cell-edge UEs. Since cell-edge UEs have a higher path loss compared to cell-center UEs, fractional path loss compensation would cause a higher scaling down of the transmit powers of UEs at the cell-edge [7]. Figure 13 illustrates the higher cell-center UE transmit power compared to the cell-edge with decreasing α. This is beneficial in the sense that cell-edge UEs cause higher interference and, therefore, powering them down could reduce interference in the system. This support for fractional path loss compensation in LTE's PC formula names this PC scheme as *Fractional Power Control* (FPC). Figure 14 illustrates the SINR distribution under varying PC settings.
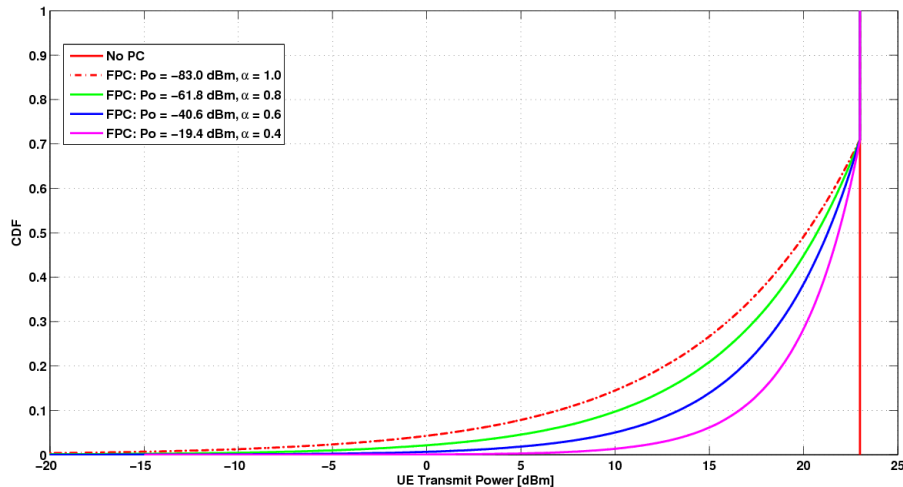

Figure 13: LTE Power Control Analysis : UE Transmit Power

It is observed from Figure 14 that PC in general improves the SINR of cell-edge UEs by controlling the transmit powers of cell-center UEs. UEs with good geometry do not need high transmit powers to satisfy their SINR targets. Also, since UEs at the cell-edge experience low SINRs due to their high path loss, reducing the interference caused by these UEs on those at the cell-center improves the SINR profile of the network. Therefore, with PC the differentiation in SINR profile between cell-center and cell-edge UEs is narrowed down . The introduction of FPC illustrates that the SINR of cell-center UEs improves considerably at the cost of low reductions in the SINR of cell-edge UEs. The earlier mentioned effect of FPC in controlling the transmit power of cell-edge UEs to reduce the overall interference in the system is, therefore, proven here.
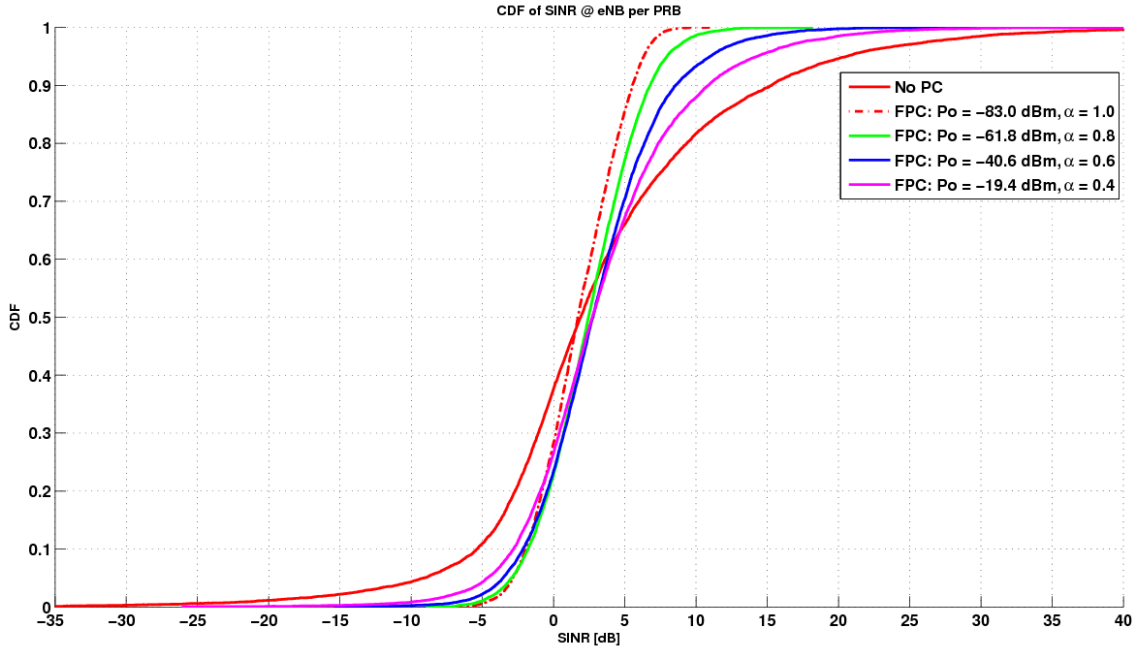
Figure 14: LTE Power Control Analysis : SINR at eNB

Now arises the question, what fraction of path loss needs to be compensated for by PC in order to achieve optimal system performance. By varying the parameter α it is observed that as α decreases, the cell-center SINR improves at the cost of the cell-edge. The setting of α is guided by two principles. Firstly, the cell-edge performance should not reduce considerably. Secondly, a large dynamic range in the received power at the eNB introduces cross-talk. Considering these principles, the value of $\alpha = 0.6$ is selected. It is worthwhile to note that compared to $\alpha = 1.0$ (i.e. *full compensation PC*), $\alpha = 0.6$ causes a reduction in cell-edge SINR for 13% of UEs in the cell. Yet, $\alpha = 0.6$ is considered as the optimum setting. This is because the primary goal of this work is to study system performance within a REC. While migrating from the eNB-only cell to REC, ideally the worst performing UEs would be served by RNs. The simulations deploy a single tier of RNs at the cell-edge and these RNs surely do cover more than 13% of the cell-edge positions. This implies that the SINR degradation of the 13% UEs is not a matter of concern. Therefore, selecting $\alpha = 0.6$ is justified. The criteria of dynamic range is also met with this PC setting.

To conclude, with respect to PC settings; the eNB-only system with $P_o = -40.6$ dBm and $\alpha = 0.6$ is selected as the baseline in this study. Since this setting is assumed to provide the best system performance in an eNB-only case, the target is to perform better than this competitive baseline setting after relay deployment. Therefore, all simulations for the eNB-only case will use this PC setting.

With the introduction of RNs, P_o is set such that the criteria of 30% UEs at P_{max} is still satisfied. With regard to α, $\alpha = 1.0$ is used. This setting could be sub-optimal. However, since the PC parameter setting is not the focus of this work, this is reasonable as long as the baseline is well set.

5.6   Throughput Computation

The throughput is computed using the following modified Shannon capacity formula that is derived by the *Hull-Curve Approximation* method [19]:

$$Throughput = W * W_{eff} * log_2 \left(1 + \left(\frac{SINR}{SINR_{eff}} \right) \right) \tag{9}$$

where

- W is the transmission bandwidth.

- W_{eff} is the bandwidth efficiency.

- $SINR_{eff}$ is the SINR efficiency.

In the simulations,

- $W_{eff} = 0.88$ (modified from [19]).

- $SINR_{eff} = 1.25$ [19].

- Thermal noise power spectral density $= -174 \ dBm/Hz$ [1].

The factor $W_{eff} * log_2 \left(1 + \left(\frac{SINR}{SINR_{eff}} \right) \right)$ in (9) represents the spectral efficiency of the transmission. The spectral efficiency is upper bounded by the adopted MCS.

A consolidated view of the adopted system parameters is available in the appendix (Section 8).

The simulator implements the LTE frame structure. As a result, all the statistics are calculated up to the granularity of per PRB. Additionally, the computed statistics can be represented as per UE measures.

6 Uplink Resource Allocation in Relay Enhanced LTE-A Networks

This section describes the methodology adopted to investigate the effects of RN deployment. The findings on the gains, losses and challenges with REC are highlighted and the underlying phenomena are explained. The section aims to analyze the mutual interference caused by concurrent direct link and access link transmissions. Then, based on the analysis, a resource partitioning mechanism is proposed to reduce the negative effect on system performance. The goal of investigating the resource allocation in RECs is to provide a clear picture of the system dynamics and its dependency on the resource allocation methodology.

In order to study the impact of resource allocation on system performance, only the performance of the direct and access links are considered and the relay link is ignored. The relay link is a redundant overhead in every REC and, therefore, neglecting it in the initial stages of the simulations simplifies the analysis. Upon analyzing the system dynamics with various resource allocation methodologies, the best scheme is selected. The relay link is then implemented over it to realize the true REC's performance.

6.1 Full Reuse

The investigations follow an incremental approach where the most fundamental scheme is first simulated and investigated. Depending upon the lessons learned from it, the scheme is modified so that the pitfalls are reduced. Upon the deployment of RNs into the existing eNB-only network, the simplest resource allocation scheme in a REC is to have a full reuse 1 network. This means that the eNB and RNs transmit on the same spectrum. The simulations of this reference case form the basis of the thesis work since they give an idea of the impact of dropping RNs in an eNB-only network and allowing the UEs to transmit in an uncoordinated manner. Figure 15 depicts the full reuse REC resource allocation scheme on the time-frequency grid.

This scheme is abbreviated as *FR/R1*. Here, FR and R1 stand for *Full Reuse* and *Reuse 1* respectively.

The CDF plot of the SINR at eNB in Figure 23 reveals that the concurrent access link transmission causes significant reduction of SINR on the direct link. Even though the UEs connected to the access link are power controlled, the interferers in the REC originate within the eNB-only coverage area itself. Thus, the existence of close interferers reduces the SINR of the REC to some extent. Also, a full reuse REC introduces more interferers at the eNB of interest. Taking into account that in LTE, intra-cell interference is theoretically zero, if UEs within the cell are allocated
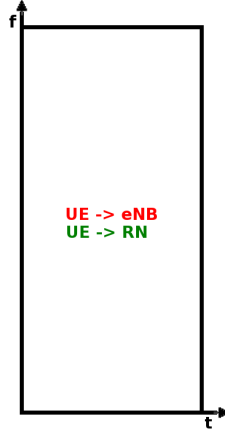
Figure 15: Full Reuse - Reuse 1 : Time vs Frequency

orthogonal resources, only ICI would exist. For the sake of analysis, the number of eNBs in the region and RNs per sector are denoted by N and n respectively. In the eNB-only case, each UE had a maximum of $N - 1$ interferers whereas a UE in a REC has a maximum of $(N - 1) + Nn$ interferers. The additional Nn interferers (a maximum) are responsible for the SINR drop for UEs on the direct link. By comparing the CDF curve of the UEs that remain connected to the direct link even after RN deployment, it is observed that RN deployment with full reuse drastically reduces their performance.

The CDF plot of the SINR at RN in Figure 24 is quite as expected, i.e. RN deployment improves the SINR of the cell-edge UEs. Upon RN deployment, the cell-edge UEs of the eNB-only cell now connect to a closer RAP - the RN. Therefore, such UEs are no longer power limited. As a result, they are received with powers that are good enough to overcome a maximum of $N + (Nn - 1)$ interferers. It is worthwhile to note that a low percentage of UEs at the cell-edge experience a performance degradation in a REC. This is contributed to by the UEs which are located at the hand-over region between neighboring RNs. Also, a UE connected to the direct link and located far from the eNB (i.e. close to the RN) could transmit at high enough power (possibly as high as P_{max}) to degrade the SINR of a UE connected to the access link.

The analysis of throughput per UE shows that the performance with regard to SINR at the eNB is proportionally translated to throughput. This implies that compared to the eNB-only cell, the throughput for the UEs on the direct link in a REC degrades. The throughput per UE connected to the RN is interesting in the sense that these UEs now experience a significantly higher throughput compared to the eNB-only case. The reason for such a multi-fold increase in throughput per UE is due to the fact that with the adopted system parameters, a RN typically has a coverage radius of approximately 20 m and occupies 3% of the sector's coverage

area. Therefore, the number of UEs connected to a RN on average is 3% of the total UE density in the sector. With such a few number of UEs connected to a RN that still has the freedom to transmit on the complete bandwidth W, the multi-fold improvement in per UE throughput on access link is experienced.

6.2 Full Reuse - Reuse 3 at Relay Nodes

The analysis of FR/R1 illustrated that the radio conditions of UEs on the direct link deteriorate when the direct link and access link transmit simultaneously on the same PRBs. Since the increase in the number of interferers by up to Nn times could contribute to this behavior, a scheme is thought to reduce the number of interferers. It is reasoned that since per UE throughput on the access link is quite high, the number of PRBs allocated to each access link could be reduced. This in turn would reduce the number of the access link's PRBs interfering with those of the direct link. The straight forward approach to realize this is to reduce the number of PRBs allocated to the access link according to some performance metric. An alternative approach is taken here. The RNs are visualized to form a hexagonal cellular network among themselves. Since frequency reuse is a mature and accepted concept, a frequency (subcarrier) reuse greater than 1 is thought of. Therefore, a reuse 3 is now introduced by modifying the FR/R1 scheme. Figure 16 depicts the resource allocation on the time-frequency grid.

This scheme is abbreviated as *FR/R3* where R3 stands for the *Reuse 3* on the access link.
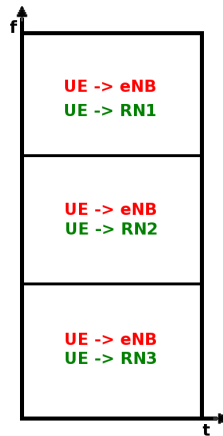

Figure 16: Full Reuse - Reuse 3 : Time vs Frequency

The reuse 3 on the access link is advantageous in two ways. Firstly, it now reduces the maximum number of interferers on the direct link to $(N-1) + \frac{Nn}{3}$ which means that there are $\frac{2Nn}{3}$ lesser interferers with FR/R3 compared to FR/R1. Secondly,

even though the number of PRBs per access link is reduced, the reuse 3 improves the SINR of these resources due to lower interference from access link transmissions. Translating the SINRs to per UE throughput, FR/R3 improves the per UE throughput on the direct link. On the access link, the per UE throughput reduces. The throughput experienced by these UEs has not scaled down in proportion to the reduction in PRBs due to gains from the reuse 3 on the access link. In other words, the access link UEs still experience a significantly high throughput.

6.2.1 Offset-Reuse 3

The reuse 3 employed at the RN is a variation of the traditional reuse 3 pattern. Since RNs are deployed at the cell-edge, the reuse 3 should also assist in mitigating interference among inter-sector RNs. In order words, RN carriers are reused in such a way that no two adjacent RNs are allocated the same set of subcarriers. To meet this criteria, RN carrier planning is done such that each sector uses an offset version of its neighboring sector's subcarrier reuse pattern. As a result, no two adjacent RNs use the same set of subcarriers even at the cell-edge. Figure 17 illustrates the *Offset-Reuse 3* subcarrier planning at RNs. Each of the three shades in the RN coverage area represents a set of reuse 3 subcarriers.
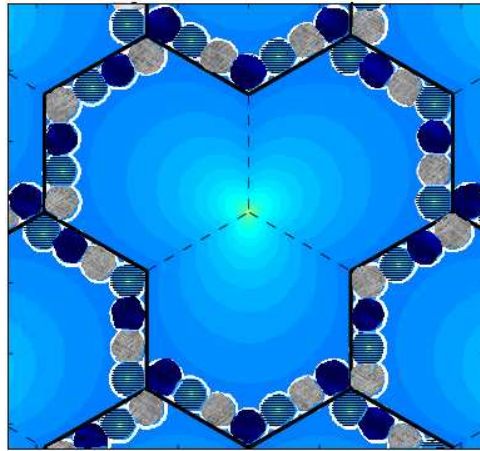

Figure 17: Offset-Reuse 3 Subcarrier Planning at RNs

Throughout this thesis work, the Offset-Reuse 3 pattern at RNs is implemented whenever RNs employ a reuse 3 among themselves.

6.3 Isolated Reuse

FR/R1 and FR/R3 provided a good insight into the impact of interference when REC transmissions occur in an uncoordinated manner. The next step that is considered is to partition the bandwidth W among the direct and access links. The aim

of this approach is to ascertain the variation in system performance when the UEs connected to the eNB and RN are allowed to transmit only on exclusively reserved portions of the resource frame. The number of resources to be given to the direct and access link is based on the mean of the total offered traffic on either link. All the UEs that are dropped into the sectors are assumed to belong to the same QoS class. In such a setting, the mean offered traffic on each link is proportional to the number of UEs served by the link. Since the UEs are dropped in a random manner over numerous iterations to collect a reliable number of samples of system statistics, the overall UE drop pattern takes the form of a uniform distribution. Thus, on average the offered traffic on a link is proportional to the portion of the sector area that is served by the RAP. So, to conclude, the spectrum W is partitioned based on the coverage area. In this particular simulation setup, the eNB covers (approximately) 80% of the sector area. Therefore, an eNB is allocated 80% of the resources while each RN is allocated the remaining 20%. This approach is taken since it is simple as well as good in terms of low blocking probability. In the terminology of tele-traffic theory, this method converges such that the carried traffic is almost equal to the offered traffic. Figure 18 depicts the resource allocation on the time-frequency grid.

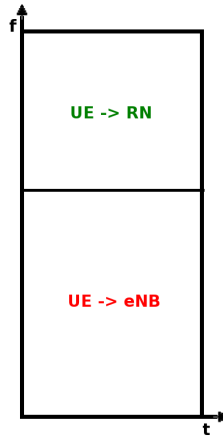This scheme is abbreviated as *IR/R1* where IR stands for *Isolated Reuse*.

Figure 18: Isolated Reuse - Reuse 1 : Time vs Frequency

The simulation of REC with isolated resources for the eNB and RN is aimed at ascertaining the improvement in radio quality in the absence of interference between concurrent direct and access link transmissions. Also, the extent to which the improvement in radio conditions could compensate for the reduced resources on each link is an interesting aspect.

Compared to FR, IR improves the low-end SINR of UEs connected to the eNB. This is because with IR the worse performing UEs on the direct link are protected

by non-interfering RN coverage areas. The protection means that with IR/R1, the average distance of an interferer on the direct link is higher compared to both eNB-only and FR REC implementations. Also, compared to FR, IR/R1 improves the high-end SINR but does not over-perform those eNB-only case UEs. The latter behavior is due to the fact that the eNB-only case has been optimized with FPC where the cell-center UEs gain. So, comparing the performance of REC with $\alpha = 1.0$ and eNB-only with $\alpha = 0.6$ might misrepresent the performance. But, since the goal is to outperform the optimal $\alpha = 0.6$ eNB-only setting, the comparison is continued. The SINR at the RN improves with respect to both the eNB-only and FR implementations. Compared with the former and latter implementations, this performance gain is logical because of the UE's communication with a closer positioned RAP (i.e. the RN) and the absence of the direct link's interference respectively.

The SINR experienced by a UE is critical to view the radio channel quality and spectral efficiency since meeting service-oriented SINR targets is one of the primary goals of communication system design. Technically, the throughput is dependent on the SINR. The system capacity and throughput per UE, however, are dependent on the allocated bandwidth. Therefore, since IR allocates a reduced transmission bandwidth for each RAP, finding the throughput experienced per UE is an important performance metric. The throughput per UE connected to the eNB follows the behavior of SINR at the eNB. This means that for a UE connected to the eNB, the improved radio conditions makes up for the reduced resources and does not degrade per UE throughput. Compared to FR, the throughput per UE at the RN is reduced since each RN now gets only 20% of resources. But, the simulation is in the right direction since with IR, the cell-edge performance has multi-fold improvement compared to the eNB-only case. Also, these UEs continue to perform much better than their eNB-connected IR counterparts.

6.4   Isolated Reuse - Reuse 3 at Relay Nodes

The simulation of IR/R1 showed that by isolating the resources that are allocated to direct and access link, the interference in the REC is efficiently controlled. IR/R1 is varied such that a reuse 3 similar to FR/R3 is applied at RNs. Figure 19 depicts the resource allocation on the time-frequency grid.

This scheme is abbreviated as *IR/R3*.

The simulation of IR/R3 illustrates that the SINR at the eNB is unchanged compared to IR/R1. This is because the direct and access links transmit on mutually exclusive portions of the resource frame and, therefore, a variation of resource allocation in the access link does not affect the performance on the direct link. Compared to IR/R1, IR/R3 reduces the number of access link interferers by a factor of $\frac{2Nn}{3}$;
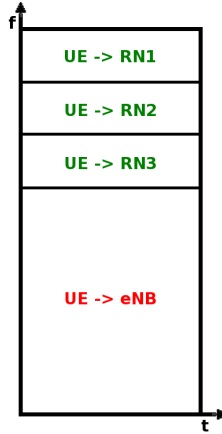
Figure 19: Isolated Reuse - Reuse 3 : Time vs Frequency

thus bringing in a further improvement in the SINR of UEs connected to RNs. Analogous to the SINR at the eNB, throughput per UE connected to the eNB is unaffected between the transition from IR/R1 to IR/R3 for the same stated reason. With regard to throughput per UE connected to RNs, it is observed that the performance of IR/R3 is a compromise of IR/R1. This is because with the reuse 3, UEs at the relay-edge are benefited with the reduced interference which outweighs the impact of reduced resources. Alternately, since the relay-center UEs are less impacted by interference, their SINR gains are lower. Thus, the net effect is that these UEs are weighed down by the reduced resource allocation which results in their lowered performance. Thus, the difference in per UE throughput such as the relay-edge improvement against the relay-center degradation is observed. This effect indirectly reduces the differentiation between relay-edge and relay-center UE performance. The presence of throughput saturation intervals are seen when the PRBs allocated to the UE experience high SINRs that surpass the maximum spectral efficiency of the MCS. In the simulations, the adopted 64-QAM MCS limits the maximum spectral efficiency to 6 bps/Hz. The saturation intervals observed at equally spaced throughput intervals indicate the scenario of a UE's multiple allocated PRBs experiencing the spectral efficiency threshold. The effect of PRBs being upper bounded by the spectral efficiency threshold indicates the success in reducing interference with IR/R3.

These results are important since it gives an insight into the system performance when the eNB and RNs operate on mutually exclusive resources that are constrained by the constant system bandwidth W. It highlights the fact that the interference limited scenario of FR can be overcome with IR. The improved system performance with IR illustrates that resource partitioning (or coordinated direct and access link transmission) is one of the critical requirements to gain from RN deployment. This provides the basic guiding principles in the formulation of advanced resource partitioning methodologies expressed in this work.

6.5   Grouped Reuse

FR and IR based resource allocation provided a good understanding of the impact of resource allocation on interference fluctuation at different positions in the cell. An overview of the dependency of the number of PRBs allocated to a RAP in determining the per UE throughput is also obtained. Since the performance of UEs is a function of their geometry, the performance of different resource allocation schemes is analyzed based on their impact on different positions in the cell. In order to make the description of these positions easier, each point in a sector is broadly defined to fall into one of the three regions - A, B or C where

- A is the subset of closer positions (region) served by an eNB.

- B is the subset of farther (i.e. other than closer) positions (region) served by an eNB.

- C is the set of positions (region) served by a RN.

It is to be noted that this nomenclature is adopted with the sole purpose of making the description more concise. Figure 21 illustrates the defined regions.

As mentioned in the description of the behavior of FR, the UEs in A have improved SINRs even under the influence of additional interference from C. On the other hand, the UEs in B are affected by the interference from C. As a result, the pattern of UE transmissions in B and C is detrimental to overall system performance. IR revealed that resource partitioning is needed in a REC if the UEs connected to eNB should be less affected by RN deployment. Both FR and IR coherently illustrated that the throughput per UE in A and B is much less than in C. Combining the results of FR and IR, a holistic view of the criticality of interference and resource allocation is obtained.

In proposing an alternate resource allocation scheme, four observations have been taken into account. Firstly, a UE in A is least affected by the concurrent transmission in C. Secondly, a UE in B is affected by concurrent transmission in C. Thirdly, resource partitioning is necessary in an REC. Fourthly, in the REC, UEs connected to the RN outperform those UEs connected to the eNB. The solution is formulated on the basics of the third observation with the others providing supporting guidelines in its design. The first and second observations suggest that the REC should have interference coordination so that the gains from RN deployment are not lost due to uncontrolled interference. Concerning the third observation, it is to be noted that an eNB is the master RAP in the cell. Therefore, the UEs connected to the eNB should actually gain from RN deployment. Also, since eNBs cover the majority of the cell area, improving the performance of the UEs connected to the eNB is of paramount importance to exhibit an overall gain in REC performance. An improved resource

allocation methodology to eNB could improve the performance of UEs connected to it. UEs with good geometry are neither interference nor power limited, therefore a higher resource allocation can improve the performance of such UEs.

RN deployment introduces the need for intra-sector interference coordination in a REC because the extent of intra-sector orthogonality is now dependent on the resource allocation scheme. Based on the discussed results of FR and IR, a modified resource allocation is proposed. The gains from the assigning orthogonal resources to UEs in B and C are considered. Also, in such a case since A and C are isolated by B, reusing the resources assigned to C by A is also considered. The assignment of resources to a UE based on its geometry is an application of the principle of *user grouping*. In order to coordinate interference in the DL, [17] implemented a user grouping scheme. Contrary to [17], this work focuses on the UL transmission scheme. This resource allocation scheme is termed as *Grouped Reuse* due to the consideration of a UE's geometry (i.e. indirectly a group) during resource allocation. Also, the term reuse is justified because the resources of C are reused by A. This is a distinguishing aspect of the proposed resource allocation scheme. Figure 20 depicts the resource allocation on the time-frequency grid.

This scheme is abbreviated as *GR/R1* where GR stands for *Grouped Reuse*.
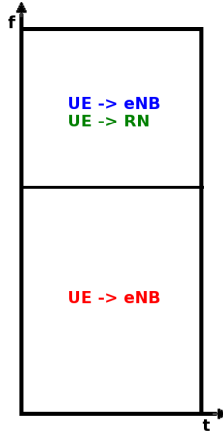

Figure 20: Grouped Reuse - Reuse 1 : Time vs Frequency

The reuse of C's resources by A introduces the concept of the *Grouping Radius*. Grouping Radius defines the maximum distance from the eNB where the resources used by C can be reused by A. The grouping radius is derived upon the principle of proportional allocation. Mathematically, it can be expressed as follows:

$$numPRB_A = numPRB_C = numPRB_{tot} * \left(\frac{Area_C}{Area_{tot}} \right) \qquad (10)$$

$$Area_A = Area_{A+B} * \left(\frac{numPRB_A}{numPRB_{tot}} \right) \tag{11}$$

where

- $numPRB$ and $Area$ are the respective number of allocated PRBs and the area of the region indicated in the subscript.

- The subscript tot refers to the word total.

The grouping radius is then computed by calculating the maximum distance from the eNB such that the area under the arc equals $Area_A$. With the adopted simulation setup, the grouping radius is computed to be 102 m.

It is to be noted that $numPRB_C$ is the same in both IR and GR. With respect to eNBs, GR permits the allocation of all resources for the eNB which, therefore, emulates the reuse 1. Thus, in terms spectral efficiency; the possibility of maintaining a reuse 1 at eNB in RECs is a highlight of the GR resource partitioning scheme.

Figure 21 illustrates the region-wise break up of the sector and the Grouping Radius.
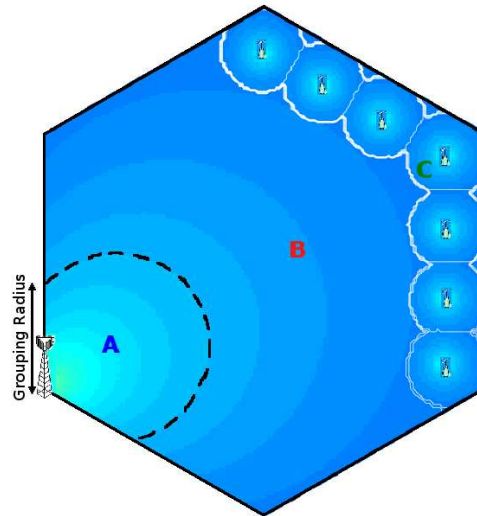

Figure 21: A sector with Grouped Reuse

With GR/R1, the performance of the direct link is analyzed in terms of the regions served by the eNB namely A and B. Compared to IR, GR/R1 has slightly lower SINR at A because it experiences additional interference from C. The SINR at B is more or less similar to IR. Concerning B and C, IR and GR have similar orthogonal

resource allocation between them. The minor difference in SINR is because user grouping reduces the variance of interference perceived by a UE. This result is in accordance with [12]. Compared to IR/R1, the SINR at RNs (i.e. Region C) does not vary much with GR/R1. This illustrates that at RNs, the interference among RNs is the dominating factor and, therefore, the additional interference from A is almost ineffective in degrading their SINR.

With GR/R1, the throughput per UE connected to the eNB shows promising improvement. This performance is achieved due to the reuse 1 that is maintained at the eNB even after RN deployment. Since the SINR analysis revealed that the interference caused by UEs in C on those in A is low, the reuse 1 allocation is able to outweigh the negative effect of interference. If the interference between the direct and access link is approximated to be almost negligible, then the eNB can be visualized to be serving a smaller area with the added isolation between cell-edges by RN deployment. The reduced eNB coverage area coupled with the availability of the same number of resources as in the eNB-only cell provides the leverage for improved performance as seen with GR/R1. GR/R1 provides clear gain in per UE throughput for all the UEs that remain connected to the eNB even after RN deployment. This result illustrates that GR can undo the effects of access link originated interference in a REC. The throughput per UE connected to RN remains coherent with its SINR behavior. The reason for the direct mapping between the SINR and throughput of UEs connected to RNs is because both GR and IR have the same number of allocated resources on the access link.

6.6   Grouped Reuse - Reuse 3 at Relay Nodes

GR/R1 proved to be an improved resource partitioning scheme because of its success in mitigating the interference effects of RN deployment without compromising the per UE throughput. Now, similar to FR/R3 and IR/R3, the gains from a reuse 3 on access link is foreseen. Therefore, GR/R1 is modified with the reuse 3 among RNs. Figure 22 depicts the resource allocation on the time-frequency grid.

This scheme is abbreviated as *GR/R3*.

The SINR at eNB shows the expected improvement for UEs in region A. This is attributed by the same reasoning as stated earlier, i.e. reduced number of interferers from C. The important development with the reuse 3 is that the SINR of A and B with GR/R3 edges closer to the eNB-only case. This is significant since the improvement illustrates that the SINR for UEs connected to the eNB is not degraded by a large extent due to in-band relay deployment. Compared to IR/R3, the interference from UEs in A on C reduces the SINR at RNs. But, this reduced SINR is still much higher than GR/R1, eNB-only, FR/R1, FR/R3 and IR/R1 schemes. The saturation intervals in throughput CDF indicates that PRBs continue to be upper bounded by
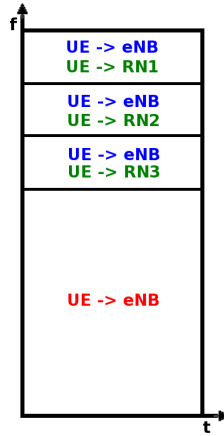
Figure 22: Grouped Reuse - Reuse 3 : Time vs Frequency

the maximum spectral efficiency of the adopted MCS. Therefore, in terms of SINR targets, GR/R3 performs well.

The throughput per UE connected to the eNB improves in accordance with the same reasons as stated for SINR improvement. Also, the throughput per UE connected to RNs remains coherent with its SINR.

Thus, among all the resource allocation methodologies; GR/R3 provides the best performance for UEs connected to the eNB in a REC. At the same time, the UEs connected to RNs show improved performance by a large extent. GR/R3 controls the performance of UEs connected to RNs and reduces the disparity between UE throughputs on the direct and access link.

GR provides the possibility to improve the performance of UEs in A by reducing the transmit powers of UEs in C. Since UEs in C experience better performance, they can be powered down in order to reduce the interference they cause on A. Therefore, the SINR and per UE throughput at the eNB can potentially be increased and higher gains can be illustrated. To summarize, GR can exploit PC settings for UEs on the access link in order to benefit the UEs on the direct link. If this means to set different P_o values for UEs connected to direct and access links, then the LTE-A protocol specifications would need to support the broadcast of a RAP specific rather than cell specific PC parameters. The feasibility to accommodate this proposal into the 3GPP LTE-A standards is indeed interesting.

7 System Performance Analysis

The simulations of the different resource allocation schemes in Section 6 provided insight into the effects of resource allocation in a REC. The performance of UEs connected to the eNB and RN were analyzed separately. This section discusses the simulation results from a holistic point of view and concludes on the improvement in system performance with resource partitioned RECs.

7.1 SINR on Direct Link

Figure 23 compares the SINR of an eNB-only network with that of a REC's direct link.
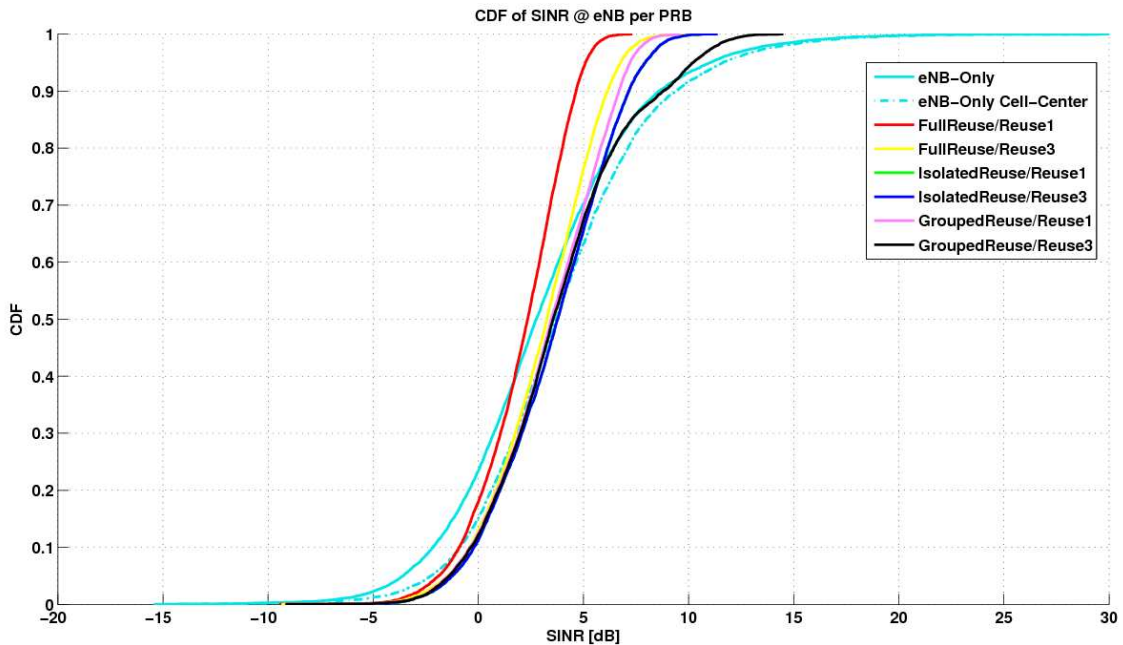

Figure 23: SINR on Direct Link

Figure 23 illustrates that:

- FR/R1 and FR/R3 do not mitigate interference and, therefore, reduce the SINR on the direct link. For this reason, UEs on the direct link could experience higher outage if resources are not partitioned in a REC.

- IR/R1 and IR/R3 cancels the interference between the eNB and RNs and provides SINR improvement. Partitioning reduces the number of resources allocated to a RAP. Therefore, the effect of reduced resources on throughput would rate the effectiveness of this allocation scheme.

- GR/R1 and GR/R3 provides SINR improvement to the subset of poor geometry UEs that remain connected to the eNB even after RN deployment. In terms of SINR, GR/R3 is the best scheme since it loses the least (alternatively gains the most) after RN deployment. A degradation in high-end SINR is experienced even though GR/R3 performs well for most parts of the cell. Since per UE throughput is the final evaluation criteria, it remains interesting to observe from the per UE throughput plots in Figure 25 if the reduced SINR for these UEs is compensated for by the GR resource allocation.

7.2 SINR on Access Link

Figure 24 compares the SINR at the cell-edge of an eNB-only network with that of a REC's access link.
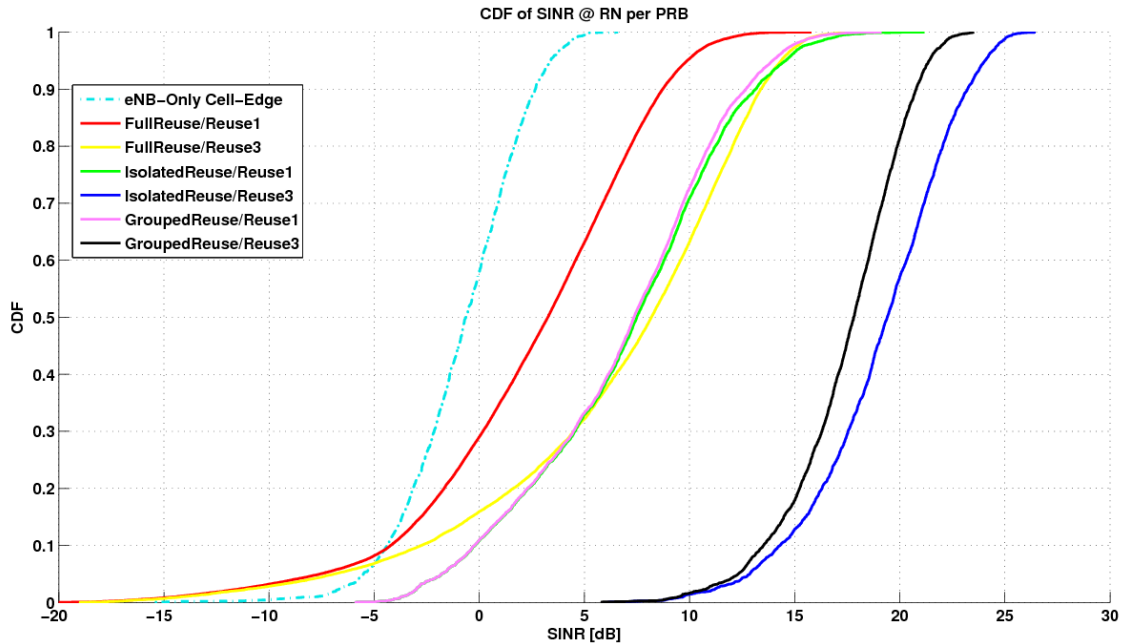

Figure 24: SINR on Access Link

Figure 24 illustrates that:

- FR/R1 and FR/R3 can improve SINRs for the cell-edge UEs post RN deployment. But, an average of 8% of these UEs may still face degraded performance than in the eNB-only network. This is observed because FR in REC introduces a scenario where a cell-edge UE on the direct link transmits at such high power that it kills the power controlled transmission of a UE on the access link due to the large difference between their respective path losses.

- IR/R1 and IR/R3 improves the SINR on the access link due to the absence of

interference from the direct link. The trade-off between improved SINR and reduced resources can be observed from per UE throughput plots in Figure 27.

- GR/R1 and GR/R3 provides SINR improvement for cell-edge UEs. The note on the performance trade-off of IR/R1 and IR/R3 is also valid in this case.

7.3   Throughput per UE on Direct Link

Figure 25 compares the throughput per UE in an eNB-only network with those in a REC's direct link.
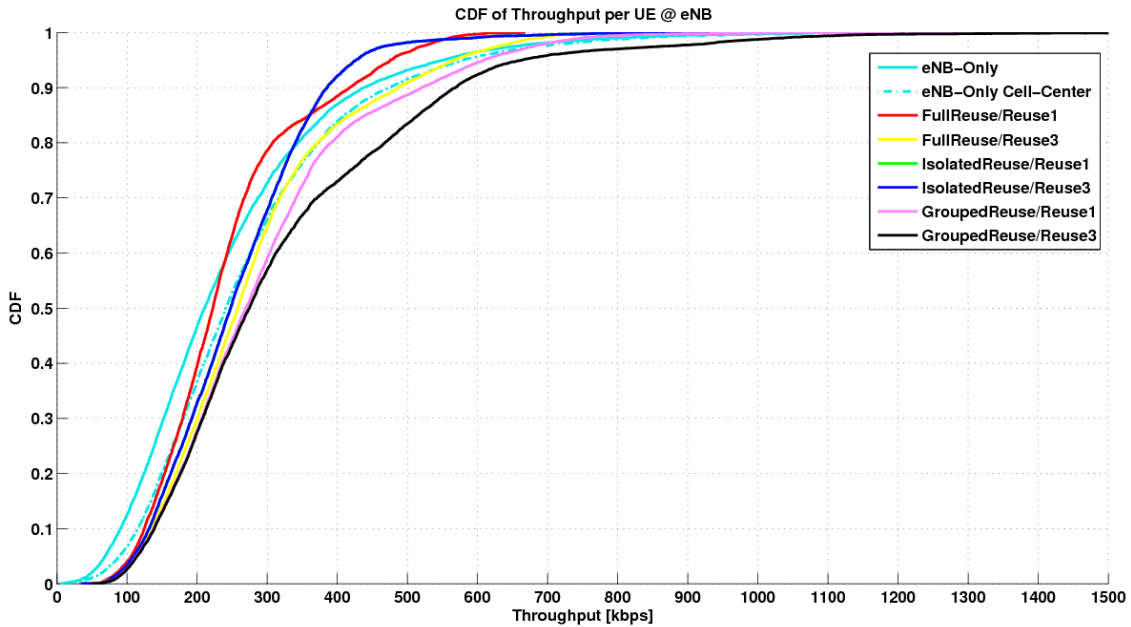

Figure 25: Throughput per UE on Direct Link

Figure 25 illustrates that:

- FR/R1 degrades the per UE throughput on the direct link. Therefore, FR/R1 cannot be used as it is. FR/R1 with refined PC settings may possibly improve the performance. But, this is not investigated since it is not within the focus of this work.

- FR/R3 improves the performance of the direct link in a REC.

- IR/R1 and IR/R3 do not improve the per UE throughput over the complete direct link. With IR, the performance of the poor geometry UEs improves and the good geometry UEs degrades. A poor geometry UE is generally interference and power limited. IR reduces the probability of interference limited

transmissions. Also, with regard to power limitation, IR is beneficial in the following way. Compared to FR, IR allocates lesser resources per UE. As a result, a UE now transmits with a higher probable PSD value of $P_o + 10\ log_{10}M + \alpha\ L$ than $\dfrac{P_{max}}{M}$. Thus, with IR, a UE is more probable to be received by the eNB with a PSD of P_o. The reception of the UE at the PSD set by the network operator assists in overcoming interference with power. With regard to the behavior of good geometry UEs, these not being power limited can transmit on a large number of subcarriers. Thus, the lower resource allocation with IR reduces the throughputs of such UEs. The important gain illustrated with IR is with respect to the 5%-ile UE throughput.

- GR/R1 and GR/R3 perform the best because of reduced interference with user grouping as well as high (i.e. full) resource allocation with reuse 1 on the direct link.

Figure 26 illustrates the mean throughput per UE on the direct link for each of the scenarios.
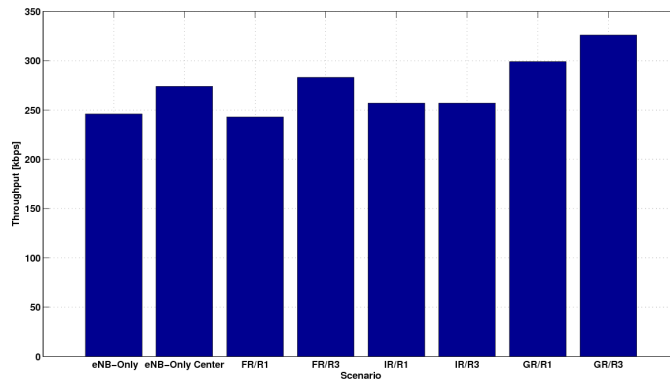

Figure 26: Mean Throughput per UE on Direct Link

It is again observed that GR/R3 provides the highest mean throughput for UEs served by the direct link.

7.4   Throughput per UE on Access Link

Figure 27 compares the cell-edge throughput per UE in an eNB-only network with those in a REC's access link.
Figure 27 illustrates that:

- The introduction of the access link in RECs contributes to the drastic improvement in cell-edge UE throughput.
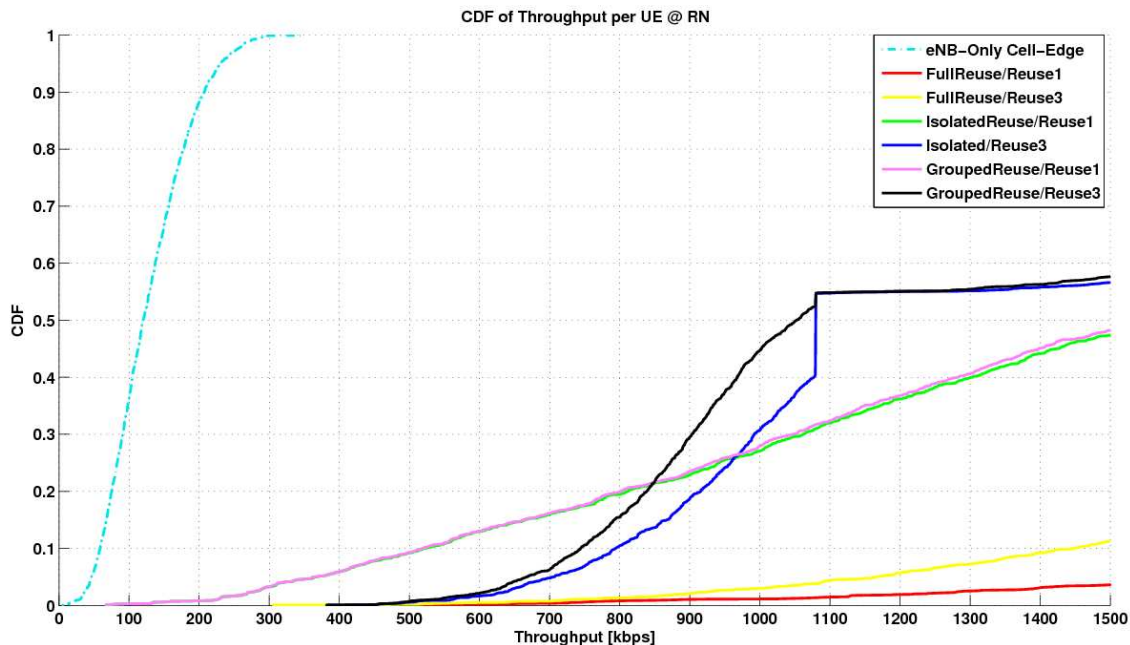
Figure 27: Throughput per UE on Access Link

  - Resource allocation can provide varying throughput with its effects on inter-
    ference and subcarrier allocation metric.

Figure 28 illustrates the mean throughput per UE on the access link for each of
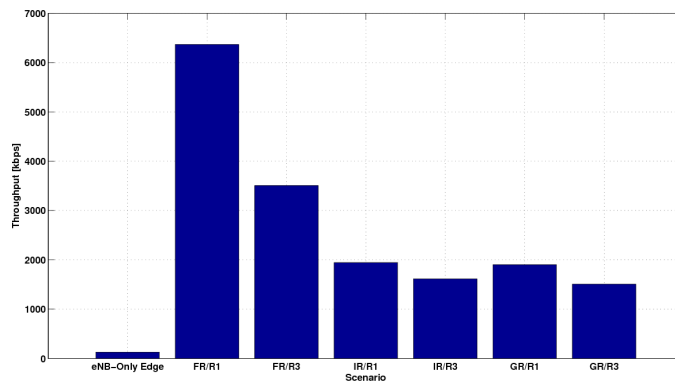the scenarios.

Figure 28: Mean Throughput per UE on Access Link

It is observed that the respective variants of IR and GR are almost equal in terms
of their spectral efficiency on the access link. Also, the mean throughput per UE on
the access link always remains much higher than on the direct link.

7.5   Throughput per UE in the Sector

Figure 29 compares the sector-wide throughput of the eNB-only and REC networks. It constitutes the combined statistics of UEs on the direct and access links.
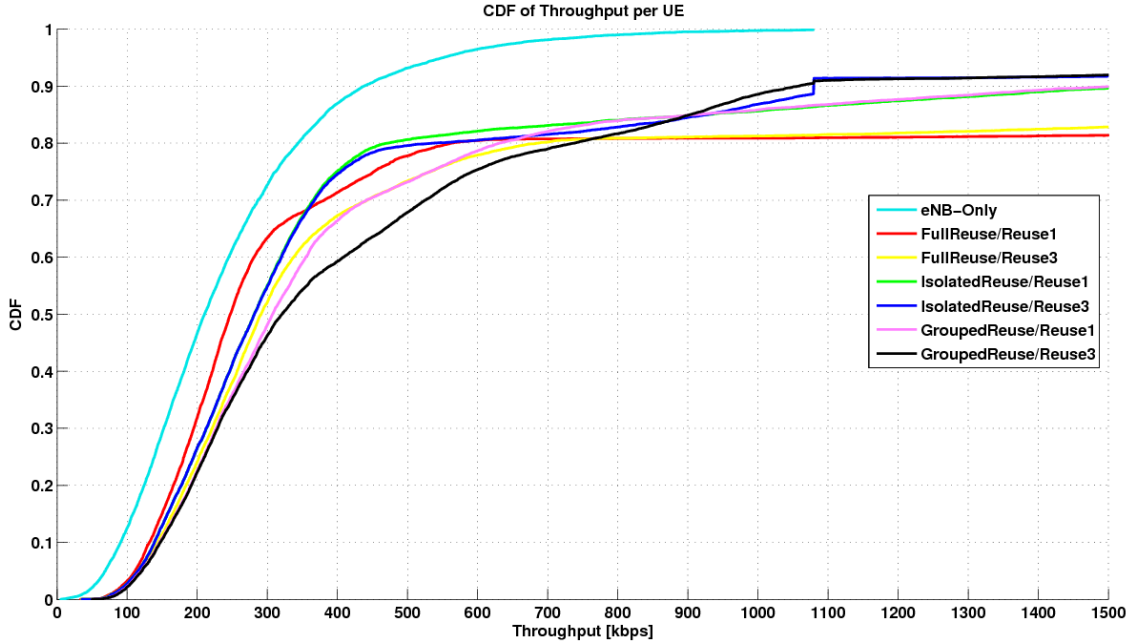

Figure 29: Throughput per UE in the Sector

Figure 29 illustrates that:

- FR/R1 and FR/R3 seem to improve the per UE throughput in the sector. In reality, the REC's direct link performance degrades when the access link transmits in an uncoordinated manner. The gain observed at sector level is attributed to the excessively high throughputs experienced by UEs on the access link. Since the eNB is the master RAP and serves the majority of UEs in the sector, its improved performance is of paramount importance. Therefore, in reality, the FR plots show no gain in sector-wide throughput.

- IR/R1 and IR/R3 seem to improve the per UE throughput in the sector. Similar to FR, IR does not always improve the performance of UEs connected to the direct link. Therefore, the per sector throughput gains seen with IR could mislead it to be considered as a good scheme. Even though IR is not the perfect way to partition resources, it revealed invaluable information of the REC's system dynamics.

- FR/R1 and FR/R3 prove to be the best for per UE throughput in the sector. This is attributed by a gain on both the direct and access links. The major highlight of FR is that every UE's direct link performance in a REC is improved compared to an eNB-only cell.

- All the simulations indicate that a REC improves the performance of the 5%-ile UEs.

Figure 30 illustrates the mean throughput per UE in the sector for each of the scenarios.
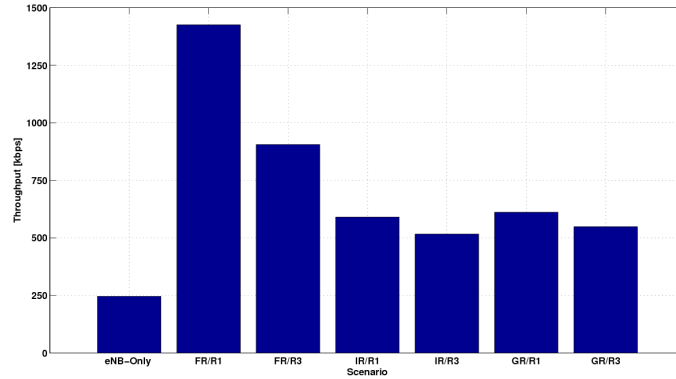

Figure 30: Mean Throughput per UE in the Sector

It is observed that with RN deployment, the mean throughput per UE at least doubles.

The simulation of the 3GPP Case 3 propagation scenario exhibits similar system behavior and the plots are available in the appendix (Section 8).

7.6 Inter-Cell Interference Coordination with User Grouping

The analysis in this section aims to illustrate that resource partitioning on the basis of GR/R3 is meritorious towards improved system performance. An objective of relay deployment and resource partitioning is to reduce the interference in the system and improve spectral efficiency. [12] discussed how user grouping is beneficial in coordinating ICI in OFDMA-based systems. Interference coordination assists in reducing interference by applying restrictions on a UE's resource allocation and/or transmit power. The GR/R3 scheme proposed in this work combines an idea of resource allocation and user grouping in RECs and achieves interference coordination among eNB and RNs. Figure 31 illustrates the CDF of interference experienced by a subcarrier during the simulations.

The CDF plots for the eNB-only case illustrate that all PRBs experience a similar interference pattern irrespective of its allocation to different positions on the
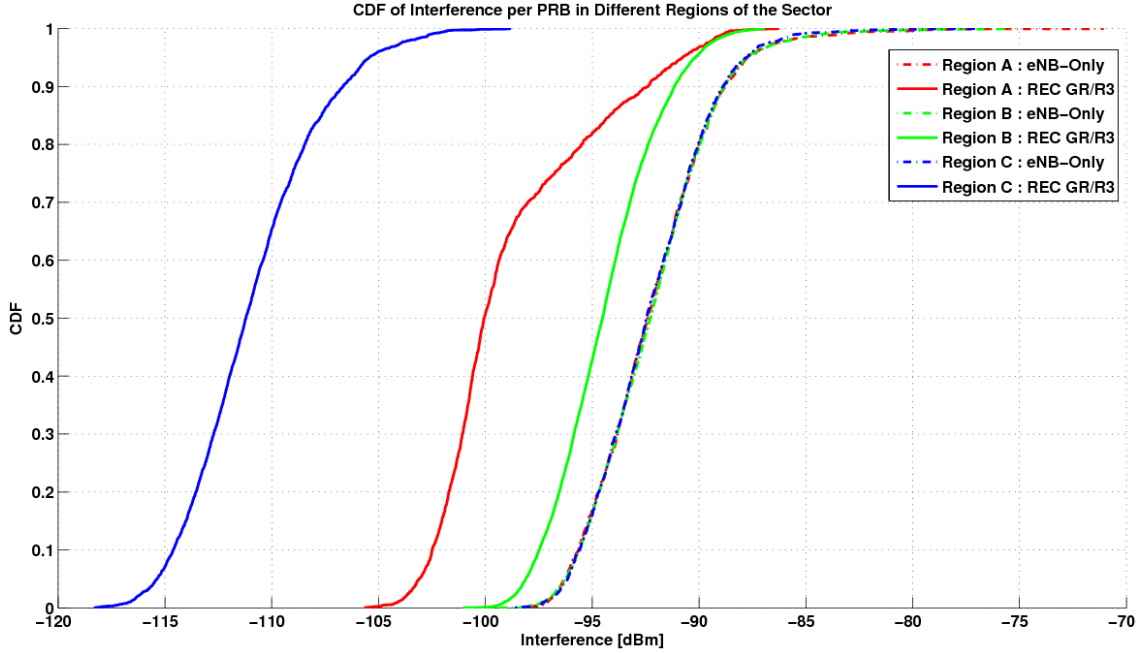
Figure 31: Interference per PRB : Separated by Region

cell. This behavior is observed because LTE organizes its transmission over multiple orthogonal flat fading subcarriers. In the case of no user grouping, since each sub-carrier can be allocated to any of the UEs in the cell, every interferer is randomly positioned. As a result, the perceived interference is uncorrelated and averages out to generate position independent statistics. GR/R3 realizes user grouping by allo-cating resources based on UE geometry. The success of user grouping in reducing ICI is illustrated by the reduced interference with GR/R3. Every region in GR/R3 experiences lower interference levels than the eNB-only case. The decreased inter-ference in GR/R3's A and B regions is attributed to the degree of isolation provided by user grouping. Also, PC aided in reducing the interference among the interfering groups. The reduced interference in region C is attributed by PC and offset-reuse 3 on the access link. Also, the user grouping on the direct link reduced the intra-sector interference by reusing C's resources at A with a high reuse distance.

Figure 32 illustrates the CDF of throughput per UE in each of the regions in the sector.

The CDF plots of throughput per UE in each region reveals that RN deploy-ment could improve user experience. A couple of observations from this plot are worth highlighting. Firstly, with regard to region C, a huge improvement in per UE throughput is experienced when the same UE migrates from the direct link (in the eNB-only cell) to the access link (in the REC). This effect has been well discussed throughout this section. Secondly, with regard to region A, it is observed that the low-end per UE throughput degrades in a GR/R3 REC compared to an eNB-only
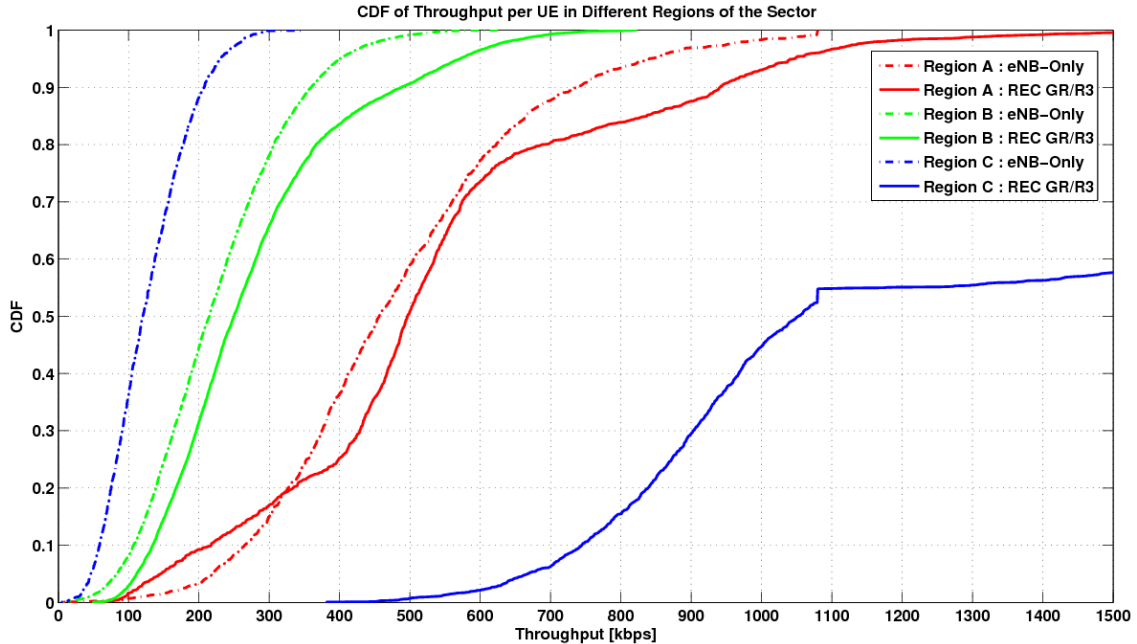
Figure 32: Throughput per UE : Separated by Region

cell. This is reasoned as follows. As mentioned in Section 5.5, the PC parameter α equals 0.6 for an eNB-only cell and 1.0 for a REC. In such a case, since P_o is set such that 30% of UEs transmit at P_{max}, the P_o for an eNB-only cell is much higher than a REC. Additionally, when $\alpha = 0.6$, it has a much reduced effect on the transmit powers of UEs in region A due to their low path loss. Therefore, the higher P_o dominates the setting of the transmit power of these UEs. This results in a higher received power for the good geometry UEs in an eNB-only cell. The comparatively higher transmit power of these UEs is sometimes good enough to overcome the higher interference (compared to REC) that they experience. As a result, the SINR of a set of UEs in region A could be better in an eNB-only cell than in a REC. Such UEs translate the higher SINRs into higher throughput. To conclude, it should be noted that this behavior in region A is observed due to the different PC settings used in both the simulations and, therefore, should not be misinterpreted as a negative effect of the GR/R3 scheme. In fact, the higher resource density on the direct link with GR/R3 overcomes the effect of reduced SINR for the majority of the UEs that were affected by the asymmetrical PC settings. This observation strengthens the scope for a further improved performance of GR/R3 when REC PC parameters are more optimally set.

7.7   End-to-End Performance

Multi-hop networking requires the need for a communication link to forward data between the master network device and the end user. In this particular case of relay enhanced LTE-A cellular networks, the *End-to-End* (E2E) performance between the

UE connected to a RN and an eNB is the point of interest. The relay link forwards the data from the UE connected to a RN to an eNB. The impact of the relay link in determining the E2E performance of all the UEs in a REC is presented in this section.

A DF RN operates in half-duplex mode [23]. As a result, in the UL, the UE transmits to the RN first and then the RN forwards the data to the eNB in a subsequent TTI. In all the REC simulation results explained so far, only the access and direct links were in operation. Since the REC performance illustrated significant gains with GR/R3, the E2E performance of GR/R3 is compared against the eNB-only case. The half-duplex nature of the RN implies that the TTI in which the relay link is in operation, the only other link that could work in parallel to it is the direct link. Since LTE aims to maximize spectral efficiency, a reuse 1 operation is aimed. A reuse 1 in the TTI where a relay link is active implies that a UE connected to eNB transmits simultaneously on the same PRB. The received power at the eNB from the direct link (i.e. UE transmission) as well as the relay link (i.e. RN transmission) is plotted in Figure 33.
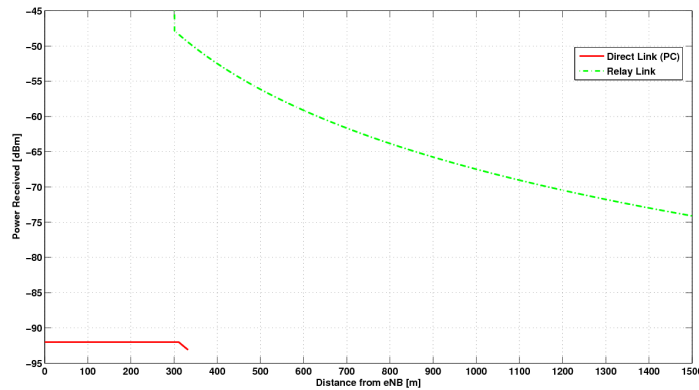

Figure 33: Distance vs Power Received at eNB

Figure 33 illustrates the variation of received power on the direct and relay link with respect to distance. In a REC with an ISD of 500 m, the set of distances possible for a UE and its interfering RN are depicted. It is evident that the received power on the relay link is significantly high even if the RN is located in the second tier of interfering cells. Since multiple RNs are deployed within a sector, the direct link experiences a much higher interference from the relay link. Therefore, it can be concluded that a reliable direct link is not feasible with parallel relay link transmission. This highlights the need for dedicated relay link resource allocation.

7.7.1 Resource Allocation

In this work, the RNs are deployed at the cell-edge to cover the poor geometry regions of the cell. Therefore, RN transmissions from the cell-edge could cause significant interference if they transmit on the same PRBs. To overcome this interference effect, a reuse 3 is proposed among the relay links of each sector. Upon numerical calculations, it is deduced that a reuse 3 based relay link's resource allocation realizes a mean throughput of 525 *kbps* per PRB. Since this throughput is much higher than the mean per PRB and per UE throughputs on the direct link, allocating a single PRB for each RN's relay link is considered. Due to the need for reuse 3 on the relay link, a total of three times the number of RNs per sector is reserved for the relay link in the forwarding TTI. The remaining PRBs in the TTI are allocated to comparatively poor performing UEs of the non-forwarding TTI i.e. UEs in region B. Figure 34 depicts the overall resource allocation with GR/R3 on the time-frequency grid.
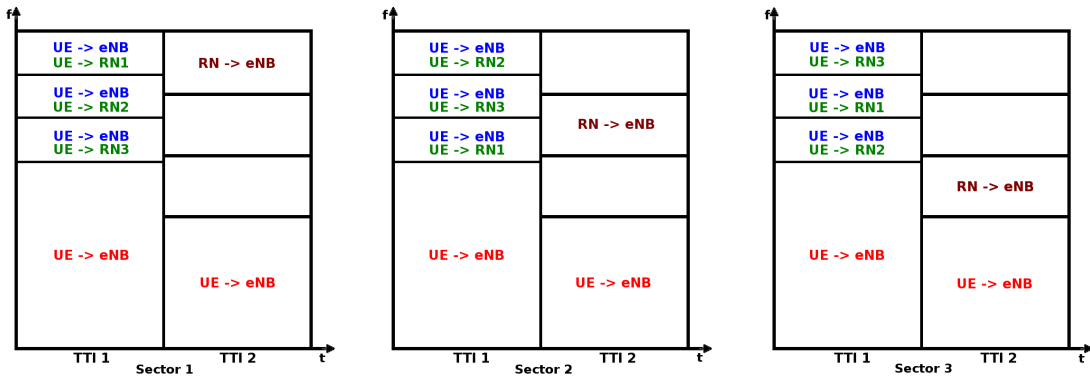

Figure 34: GR/R3 based REC Resource Allocation : Time vs Frequency

7.7.2 Throughput per UE

With the implementation of the relay link, the E2E throughput per UE connected to a RN is dependent on the independent aggregate capacities of the access and relay links. In order to maximize the E2E throughput, the capacities of the access link and relay link should be equal. As already mentioned, the relay link is dimensioned on the basis of the direct link's performance. Therefore, it is the access link which needs to match the relay link. The throughput plots in Figure 27 illustrate that the access link's performance is much higher than the dimensioned relay link. Therefore, since the relay link is the bottleneck in the E2E connectivity, the access link performance needs to be matched with the relay link. This means that the throughput on the access link could be reduced, since such a high throughput will not finally be forwarded by the dimensioned relay link. Since, the access link transmissions are not interference limited, the reduction in access link's throughput is realized by reducing the transmit powers of UEs connected to RNs. With regard

to the P_o for REC used in the simulations in Section 6, a P_o lower by 18 dB is set for UEs connected to RNs. By adopting this comparatively lowered value of P_o for UEs connected to RNs, the access link and relay link performances are matched. As discussed in Section 6.6, GR/R3 gains from lowering the P_o for UEs connected to RNs by experiencing reduced interference caused by the same on UEs in region A. A support for RAP specific broadcast of P_o rather than 3GPP's currently defined cell specific method could be an interesting proposal for 3GPP LTE-A standardization.

As discussed, in the multi-hop case of RECs, the carried relay link throughput is as follows:

$$Throughput_{relay\_link} = min\ (Capacity_{relay\_link}, Throughput_{access\_link}) \qquad (12)$$

where

- $Capacity_{relay\_link}$ is the capacity of the particular RN's relay link.

- $Throughput_{access\_link}$ is the buffered throughput from the particular RN's access links.

The RNs that have buffered data from the access link in earlier TTIs are scheduled in RR within the PRBs allocated to the relay link. This buffered data dependent scheduling of the RN's relay link is adopted due to the following reason. With the system parameters adopted in the simulations, a RN's coverage area is approximately 3%. As a result, it is possible that even a uniform UE distribution may not guarantee that a UE is dropped under every RN in the sector. Therefore, it is not worthwhile to allocate resources to every RN. Also, since the relay link acts as the bottleneck in carrying the high throughput of the access link, scheduling the relay link's resources based on the traffic profile of the access link gains more importance. Therefore, the set of fixed relay link resources are dynamically allocated to particular RNs based on their buffered traffic. To realize the dynamic resource allocation for the RN's relay link, an exchange of buffered traffic specific information in a centralized or distributed manner would be necessary. 3GPP LTE-A standardization could study the feasibility of incorporating a protocol to optimize the multi-hop performance.

With the discussed resource allocation in the forwarding TTI and the further optimized PC settings, the E2E system is simulated. It is to be noted that the simulation with REC now runs for 2 TTIs with the resource allocation being in accordance with the depiction in Figure 34. The CDF plot of the E2E throughput per UE in the GR/R3 based REC is illustrated in Figure 35.

Figure 35 proves that it is possible to gain with RN deployment for a majority of UEs in the cell, even with the dedicated resource allocation for the relay link. Significantly, the improvement in the 5%-ile UE's E2E throughput is an accomplishment
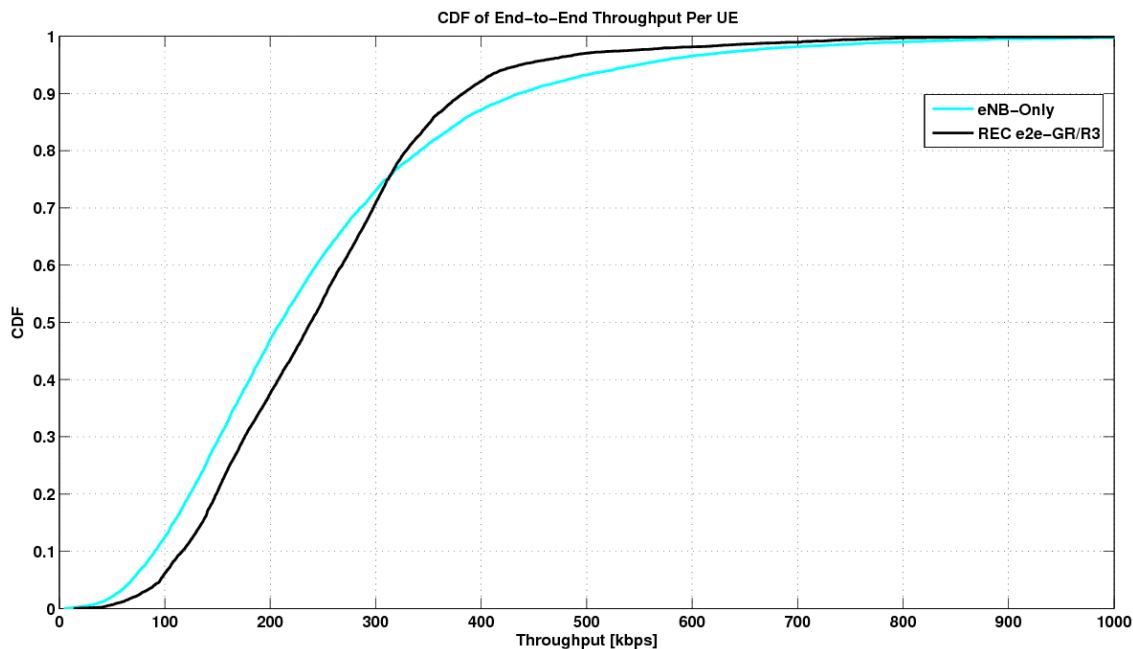
Figure 35: E2E Throughput per UE in the Sector

for the GR/R3 based REC. It is to be noted that the relay link's resource allocation overhead considerably reduced the performance gains of a REC. Figure 36 provides a deeper insight into the E2E GR/R3 performance with the region-wise breakup of E2E per UE throughput.
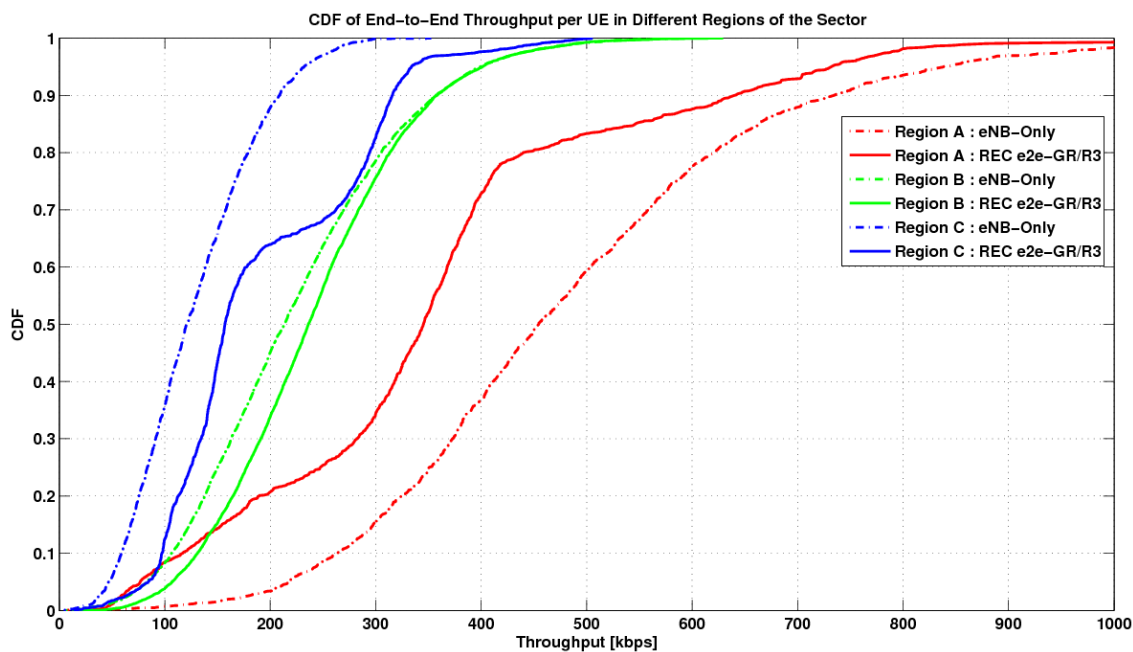

Figure 36: E2E Throughput per UE : Separated by Region

Figure 36 illustrates that both the worse performing regions of an eNB-only cell namely B and C have gained from RN deployment. Therefore, RN deployment based on GR/R3 has improved the E2E throughput of those UEs which needed it the most. The degraded E2E performance of region A is attributed to its reduced resource allocation upon relay link implementation. UEs in region A get to transmit with equal opportunity in a round robin based eNB-only scheme but not in the GR/R3 based E2E REC scheme that is simulated in this work. This is because the UEs in region A are shut down in TTI 2 to accommodate resource allocation for the relay link. This loss in E2E throughput for region A is acceptable since they still remain the best performing set of UEs in the cell.

Based on the studies, the following proposals could improve the E2E system performance of a REC by reducing the relay link overhead.

- The relay link channel model defined by (6) is based on zero penetration loss. This is reasonable for the RNs that are deployed in the sector of interest because they are ideally placed at strategic locations that have a *Line-of-Sight* (LOS) with the eNB. But, with regard to the RN in another sector, the LOS may not be realized in reality due to the urban nature of the radio propagation environment. Therefore, introducing a penetration loss like *Non-Line-of-Sight* (NLOS) component into the channel model could make the relay link more realistic. This modification would then reduce the interference among relay links and thereby improve its performance.

- The RNs have an omni-directional antenna [6]. Since RNs are stationary RAPs that are deployed at the cell-edge, a proposal to have beam forming antennas for relay link communication could reduce the interference effects and thereby improve relay link performance.

7.7.3 UE Transmit Power

RECs provide an opportunity to the UEs connected to RNs to transmit at a lower PSD due their proximity to the RAP. With RN deployment, a reduction in transmit powers of the former cell-edge UEs in an eNB-only system reduces interference in the system. As a result, in GR/R3, the transmit PSD of the UEs connected to the eNB is also lowered. By allocating an optimum number of PRBs to a RAP, the total transmit power of UEs can be minimized. Figure 37 illustrates the reduced UE transmit power in a REC compared to an eNB-only cell.

The CDF plot of UE transmit power in Figure 37 reveals that RECs can effectively reduce a UE's battery consumption thus leading to higher talk times.
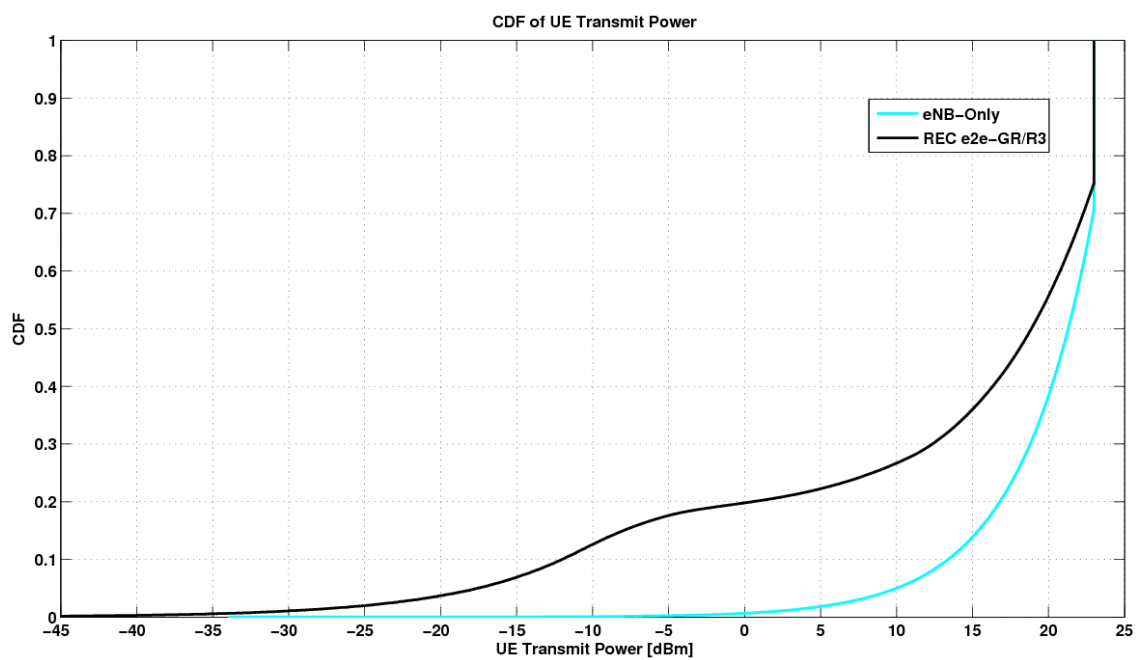
Figure 37: UE Power Saving with RECs

8 Conclusions and Future Work

Conclusions

The thesis work investigated the performance of LTE-A REC with respect to UL resource allocation (and power control to some extent). The simulation of different resource allocation schemes discussed in Section 6 provided specific insights into the dynamics of system performance.

The performance of a full reuse 1 REC is analyzed by simulating the FR resource allocation scheme. System level simulations reveal that such a transmission scheme reduces the radio link quality of the system. The performance of a FR REC degrades to such an extent that it sometimes underperforms the eNB-only scenario. Similar to reducing interference with frequency reuse in legacy cellular systems, a reuse 3 at RNs proves to be a beneficial approach in RECs too. The suggested *Offset-Reuse 3* subcarrier planning among RNs introduces a good paradigm in access link resource allocation in RECs.

A REC operating with an isolated UE-eNB and UE-RN transmissions is analyzed with the aid of the IR resource allocation scheme. This approach improves the radio link quality but reduces the spectral efficiency of the system. In order to improve the spectral efficiency and still maintain acceptable radio link quality, a user grouping based approach is proposed. The concept of UE geometry based GR resource allocation enhances REC performance.

While extending the simulation results to E2E system performance, it is observed that the relay link is an overhead in system design. The proposed E2E REC setup concludes that even though successful REC deployment is a challenging task, well-defined operating points can realize performance gains. It is expected that with the study phase of relaying in 3GPP, related technical contributions from research companies/institutes will provide further direction to implement RECs that clearly outperform existing eNB-only deployments.

Future Work

Due to the constraints on the duration of Master's thesis work, a complete simulation environment could not be developed. PC plays a major role in determining the system performance and, therefore, this work could be extended such that optimal PC parameters are set for the GR/R3 based REC. It is foreseen that the introduction of non-uniform user distribution and spatially correlated shadowing into the system would provide better insight into relaying performance. Due to the flexibility provided by LTE's time-frequency domain scheduling, the availability of CSI assists in maximizing system utility. Therefore, the implementation of a smart scheduler is important for optimal system performance. Furthermore, the simulations could be enhanced to cover PHY and MAC layer functionalities such as AMC and HARQ.

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Appendix

Simulation Parameters

Carrier Frequency	$2\ GHz$
Transmission Bandwidth	$10\ MHz$ (i.e. $48 + 2$ PRBs)
Propagation Scenario	Macro 1 (i.e. $500\ m$ ISD)
Cellular Layout	19 Tri-Sectored Hexagonal Cells
User Drop	Random
UE Density	48 per Sector
RN Density	7 per Sector (1 Tier)
TD-FD Scheduling	Round Robin
Traffic Model	Full Buffer
Simulation Window	2 TTIs
Margins	Nil
Modulation Scheme	64-QAM
UE Transmit Power (Maximum)	$23\ dBm$
UE Transmit Power Control Formula	$P = \min \{P_{max},\ P_o + 10\ log_{10}M + \alpha\ L\}$ $\alpha = 0.6$: eNB-only $\alpha = 1.0$: REC
eNB Transmit Power	$46\ dBm$
RN Transmit Power	$30\ dBm$
Thermal Noise PSD	$-174\ dBm/Hz$
eNB Antenna Pattern	$A(\theta) = \text{-}\min\left[12\left(\dfrac{\theta}{\theta_{3dB}}\right)^2, A_m\right]$ $\theta_{3dB} = 70\,^{\circ}$ and $A_m = 25\ dB$
RN Antenna Pattern	Omni-directional
UE Antenna Configuration	Tx-1, Rx-2
eNB Antenna Configuration	Tx-2, Rx-2
RN Antenna Configuration	Tx-2, Rx-2
UE Elevation Gain	$0\ dBi$
eNB Elevation Gain	$14\ dBi$
RN-UE Elevation Gain	$5\ dBi$
RN-eNB Elevation Gain	$7\ dBi$
UE Noise Figure	$9\ dB$
eNB Noise Figure	$5\ dB$
RN Noise Figure	$7\ dB$
Direct Link Channel Model	$128.1 + 37.6\ log_{10}R_{km}$
Access Link Channel Model	$140.7 + 36.7\ log_{10}R_{km}$
Relay Link Channel Model	$124.5 + 37.6\ log_{10}R_{km}$
Penetration Loss	$20\ dB$
Bandwidth Efficiency	0.88
SINR Efficiency	1.25

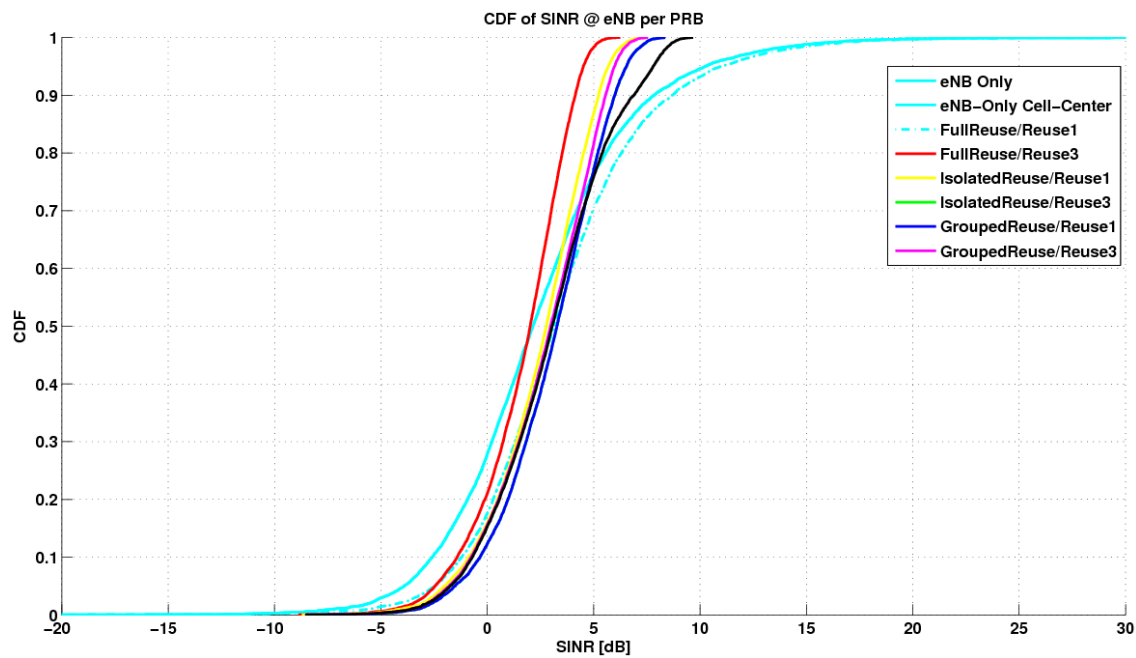# Simulation Plots - 3GPP Case 3 (i.e. 1732 ISD)

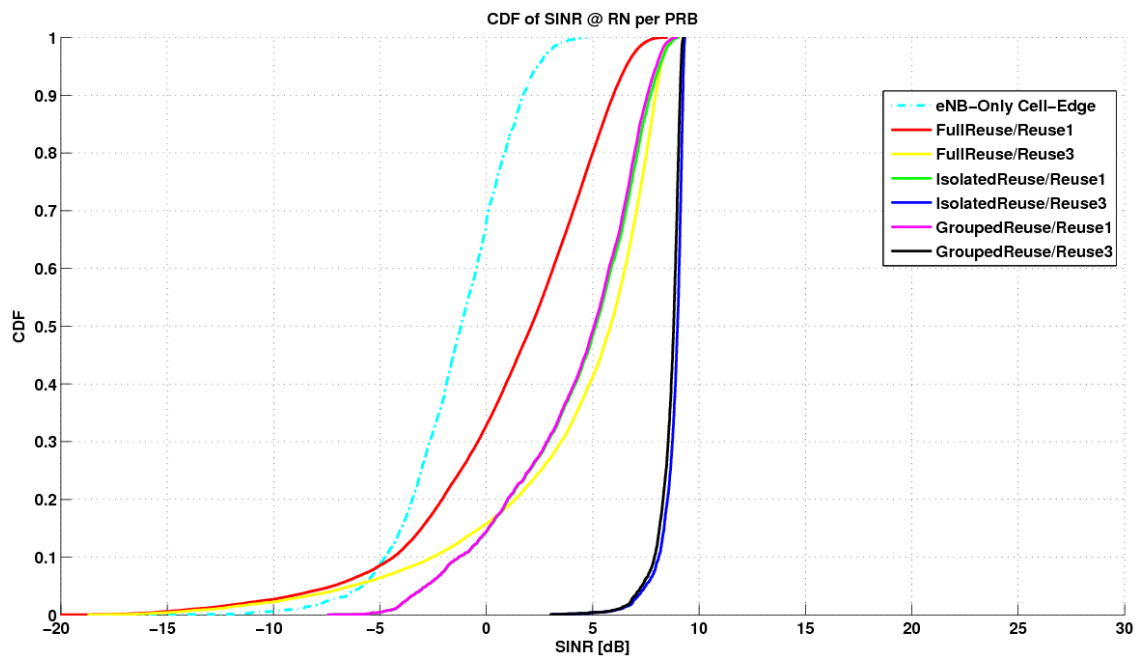Figure 38: SINR on Direct Link (3GPP Case 3)

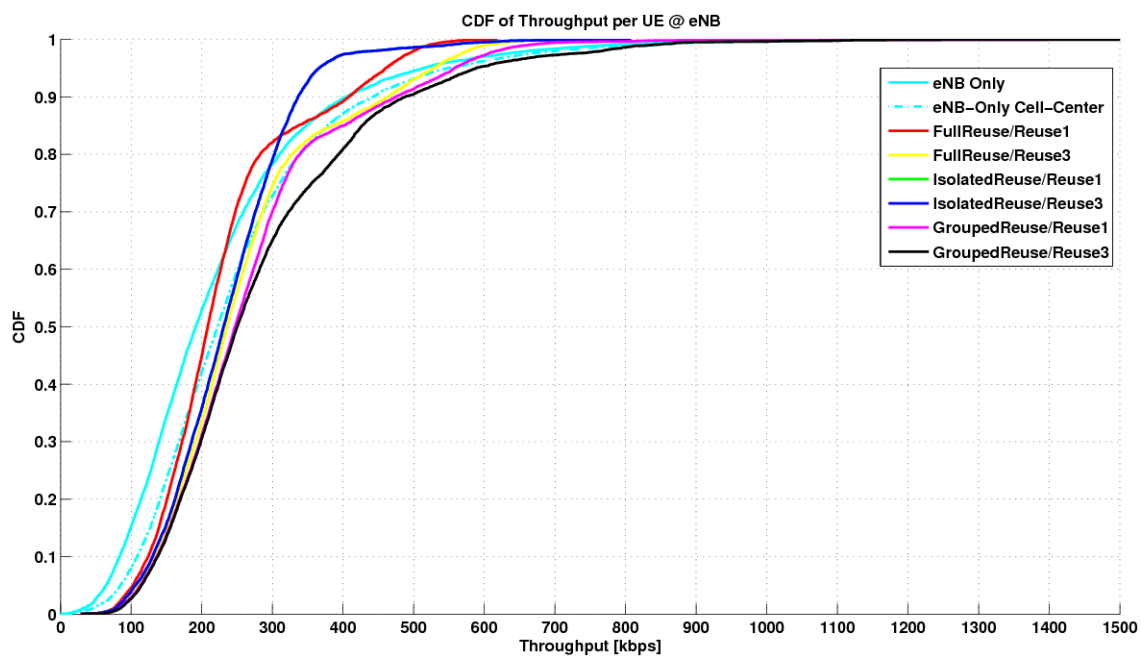Figure 39: SINR on Access Link (3GPP Case 3)

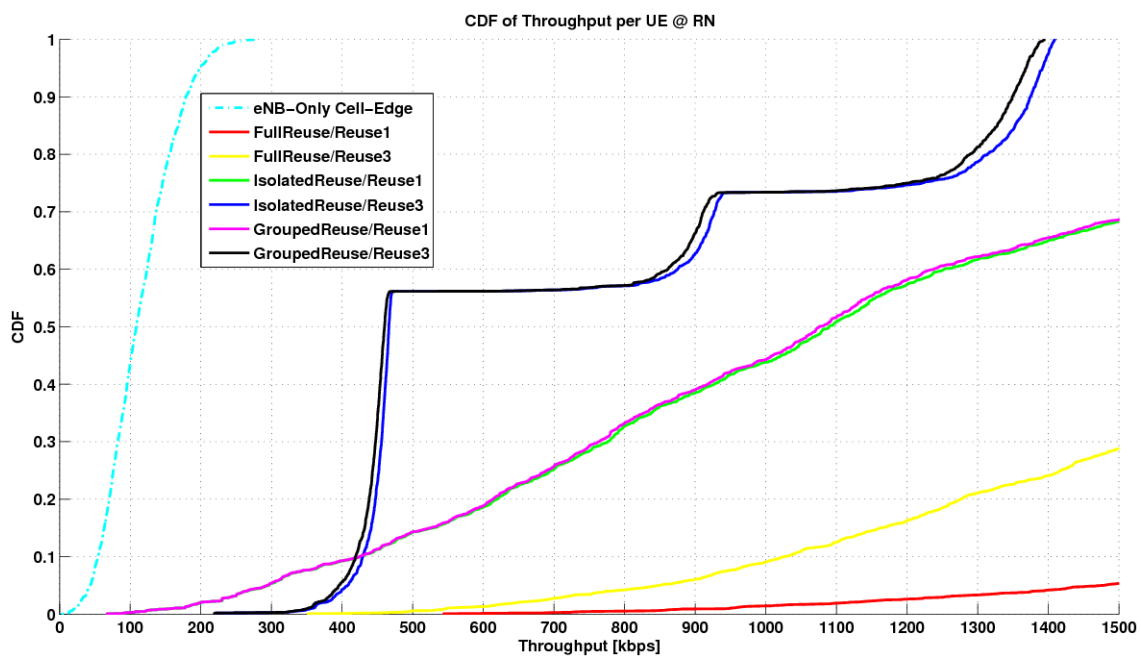Figure 40: Throughput per UE on Direct Link (3GPP Case 3)
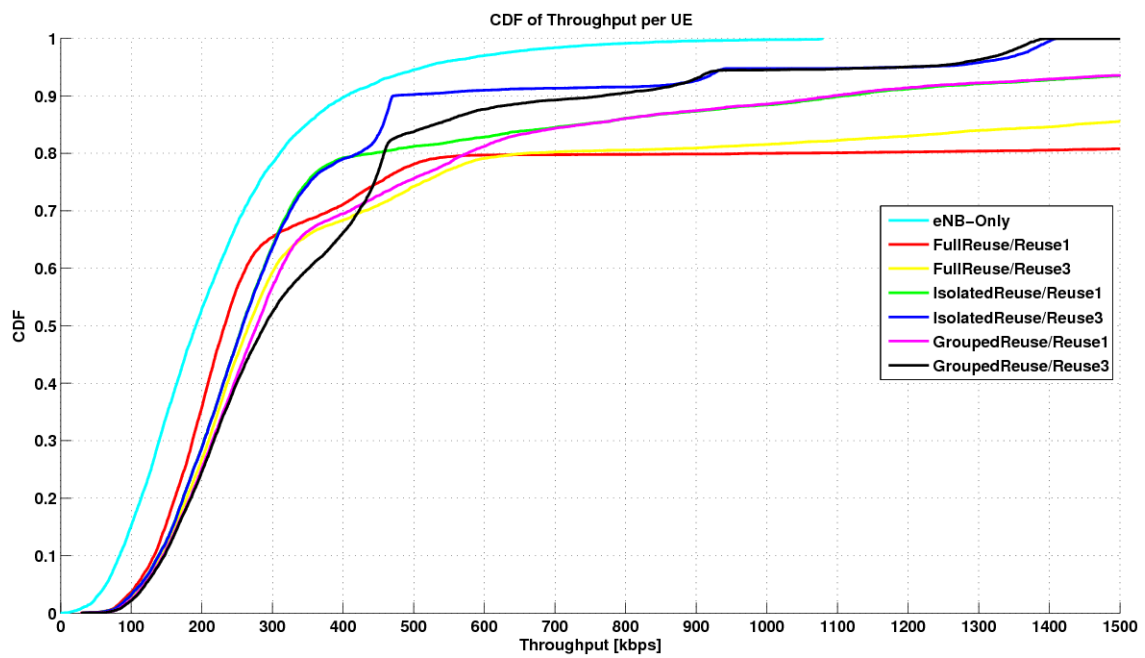

Figure 41: Throughput per UE on Access Link (3GPP Case 3)

Figure 42: Throughput per UE in the Sector (3GPP Case 3)