Master's Thesis

# Impact of Downlink Reference Signal Planning on LTE Network Performance

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By


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*To My Parents, Brother and his family!*

# Abstract

CRS frequency planning strategies impact system performance in LTE networks. System performance in terms of mean user bitrates is of main focus of the current thesis. In this thesis different CRS frequency planning strategies are studied. Advantages and disadvantages of these planning strategies towards system performance are analyzed. It is observed from our studies that Channel State Information (CSI) which is responsible for rank, modulation and coding scheme selection is affected by CRS frequency planning. Impact seen on CSI selection transcends as impact on system performance. To identify best possible CRS frequency planning for LTE networks which boosts system performance, a CSI optimization technique is employed. CSI optimization technique tries to compensate for systematic errors and reduce the effect of CRS planning over CSI selection such that neither a pessimistic or optimistic CSI selection is made. A UE based and Network (eNB) based CSI optimization technique is proposed. Studies performed indicate that a joint UE-eNB based CSI optimization technique results in most optimal CSI selection, thus improving system performance.

Proposed solution is brute-force in nature and is applied to homogeneous- Macro only, heterogeneous- sparse, dense and ultra-dense, network deployments. Varied system realisms starting from technology potential to practical cases are considered. A MATLAB based in house simulator is used to perform all the analysis. Many performance criteria like Resource Utilization, Mean Rank, Mean User bitrates, Cell Edge bitrates are considered while performance evaluations. These realisms give a measure of how close the system performance approaches technology potential (upper bound) after employing the proposed solution. Different traffic conditions and receiver architectures are also considered. On application of proposed solution to different CRS frequency planning strategies, network deployments, traffic conditions and receiver architectures it was observed that *frequency non-shifted CRS* planning gave the best possible system performance at low and medium loads in comparison to other strategies. At high traffic conditions system performance of all CRS frequency planning strategies studied showed almost no performance difference. The findings, analysis and performance evaluations show that contamination of data brings down the system performance drastically in comparison to contamination seen on CRS.

# Acknowledgments

My quest to pursue Masters in Wireless Communications began in 2008, the year when I started my professional career as a researcher and developer of LTE Physical layer. The 3GPP specifications which I used to go through for developing LTE physical layer solution always posed questions like ‘Why the Cell Specific Reference Signal (CRS) time-frequency positioning is defined as such?’, ‘Why a systematic encoder is used not a feed forward in LTE?’, ‘Why the length of Physical Random Access Channel (PRACH) signature is of length 839 and not something else?’ and many more. After going through lot of literature I was able to convince myself with answers for many of the questions I had. In the course of finding these answers I personally felt that a planned curriculum exclusive to wireless would help me to get a solid and in-depth understanding of the subject. After extensive search for universities which had concentration in wireless. I applied for Lund University. I got an opportunity to pursue my masters at Lund University and started my master’s program in wireless communications in 2011.

Two years have passed on now and I am about to successfully complete my master’s program with this thesis. These two years were without question the toughest and best two years of my life. The amount of learning and the overall growth which I had, both personally and technically is unprecedented. I could only tell that all the experiences which I had these two years made me mentally stronger and confident than ever before. I want to take this opportunity to express my heartfelt gratitude to all the people who have been part of my success directly or indirectly. First and foremost I would like to thank Helene von Wachenfelt my international coordinator at the university. She was instrumental in helping me to start my master’s program at Lund University. The entire faculty at Lund University especially my supervisor Fredrik Rusek, for all the guidance and inputs he gave throughout my master’s program.

I always wanted to meet someone who had contributed to the 3GPP specifications but I never ever dreamt that I would be working amidst them. This was possible only because I got the opportunity to perform my master’s thesis here at Ericsson Research. So i want to thank profusely Claes Tidestav, my manager here at Ericsson Research for giving me this fantastic opportunity to carry out my master thesis. Without proper supervision and guidance success cannot be achieved. I want to thank both of my supervisors, Chrysostomos Koutsimanis and Per Skillermark for being patient with me and guiding me to a successful completion of master’s thesis. I owe most of my success in my master’s thesis to both my supervisors. The amount of learning I had here in Ericsson Research was invaluable. I have learnt something or the other from all my colleagues here at Ericsson Research and I want to thank them all. I have to admit that after working here in Ericsson Research, I have developed and improved both technically as well as personally.

I want to thank all my friends and relatives who have been directly or indirectly part of my success. Many people have taught me so many valuable things throughout my life till date. I would like to take this opportunity to thank them all. Lastly I want to pay my utmost gratitude to my parents, my brother and his family for all the uncompromised sacrifices they have made for me throughout their lives, without which I would not be for what I am today!

Govardhan Madhugiri Dwarakinath

# Contents

# Chapter 1

## Introduction

Information/Data can be broadly categorized into Text, Voice (Audio) and Video. In 1890s Guglielmo Marconi performed first experiments showing that Electromagnetic Signals can be used to carry Information [1]. This was the first sign of information being transmitted over Wireless medium. Almost 100 years later in 1980s Nordic Mobile Telephone (NMT) in Europe and Analogue Mobile Phone System (AMPS) in America were the first mobile communication systems commercially deployed [1]. These systems were termed as ‘First Generation’ or ‘1G’ systems and they targeted only voice transmission over wireless medium. The advent of Digital communication during 1980s [1] showed that information transmitted digitally had better reliability, quality and most importantly increased system capacity. This development paved way for ‘Second Generation’ or ‘2G’ systems. Global System for Mobile Communications (GSM) in Europe and Code Division Multiple Access (CDMA) in US were couple of famous 2G standards. 2G systems were ‘Narrowband’ systems as they targeted low bandwidths. Apart from digital telephony, for the first time text data transmission (Short Message Service-SMS) was possible over wireless in 2G standards. Full fledge packet data transmission over wireless came into existence with the introduction of General Packet Radio Services (GPRS) in GSM standard. Packet based data transmission enabled transmission of text, voice or video in the form of packets hinted various forms of services that could be offered in future standards. But these services required higher bandwidth, which the 2G and post 2G standards (2.5G) [1] couldn’t cater for as they were still low bandwidth standards. ‘Third Generation’ or ‘3G’ standard was the first step towards higher bandwidth transmission which promised varied applications and services to be catered over wireless. Wideband Code Division Multiple Access (WCDMA) is one of the noteworthy 3G standards.

The consistent development of various standards created opportunities for unified services like voice and IP-based services, large file transfers, web browsing, High Definition (HD) video streaming, online gaming, and many more. In parallel there was a tremendous development seen even in consumer electronics field especially producing power efficient, high data storage and cost efficient (affordable by everyone) mobile and wireless enabled devices. The culmination of these two developments created the need for more evolved standards beyond 3G with higher bandwidth and which could handle broadband data rates over wireless [1]. Wireless Broadband poses many challenges like providing high data rates, reduced latency (delay) and improved system capacity [1]. To provide unified services mentioned above, a post 3G standard (or 4G) was required which was capable of delivering data rates close to Gigabits per second (Gbps). At the same time the standard was expected to handle time critical services with reduced latency-wireless medical services are one such example where reliable and fast services are required. Wireless Bandwidth is very expensive to buy when seen from an operator’s point of view. With mobile and wireless enabled devices being affordable to everyone there is a considerable increase in wireless consumers (technically called traffic generators). Hence the post 3G standard required to use the limited bandwidth resources judiciously and maintain a good Quality of Service (QoS). Serving varied traffics with efficient bandwidth usage and good QoS means improved System Performance. These were some of the challenges and requirements which hinted towards structuring of post 3G wireless standards.

International Telecommunication Union (ITU) which is responsible for defining wireless standards around the world, proposed Future Public Land Mobile

Telecommunications Systems (FPLMTS) in 1980s -later changed to International Mobile Telecommunications-2000 (IMT-2000) -foreseeing the wireless broadband requirements in future [1]. IMT-2000 was proposed aiming third generation wireless technologies. 3G research developments around the world kicked off in full fledge in 1990s. To achieve global alignment of standards a global co-operative group called ‘Third Generation Partnership Project’ (3GPP) came into existence [1]. Global success of 3G and ever increasing hunger for wireless broadband data rates led ITU to propose International Mobile Telecommunications-Advanced (IMT-Advanced), consisting of requirements for a standard to be called as ‘Fourth Generation’ or ‘4G’. 3GPP came up with specifications for Long Term Evolution (LTE) Rel-8 in the year 2008 which was also called as ‘3.9G’ [1]. This release is considered as the first step towards achieving IMT-Advanced requirements and one of the post 3G wireless standards developed to bridge the gap between 3G and 4G. LTE Rel-8 was followed by, LTE Rel-9 in December 2009 and Rel-10 in March 2011 [1]. Every new release was a step towards achieving IMT-Advanced requirements. LTE Rel-9 had some improvements over Rel-8 but not considerable enough. LTE Rel-10 came out very strong with new concepts like Carrier Aggregation (using multiple bands over different carriers), enhanced Multi-Antenna techniques, enhanced Heterogeneous Network deployments (to handle over-densified networks) and Inter-Cell Interference Co-ordination. With the addition of these new concepts LTE Rel-10 was considered as LTE-Advanced and also met the requirements of IMT-Advanced. Other releases like Rel-11, Rel-12 are expected to surpass the requirements of IMT-Advanced and can be even called as post 4G standards.

There has been a tremendous growth in the usage of mobile and wireless enabled devices over the past few years. ITU announced some statistics on February 2013 which showed that by the end of 2012 the number of mobile subscriptions in the world was around 6.8 billion i.e. approximately 96% of the world’s population [2]. Along with mobile subscriptions, innumerable wireless enabled (Mobile/Fixed) devices are coming into market every day. With this rapid growth in usage of wireless devices it may result in future that number of wireless enabled devices may cross 50 billion mark. To cater all these users efficiently we need standards which can provide excellent System Performance & QoS. LTE standard and its releases have proved till date that they are the standards for future and have answers to cope with these challenges. Addressing these challenges might increase the complexity of the standard. So Engineers around the world are trying to build solutions to strike a balance between addressing the challenge and reducing the complexity of the standard. Being part of such Engineering fraternity, in this thesis we try to address one of the challenges, ’Improving System Performance of LTE networks’, especially for LTE Rel-8 networks which has already seen full fledge commercial deployment.

In 2008 Sweden’s Post & Telestyrelsen, PTS conducted a spectrum auction for 15 years of 4G licenses for a total bandwidth of 190MHz in a 2.6GHz band [3]. The auction ended with a winning bid of 2 billion Swedish Kronor or approximately 314 million US Dollars. This gives a rough estimate of the cost of wireless spectrum. Once the operators purchase this spectrum they want to use them as efficiently as possible. So they strive to achieve the best possible system performance satisfying as many users as possible in the network. Signal to Noise and Interference Ratio (SINR) is one of the key factors influencing system performance. There are varied factors on to how SINR gets affected in a system. Channel Noise and Interference are one of those major factors which impair SINR and in-turn the system performance. Interference can be of two types, Inter-cell and Intra-cell. Inter-cell interference can be created by data signals or system dependent signals. Cell Specific Reference Signals (CRSs) are one of those mandatory system dependent signals introduced in LTE Rel-8. There are two configurations of CRS, frequency Shifted & Nonshifted, more detailed description about the configurations is given in section 2.2. Inter-cell interference created by these CRS configurations result in Channel-State Information[1] (CSI) estimation error and impacts system performance in LTE Networks.

## 1.1 Problem formulation

In this Thesis we will analyze and evaluate which of the two CRS configurations maximizes LTE Rel-8 DL system performance, in terms of 'Mean User bitrates' under CSI estimation error adjustment.

$$\underbrace{max \sum_{i} \frac{R_i}{N}}_{(CRS\ configuration, CSI\ estimation\ error\ adjustment)} \qquad (1)$$

Equation (1) is the crux of this thesis, where $R_i$ is bitrate of $i^{th}$ user in the network, $N$ being the number of users in the network. Enhancing system performance can be interpreted as mitigating interference and noise which further implies enhancing SINR or utilizing the existing SINR to the best possible extent by transmitting as many data bits as possible.

While addressing the system performance maximization problem, a wide variety of realism, SINR optimization techniques, traffic conditions, deployment strategies and receiver architectures are considered. Other questions which are addressed over the course of this thesis are- what are the advantages and disadvantages of different CRS configurations? How realism affects the system performance? What steps are taken into account for achieving better SINR thus improving system performance? What is the system performance for different network deployments under different CRS configurations? How SINR optimization is performed? Which are the key measurement parameters used to analyze system performance and how these parameters are interrelated?

## 1.2 Overview of Previous Work and Thesis Contribution

There have been some studies [4, 5] performed previously where impact of CRS configurations on system performance for LTE Rel-8 networks are analyzed. The simulators used in these studies were static (time invariant) in nature which might not capture the realistic system behavior. Out of the two CRS configurations only Nonshifted CRS was considered in the studies. Full Buffer[2] traffic was considered. Sparse Heterogeneous Network deployment (4 Hotspots[3] & 4 Picos[4]) was considered. Proportional Fair Time (PFT) scheduling algorithm was used. Transmission mode 4 (TM 4) was considered in the analysis. These were some of the scope of previous studies.

We start our thesis study by understanding the characteristics of both the CRS configurations unlike the previous study where only Nonshifted CRS was considered. Pros and Cons of different CRS configuration and their Interference pattern in a network are discussed. Once the basic understanding of these concepts is carried out, we undertake system level performance evaluation on an in-house MATLAB based simulation tool[5]. In this performance evaluation we consider Macro-Only and Heterogeneous network deployments.

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[1] Information about the degree of goodness of the channel.
[2] Infinitely large file size.
[3] Short range of geographic area that needs to be enabled with wireless coverage. In our context, an airport or shopping mall can be taken as an example.
[4] Miniature form of Base station.
[5] See appendix 3.1 for further details on the simulator.

Macro-only deployment is unique to this study as there is no study which is carried out exclusively for this deployment previously. In heterogeneous deployments, sparse (4 Hotspots & 4 Picos), dense (1 Hotspot & 4 Picos) and ultra-dense (1 Hotspot & 10 Picos) scenarios are considered which is also unique to this study in comparison to the previous studies [4, 5] where only sparse scenario was considered. Non full buffer traffic model with different traffic conditions is considered apart from the full buffer type used in previous studies. Transmission Mode 4 (TM4) is considered. Round-Robin (RR) scheduling algorithm is used unlike the PFT used in previous studies. Most importantly the simulator used in this study is a dynamic simulator (Is a time-varying simulator, where network parameters are varied over time) which is far more realistic than the static simulators used in previous studies. Different realisms are used, starting from a genie[6] approach, where the system is considered to be in an Ideal condition (system has full knowledge of the network parameters), to a more realistic/practical condition. Keeping these features in mind a brute-force solution is formulated to obtain an upper bound for the system performance. This solution is called brute-force as all possible combinations of optimization parameters[7] are taken into account. The combination that gives the best SINR and thus improving the system performance is considered as an optimal solution.

## 1.3 Thesis Outline

Chapter1 introduces the reader to the problem being addressed in this thesis, along with previous work, contributions made in this thesis and difference between current and previous work. Chapter2 targets explaining the basic concepts of LTE Rel-8 required for understanding the work carried out in this thesis. The concepts of focus in chapter2 are, CRS in LTE Rel-8, DL transmission schemes (especially Transmission Mode 4), advantages and disadvantages of CRS in LTE. Chapter3 explains concisely the proposed solution for the problem studied in this thesis. System parameters, assumptions made, simulation setup and performance measures used to analyze the problem is explained in chapter4. From chapter5 onwards the simulation results are showcased and explained. Chapter5 focuses on homogeneous network deployment (Macro-Only). In this chapter key and interesting results are proposed trying to cover a wide horizon of results available. Technology potential results, results for practical case after applying the proposed solution and practical results for different receivers are captured and presented in chapter5. Chapter6 talks about heterogeneous network deployment, covering sparse, dense and ultra-dense deployments. Once again the results in this chapter touch upon technology potential and practical case. Thesis conclusions, findings and future work are explained in chapter7. Exhaustive list of material which was referred in this study is listed out in references section. Quite substantial amount results were obtained while performing this study. Some of the interesting results are also showcased in the appendices for readers who are interested to analyze and understand the problem addressed in this thesis further more.

[6] Ideal system scenario
[7] $(\kappa, \Delta)$

# Chapter 2

# Long Term Evolution an Introduction

3G to 4G evolution was a giant leap towards Broadband Wireless Communications. Some of the key drivers for this evolution was, need for very high data rates, reduced latency, increased system capacity, bandwidth flexibility, greater coverage, seamless connectivity and reduced power consumption. Development of LTE standard was started targeting these objectives. Some of these objectives were successfully realized in the first release of LTE i.e. Rel-8. Achieving these objectives required considerable changes in physical layer of LTE compared to previous generation mobile systems. Concentrating on physical layer, the two key technologies that shaped the radio interface of LTE were multicarrier technology and multi-antenna technology [6]. Multicarrier technology comprises of Orthogonal Frequency-Division Multiple Access (OFDMA) and Single-Carrier Frequency-Division Multiple Access (SC-FDMA). Multi-antenna technology can be utilized in three fundamental ways. To achieve Diversity gain- Increases reliability of data based on the diversity achieved by multiple antennas, Array gain- Focusing the energy in a desired direction by using specific pre-processing (Precoding) techniques and Spatial Multiplexing gain- Helps in increasing the data rates by transmitting parallel streams of data over un-correlated antennas. LTE Rel-8 came with all these necessary baseline technologies to cater for some of the challenges (drivers).

## 2.1 LTE Rel-8

As in any previous generations, LTE network comprises of at least one base station (or specifically called as evolved NodeB-eNB) and mobile device (or User Equipment-UE). The link between eNB to UE is called as Downlink (DL) and UE to eNB as Uplink (UL). Multicarrier technologies like OFDMA and SC-FDMA are used in DL and UL respectively. LTE Rel-8 supports scalable bandwidths starting from 1.25MHz to 20MHz [7] and it operates in Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) modes. There are two types of frame structures Type 1 and Type 2 based on FDD and TDD modes. FDD is the scope of this thesis hence we will dwell upon Type 1 frame structure[8]. Hierarchically speaking frame structure can be divided into Resource Elements (REs), Slots, Subframes and Radio Frames. Resource Elements are the smallest entity and Radio Frame being the biggest. One radio frame spans 10ms in time, which has 10 subframes each spanning 1ms as illustrated in figure 1. Every subframe has two slots of 0.5ms each. Each subframe is divided into time and frequency which is termed as Time-Frequency resource grids as shown in figure 2. In frequency the resources are divided into sub-carriers with a sub-carrier spacing of 15 KHz. The number of sub-carriers depends upon the bandwidth usage[9]. In time the resources are divided into 14 Orthogonal Frequency Division Multiplex (OFDM) symbols for normal Cyclic Prefix[10] (CP). Each of the OFDM symbols has 66.67µs time spacing. A

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[8] The evaluations and results obtained for FDD are also valid for TDD.
[9] For 10MHz we have 600 sub-carriers and for 20MHz, 1200 sub-carriers.
[10] CP is used as guard against dispersive nature of the channel to avoid inter-symbol-interference. There are two types Normal and Extended CP

transmission in DL or UL happens with a subframe granularity. Any UE in the Network is always scheduled in multiple of Resource Block (RB) pair. A RB pair comprises of 12 subcarriers (180 KHz in frequency) and 14 OFDM symbols as in figure 2. 'l' and 'k' are used to represent OFDM symbols and sub-carriers in the figure.

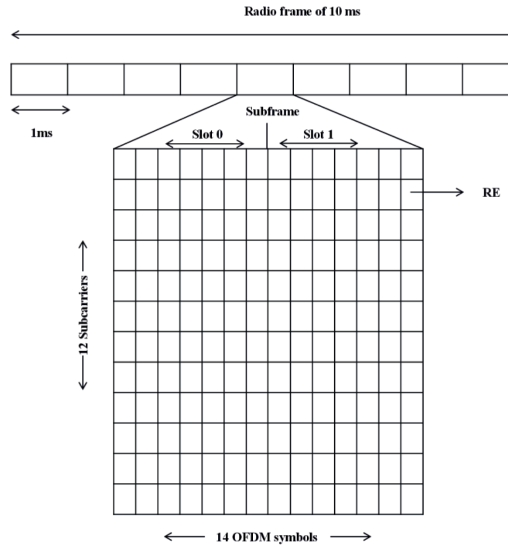


**Figure 1**: LTE frame structure

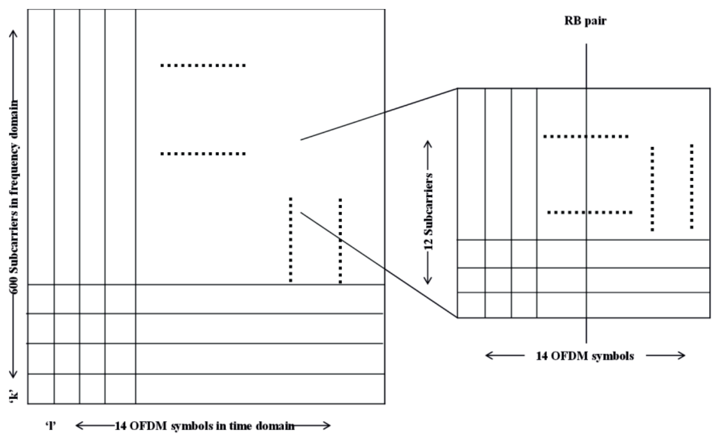


**Figure 2**: Resource Block pair

There are Physical Channels and Signals available in LTE DL and UL. Physical Channels corresponds to physical resources on which data is carried over air. These channels carry information from higher layers (for example Protocol Stack), whereas Physical Signals are exclusive to Physical layer and doesn't carry any information from higher layers. These signals are solely generated in Physical Layer. LTE Rel-8 DL has five Physical Channels and two Physical Signals. In UL there are three Physical Channels and two Physical Signals. Focusing on DL Physical Channels and Signals, the functional features of them are as follows.

### 2.1.1 Physical Channels

- Physical Broadcast Channel (PBCH) carries System/Network Information like Bandwidth, Cyclic Prefix (CP) etc. which is necessary for the UE when it initially enters the network.
- Physical Downlink Shared Channel (PDSCH) carries user data to UE/UEs in DL. As mentioned earlier the UE is scheduled in multiple of RB pair. This scheduling happens based on the Channel State Information (CSI) sent from UE to eNB[11].
- Physical Downlink Control Channel (PDCCH) has several formats and carries Control information to the UE. This channel also informs about the location of PDSCH information intended for a UE in subframe.
- Physical Control Format Indicator Channel (PCFICH) carries information about PDDCH control formats and indicates how many OFDM symbols are allocated for PDCCH.
- Physical HARQ Indicator Channel (PHICH) carries information in DL and informs UE whether the information packet in UL is successfully received or not.

### 2.1.2 Physical Signals

- Cell Specific Reference Signals (CRSs) are pilot signals which are present at specific time-frequency locations in a subframe and are known by both the eNB and UE. These signals are used for coherent demodulation and CSI estimation at UE side. CRS is transmitted over all subframes, over the entire bandwidth and at all times.
- Primary Synchronization Signals/Secondary Synchronization Signals (PSS/SSS) are used to perform time and frequency synchronization. They are also used to extract Physical Cell Identity (PCI represented as$N_{ID}^{cell}$) of a cell at the UE side.

A typical RB pair in a subframe carrying physical channels and signals is shown in figure 3. First three[12] OFDM symbols consist of PDCCH, designated REs are occupied by CRS and other time-frequency resources consist of PDSCH. Only a few physical signals and channels are showcased in the figure.

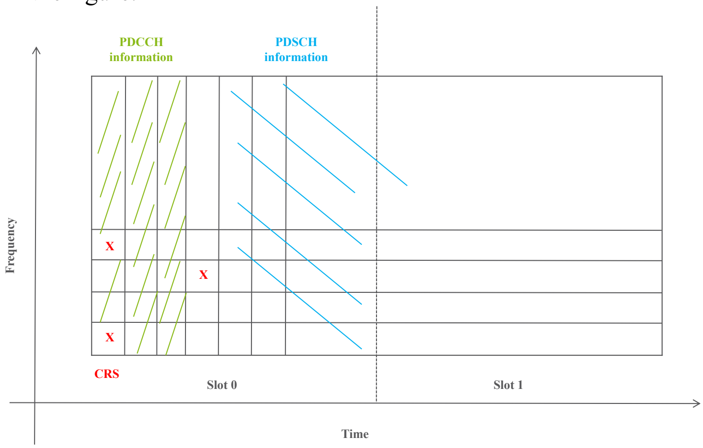


**Figure 3**: Typical Subframe carrying Physical Signals and Channels

[11] At times eNB schedules the UE independently without CSI information from the UE.
[12] Number of OFDM symbols used for PDCCH depends on the Control Format Indicator (CFI).

## 2.1.3 Transmission Schemes in LTE-DL

Multiplexing of different DL Physical channels and signals over time-frequency resources in a subframe as shown in figure 3 is possible due to DL multi-carrier scheme, OFDMA. DL transmission in LTE happens in three dimensions including time, frequency and space. Time and frequency dimensions are seen in figure 2, but spatial dimension is accessible using Multi-antenna technology and is measured in terms of 'layers' [6]. A typical multi-antenna technology accessing spatial dimension via layers is shown in figure 4.

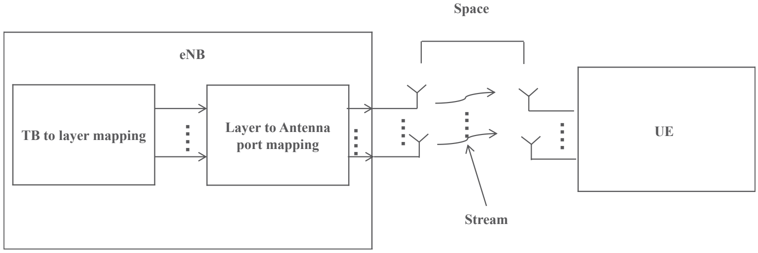


**Figure 4**: Multi-Antenna technique accessing spatial dimension

In figure 4 at the eNB transmitter we see two modules 'Transport Block (TB) to layer' mapping and 'Layer to Antenna port' mapping. Data from higher layers (like protocol stack) is sent to Physical layer in the form of TBs[13]. TBs consist of information bits (0s and 1s). This data will be fed to the Physical layer where several signal processing operations are performed on it. Transport Block to layer module is one such signal processing operation where TB/TBs are mapped on to layer/layers. This layer mapping enables access to spatial dimension. There are specific definitions of TB to layer mapping in LTE which is shown in figure 5.

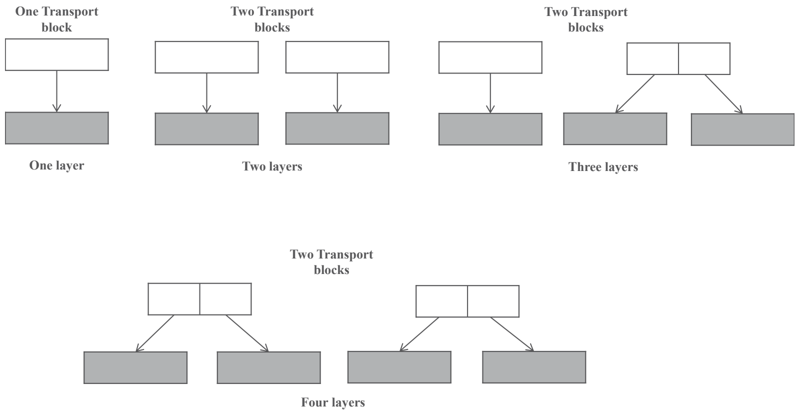


**Figure 5**: Transport Block to Layer mapping

From the above figure we can infer that the maximum number of TBs is two and maximum number of layers is four. Antenna ports are the logical antennas mapped to physical antennas. These physical antennas are responsible for transmitting information over air. 'Layer to Antenna port mapping' is the second module which is also a signal processing block where

[13] More specifically MAC PDUs [6]

layers are mapped to antenna ports. It is defined in LTE that number of layers are less than or equal to the number of antenna ports. The inter-relationship between number of TBs, layers and antenna ports depends on the different ways of using Multi-antenna technology. To achieve diversity gain the maximum TB that can be used is one, maximum number of layers can be four and maximum ports can be four. For spatial multiplexing gain, maximum TB is two, maximum layers can be four and maximum antenna ports can be four. This inter-relation helps in accessing the spatial dimension which results in individual streams of data from different physical antennas.

Multi-antenna or Multiple Input Multiple Output (MIMO) technology in LTE Rel-8 for DL has, *2* x *2*[14], *4* x *2* and *4* x *4* Physical antenna configurations. In UL *1* x *2*, *1* x *4* antenna configurations are available [7].Peak data rates which can be achieved for 20MHz in DL is 173 and 326 Mbps for *2* x *2* and *4* x *4* configurations respectively [7]. For the same bandwidth in UL peak data rates of 86 Mbps is achieved with *1* x *2* antenna configurations [7]. As we know MIMO technology can be used to achieve, diversity gain, array gain and spatial-multiplexing gain. With different antenna configurations and objectives to achieve, there are a wide range of possible system operations. To utilize different antenna configurations and to achieve efficient and reliable system operation between eNB and UE, it's important to have a common understanding, which type of transmission is suitable for what scenario [8]. To achieve this common understanding between eNB and UE 'Transmission Modes' are defined. LTE Rel-8 has seven transmission modes in DL [1]

- Transmission mode 1: Single-antenna transmission.
- Transmission mode 2: Transmit diversity.
- Transmission mode 3: Open-loop codebook-based precoding for more than 1 layer, transmit diversity for rank-1 transmission.
- Transmission mode 4: Closed-loop codebook-based precoding.
- Transmission mode 5: Multi-user-MIMO similar to Transmission mode 4.
- Transmission mode 6: Spatial closed-loop codebook-based precoding for single-layer transmission.
- Transmission mode 7: Rel-8 non-codebook-based precoding for only single-layer transmission.

Out of these seven modes, perhaps the most interesting mode for our study is Transmission Mode 4 (TM 4) which is a closed-loop MIMO scheme and allows spatial multiplexing. In closed-loop mechanism CSI is reported back to eNB with information about downlink channel condition. CSI gives eNB an indication of the sort of channel UE is approximately experiencing when it receives data in DL. Based on the CSI obtained future scheduling for the UE is performed. A simple schematic of closed-loop mechanism is shown in figure 6.

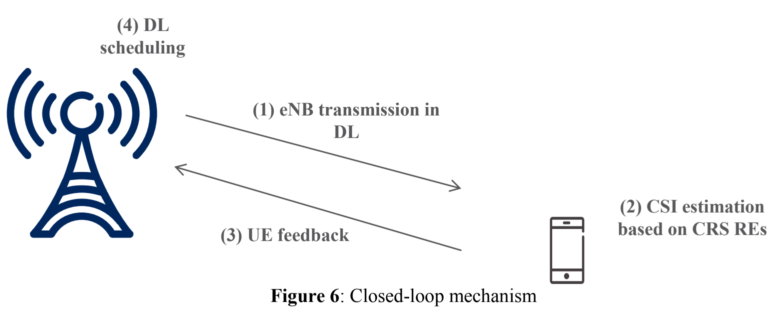


**Figure 6**: Closed-loop mechanism

[14] Should be read as *Transmitting antennas* x *Receiving antennas*.

There are four steps involved

1. Transmission of CRS from eNB in DL.
2. CSI estimation based on CRS at UE.
3. UE reporting back the CSI to the eNB.
4. DL scheduling of UE based on the CSI received.

Closed-loop mechanism in TM4 helps in adaptive improvement of system performance. Adaptive improvement refers to continuous channel based scheduling of data for UEs in DL. This improvement is due to the fact that available SINR is judiciously used to increase data rates. We had posed our problem statement in chapter 1 section 1.1 claiming that different CRS configurations impact the system performance differently. This impact is studied under Transmission Mode 4 in this thesis. Before venturing into understanding TM4 we will understand CRS. This understanding of CRS gives a concrete base to analyze the impact of CRS configurations on system performance.

## 2.2 Cell Specific Reference Signal (CRS) in LTE and its Significance

Cell Specific Reference Signals (CRSs) are physical signals which were first introduced in LTE Rel-8. Generation of CRS happens exclusively in physical layer, using Pseudo Random sequence (PN-sequence) as the base and QPSK modulation [9]. Mapping of CRS at eNB is performed based on the number of Antenna ports. UE distinguishes between different antenna ports based on the CRS mapped to them. In LTE Rel-8 there are three possible CRS mapping in a cell as per 1, 2 or 4 antenna port combinations. Antenna port is indexed as 0, 1, 2 and 3 in case of 4 antenna ports. In time domain CRS mapping on OFDM symbols is fixed. $0^{th}$ $4^{th}$ $7^{th}$ and $11^{th}$ OFDM symbols (this indexing is valid if we start to count OFDM symbols from 0 to 13 in a RB pair else $0^{th}$ and $4^{th}$ if each RB is treated separately in a RB pair) are used in case of normal CP. In frequency the CRS positions are dependent on $v$ and $v_{shift}$ parameters. $v$ is dependent on antenna port and OFDM symbol, it is fixed for a given antenna port and OFDM symbol. This dependency of $v$ on OFDM symbols and antenna ports is shown in Table 1, $p$ represents the antenna ports and $l$ the OFDM symbols.

**Table 1[9]**: $v$ shift based on antenna ports and OFDM symbols

$$v = \begin{cases} 0 & \text{if } p = 0 \text{ and } l = 0 \\ 3 & \text{if } p = 0 \text{ and } l \neq 0 \\ 3 & \text{if } p = 1 \text{ and } l = 0 \\ 0 & \text{if } p = 1 \text{ and } l \neq 0 \\ 3(n_s \bmod 2) & \text{if } p = 2 \\ 3 + 3(n_s \bmod 2) & \text{if } p = 3 \end{cases}$$

The dependency of CRS mapping on antenna ports, OFDM symbols and $v$ is evident from figure 7.

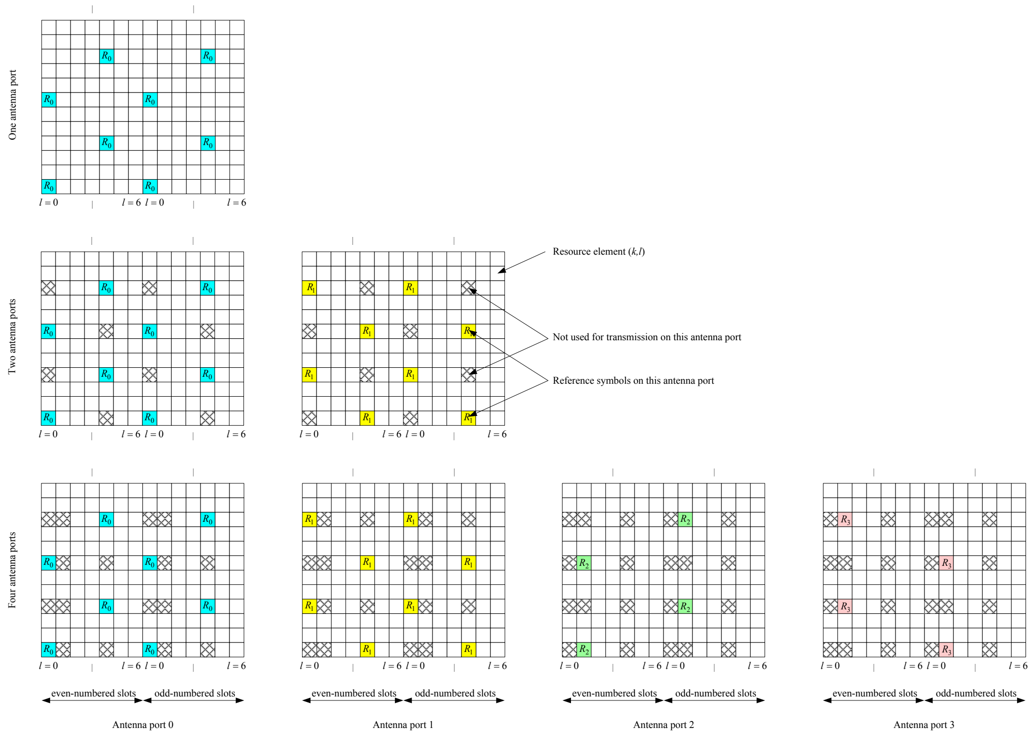


**Figure 7[9]**: CRS mapping based on antenna ports

It can be observed from the above figure that REs used for CRS mapping for multiple antenna ports don't overlap. The 'X' marks over the REs represent un-used or muted REs which are used for CRS mapping in other antenna ports, other than the one in consideration.

$v_{shift}$ is another parameter which determines the frequency positioning of CRS. This parameter is of at most importance in our study. $v_{shift}$ is generated based on equation (2) [9].

$$v_{shift} = N_{ID}^{cell} \, mod \, 6 \quad (2)$$

$N_{ID}^{cell}$ is called as Physical Cell-Identity (PCI). It is a unique but specific identity used to identify each Sector/Cell in a network. This identity is generated using equation (3) [9].

$$N_{ID}^{cell} = 3\, N_{ID}^{(1)} + N_{ID}^{(2)} \quad (3)$$

$N_{ID}^{(1)}$ takes values from 0-167 & $N_{ID}^{(2)}$ can take values 0-2, hence $N_{ID}^{cell}$ can take values from 0-503. The definition of frequency shifted or nonshifted CRS is based on the relative values of $v_{shift}$ among cells. Let's consider a cluster[15] with 7 sites[16] and 3 sectors per site. Each of the sectors is assigned with a PCI. PCI value in-turn decides the $v_{shift}$ for the respective sectors. If a site has sectors with the same $v_{shift}$ for a fixed $v$ and such sites are present in the entire

[15] Collection of sites
[16] Collection of sectors/cells

cluster then we consider the network to have Nonshifted CRS configuration. Figure 8 shows a schematic of such a cluster.

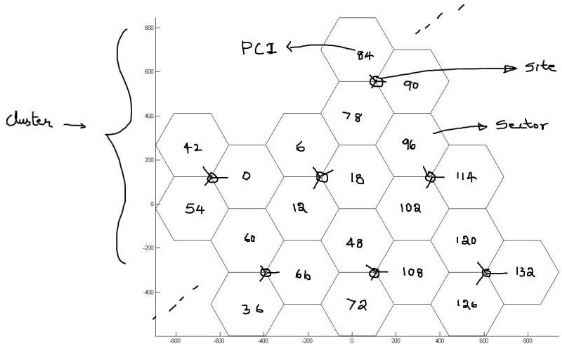


**Figure 8**: PCI planning for Nonshifted CRS configuration

In figure 8, $v_{shift}$ based on the PCI for each of the sectors is '0'; this can be verified using equation 2. We can observe that the CRS shift used across all the sectors in a site and over the entire cluster is identical. The maximum value of $v_{shift}$ is 5 due to modulo 6 operation in equation 2. For $v_{shift}$=0 the Nonshifted CRS seen from a time-frequency resource grid perspective is shown in figure 9. All sectors in figure 8 will have the same CRS pattern as shown in figure 9 throughout the cluster and across the entire bandwidth. For $v_{shift}$=3 the time-frequency CRS pattern looks as in figure 10.

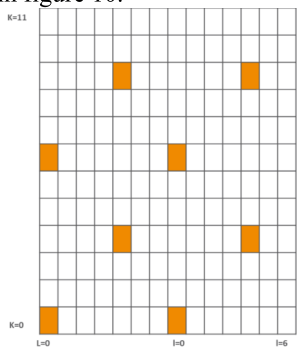


**Figure 9**: Resource grid pattern Nonshifted CRS, $v_{shift}$=0

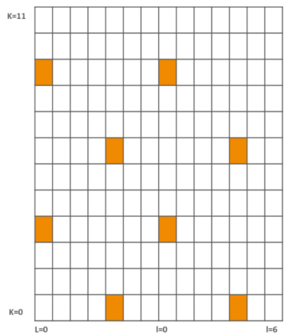


**Figure 10**: Resource grid pattern Nonshifted CRS, $v_{shift}$=3

Similarly for $v_{shift}$=3 all sectors present in the network will have the CRS shift pattern shown in figure 10 throughout. Starting from figure 8-10 we have discussed Nonshifted CRS configuration when eNB transmitter has single antenna port[17]. For antenna ports 2 and 4 the number of possible non-repeating $v_{shift}$ is three. To explain non-repeated CRS shifts let's consider 2 antenna port case (refer to figure 7). CRS shift pattern for antenna port 0 when $3 \leq v_{shift} \leq 5$ is same as $0 \leq v_{shift} \leq 3$ for antenna port 1 resulting in only three possible $v_{shift}$ for a 2 antenna port case. But for nonshifted CRS configuration there won't be any difference irrespective of the antenna ports used as all sectors have same shift. In shifted CRS configuration antenna ports play a major role in PCI planning.

In Shifted CRS configuration different $v_{shift}$ is present for each sector inside a site and such site pattern is replicated throughout the cluster. The PCI planning for a network with Shifted CRS configuration is such that no adjacent sectors will have the same $v_{shift}$. Such planning is shown in figure 11.

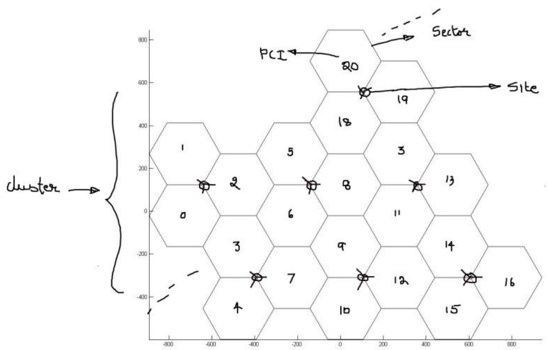


**Figure 11**: PCI planning for Shifted CRS configuration

$v_{shift}$ obtained by the PCI values in the above figure is such that sectors have different $v_{shift}$ relative to each other resulting in Shifted CRS configuration. The example shown in figure 11 is for single antenna port hence the number of possible shifts is 6 i.e. (0-5). In case of 2 antenna ports the number of non-repeated shifts is 3 (0-2). PCI planning for Shifted CRS for 2 antenna ports at eNB transmitter should result in $v_{shift}$ as shown in figure 12.

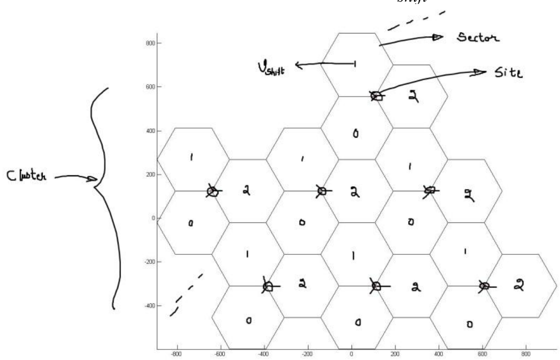


**Figure 12**: $v_{shift}$ pattern for Shifted CRS configuration

[17] Refer figure 7.

## 2.3 Transmission Mode 4 (TM4) in LTE

Out of the different multi antenna configurations *2* x *2* is of primary interest in our study. A schematic of TM4 with *2* x *2* antenna configuration is shown in figure 13. TM4 is a closed loop mechanism with codebook based precoding which supports spatial multiplexing.

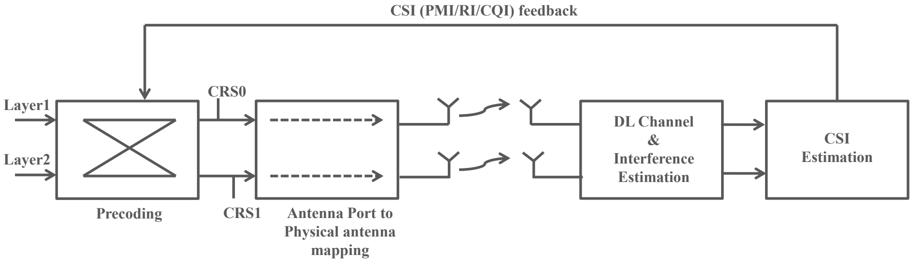


**Figure 13**: Transmission Mode 4 with 2X2 antenna configuration

Figure 13 is a more detailed version of figure 6 concentrating exclusively on TM4 with *2* x *2* antenna configuration. Based on the antenna configuration the maximum number of possible layers is two. This constraint brings down the number of 'TB to layer' mapping combinations shown in figure 4 to just two i.e. one TB to one layer and two TBs to two layers. TBs sent to physical layer undergo Digital Modulation. LTE Rel-8 supports BPSK[18]/QPSK/16QAM/64QAM modulation techniques. These digitally modulated TBs are used in 'TB to layer' mapping. In case of one TB to one layer mapping all the modulated symbols are mapped directly onto one layer. For two TBs to two layers there is a one-to-one mapping between TB and layer. In case of multi-antenna transmission, layers are also called as 'Transmission Ranks' [1]. Layer mapping is followed by 'Precoding', which helps to perform layer to antenna port mapping. $N_L$ modulated symbols are available from each layer after layer mapping. These symbols are linearly mapped on to $N_A$ antenna ports using a precoding matrix of dimension $N_A$ x $N_L$. Mathematically this transformation is written as $y_i$ = $\mathbf{W} \,.\, x_i$ where $x_i$ is a column vector of size $N_L$ consisting of one symbol from each layer. **W** is a precoding matrix of dimension $N_A$ x $N_L$. The product of **W** and $x_i$ results in a column vector $y_i$ of size $N_A$ consisting of one symbol per antenna port. As per the focus in our study $N_L$ can be either one or two and $N_A$ is fixed to two. Hence the dimension of a precoder matrix is either *2* x *1* or *2* x *2*. The list of precoder matrices used in our study is given in table 2. This list is also termed as codebook.

**Table 2[1]**: Precoder matrices

| **Precoder Matrices for Two Antenna ports, One and Two Layers** | | | | |
|---|---|---|---|---|
| **One Layer** | $\frac{1}{\sqrt{2}}\begin{pmatrix}+1\\+1\end{pmatrix}$ | $\frac{1}{\sqrt{2}}\begin{pmatrix}+1\\-1\end{pmatrix}$ | $\frac{1}{\sqrt{2}}\begin{pmatrix}+1\\+j\end{pmatrix}$ | $\frac{1}{\sqrt{2}}\begin{pmatrix}+1\\-j\end{pmatrix}$ |
| **Two Layers** | $\frac{1}{\sqrt{2}}\begin{pmatrix}+1 & +1\\+1 & -1\end{pmatrix}$ | $\frac{1}{\sqrt{2}}\begin{pmatrix}+1 & +1\\+1 & -j\end{pmatrix}$ | | |

[18] Used for control channels in LTE, data channels don't use this modulation scheme.

Precoding is followed by CRS mapping over individual antenna ports. The mapping of CRS to antenna ports is as per section 2.2. Information mapped on antenna ports is transmitted over air using the physical antennas. Antenna port to physical antenna mapping is one-to-one in our study.

Signals transmitted from the eNB transmitter are picked up by the UE receiver. At the UE receiver, channel and CSI estimation is performed. Figure 14 shows a concise method as to how channel and CSI estimation is performed at UE receiver[19].

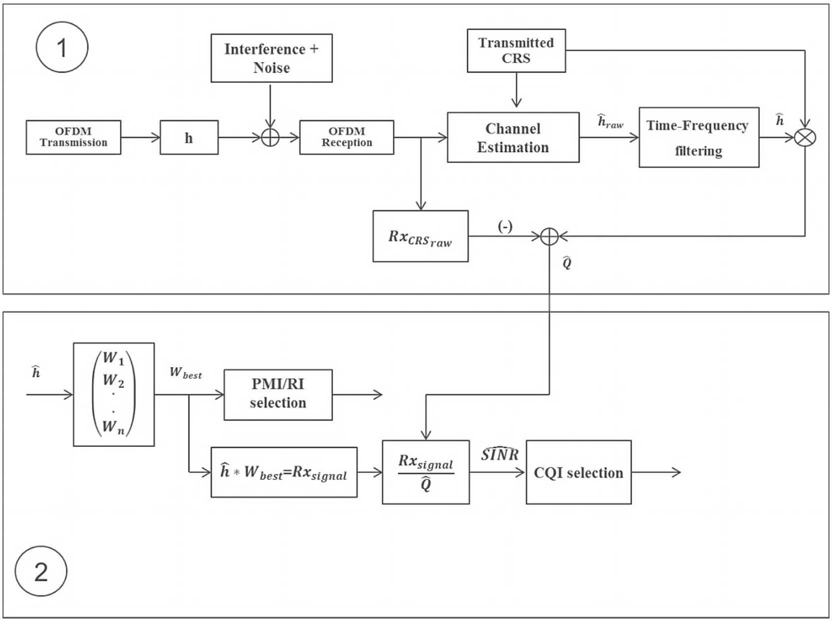


**Figure 14**: CSI estimation at UE receiver

In block 1, received signal undergoes channel estimation where channel estimates $\widehat{H}_{raw}$, for CRS REs are extracted. Extracted estimates are time-frequency filtered to reduce noise on the channel estimates and to cover the data REs. Filtered channel estimate $\widehat{H}$ is used to obtain interference $\widehat{Q}$.

$$\hat{Q} = \left(Rx_{CRS_{raw}} - Tx_{CRS} * \widehat{H}\right) * \left(Rx_{CRS_{raw}} - Tx_{CRS} * \widehat{H}\right)^{*} \quad (4)$$

$\widehat{Q}$ is later used in calculating SINR in block 2. In block 2 the filtered channel estimate is multiplied with all possible precoder matrices from table 2. The precoder matrix $W_{best}$ which gives the best throughput is recommended by the UE to eNB. The rank of $W_{best}$ matrix gives the number of layers to be used. Index of the best precoder matrix and its rank is stored as Precoder Matrix Indicator (PMI) and Rank Indicator (RI). SINR on the data REs is used for Channel Quality Indicator (CQI) acquisition. SINR is calculated as

[19] This method is specific to our study.

$$\widehat{SINR} = \frac{\left|W_{rx_{weights}} * \hat{H} * W_{best}\right|^2}{|W_{rx_{weights}} * \hat{Q}|^2} = \frac{|W_{rx_{weights}} * Rx_{signal}|^2}{|W_{rx_{weights}} * \hat{Q}|^2} \quad (5)$$

CQI, PMI and RI extraction shown in figure 14, is the CSI, which is fed back from the UE to the eNB. In equation 5, $W_{rx_{weights}}$ are the receiver weights.

CQI is the index extracted based on the channel condition experienced by the data REs suggesting the modulation and coding schemes to be used in DL transmissions after CSI feedback. SINR experienced by the data REs is the parameter used for CQI extraction and it is highlighted in figure 14. Table 2 gives a comprehensive mapping of CQI to modulation and coding scheme (MCS).

**Table 3[11]**: CQI to MCS mapping

| CQI index | modulation | code rate x 1024 | efficiency |
|---|---|---|---|
| 0 | out of range | | |
| 1 | QPSK | 78 | 0.1523 |
| 2 | QPSK | 120 | 0.2344 |
| 3 | QPSK | 193 | 0.3770 |
| 4 | QPSK | 308 | 0.6016 |
| 5 | QPSK | 449 | 0.8770 |
| 6 | QPSK | 602 | 1.1758 |
| 7 | 16QAM | 378 | 1.4766 |
| 8 | 16QAM | 490 | 1.9141 |
| 9 | 16QAM | 616 | 2.4063 |
| 10 | 64QAM | 466 | 2.7305 |
| 11 | 64QAM | 567 | 3.3223 |
| 12 | 64QAM | 666 | 3.9023 |
| 13 | 64QAM | 772 | 4.5234 |
| 14 | 64QAM | 873 | 5.1152 |
| 15 | 64QAM | 948 | 5.5547 |

The CQI index in table 3 represents the degree of goodness of the channel. CQI index 0 being the worst and 15 being the best. Higher modulation schemes are used when the channel quality is better which also improves spectrum efficiency (bits/sec/Hz). Using a higher modulation scheme in low quality channel is not suitable as the data is more prone to interference and noise affects. Code rate refers to the channel coding rate used to perform data encoding. In LTE Rel-8 1/3 code rate encoders are used to perform channel coding. Channel coding introduces an intelligent redundancy to the data which helps in efficient decoding. Redundant data introduced gives robustness to cope with diverse channel conditions. The amount of redundancy can be altered based on different code rates; this is achieved by 'Rate Matching' [10] block in physical layer. Redundancy can be reduced as the channel quality becomes better and better helping in efficient usage of the bandwidth. Reduction in redundancy means increase in code-rate. In a low quality channel conditions, higher redundancy is used hence lower code-rate. In good channel conditions lower redundancy is used hence higher the code-rate.

PMI and RI specify the index of the precoder matrix and number of layers to be used from the codebook (table 2). Indexing scheme was introduced with a purpose to reduce feedback information to mere numbers (indices) [1]. Possible precoder matrix dimensions in our study are *2* x *1* and *2* x *2*. Once CSI is estimated, it is relayed back to the eNB. The eNB can take this suggestion given by the UE on the modulation, coding rate, precoder matrix and rank to be used or it can override the CSI obtained and specify its own parameters. Closed-loop codebook based transmission happens constantly adapting to different channel conditions serving UEs in the network efficiently by providing the best possible QoS. The process of extracting CQI, PMI and RI explained above is called as CSI estimation. Based on the CRS configurations used in DL a CSI estimation error can be incurred. This error is due to the SINR bias experienced by CRS and data REs. SINR bias experienced varies based on the CRS configurations. In the next section we will discuss in detail the SINR experienced by the CRS REs for different CRS configurations and its repercussions.

## 2.4 Pros and Cons of CRS configurations in LTE

System Performance depends on SINR which is affected by interference and noise components. Noise in our study is considered to be thermal and Gaussian in nature. Interference is of two types Inter-cell and Intra-cell. Inter-cell interference is seen when serving cell signals are interfered by aggressor cell signals. Figure 15 shows a schematic of inter-cell interference.

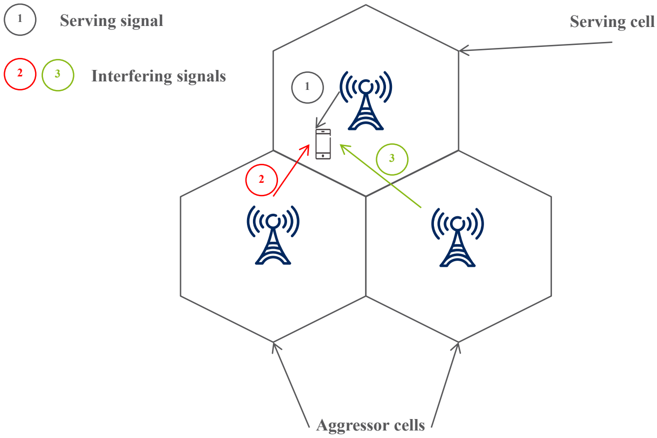


**Figure 15**: Typical Inter-cell Interference

Intra-cell interference is due to inter-stream interference. From equation (5) it is evident that higher the interference lower is the SINR. In this section we will denote inter-cell interference as *'Q'*. CRS configurations experience different Inter-cell interference pattern hence experiencing different SINR and thus different CSI acquisition. For a given CRS configuration the inter-cell interference is also dependent on the number of scheduled users (or traffic) in the network.

For nonshifted CRS all the sectors in a site have the same CRS frequency shift and these sites are replicated throughout the cluster. In low traffic scenario i.e. when minimal or no UEs are scheduled in aggressor cells of the network, the inter-cell interference for a nonshifted CRS configuration is as shown in figure 16.

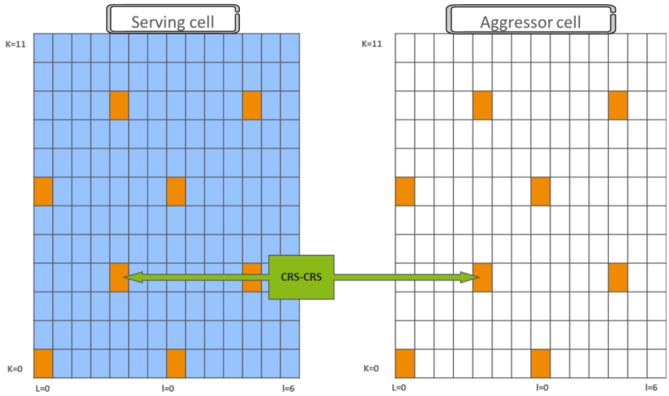

**Figure 16**: Nonshifted CRS inter-cell interference at low loads

In the above figure only two cells i.e. serving cell and one aggressor cell is shown, it should be noted that there are several other aggressor cells in the network creating interference to the serving cell signals. Even though the traffic is low in the network, all the eNBs will be transmitting CRS at all times over the entire bandwidth. These CRSs pose interference to the serving cell signals. Such interference is also termed as CRS-only interference. From the above figure we can see that serving cell CRS REs experience interference from aggressor cell CRS REs, but the data REs for a scheduled UE in the serving cell experiences no interference. Interference seen over CRS REs reduces the SINR on them. Just by doing eye-balling on figure 16 we can say that actual interference experienced by CRS REs – '$Q_{CRS}$', is not equal to the actual interference experienced by data REs – '$Q_{DATA}$', hence the actual SINR experienced by CRS REs – '$SINR_{CRS}$' is not equal to actual SINR experienced by data REs – '$SINR_{DATA}$'. Mathematically this can be written as

$$Q_{CRS} \neq Q_{DATA} \rightarrow SINR_{CRS} \neq SINR_{DATA} \quad (6)$$

For practical interference estimation the estimated interference on CRS REs – '$\hat{Q}_{CRS}$' is greater than the actual interference experienced by the data REs. Hence in practical scenarios SINR estimated over CRS REs – '$\widehat{SINR}_{CRS}$', is less than the actual SINR experienced by the data REs. Equation (7) shows the relation between interference and SINR for practical scenarios.

$$\hat{Q}_{CRS} > Q_{DATA} \rightarrow \widehat{SINR}_{CRS} < SINR_{DATA} \quad (7)$$

In section 2.2 we discussed how CRS REs are used to deduce the CSI. From figure 16 it is evident that data REs hardly experience any interference, but on the other hand CRS REs see heavy interference from aggressor cell CRS REs. CSI deduced from such CRS REs is suboptimal w.r.t the data REs as lower CSI selection is made. This selection is not justified for the data REs as they experience no or very less interference. Such unjustified CSI selection is due to the 'Bias in SINR' between CRSs and data REs. This bias causes systematic CSI estimation error. SINR bias not only results in pessimistic selection of CQI/PMI/RI but also affects system performance. CSI estimation error results in selection of lower rank and Modulation & Coding Scheme (MCS), which results in reduction of data rates and thus reduction in system performance. SINR bias seen is very predominant at low and medium traffic conditions for nonshifted CRS. This bias can be compensated by SINR adjustment – '$SINR_{adj}$'. Equation (8) gives an insight on to how this is done. Compensation is added to the estimated SINR on CRS REs such that it matches the actual SINR on data REs. SINR adjustment for low and medium loads is greater than zero.

$$\widehat{SINR}_{CRS} + (SINR_{adj}) = SINR_{DATA} \quad (8)$$
$$SINR_{adj} > 0$$

For nonshifted CRS at high traffic (load) conditions the inter-cell interference pattern and SINR experienced is different in comparison to low load condition. Figure 17 shows a schematic of interference pattern at high load condition.

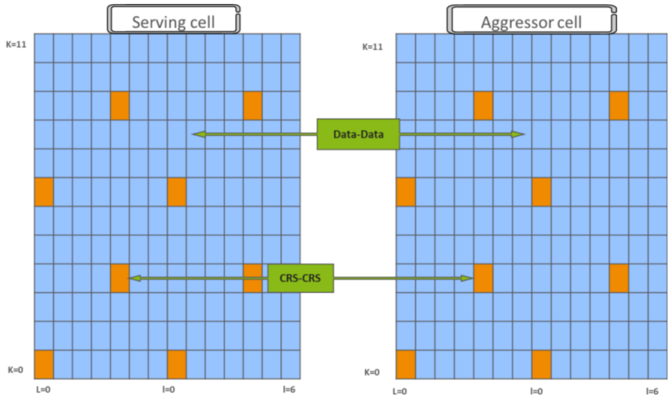


**Figure 17**: Nonshifted CRS inter-cell interference at High loads

CRS and data REs in serving cell experience equal amounts of interference at high load conditions. Aggressor cell CRS REs collide with serving cell CRS REs and similarly aggressor cell data REs collide with serving cell data REs. The interference experienced by both CRS and data REs results in almost equal SINRs on both REs. Actual interference experienced by CRS REs is equal to actual interference experienced by data REs implying that actual SINRs of CRS and data REs are the same.

$$Q_{CRS} = Q_{DATA} \rightarrow SINR_{CRS} = SINR_{DATA} \quad (9)$$

For practical scenarios the relation is as shown in equation 10.

$$\hat{Q}_{CRS} \cong Q_{DATA} \rightarrow \widehat{SINR}_{CRS} \cong SINR_{DATA} \quad (10)$$

Estimated interference over CRS REs is approximately the same as actual interference over data REs. This relation conveys estimated SINR over CRS REs is approximately the same as actual SINR experienced by data REs. It can be observed that there is no bias in SINR at high load conditions hence no need of SINR adjustment, equation 11 supports this claim.

$$\widehat{SINR}_{CRS} + (SINR_{adj}) = SINR_{DATA} \quad (11)$$
$$SINR_{adj} \cong 0$$

As the SINR bias is almost zero at high loads there is hardly any CSI estimation error. A keen observation shows that irrespective of the load conditions and assuming all sectors in the network is time-frequency synchronized, that there is a constant interference of aggressor cell CRS REs on serving cell CRS REs.

Frequency Shifted CRS experiences a different interference pattern and SINR in comparison to nonshifted CRS. Referring back to figure 12[20] for a shifted CRS configuration all sectors in a site are shifted w.r.t each other and this pattern is replicated throughout the cluster. Let's consider a site from this cluster.

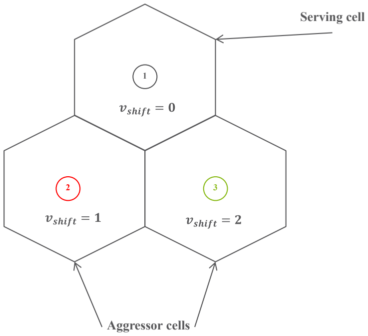


**Figure 18**: A typical site in a network using Shifted CRS

In the above figure 18, three sectors with $v_{shift}$ 0, 1 and 2 is considered. For the sake of analysis if we consider sectors with $v_{shift}$ 0 and 1 the interference pattern at low load condition looks as in figure 19.

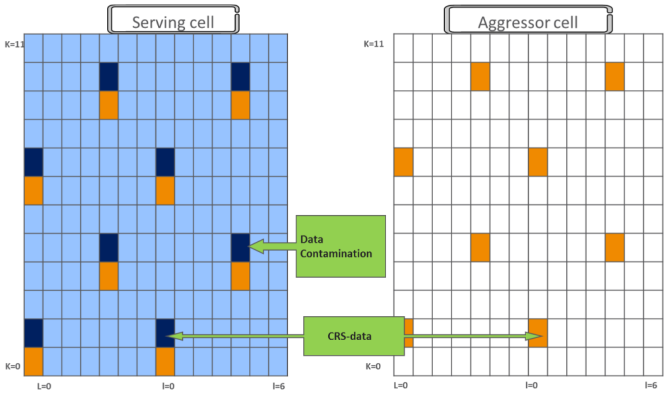


**Figure 19**: Shifted CRS inter-cell interference at low loads ($v_{shift} = 1$)

The relative shift causes a different interference pattern, in Shifted CRS configuration. Serving cell data REs experience interference from aggressor cell CRS REs. On the other hand CRS REs of serving cell experience very low or no interference. Actual interference seen by CRS REs is less in comparison to the interference seen by data REs in the serving cell. This infers actual SINR on CRS REs is greater than the SINR on data REs.

$$Q_{CRS} < Q_{DATA} \rightarrow SINR_{CRS} > SINR_{DATA} \quad (12)$$

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[20] *2* x *2* configurations are chosen here for explanation due to the scope of the thesis.

While performing practical estimation of interference and SINR, estimated interference seen by CRS REs is less in comparison to the actual interference seen by data REs, implying estimated SINR over CRS REs is greater than the SINR over data REs.

$$\hat{Q}_{CRS} < Q_{DATA} \rightarrow \widehat{SINR}_{CRS} > SINR_{DATA} \quad (13)$$

CSI deduced from such CRS REs in this case seems to be optimistic as data REs are experiencing collision from aggressor cells. Performing optimistic CSI selection results in a situation where in better CSI is chosen for the data experiencing a poor channel quality. Even here we see SINR bias but it is negative in nature[21]. As in case of nonshifted CRS there can be SINR adjustment made to compensate for the bias experienced. Equation 14 shows this compensation mathematically.

$$\widehat{SINR}_{CRS} + \left(SINR_{adj}\right) = SINR_{DATA} \quad (14)$$
$$SINR_{adj} < 0 \; or \text{ around } 0$$

The compensation is done by de-boosting SINR on CRS REs hence the SINR adjustment is less than zero. In our analysis we considered two sectors but it should not be overlooked that the serving cell signal is also experiencing interference from the third sector of the site and first tier sectors. Taking this interference into account the SINR adjustment can be considered to be around 0 rather than strictly negative. Interference from the third sector of the site affects different set of data REs in the serving cell. Third sector with $v_{shift} = 2$ generates an interference pattern as shown in figure 20.

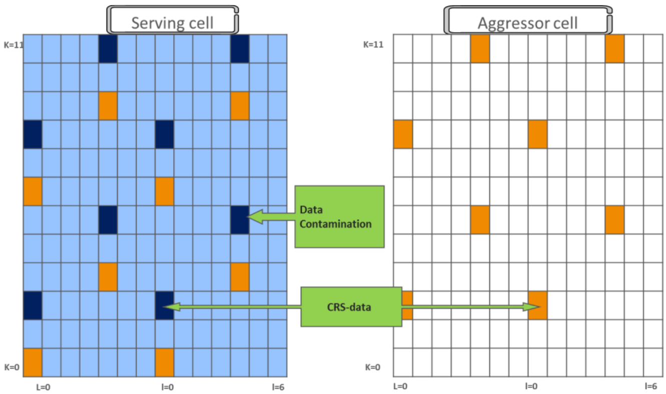


**Figure 20**: Shifted CRS inter-cell interference at low loads ($v_{shift} = 2$)

If figure 19 and 20 are seen together it's evident that lot of data REs experience heavy interference. To give an idea about the percentage of data REs affected, we will consider one of the examples from our study. Before beginning with the example let's acquire some background. TBs arriving from higher layers undergo channel encoding. Redundant bits are added to actual information bits in channel encoding. The data obtained after encoding is termed as Code Blocks (CBs). These CBs further undergo specific signal processing

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[21] It is seen from our performance evaluations that the SINR adjustment is not strictly zero, as serving cell CRS REs experience interference from 1st tier sectors which use the same CRS shift as the serving cell. This balances out the SINR bias and it was seen that SINR adjustment is around zero.

techniques like modulation, layer mapping and then resource grid mapping. After all these processing the data is transmitted over a subframe. In the example considered total number of REs in a subframe is 8400 (excluding first three OFDM symbols of the subframe used for PDCCH), with 6000 data REs and 2400 CRS REs. In this example it was seen that the whole subframe was divided into five Code Blocks (CBs). Due to the CRS-to-Data interference it was seen that out of these five CBs, 30% of data REs present in two of the CBs experience interference and 16% Data REs in one of the CB. High load condition for shifted CRS is very much the same as in nonshifted CRS configuration shown in figure 17. It should also be observed that in shifted CRS configuration data REs experience interference irrespective of the load conditions. We have seen the interference pattern and SINR experienced due to different CRS configurations for different loads. It's understandable that due to interference experienced there is a pessimistic or optimistic selection of CSI. Such selection doesn't favor system performance, by saying this we can confidently state that 'Different CRS configurations impact system performance differently in DL for LTE-Rel8'. Table 4 summarizes the pros and cons of different CRS configurations.

**Table 4**: Different scenarios in macro-only deployment

| Configurations | Pros | Cons |
|---|---|---|
| Non-Shifted CRS | • Zero Interference on DATA at Low loads. | • Larger Bias on the estimated SINR.<br>• High Interference observed on CRS irrespective of load conditions. |
| Shifted CRS | • Low Interference on CRS at Low loads.<br>• Lower Bias on the estimated SINR.<br>• Less or no contamination of Channel estimates at low loads. | • Relatively high interference seen on DATA from the CRS of aggressor cells irrespective of load conditions. |

# Chapter 3

# Proposed solutions for System Performance Optimization

## 3.1 Introduction

In Chapter 2 section 2.4 we analyzed the interference pattern and SINR experienced by CRS REs. For nonshifted CRS configuration a heavy bias was seen on the SINR experienced between data and CRS REs at low and medium loads. Similarly a negative bias (for 2 cell scenario) was seen between data and CRS REs for shifted CRS configuration at low and medium loads. Until heavy load condition was reached there was some amount of bias for both nonshifted and shifted CRS. This bias causes either suboptimal selection of CSI resulting in reduced system performance. To tackle this problem there could be two methods. In the first method eNB can override the CSI suggested by the UE and suggest its own. The first method includes CQIadj or Δ override. Second method is by performing SINR adjustment such that CSI estimation error is adjusted. It can be recalled that SINR adjustment technique was briefly introduced in equation 8, 11 and 14 before. In our study SINR adjustment is introduced in the system using two parameters, Power Measurement Offset (PMO also denoted as κ) and CQIadj (denoted as Δ). In this chapter we discuss about PMO and CQIadj individually and understand how they impact the SINR bias and in turn the CSI selection. Selection of PMO and CQIadj has to be relative in nature because of the fact that SINR bias varies for different CRS configurations, load conditions and deployment strategies. From the performance evaluations we have seen that when κ and Δ adjustment is done jointly the system performance is improved even more.

## 3.2 PMO (κ) Adjustment

SINR adjustment – '$SINR_{adj}$' can be performed by balancing the power ratio between CRS and data REs at UE side based on the SINR bias experienced. eNB can suggest the UE to hypothetically assume a power ratio between CRS and data REs before performing CSI estimation. The goal of power ratio balancing is to reduce the SINR bias which in-turn helps in optimal selection of CSI parameters. A power offset called PMO is added to the received signal at the UE receiver which helps in balancing the SINR bias. Equation (15) shows this addition of power offset.

$$SINR = \frac{Transmitted\ Signal\ power * pathloss * PMO}{Interference\ power + Noise\ power} \quad (15)^{22}$$

In case of nonshifted CRS configuration at low loads and medium loads the bias is high hence a strong positive PMO could be used to compensate for the bias. At high loads this compensation is very minimal or not needed as data and CRS REs experience almost the same SINR. For shifted CRS configuration at low and medium loads there is a negative bias

[22] PMO is in linear scale in this equation.

which can be compensated by de-boosting the power on received CRS REs. To perform de-boosting PMO close to zero or negative values is favorable. Similar to nonshifted CRS configuration even for shifted CRS there is no need of any compensation for SINR bias at high loads as there is very minimal or no bias experienced. For LTE Rel-8 [-2 0 2 4 6 8 10 12] dB [12] PMO values are defined. PMO is referred to as *nomPDSCH-RS-EPRE-Offset* [11] in LTE specifications. A typical example of PMO selection is as follows. For nonshifted CRS configuration at low loads PMO of 8 dB and beyond will be optimal enough to compensate for the bias. Shifted CRS at low loads PMO of 2 dB or below should be good enough to compensate the bias. It should be noted that these values are just an average across all cases and scenarios obtained after rigorous evaluations. It is also observed from our study that Δ adjustment boosts the rank selection.

## 3.2 CQIadj (Δ) Adjustment

In this adjustment SINR bias compensation is done at the network side. The CQI calculated at the UE receiver is relayed back to the eNB, this CQI can be suboptimal based of the SINR bias experienced. CQIadj or Δ adjustment is added to the reported CQI for compensation.

$$CQI = CQI_{report} + \Delta \quad [dB] \quad (16)$$

Equation (16) gives the mathematical interpretation of this adjustment. This adjustment is not specified in any of the LTE specifications it is up to the vendor. The CQIadj takes values depending on the load condition, CRS configuration and deployment strategy. The range of values for CQIadj has been derived by performing extensive evaluations. Positive values of adjustments are used for low and medium load conditions for nonshifted CRS configuration. Negative values of adjustments are more suitable for shifted CRS configuration at low and medium loads. At high loads CQIadj of 0 dB is promising enough for both the CRS configurations as an equal amount of interference is seen on both data and CRS REs. From table 3 we know that CQI is mapped to obtain the MCS, this means that Δ adjustment performed influences the MCS selection such that any CSI estimation error incurred on MCS selection is reduced. Apart from κ and Δ adjustment there is also one more adjustment called the Outer Loop Link Adaptation (OLLA) [18] which is a dynamic adjustment in comparison to Δ adjustment which is a fixed start value. Based on the successful or unsuccessful reception of TBs in DL, ACK/NACK[23] is sent from UE to the eNB. If there is an ACK received then OLLA increases the CQI slightly, so that better MCS is used for the next DL transmission to that intended UE. This increase in CQI by OLLA happens until a NACK is received. On receiving NACK the CQI is reduced. Hence these adjustments of CQI made by OLLA are dynamic in nature in comparison to the Δ adjustments made. In the next section a joint adjustment of κ and Δ is analyzed which is a key solution in this thesis.

[23] Acknowledgment/Negative Acknowledgement

## 3.3 Joint Adjustment of PMO (κ) & CQIadj (Δ)

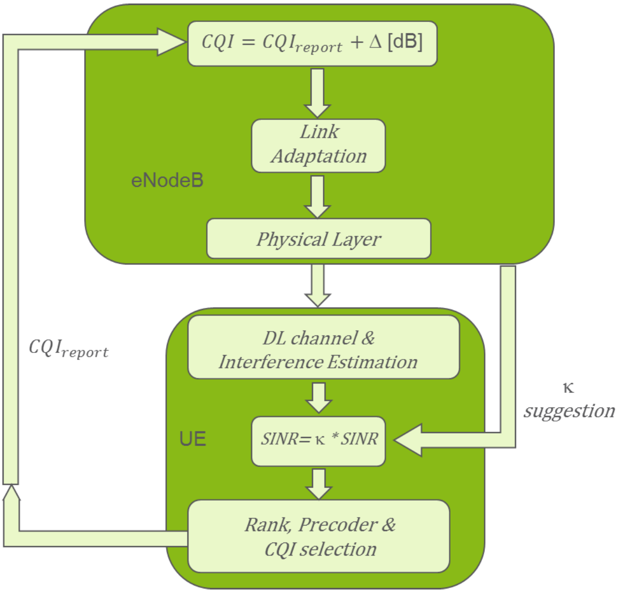



**Figure 21**: κ and Δ joint adjustment

Figure 21 gives a comprehensive description of joint κ and Δ adjustment in the system. The moment UE picks up the signal from eNB it is fed to the channel and interference estimation block to extract channel and interference estimates. These estimates obtained are interpolated and extrapolated on the data REs. SINR for data REs are obtained based on these extended estimates and best precoding matrix, which gives highest throughput. SINR obtained on the data REs is fed to a block where κ adjustment is performed based on the suggestion given by eNB. PMO or κ is also termed as rank adjustment in our study. Referring back to figure 14 and equation 15 we can understand how κ helps in rank boosting. A positive PMO addition boosts the channel gain. This channel gain helps in selecting $W_{best}$ with the highest rank hence boosting the rank. The adjusted SINR is further used to extract PMI, RI and CQI. Extracted PMI, RI and CQI are relayed back to eNB in the form of CSI. eNB after receiving CSI, tries to compensate the CQI by merely adding an Δ adjustment to the reported CQI. The adjusted CQI is then used to obtain better MCS value in 'Link Adaptation' block. Thus κ and Δ is jointly adjusted. But to extract the optimal κ and Δ combination we will refer to figure 22 where Mean user bitrate is plotted as a function of κ and Δ for a Macro-Only deployment, Scenario 2 for 80 Mbps/km$^2$ traffic. Fixing κ different Δ values are scanned across and mean user bitrates in the network is calculated. This process is under taken for different κ values and peak mean user bitrates is captured. Out of these peak bitrates the maximum is selected and (κ,Δ) duplet for the maximum is considered to be optimal combination. This (κ,Δ) optimal duplet when plugged back in figure 21 the SINR bias is reduced to the best possible extent and thus improve the system performance. For the selected example in figure 22 the optimal (κ,Δ) duplet is (0, 0).

There is a relationship between (κ,Δ) which is shown in figure 23 below, this figure corresponds to the same example as considered in figure 22. It can be seen that as κ increases

Δ decreases. This means to say that if we keep increasing the κ and Δ in tandem it not necessarily increases the system performance.

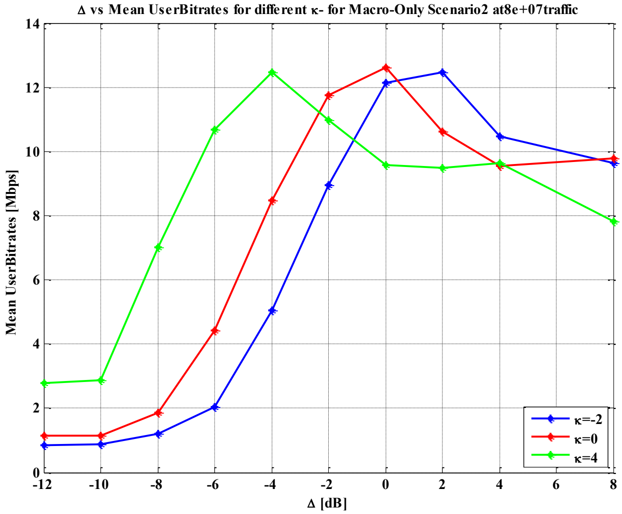



**Figure 22**: Mean user bitrates as a function of κ and Δ

There is a sort of balance which has to be maintained. The Δ in figure 23 are the optimal values for a given κ. This means to say that if we collect the (κ,Δ) values for all the peaks seen in mean user bitrate in figure 22 and plot them, we end up with κ and Δ relationship shown below.

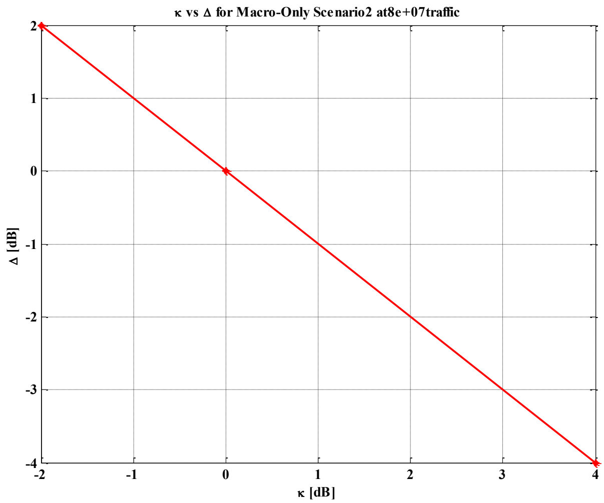



**Figure 23**: Relationship between κ and Δ

Our proposed solution is brute force in nature hence for a given load, CRS configuration and deployment strategy several combinations of (κ, Δ) duplet is formulated. Before formulation an extensive logical and analytical process is undertaken on to how system performance is either impaired or improved based on these combinations. In the coming chapters each of the deployment strategies with different load conditions and CRS configurations are treated individually using the proposed solution. A genie approach is also considered to get an upper bound on the system performance. Improvisation of system performance is characterized and analyzed using five important parameters, mean user bitrates, mean rank, resource utilization, cell edge user bitrates and average adjusted SINR error.

# Chapter 4

# Simulation Setup, Parameters and Performance measures

Discussion of system performance evaluation requires background of simulation setup and how system performance is measured. This section gives a generic explanation of how a network setup is emulated and how it is used to analyze the impact of CRS configuration on system performance. Along with simulation setup we also discuss parameters used to measure the system performance.

## 4.1 Simulation Setup

A network with $L$ sectors is considered with a specific CRS planning. All sectors are considered to be time-frequency synchronized. UEs enter into this network according to Poisson distribution. Each UE measures reference signal power and latch onto the eNB with the strongest Reference Signal Received Power (RSRP). Once UE/UEs are connected to their serving cells they start downloading a file of $X$ Mbytes [15]. Each of the UEs undergoes an adjustment as shown in figure 21 while downloading the file. After the completion of file download UEs are released from the network. This process of UEs entering the network, file download and $(\kappa, \Delta)$ adjustment goes on for a stipulated amount of super frames (Radio frames), specific CRS configuration, load condition and for all formulated $(\kappa, \Delta)$ duplets. Data rate experienced by each of the UE in the network is calculated and an average across all the UEs is taken. Then a duplet which gives the best mean user bitrate is selected as the optimal solution for that specific CRS configuration at a given load and system performance is plotted as a function of served traffic.

## 4.2 System and Simulation Parameters

Key system and simulation parameters used in performance evaluations of Macro-Only scenario are listed in the table 5 below.

**Table 5**: Simulation parameters

| ***Parameter*** | ***Value*** |
|---|---|
| Node Deployments[14] | Seven 3-sector macro sites, 4 Picos/ 4 Hotspots, 4 Picos/1 Hotspot, 10 Picos/ 1 Hotspot |
| Inter Site Distance | 500 m |
| Carrier Frequency | 2 GHz |
| System Bandwidth | 10 MHz |
| Propagation Model | ITU Urban Macro |
| Sub-carrier frequency | 15 KHz |
| Cyclic Prefix | Normal |
| Network Synchronization | Synchronized |
| UE Indoor Probability | 0.8 |
| UE Speed | 3 km/h |
| Traffic Model | FTP model 1 |
| File Size | 100kB or 500kB |

| *Parameter* | *Value* |
|---|---|
| Control Channel Overhead | 3 OFDM symbols |
| Macro Tx Power | 46 dBm |
| Small Cell Tx Power | 30 dBm |
| Cell Selection Offset | 0 dB and 6 dB |
| Noise Figure | 9 dB in UE |
| DL Transmission Scheme | 3GPP LTE TM4, 2x2 |
| Receiver (Demodulation+CQI) | S-IRC and IRC |
| Scheduling | Round Robin |
| CSI Reporting Period | 5 ms |
| CSI Delay | 6 ms |
| CSI Mode | PUSCH 3-1 (sub-band CQI, wideband PMI) |
| HARQ | Incremental Redundancy, 7 ms delay, 8 processes |

Some of the system and simulation parameters are self-explanatory but a few require some insight. Statistics of the UE distribution in the network is such that 20% of them are outdoors and 80% indoors. File Transfer Protocol is used as traffic model. UE receiver has Stream-Interference Rejection Combining (SIRC) and Interference Rejection Combining (IRC). CSI mode is in accordance with [11].

## 4.3 Performance measures

**Mean user bitrate:** Bitrate for each UE in the network is the ratio of file size downloaded to the total time taken to download. The time taken for downloading the file depends on the file size, transmission time and waiting time of the UE in the network to access the resources (in other words 'traffic in the network creates queuing resulting in longer waiting time'). Mathematically the ratio is given as

$$R_i = \frac{X}{T_i} \quad (17)$$

$R_i$ is the bitrate for any $i^{th}$ user in the network $X$ is the file size in Mbytes and $T_i$ is the total time taken to download the file. Such user bitrate is calculated for all the UEs in the system and an average across all UEs is taken. Mathematically

$$R = \sum_i \frac{R_i}{N} \quad (18)$$

$R$ is the mean bitrate, $R_i$ is the data rate for each of the UEs in the network and $N$ being the number of UEs in the network.

**Cell Edge user bitrate:** A cumulative distribution function of user bitrates in the network is used to calculate the Cell edge or 5$^{th}$ percentile user bitrate. The UEs falling inside the 5% CDF is used to calculate 5$^{th}$ percentile user bitrate. Similarly 50% CDF is used for 50$^{th}$ percentile and UEs in 95% CDF is used to find 95$^{th}$ percentile. As 5$^{th}$ percentile users are considered to be cell edge users, 50$^{th}$ percentile users are considered to be present in median range from the eNB and 95$^{th}$ means UEs very close to eNB. This is an important measure to analyze because it's easier to provide good QoS to the UEs in close and median range but it's also important to provide good QoS to the cell edge UEs which experience higher path loss and inter-cell interference.

**Average Resource Utilization:** Resource utilization averaged across all the sectors in a network results in average resource utilization of the network. Average Resource utilization indicates the percentage usage of time-frequency resource grid. It increases as the load increases in the network. Higher resource utilization means longer waiting time for the UEs to access the resources which in-turn means lower bitrates and thus reduced system performance. Higher resource utilization also means high interference thus reducing data rates. A system may become unstable when there is very high resource utilization and the offered traffic cannot be served by the system. To measure the system performance at least 50%-60% of average resource utilization has to be seen else very low utilization gives an over dimensioned network w.r.t the traffic demand.

**Mean Rank:** For a given scenario in a network all the UEs individually select some rank based on the channel and interference experienced. All these ranks which are reported back to the eNB are averaged out across all the UEs in the network, giving an average rank.

**Average adjusted SINR error:** The difference between average estimated adjusted SINR and average actual SINR experienced gives average adjusted SINR error. This measure gives a quantitative figure of how much the SINR bias is reduced. Average adjusted SINR error zero means the bias is fully compensated or there is no SINR bias existing. Based on the amount of average adjusted SINR error we can judge how good the proposed solution has bridge the gap between average estimated adjusted SINR and average actual SINR.

# Chapter 5

## Performance Evaluations - Homogeneous Deployment

In homogeneous network deployment, parameters like sector radius, inter site distance, sectors per site, eNB transmit power and height of the eNB antennas is uniform throughout the network. In our study we consider Macro-only case as an example for homogeneous network deployment. In macro-only deployment we consider three different scenarios. Scenario1- All sectors in a site and all sites in a cluster have same CRS frequency shift. This is also known to us as Nonshifted CRS. The figure 24 below shows a pictorial representation of Nonshifted CRS.

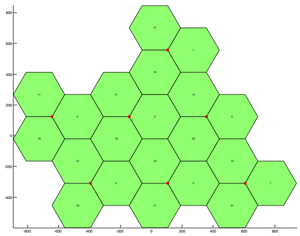
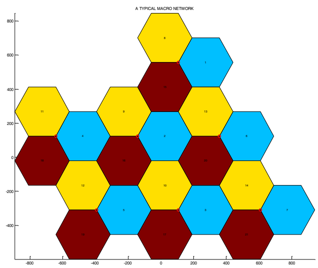


**Figure 24**: Network with Nonshifted CRS configuration

Scenario2- Sectors with in a site have different CRS frequency shifts w.r.t each other, such sites are replicated throughout the cluster. This can be visualized as shown in figure 25. Same CRS shift is indicated by same color.




[24]

**Figure 25**: Network with Shifted CRS configuration

Scenario3- Sectors with in a site has same CRS shifts but differ across sites. Such pattern is replicated throughout the cluster. It should be noted that no two adjacent sites must have the same CRS shift. This scenario is considered to be more practical because such deployment is more possible to be in real networks. Figure 26 helps understanding this scenario intuitively.

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[24] Figure shown is for 2 X 2 antenna configuration hence only 3 possible frequency shifts.

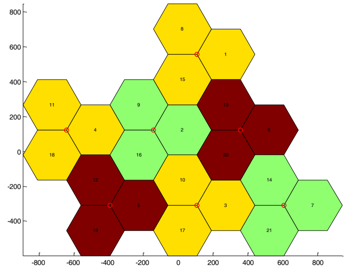


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**Figure 26**: Network with Shifted and Nonshifted CRS configuration

Each of the above scenarios experience different interference pattern and SINRs, leading to different system performance. System performance evaluations for these three scenarios are treated in depth in the following sections.

## 5.1 CSI estimation using data REs with Ideal LA (Technology Potential)

CSI estimation using data REs with Ideal LA is a genie approach where the whole system behaves as an ideal system. Receiver has full knowledge of the channel and interference experienced in DL transmission. It also has knowledge of all the network parameters and LA is ideal. In this setup data REs are used to perform CSI estimation which means that there is no SINR bias to be taken into account and optimal PMI, RI and CQI selection is made. As there is no SINR bias there is no question of (κ, Δ) adjustment. Ideal LA means actual SINR experienced by the data REs are used to extract CQI, which is later on mapped to obtain MCS. Flow graph shown in figure 21 holds good here as well, with an exception that data REs are used to perform channel and interference estimation and no adjustment of (κ, Δ).

### 5.1.1 Performance comparison between Scenario 1, 2 and 3

Under Ideal LA with CSI estimation using data REs, performance of scenario 1, 2 and 3, is discussed in this section. Key Performance parameters like, mean user bitrate, resource utilization, cell edge user bitrate and mean rank is used in performance comparison. Average Resource utilization shown in figure 27 is a monotonically increasing function of the served traffic. Resource utilization is captured for very low load such as 1Mbps/km$^2$ to very high load like 140Mbps/km$^2$. The maximum resource utilization seen is around 60% which is a stable point for the system. The utilization varies between scenarios due to the interference experienced which results in different transmission times. The mean rank selection shown in figure 28, between all 3 scenarios is almost the same, but scenario 2 has slightly lower rank selection in comparison to other two scenarios this is due to the fact that CRS-to-DATA[26] interference is experienced in scenario 2. The mean rank selection for all scenarios is load sensitive because the interference experienced by data REs keeps increasing as load increases.

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[25] Figure shown is for 2 X 2 antenna configuration hence only 3 possible frequency shifts.
[26] AGGRESSOR CELL-to-SERVING CELL

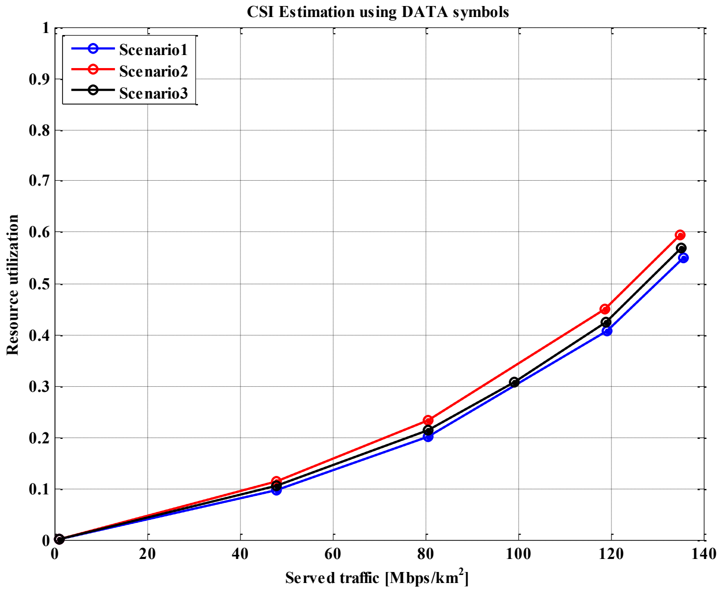


**Figure 27**: Resource utilization as a function of Served traffic for technology potential in macro-only case

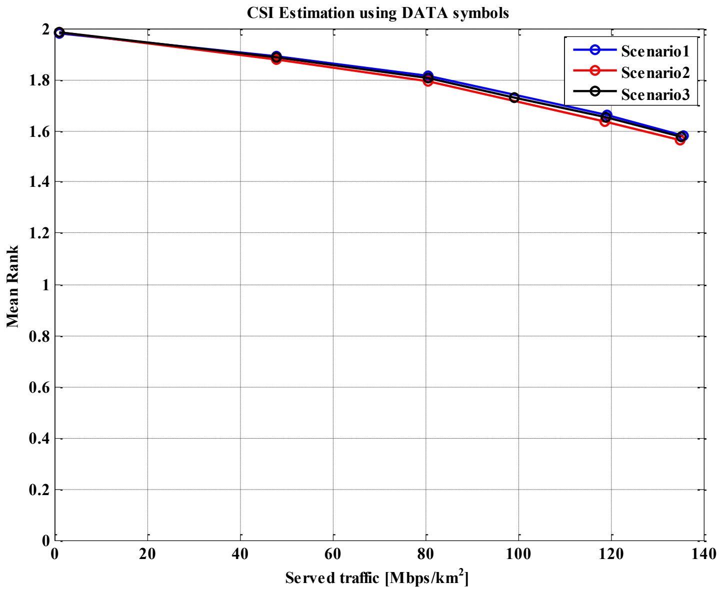


**Figure 28**: Mean Rank as a function of Served traffic for technology potential in macro-only case

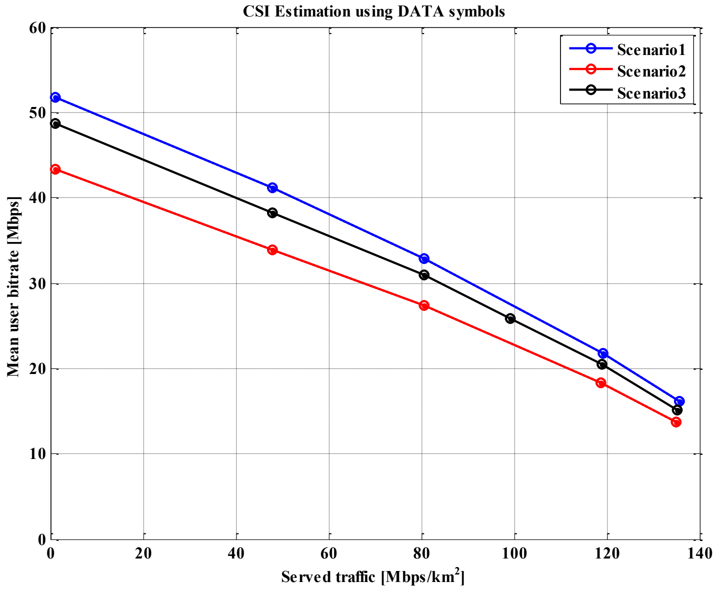


**Figure 29**: Mean user bitrate as a function of Served traffic for technology potential in macro-only case

To comment on the mean user bitrates obtained for Ideal LA with CSI estimation using data REs it's important to know interference experienced by data REs in all three scenarios. In scenario 1 at low loads data REs doesn't experience any interference from aggressor cells, at medium loads data REs experience some interference from aggressor cell data REs and at high loads data REs experience heavy interference as many UEs are scheduled in the network. This interference trend coveys that data rates monotonically starts decreasing as load increases. This trend can be confirmed from figure 29 above for scenario 1. It should also be kept in mind that there is no CRS-to-DATA interference irrespective of the loads for Scenario 1. Scenario 2 is shifted CRS configuration, there is a constant CRS-to-DATA collision seen irrespective of the loads. This collision contaminates the data REs and brings down the SINR on them resulting in reduced bitrates. The mean user bitrate vs served traffic trend seen in scenario 1 is seen even in scenario 2 as well, but there is sizable reduction in the bitrates due to the CRS-to-DATA collision. Scenario 3 can be called as a hybrid between scenario 1 and scenario 2 as there is some amount of CRS-to-DATA collision seen but not as extreme as scenario 2. At the same time some sectors might escape such collision resulting in reduced interference. Due to this interference pattern the mean user bitrates experienced is in between scenario 1 and scenario 2. As more and more UEs are scheduled in the network mean user bitrates starts to converge for all three scenarios due to DATA-to-DATA and CRS-to-DATA collision. This convergence is evident from the above figure. Average adjusted SINR error is zero as seen in the figure 31 this is due to the fact that ideal channel and interference estimation is assumed along with ideal LA in this case. As data REs are used for CSI estimation, there is no CSI estimation error and thus no SINR adjustment is required. The actual SINR and the estimated SINR are both equal thus resulting in average adjusted SINR to be zero. Results for higher file size (0.5MB) are captured for scenario1 and scenario2 for the same case. These results are available in appendix 1.1.

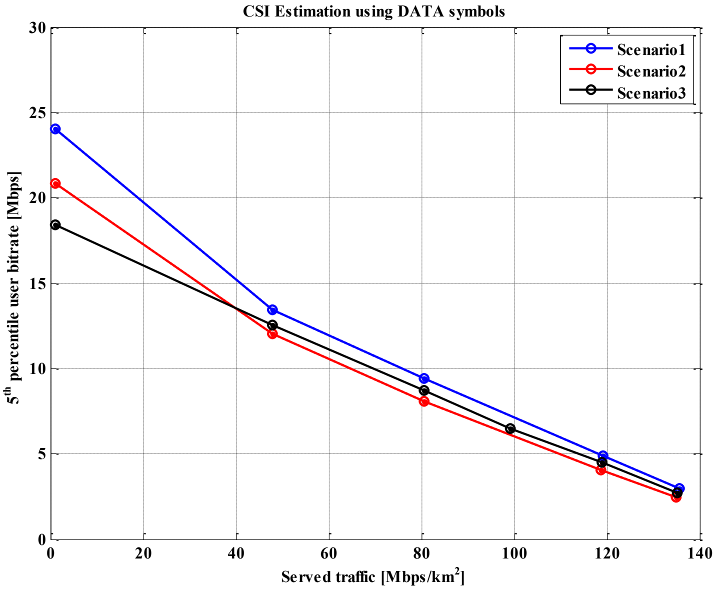


**Figure 30**: Cell edge user bitrates as a function of Served traffic for technology potential in macro-only case

In figure 30 we can see the cell edge user bitrate and a similar trend as seen in mean user bitrate is observed.

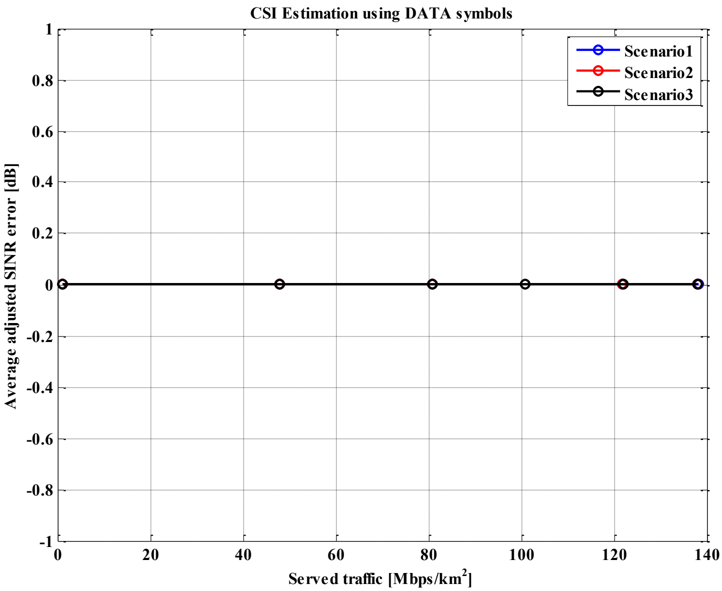


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**Figure 31**: Average adjusted SINR error as a function of Served traffic for technology potential in macro-only case

## 5.2 CSI estimation using CRS REs with Ideal LA

CSI estimation using CRS REs is almost similar to CSI estimation using data REs except that CRS REs are used to perform DL channel and CSI estimation. Due to this SINR bias needs to be considered in this case. Ideal LA makes sure that actual SINR experienced by data REs is used for CQI estimation resulting in uncompromised selection of CQI. The CQI estimation will be error free but PMI and RI selection experience error due to the fact that CRS REs which experiences SINR bias are used in DL estimation. Flow graph in figure 21 holds good here also except that CRS REs are used for DL CSI estimation and no (κ, Δ) adjustment is performed.

### 5.2.1 Performance comparison between Scenario 1, 2 and 3

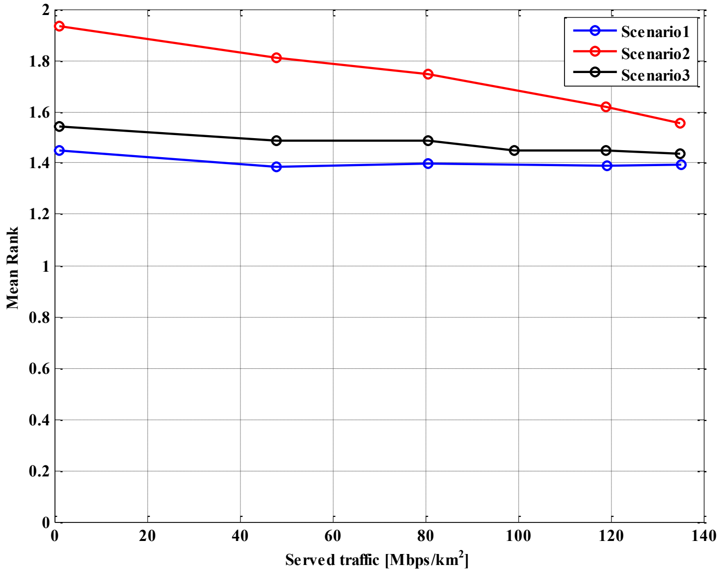


**Figure 32**: Mean Rank as a function of Served traffic for CRS based CSI with Ideal LA in macro-only case

Based on the mean rank shown in figure 32 we can derive some interesting conclusions on how rank selection differs for different scenarios. CRS REs in scenario 1 sees perennial CRS-to-CRS collision irrespective of the loads hence SINR on these REs goes down and will remain almost constant. Rank selection based on such REs results in almost constant rank selection around the mean. Mean rank selection for scenario 3 is in between scenario 1 and 2 due to the fact that some of the CRS REs escape interference and results in slightly better rank selection compared to scenario1. For scenario 2 the CRS REs are almost interference free until a high load condition is reached. This interference pattern reflects strongly in rank selection and can be seen that very high mean rank selection is made for low and medium loads and gradually decreases as loads increases. It can be summarized saying mean rank selection for, scenario1 is load independent, scenario2 is load dependent and scenario3 is in between scenario 1 and 2.

For low and medium loads we can see from figure 33 that scenario 2 has a slight upper hand over scenario 1 and scenario 3. The reason behind this is CRS REs in scenario 2 experience no interference at low loads and minimal interference at medium loads. CRS REs experiencing such interference used in CSI estimation results in selection of precoder matrix with higher rank for scenario 2 in comparison to 1 and 3. Such boost in rank lifts the mean user bitrates for scenario 2. Even though scenario 2 experiences CRS-to-DATA interference, due to the fact that CRS REs are used in PMI, RI selection a lift in the user bitrate is seen in comparison to scenario 1 and 3. But the effect of CRS-to-DATA interference becomes more predominant after crossing medium loads. It can be seen in the mean user bitrate figure below that there is a slight cross over between scenario 2 and scenario 1 at medium loads. This is due to the fact that CQI selection is based upon the data REs experiencing interference which is strong enough. MCS selection based on such data REs will be on the lower side bringing down the mean user bitrates for scenario 2 in comparison to scenario 1. It should be exclusively noted that there is a interplay between rank boosting based on CRS REs and MCS selection based on data REs. Apart from the fact of rank boosting in scenario 2 it should be noted that in scenario 1 unconditional CRS-to-CRS interference is seen from aggressor cells irrespective of loads hence the rank selection is on the lower side bringing down the mean user bitrates. As network gets heavily loaded performance of all 3 scenarios starts to converge.

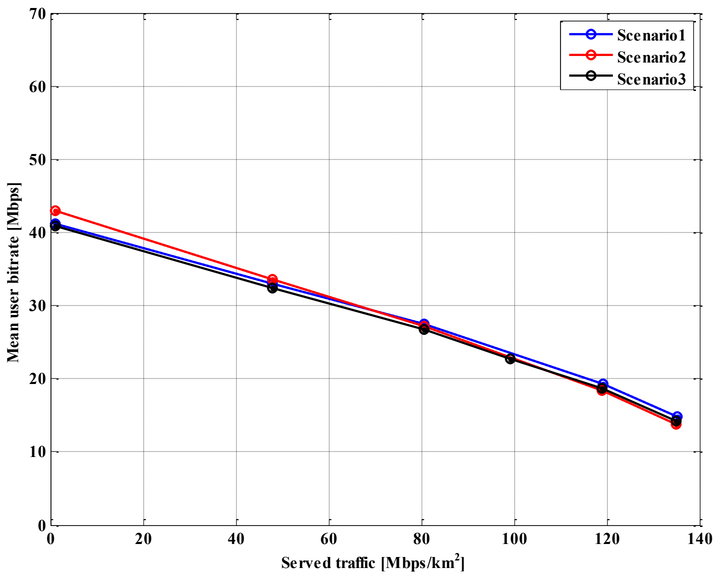


**Figure 33**: Mean user bitrate as a function of Served traffic for CRS based CSI with Ideal LA in macro-only case

Cell edge user bitrates seen in figure 34 shows that scenario2 has higher performance compared to scenario1 and 3. CRS REs escape from interference at low and medium loads this is the reason for higher performance in scenario2. In scenario1 we see that there is CRS-to-CRS collision and CSI estimation error is considered hence the performance drops compared to scenario2.

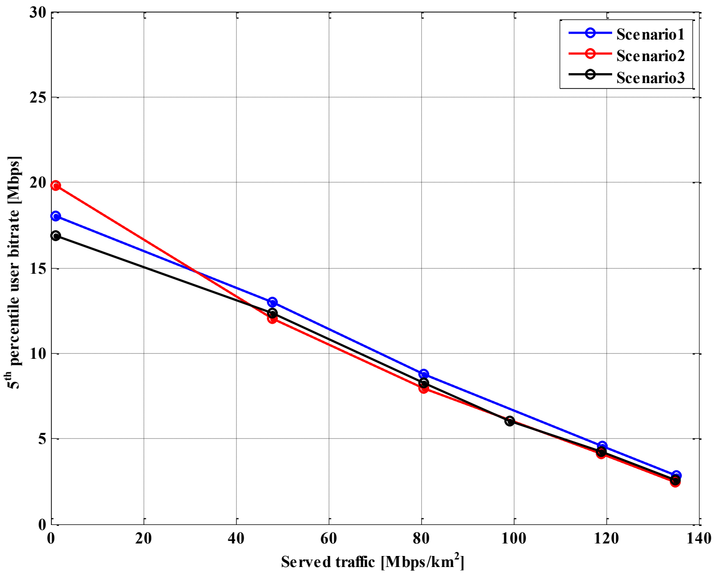


**Figure 34**: 5$^{th}$ percentile bitrate as a function of Served traffic for CRS based CSI with Ideal LA in macro-only case

Results for higher file size (0.5MB) for scenario1 and 2 for the same case is showcased in appendix 1.2.

## 5.3 CSI estimation for practical tuned case

This case is more practical and close to real systems. In this case DL Channel and CSI estimation is performed using CRS REs. Link adaptation is non-ideal and is based on CRS REs. UE receiver will not have the knowledge of actual channel and interference experienced as compared to the previous sections 5.2 and 5.1. Bias in SINR between data and CRS REs is very predominant and has to be taken into account. Flow graph mentioned in figure 21 is very much applicable to this case. Before discussing the performance comparison of different scenarios it's important to know how optimal (κ, Δ) is selected for a specific load in a given deployment and for a given CRS configuration.

For a given load, deployment strategy and CRS configuration a wide range of (κ, Δ) is formulated and mean user bitrates for each of these duplets is calculated. The (κ, Δ) combination giving the best mean user bitrate is selected as the optimal combination for a specific load in a given deployment and for a given CRS configuration. Based on explanation given in chapter 3 section 3.3 the mean user bitrates for different (κ, Δ) is generated.

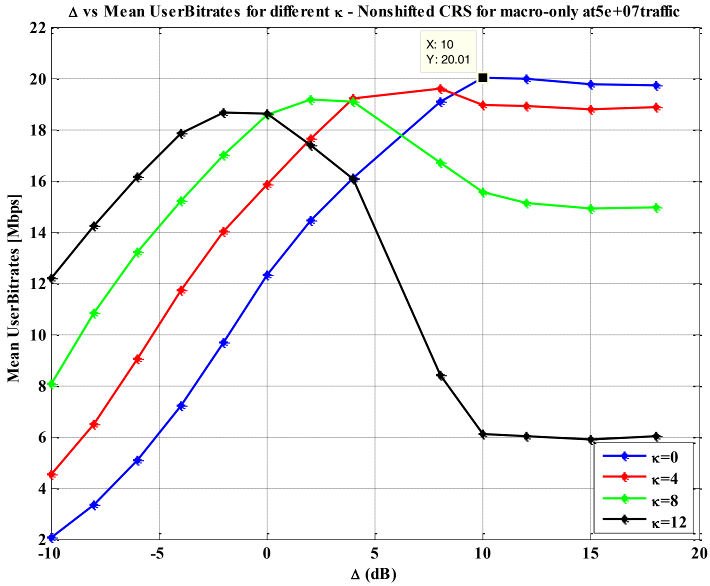


**Figure 35**: Mean user bitrates as a function of κ and Δ for Macro-only Nonshifted CRS configuration at 50 Mbps/sqkm traffic

CQIadj (Δ) values are varied for a fixed κ value which results in a bell shaped mean user bitrate curve reaching a peak. Such mean user bitrates are generated for different κ values, each of them peaking at a specific combination of (κ, Δ). Once all the combinations are exhausted for a fixed load the maximum of the performance peaks is selected, see figure 35, and respective (κ, Δ) combination is considered to be optimal. The interplay between κ and Δ selection results in a situation where SINR bias is almost minimized. This minimization results in optimal selection of CSI and thus maximizing mean user bitrates. Above figure gives a typical example as to how optimal (κ, Δ) is selected for a given scenario. Using the optimal duplet mean rank and resource utilization is also selected. Figure 36 and 37 shows the same. Just to re-emphasize the relation between κ adjustment and rank selection, in figure 36 we can see that higher the κ selection made, higher is the rank. Similar exercise is performed for all the loads and a consolidated mean user bitrate, mean rank and resource utilization is generated. This consolidated result is the optimized system performance. The optimal (κ, Δ) values obtained from mean user bitrate is used to extract the cell edge user bitrates. Referring to figure 35 we see that (κ, Δ) = (0,10) for the example considered. This value of (κ, Δ) is made use in figure 38 to extract the cell edge user bitrate. There is one more important observation to be made that the cell edge user bitrates obtained from the method explained might not be the peak cell edge user bitrates.

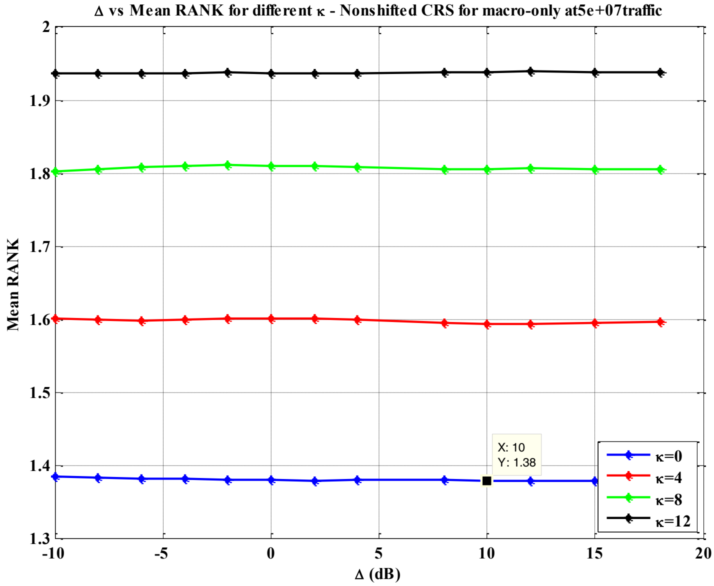


**Figure 36**: Mean Rank as a function of κ and Δ for Macro-only Nonshifted CRS configuration at 50 Mbps/sqkm traffic

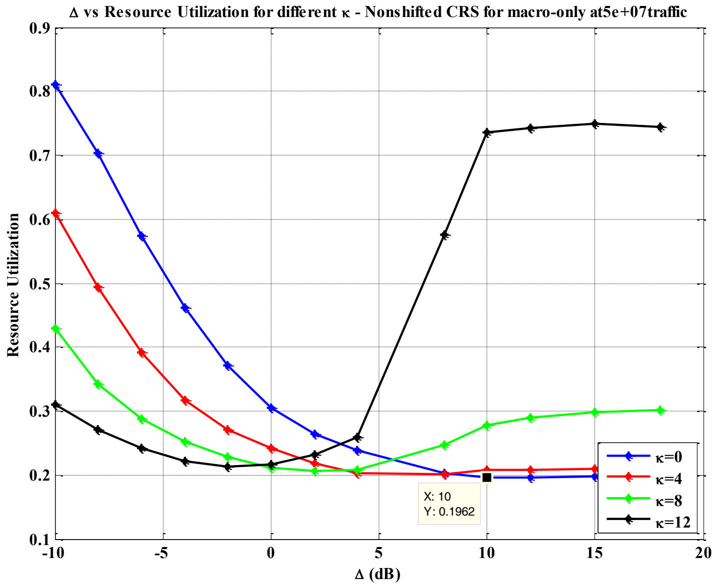


**Figure 37**: Resource Utilization as a function of κ and Δ for Macro-only Nonshifted CRS configuration at 50 Mbps/sqkm traffic

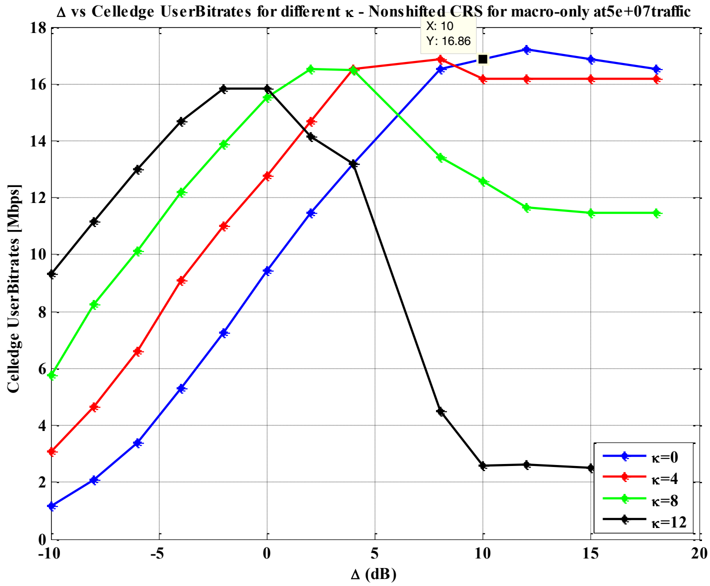


**Figure 38**: 5th percentile user bitrates as the function of κ and Δ for Macro-only Nonshifted CRS configuration at 50 Mbps/sqkm traffic

To give reader an insight into the joint (κ+Δ) adjustment performed for all the 3 scenarios a table is given below.

**Table 6**: (κ+Δ) adjustment for practical macro-only case for all scenarios

| **(κ+Δ) [dB]** | | | | |
|---|---|---|---|---|
| Loads / Scenario | 1 (Mbps/sqkm) | 50 (Mbps/sqkm) | 80 (Mbps/sqkm) | 100 (Mbps/sqkm) |
| 1 | 12 | 12 | 12 | 2 |
| 2 | 0 | 0 | 0 | 0 |
| 3 | 12 | 10 | 8 | 0 |

From the table 6 it is evident that as load increases the SINR bias reduces and at very high loads the (κ+Δ) adjustment is almost zero for all the 3 scenarios. Now we will concentrate on performance comparison of all 3 scenarios after compensation (tuning). Consolidated performance figures obtained from the procedure explained earlier will be used for comparison.

### 5.3.1 Performance comparison between practical Tuned and Nontuned case for Scenario 1

Percentage gain between non-optimized (non-tuned) and optimized (tuned) system performance is essential to understand before performance comparison of tuned scenarios. To give a brief insight into this gain let's refer to mean user bitrate in figure 39. Optimized scenario1 mean user bitrate is compared with non-optimized scenario1 in the figure. It's obvious from the figure that tuned mean user bitrate out performs non-tuned. The percentage gain between the two, at low load is around 90%. The whole purpose of optimization is to push the system performance as close as possible to technology potential which is the upper bound. Such performance gain after tuning is very much applicable to all scenarios and network deployments. Nontuned, (κ, Δ) = (0,0) mean user bitrates for the 3 scenarios is given in appendix 1.3.

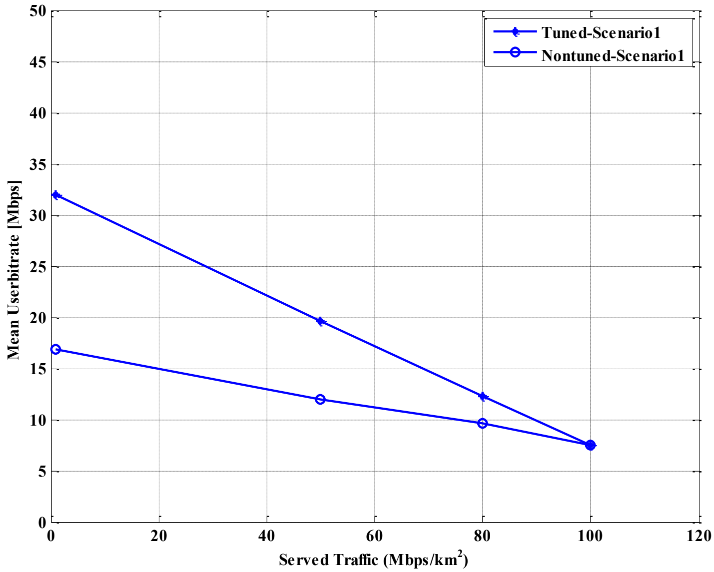


**Figure 39**: Mean user bitrate comparison between Tuned vs Nontuned for Scenario1

### 5.3.2 Performance comparison of tuned Scenario 1, 2 and 3

Average resource utilization shown in figure 40, at low and medium loads for scenario 2 has higher utilization in comparison to scenario 1 and 3 this is because of the CRS-to-DATA interference. As load increases resource utilization increases due to the increase in demand for time-frequency resources. Mean rank selection for all the 3 scenarios after tuning is shown in figure 41. In this case mean rank selection for all 3 scenarios is load dependent. CRS REs in scenario2 experience interference which is load dependent and also there is hardly any κ and Δ adjustments required. These two reasons can be given for the load dependency of the mean rank in scenario2. In scenario1 we know that there is constant CRS-to-CRS collision irrespective of the loads causing CSI estimation error. But different κ and Δ adjustments made for scenario1 during CSI optimization at different loads makes the mean rank selection load dependent. Scenario3 is a hybrid of scenario1 and 2 hence the rank selection is done in between.

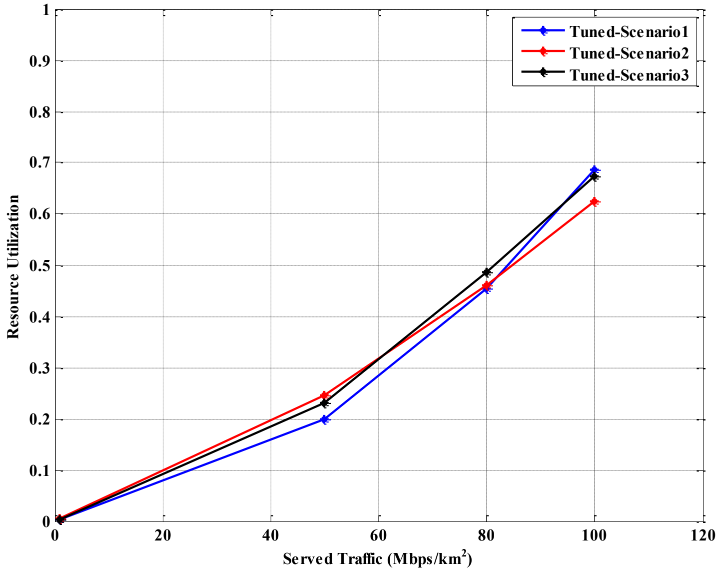


**Figure 40**: Tuned Resource utilization as function of served traffic for practical case in macro-only deployment

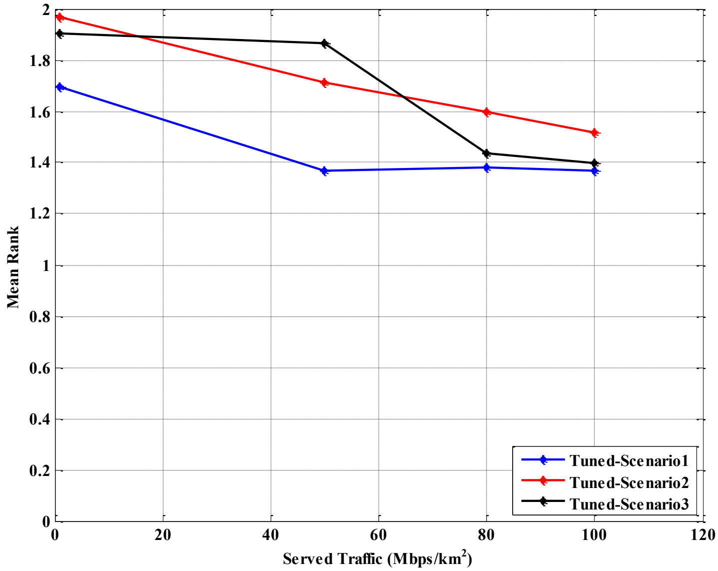


**Figure 41**: Tuned Mean rank as function of served traffic for practical case in macro-only deployment

In scenario 1 at low and medium loads interference free data REs are properly compensated for the CSI estimation error. This results in the mean user bitrate improvement in comparison to scenario 2 and 3. It is also discussed earlier that scenario 2 and 3 experiences CRS-to-DATA interference, which brings down the performance. As load increases all three scenarios experience almost equal inter-cell interference resulting in performance convergence. This explanation is showcased in the optimized tuned mean user bitrates in figure 42.

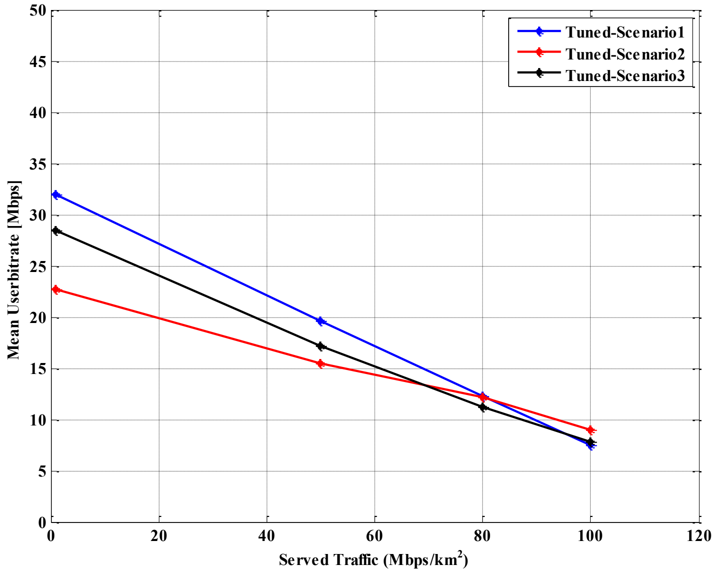


**Figure 42**: Tuned Mean user bitrate as function of served traffic for practical case in macro-only deployment

Cell edge user bitrates performance seen in figure 43 follows similar trend as in mean user bitrates.

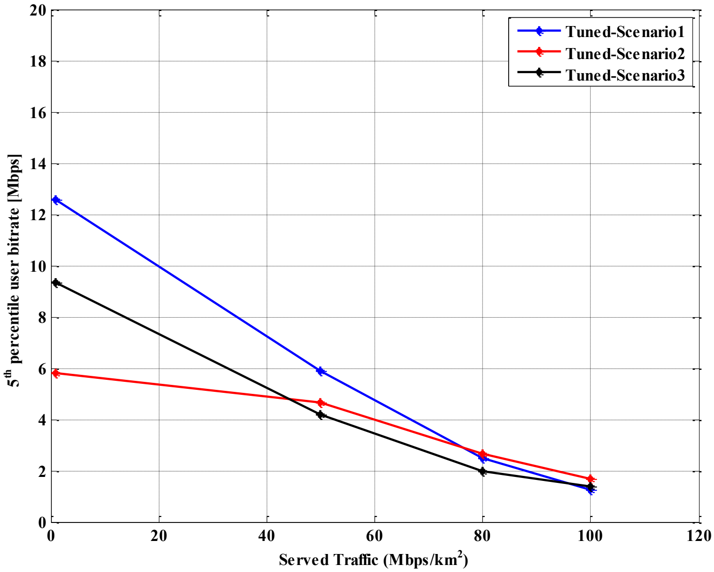


**Figure 43**: Tuned 5$^{th}$ percentile user bitrate as function of served traffic for practical case in macro-only deployment

## 5.4 CSI estimation for practical tuned case for IRC receiver

The assumptions and methodology of this section is exactly the same as section 5.3- non-ideal LA, practical channel and interference estimation- only difference is that the Interference Rejection Combining (IRC) receiver is used, instead of Stream-Interference Rejection Combining (SIRC) receiver as in section 5.3. In this section we will see how IRC performs in comparison to SIRC for different scenarios. As mentioned in earlier chapters, interference is of two types, intra-cell and inter-cell. Mathematically the total interference is written as in equation 19.

$$\hat{Q}_{total} = \hat{Q}_{intracell} + \hat{Q}_{intercell} \ (19)$$

$\hat{Q}_{total}$ is the total interference, $\hat{Q}_{intracell}$ is the intra-cell interference and $\hat{Q}_{intercell}$ is inter-cell interference. For a *2* x *2* antenna configuration $\hat{Q}_{intercell}$ is given as in equation 20.

$$\hat{Q}_{intercell} = \begin{bmatrix} \hat{q}_{11} & \hat{q}_{12} \\ \hat{q}_{21} & \hat{q}_{22} \end{bmatrix} (20)$$

On using SIRC receivers inter-cell interference or cross diagonal elements in $\hat{Q}_{intercell}$ are assumed to be zero, i.e. inter-cell interference is not considered. Equation 21 gives inter-cell interference for SIRC receivers, where the off-diagonal elements are zero.

$$\hat{Q}_{intercell\_sirc} = \begin{bmatrix} \hat{q}_{11} & 0 \\ 0 & \hat{q}_{22} \end{bmatrix} (21)$$

This assumption results in interference estimation error. In case of IRC receivers the inter-cell interference or cross diagonal elements are taken into account and treated. Hence the interference estimation error is minimized in case of IRC receivers rather than totally neglecting it.

$$\hat{Q}_{intercell\_irc} = \begin{bmatrix} \hat{q}_{11} & \hat{q}_{12} \\ \hat{q}_{21} & \hat{q}_{22} \end{bmatrix} (22)$$

With this background about SIRC and IRC we will compare the system performance of both receivers for scenario1 and scenario2 with practical system assumptions. Figure 44 shows the resource utilization comparison between IRC and SIRC for scenario1 and 2. At low and medium loads SIRC and IRC has almost similar resource utilization for both scenario1 and 2. At high loads interference seen in the network is high. IRC has the interference rejection capability compared to SIRC Hence resource utilization for IRC is less compared SIRC at high loads. Reduced interference favors faster packet download and reduced time-frequency resources. Mean rank selection for scenario1 and 2 with SIRC receiver is same as the mean rank selection of scenario1 and 2 discussed in figure 41. For scenario2 with IRC receiver we see a different trend compared to SIRC receiver. We know that in SIRC the inter-cell interference is assumed to be zero, due to this assumption interference estimation error is incurred. But in IRC inter-cell interference is taken into account and treated reducing the interference estimation error. In scenario2 at least 1/3$^{rd}$ of the sectors have same CRS shifts implying that some amount of CRS-to-CRS collision is seen. At low loads for scenario2 in figure 45 we see that SIRC has lower rank selection compared to IRC. This trend is due to the fact that SIRC receiver assumes that there is no inter-cell interference even though there is some interference by the 1/3rd of the sectors in the network. IRC on the other hand considers the inter-cell interference and treats it, helping in slightly higher rank selection compared to SIRC. At high loads SIRC has a better rank selection due to the fact that it doesn't consider inter-cell interference and assumes a pessimistic interference. This pessimism results in higher rank selection for SIRC compared to IRC. But IRC tries to treat the interference and thus a rank is selected which is as optimal as possible. It should be duly noted from table 6 and 7 that there is hardly any tuning required for scenario2 irrespective of the receiver. Scenario1 sees a constant CRS-to-CRS interference irrespective of the load. For scenario1 we can see that IRC has a lower rank selection compared to SIRC. As IRC considers the inter-cell interference and tries to minimize it but SIRC on the other hand completely ignores the interference and goes for a higher rank selection.

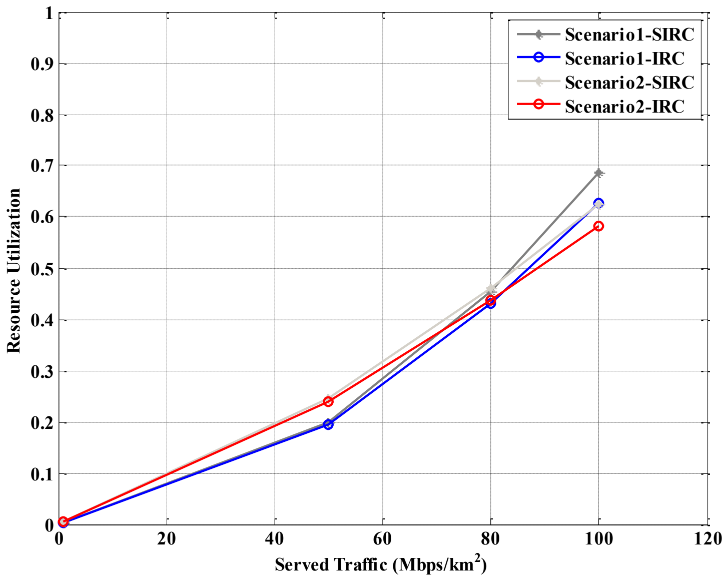


**Figure 44**: IRC vs SIRC tuned Resource utilization for practical case in macro-only deployment

System performance in terms of mean user bitrates shown in figure 46 is very interesting while comparing IRC vs SIRC. In the figure we see that improvement achieved by IRC over SIRC at low loads is very negligible. The performance improvement is seen predominantly at higher loads. At higher loads heavy interference is seen in the network and IRC has the interference rejection capability which gives an upper hand over SIRC at high loads. To give a performance gain comparison of IRC over SIRC a table is formulated. Table 7 gives a quantitative proof of the performance gain of IRC over SIRC. The summation of $\kappa$ and $\Delta$ adjustments made for IRC receiver is also listed in the table. Inside the parenthesis, summation of $\kappa$ and $\Delta$ adjustments made for SIRC receiver is also given. It is evident from the table that ($\kappa$ +$\Delta$) adjustments for both SIRC and IRC receivers are almost similar, this observation hints that CSI optimization is independent of the receiver used. Figure 47 shows the IRC vs SIRC performance comparison for a 5th percentile user bitrate for scenario1 and 2. It is evident that IRC has better performance gain over SIRC for cell edge users. Cell edge users are more prone to stronger inter-cell interference. SIRC receivers neglect the influence of inter-cell interference hence there is an interference estimation error which reduces the system performance. On the other hand IRC treats the inter-cell interference and thus a performance gain is seen over SIRC. Table 8 gives a quantitative percentage performance gain of IRC over SIRC for cell edge user bitrates.

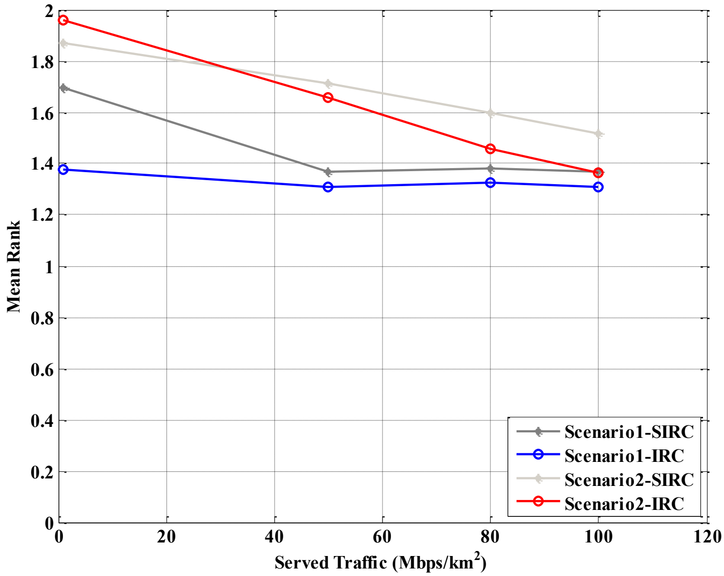


**Figure 45**: IRC vs SIRC tuned Mean rank for practical case in macro-only deployment

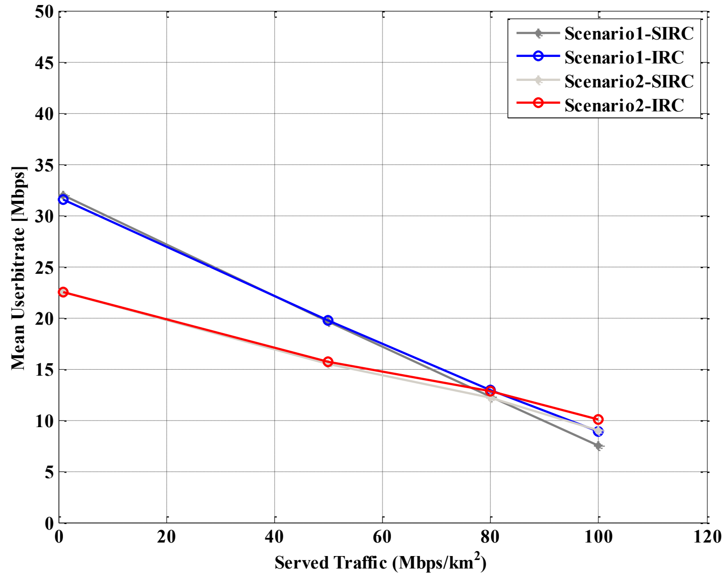


**Figure 46**: IRC vs SIRC tuned mean user bitrate for practical case in macro-only deployment

Mean user bitrates comparison between scenario1 and 2 for IRC receivers without tuning is given in appendix 1.3.

**Table 7**: Mean user bitrate percentage performance gain comparison between IRC and SIRC

| **Percentage Performance gain of IRC over SIRC** | | | | |
|---|---|---|---|---|
| Loads (Mbps/sqkm) | 1 | 50 | 80 | 100 |
| Scenario1 | -1% | 1% | 5% | 18% |
| Scenario2 | 0% | 1% | 5% | 11% |
| **(κ+Δ) [dB]** | | | | |
| Scenario1 | 12 [12] | 10 [12] | 10 [12] | 2 [2] |
| Scenario2 | 0 [0] | 0 [0] | -2 [0] | -2 [0] |

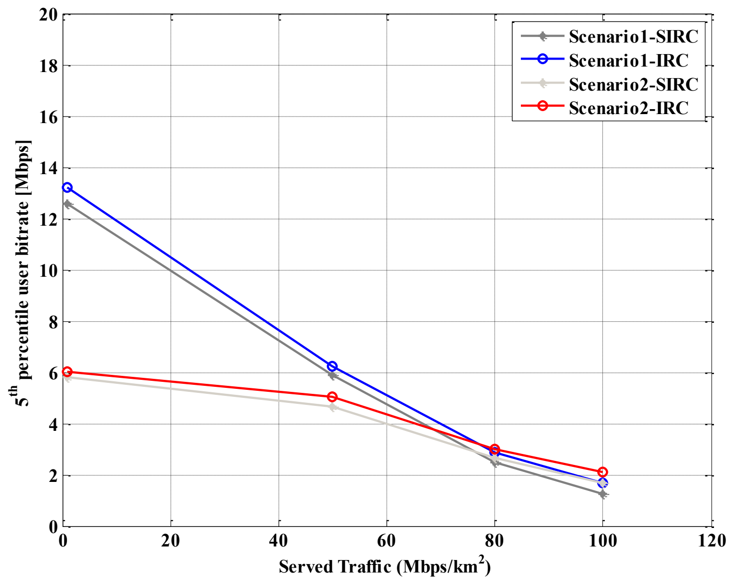


**Figure 47**: IRC vs SIRC tuned 5th percentile user bitrate for practical case in macro-only deployment

**Table 8:** Cell edge user bitrate percentage performance gain comparison between IRC and SIRC

| **Percentage Performance gain of IRC over SIRC** | | | | |
|---|---|---|---|---|
| Loads (Mbps/sqkm) | 1 | 50 | 80 | 100 |
| Scenario1 | 5% | 5% | 16% | 33% |
| Scenario2 | 4% | 8% | 13% | 26% |

# Chapter 6

# Performance Evaluations – Heterogeneous Scenario

A heterogeneous deployment was introduced to improve system performance in over-densified and smaller geographic areas. These geographic areas are termed as Hotspots. Shopping malls, airports, hotels etc. are some examples of hotspots. Macro-only deployment might not be able to cater these hotspots effectively. Hence to serve the traffic in these hotspots efficiently along with macro deployment, a lower power, low cost and low range nodes called picos are deployed. The cell area covered by these picos is termed as pico cells. A typical macro and pico cell co-existence is shown in figure 48.. Each of the picos has its own uptake area. Any UE which comes under influence of this area tries to latch on to that specific pico eNB. This uptake area can be increased such that more UEs get connected to the picos and a decent load balance exists between the macro and picos. Usage of CSO is one of the techniques to increase the pico uptake area. At the UE side a specified CSO is added to the received reference signal power, this addition results in all UEs present in cell range extension area to get connected to the picos rather than macro. In figure 48 below cell range extension is shown for a pico. CSO of 0dB and 6dB is used in our study of heterogeneous deployments. Employing CSO helps in load balancing and thus improvement in system performance. It should be noted that unnecessary increase in CSO results in unnecessary interference which does not favor system performance.

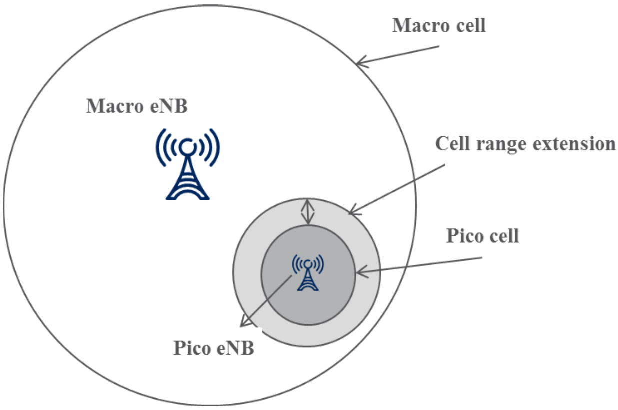


**Figure 48**: Macro and Pico cell co-existence

Pico eNB has its own set of system parameters and has limited co-ordination with the macro eNB in our study. We have selected three combination of pico deployments based on the density of the traffic and number of picos deployed in a hotspot. Sparse heterogeneous deployment- 1 pico is used to cater 1 hotspot. '4 hotspots and 4 picos per macro cell' will be discussed specifically. Dense heterogeneous deployment has 4 picos serving 1 hotspot and ultra-dense heterogeneous deployment consists of 10 picos serving 1 hotspot. Based on the CRS frequency shifts each of the three combinations have three scenarios [14]. Scenario1- same CRS shift is used across all the macros and picos in the entire network. This scenario can also be known as Macro-Nonshifted and Pico-Nonshifted. Scenario2- macro cells inside a site will have different shifts w.r.t each other and picos in each of these macros have the same shift as the macros. This scenario is known as Macro-Shifted and Pico-Nonshifted. Scenario3-macro cells in a site are shifted w.r.t each other and picos present in each of these macros have different shifts apart from the one used by their respective macro. Picos will also be shifted w.r.t each other with a 50-50 split. This scenario is also known as Macro-Shifted and Pico-Shifted. The number of hotspots and picos selected in each of the combinations is specific to this study. In general these numbers vary based on the analysis. Deployment strategies with different scenarios experience different inter-cell interference pattern experiencing different SINR and thus different system performance. To summarize different scenarios in heterogeneous network deployment refer table9 below.

**Table 9**: Different scenarios in heterogeneous deployment

| Macro layer / Pico layer | Shifted CRS | Nonshifted CRS |
|---|---|---|
| Shifted CRS | **Scenario3**-Macro sectors in a site are shifted w.r.t each other. Picos have CRS shift other than the one used by overlaying Macro. Among picos there is a 50-50 split of different shifts used | |
| Nonshifted CRS | **Scenario2**-Macro sectors in a site are shifted w.r.t each other. Picos inside the Macro sector have the same shift as in overlaying Macro | **Scenario1**-Picos and the overlaying Macro has the same CRS shift throughout the network |

## 6.1 CSI estimation using data REs with Ideal LA (Technology Potential) - Sparse

The assumptions and methodology of this section is exactly the same as 5.1 only difference is that sparse heterogeneous network deployment is considered rather than a macro-only case as in 5.1. The trend and characteristics of the performance figures is similar to that of section 5.1. But there is a new parameter called Cell selection Offset (CSO) is used. Different performance measures are showcased for the 3 scenarios under different CSO considerations. Figure 49 gives the resource utilization for sparse heterogeneous network deployment. This figure can be analyzed in two different ways, one w.r.t different scenarios, second w.r.t different CSOs. For a given CSO if we see the behavior of different scenarios, scenario1 has lower resource utilization in comparison to the other two scenarios. Scenario 1 is analogous to scenario 1 in macro-only case. Similarly scenario3 is analogous to scenario2 in macro-only case. This behavior can be seen in 1$^{st}$ and 2$^{nd}$ group of curves highlighted in the figure. 1$^{st}$ group of curves corresponds to CSO=0 for all 3 scenarios. 2$^{nd}$ group corresponds to CSO=6 for all 3 scenarios. Now the second way to look at these curves is across different CSOs. When 1$^{st}$ and 2$^{nd}$ group of curves are compared we can see that at high loads CSO=6 has reduced resource utilization, this is due to the fact that, by employing CSO there is a cell range extension. The UEs present in the cell range extension area get latched on to the picos rather than the macro.

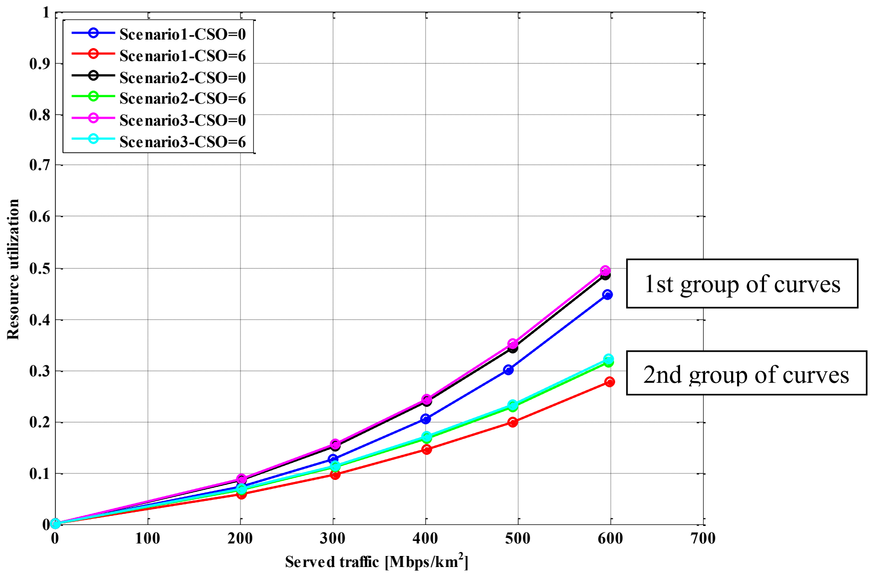


**Figure 49**: Resource utilization as a function of Served traffic for technology potential in sparse heterogeneous case

This process reduces the resource utilization for macro but pico utilization also increases. The overall effect is seen as the drop in resource utilization at high loads. The resource utilization figure shown contains utilization of both pico and macro hence the reduction in macro utilization is seen in the figure as a drop at high loads.

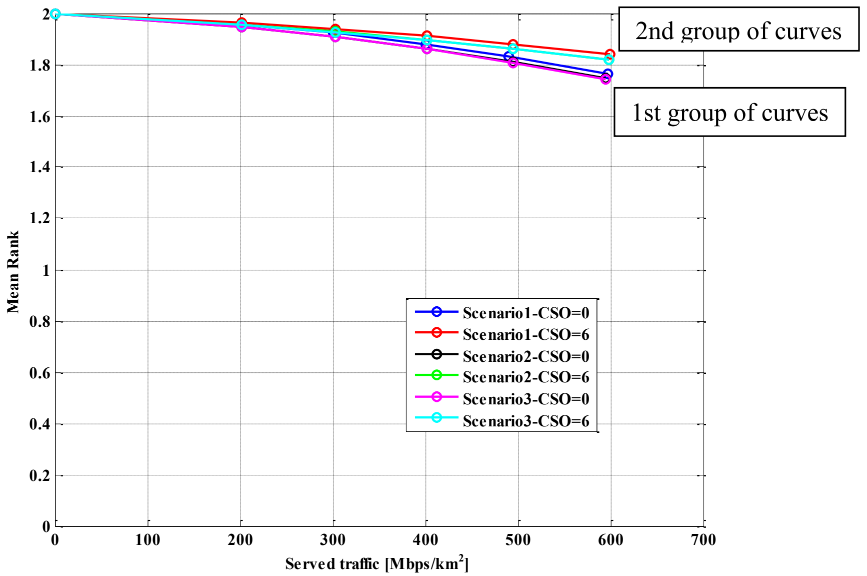


**Figure 50**: Mean rank as a function of Served traffic for technology potential in sparse heterogeneous case

From the mean rank selection shown in figure 50, we can see that there is a higher rank selection for CSO=6 when compared to CSO=0. As explained for the resource utilization, employing CSO reduces the macro utilization, this means that interference generated by macro UEs in the network is reduced and thus results in higher rank selection for CSO=6, compared to CSO=0.

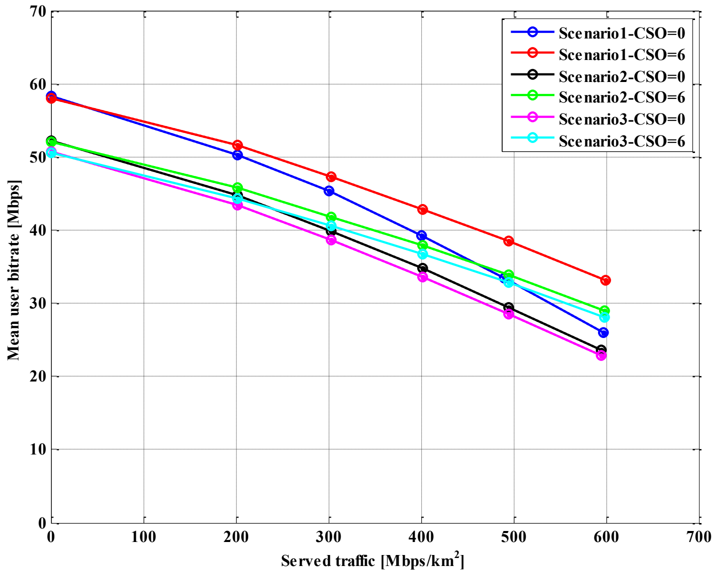


**Figure 51**: Mean user bitrate as a function of Served traffic for technology potential in sparse heterogeneous case

The general trend seen in mean user bitrates performance shown in figure 51 is that scenario 1 has better performance in comparison to other two scenarios. The interesting trend to observe here is that at high loads irrespective of the scenarios CSO=6 gives a better mean user bitrate performance in comparison to CSO=0. This gain in user bitrate for CSO=6 is because of the reduced interference by the overlaying macro users at high loads. Cell edge user bitrates in figure 52 display results which are somewhat similar to the overall mean user bitrates. It is seen that scenario1 has higher cell edge user bitrates compared to scenario2 and 3 which is also seen for mean user bitrates. The impact of CSO is evident at high loads. At high loads for CSO=6 has better system performance compared to CSO=0 irrespective of the scenarios. But at low loads we see that CSO=0 has slight upper hand compared to CSO=6. This trend at low loads is seen because, when CSO=6 is used there is cell range extension of the Pico and UEs connected to macro layer get latched on to picos even though the signal strength from macro is substantially good. Data REs for UEs present in the cell range extension sees interference from the macro layer. This interference seen on data REs for UEs when CSO=6 used transcends as reduction in cell edge user bitrates compared to CSO=0.

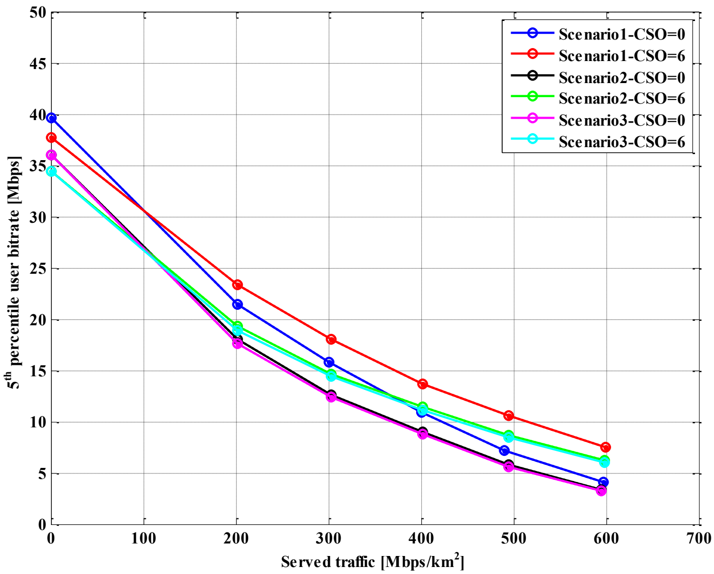


**Figure 52**: $5^{th}$ percentile user bitrate as a function of served traffic for technology potential in sparse heterogeneous case

## 6.2 CSI estimation using CRS REs with Ideal LA - Dense

CRS REs used for CSI estimation along with Ideal LA in this case. Dense heterogeneous deployment is studied with different CSOs of 0dB and 6dB. As CRS REs are used for CSI estimation, there is CSI estimation error. Ideal LA makes sure that actual SINR experienced by the data REs are used for CQI estimation. Figure 53 below shows the resource utilization. Here resource utilization for different scenarios with CSO=0 has higher utilization compared to CSO=6. This difference is due to reduction in macro utilization when CSO=6 is employed in the network. Mean rank selection in figure 54 can be analyzed with two different perspectives, one w.r.t different scenarios and secondly w.r.t different CSOs. For a fixed CSO value if we traverse across all the three scenarios we see that for scenario1 mean rank selection is load independent, as CRS-to-CRS interference is seen irrespective of the loads. For scenarios 2 and 3 the mean rank selection is load dependent, as interference experienced by CRS REs increases as load increases. Analyzing based on CSOs fixing the scenario, we see that for CSO=6 has a slightly lower rank selection in comparison to CSO=0, irrespective of the scenarios. Mean user bitrates for scenario3 is better in comparison to other two scenarios, this is due to the fact that CSI estimation is performed based on CRS REs and there is no compensation made for CSI estimation error. But here once again it can be seen that for CSO=6 gives a higher system performance at higher traffic conditions compared to CSO=0 courtsey of reduced macro utilization. This reduction is macro utilization results in reduced interference seen from UEs connected to macro eNBs in the whole network. The observations explained for mean user bitrates can be seen in figure 55. Cell edge user bitrates seen in figure 56 shows that once again the effect of CSO=6 used. At high load condition the CSO=6 gives a higher cell edge bitrate performance compared to CSO=0. Results for Ultra dense deployments for 'CSI estimation using CRS REs with Ideal LA' are given in appendix 2.1. The trends and behavior of different scenarios and CSOs is similar to that of dense.

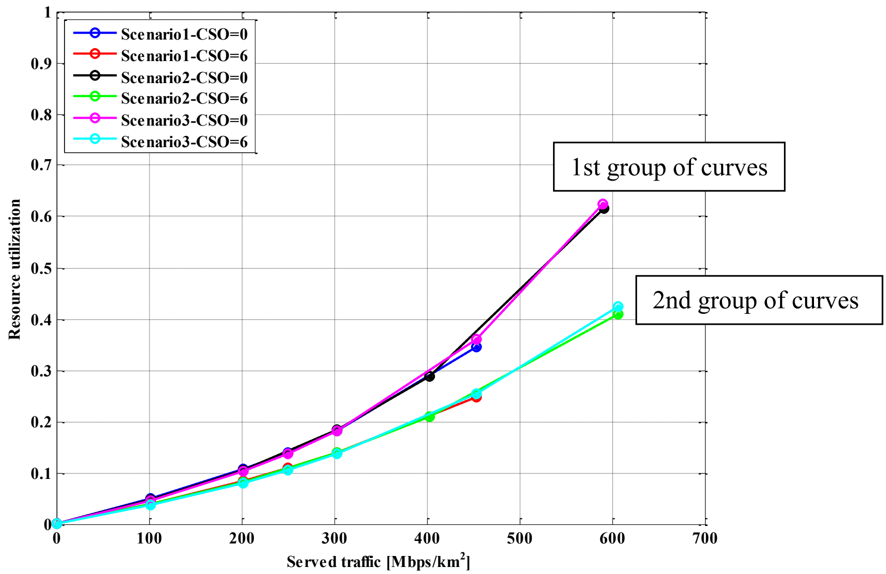


**Figure 53**: Resource utilization as a function of Served traffic for CRS based CSI estimation with Ideal LA in dense heterogeneous case

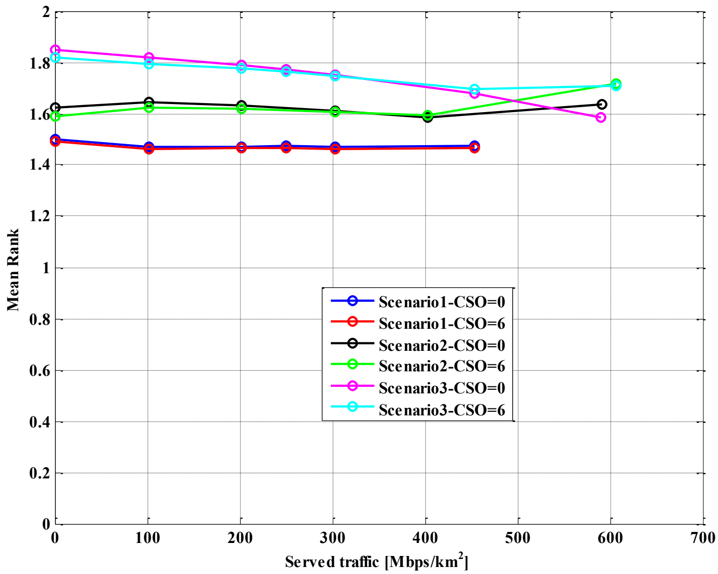


**Figure 54**: Mean rank as a function of served traffic for CRS based CSI estimation with Ideal LA in dense heterogeneous case

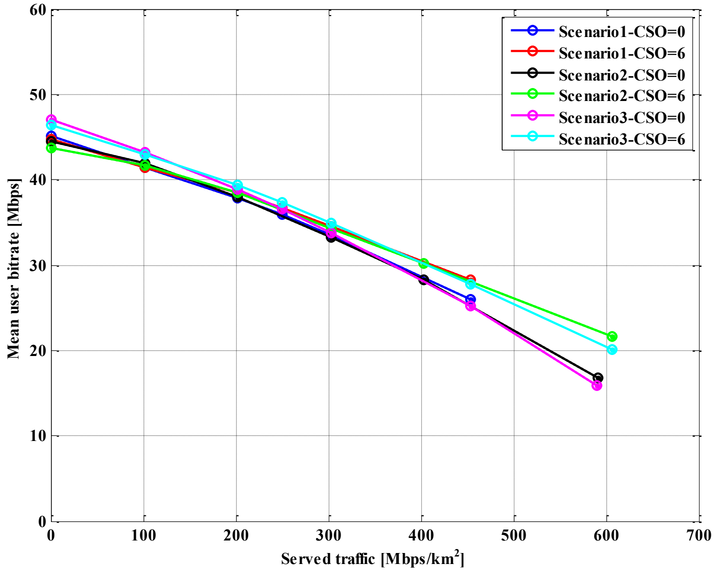


**Figure 55**: Mean user bitrate as a function of Served traffic for CRS based CSI estimation with Ideal LA in dense heterogeneous case

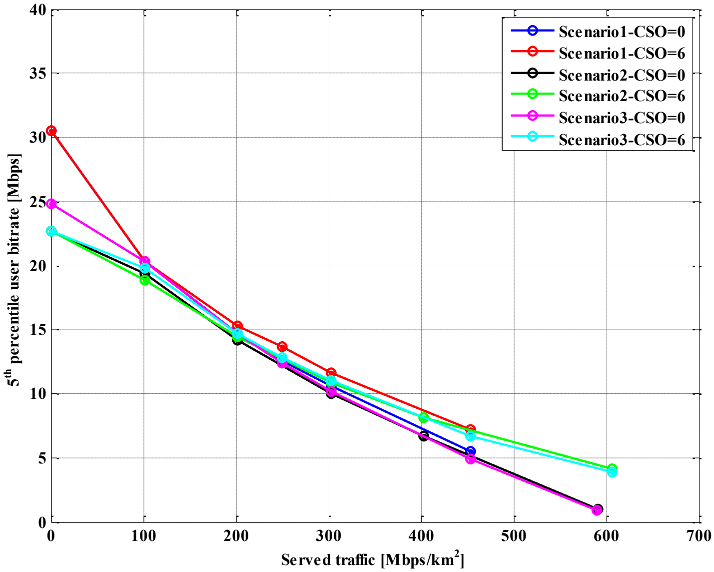


**Figure 56**: 5$^{th}$ percentile user bitrate as a function of Served traffic for CRS based CSI estimation with Ideal LA in dense heterogeneous case

## 6.3 CSI estimation for practical tuned case - Sparse

Non-ideal LA is assumed. UE receiver will not have the knowledge of the true channel and interference estimates as compared to technology potential studied in earlier sections. For heterogeneous network deployment a new parameter is also studied that is the CSO influence. Practical tuned case tires to reduce the CSI estimation error as much as possible and try to achieve system performance seen in technology potential case.

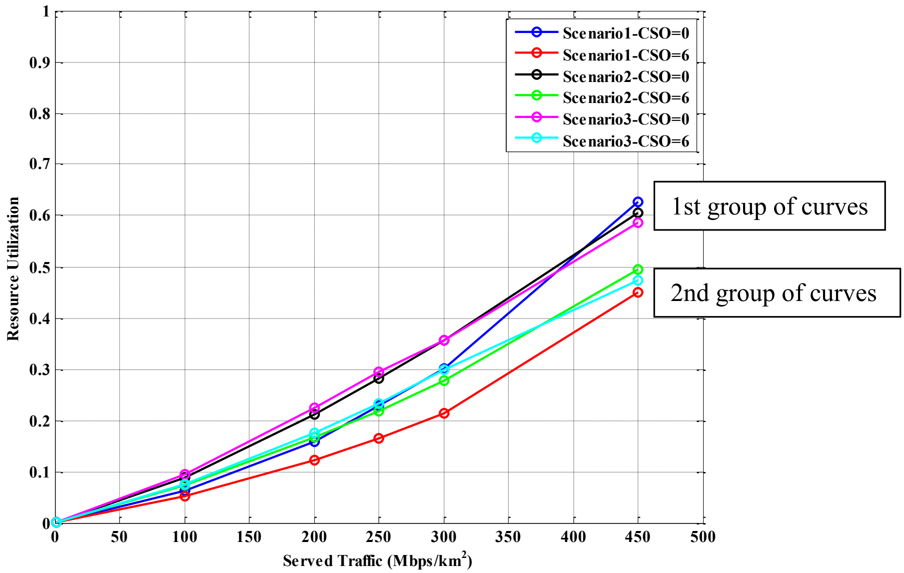


**Figure 57**: Tuned Resource utilization as function of served traffic for practical case in sparse heterogeneous case

Figure 57 shows the resource utilization for a practical tuned case. From the figure we can say that CSO=0 has higher resource utilization compared to CSO=6. The reduction in overall resource utilization of the network for CSO=6 attributes to the reduction in macro utilization in the network. Mean rank selection for different scenarios for dense deployment is shown in figure 58. It is seen that all the scenarios with different CSOs are load dependent. From section 6.1, 'CSI estimation using data REs under Ideal LA' we had seen that all scenarios had load dependent rank selection as data REs were used for CSI estimation. In section 6.2, 'CSI estimation using CRS REs under Ideal LA' we saw scenario1 was load independent due to constant CRS-to-CRS collision irrespective of loads. For scenario2 and 3 it was seen that mean rank selection was load dependent as CRS REs used for CSI estimation experience higher interference as load increases. Now from figure 58 we can see that scenario2 and 3 are load dependent and also scenario1. This dependency is seen due to different $\kappa$ and $\Delta$ adjustments used for different loads which tries to reduce the CSI estimation error. Mean user bitrates for practical scenario for different scenarios and CSOs has the most interesting result. It is seen from figure 59 that for scenario2 and 3 doesn't show the impact of CSO usage, both CSO=0 and CS0=6 for these two scenarios has similar mean user bitrates. One possible explanation is that, $\kappa$ and $\Delta$ adjustments made for the practical case is network wide. If UE specific adjustments are made then the CSO benefit might be evident. Table 10 gives a concise list of all ($\kappa+\Delta$) adjustments made for all three scenarios with different CSOs.

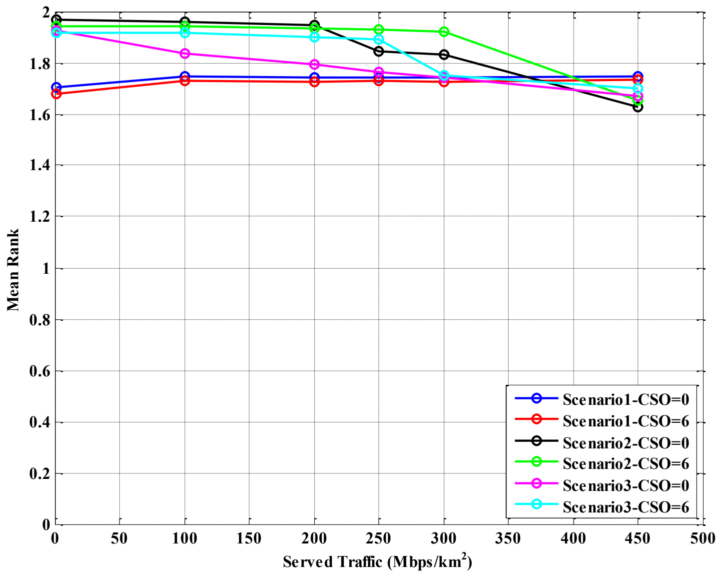


**Figure 58**: Tuned mean rank as function of served traffic for practical case in sparse heterogeneous case

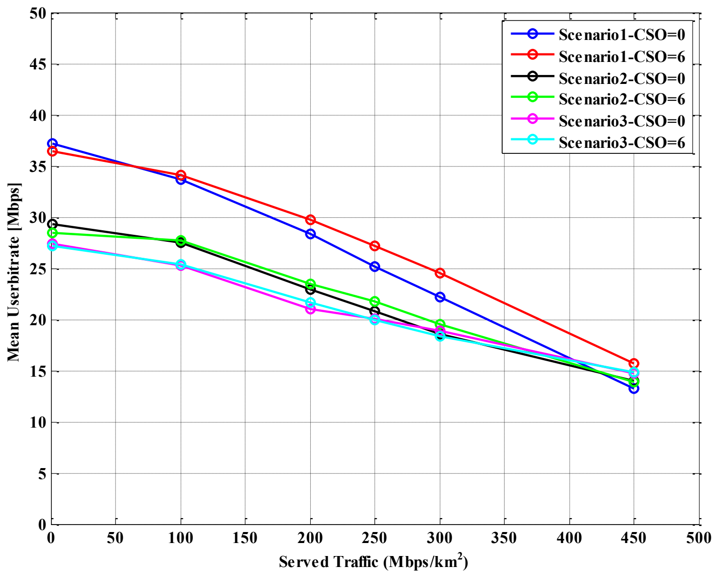


**Figure 59**: Tuned mean user bitrate as function of served traffic for practical case in sparse heterogeneous case

**Table 10**: Mean user bitrate κ and Δ adjustments for sparse deployment

| (κ+Δ) [dB] for CSO=0 | | | | | | |
|---|---|---|---|---|---|---|
| Loads (Mbps/sqkm) | 1 | 100 | 200 | 250 | 300 | 450 |
| Scenario1 | 14 | 12 | 12 | 12 | 12 | 2 |
| Scenario2 | 12 | 10 | 10 | 8 | 8 | 0 |
| Scenario3 | 14 | 10 | 8 | 0 | 0 | 0 |
| **(κ+Δ) [dB] for CSO=6** | | | | | | |
| Scenario1 | 14 | 14 | 12 | 12 | 12 | 8 |
| Scenario2 | 12 | 12 | 10 | 10 | 10 | 0 |
| Scenario3 | 12 | 12 | 8 | 8 | 0 | 0 |

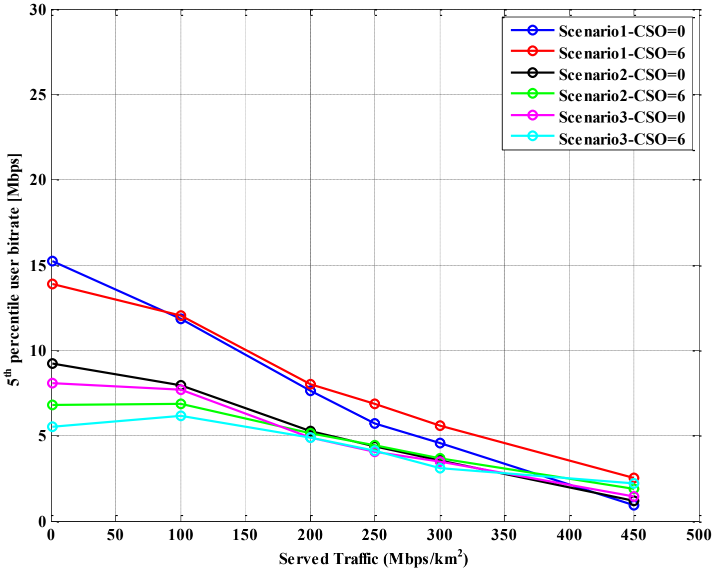


**Figure 60**: Tuned 5th percentile user bitrate as function of served traffic for practical case in sparse heterogeneous case

Tuned cell edge user bitrates are showcased in figure 60 and it can be seen that at low loads CSO=0 has better performance compared to CSO=6. At high loads CSO=6 has upper hand compared to CSO=0. To understand this behavior the reader is requested to refer mean rank explanation in section 6.1.
Results for the Dense and Ultra dense deployments for 'CSI estimation for practical case' are given in appendix 2.2. The trends and behavior of different scenarios and CSOs is similar to that of sparse.

## 6.4 Performance comparison of scenario1 and scenario3, across all three heterogeneous deployments for practical tuned case

In this section we compare the system performance for all the deployments for scenario1 and scenario3. Figure 61 shows the average resource utilization. From the figure it is evident that dense deployment has higher resource utilization in comparison to sparse and ultra-dense. When the figure is analyzed w.r.t scenario it is seen that scenario3 has higher resource utilization in comparison to scenario1 irrespective of the deployments.

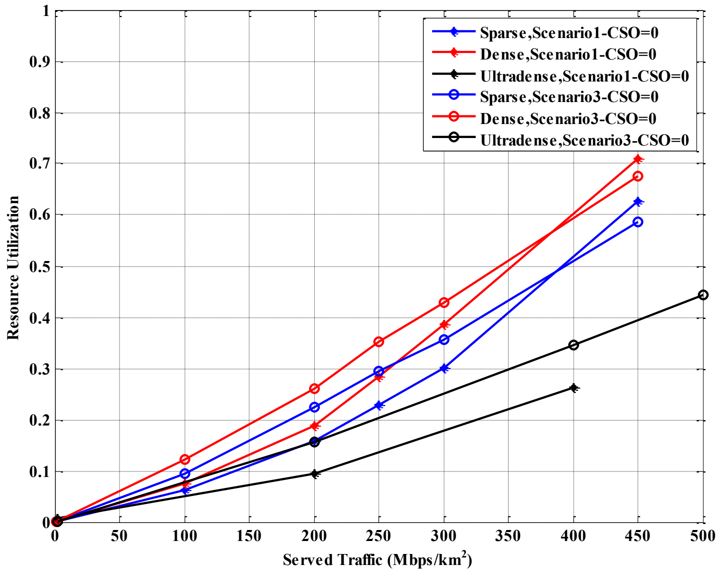


**Figure 61**: Tuned Resource utilization as function of served traffic for practical case for all heterogeneous cases

In figure 62 mean rank selection for scenario3 is higher in comparison to scenario1 irrespective of the deployments this trend is evident from the mean rank selection figure shown below. Scenario3 has higher rank selection as CRS REs escapes interference at low and medium loads. Scenario1 sees a constant CRS-to-CRS collision irrespective of the loads hence experiencing a constant rank selection around the mean. It can be seen in scenario3 that as load increases the rank selection starts to drop due to increased interference experienced by CRS REs.

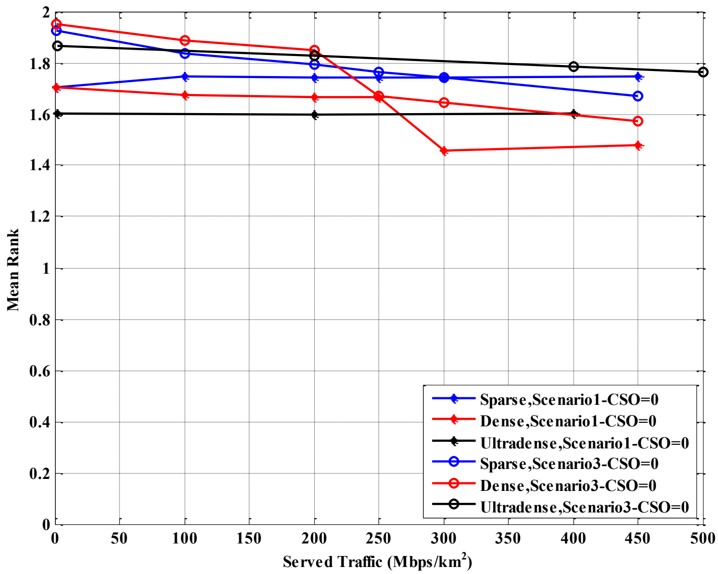


**Figure 62**: Tuned mean rank as function of served traffic for practical case for all heterogeneous cases

In figure 63 mean user bitrate for scenario1 is higher compared to scenario3 as shown in the below figure, irrespective of the deployments. On comparing the mean user bitrates across different deployments for a fixed scenario we see that ultra-dense has lower mean user bitrates compared to dense, dense deployment has lower bitrates compared to sparse at low and medium loads. This trend is due to the high interference seen in ultra-dense, then the interference seen in dense is less in comparison to ultra-dense but higher compared to sparse. Once again this interference trend is due to the number of picos catering the hotspots, ultra-dense has ten picos for one hotspot, dense has four picos for one hotspot and sparse has one pico for one hotspot. At higher loads it is seen that ultra-dense has an upper hand over dense, dense performs better than sparse. This trend at high loads is seen because as the traffic increases ultra-dense can cater more users in comparison to dense and sparse due to the number of pico eNBs present. Trend seen in figure 64 for cell edge user bitrates is similar to that of the mean user bitrates Scenario1 irrespective of the heterogeneous network deployment studied, has better performance compared to scenario3.

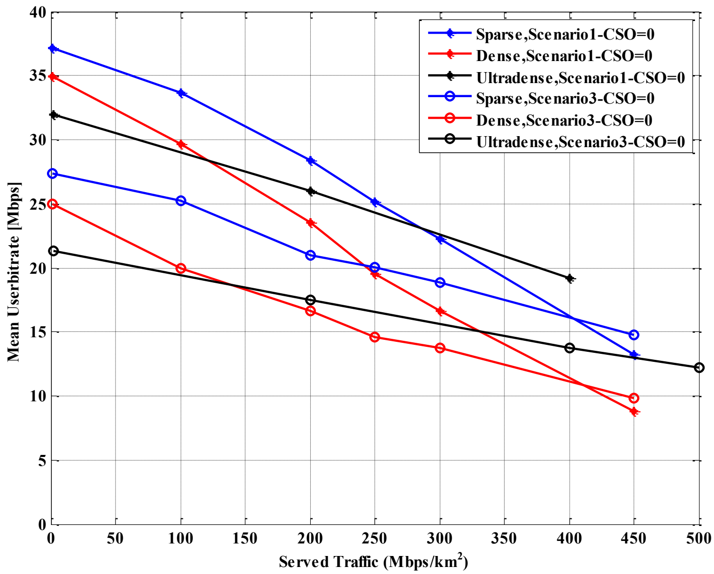


**Figure 63**: Tuned mean user bitrate as function of served traffic for practical case for all heterogeneous cases

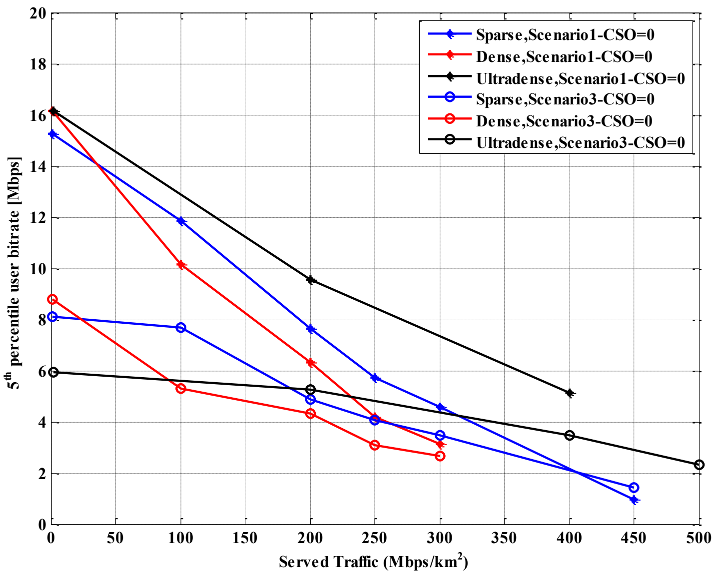


**Figure 64**: Tuned $5^{th}$ percentile user bitrate as function of served traffic for practical case for all heterogeneous cases

# Chapter 7

## Conclusion and Future work

### 7.1 Conclusion

Addressing the problem of system performance maximization in terms of mean user bitrates for different CRS frequency planning strategies, we have covered two network deployments and three CRS frequency planning strategies. There were some very interesting findings in the course of this thesis. To begin with homogeneous network deployment, it was observed that *Nonshifted CRS* configuration had better system performance compared to other CRS frequency planning strategies in technology potential. This result conveys that, with no CSI estimation error incurred in the network *Nonshifted CRS* configuration boosts system performance. In practical case with no compensation for CSI estimation error it was seen that *Shifted CRS* configuration performs better compared to other frequency planning strategies. Optimizing the CSI selection, by reducing CSI estimation error it was seen that *Nonshifted CRS* configuration maximized the system performance compared to other CRS frequency planning strategies. A practical case with CSI estimation error compensation is analogous to technology potential. All the above mentioned observations were also made in case of large file size. As mentioned in the problem statement different UE receiver architectures like SIRC and IRC were analyzed. It was noted that for practical tuned and nontuned case IRC had no improvement at low loads compared to SIRC but there was considerable improvement seen at high load when compared to SIRC. This improvement is due to its interference rejection capabilities. When seen from CRS frequency planning perspective it was seen that *Nonshifted CRS* planning performed better in comparison to other CRS configurations after CSI optimization.

Heterogeneous deployment study for the same system maximization problem showed some interesting and promising results. Technology potential for sparse deployment showed once again that with no CSI estimation error, *Nonshifted CRS* scenario performed better compared to other scenarios. CSI estimation performed with CRS REs with Ideal LA for dense and ultra-dense deployments, brought CSI estimation error into picture. For both dense and ultra-dense in this case it was seen that *Shifted CRS* configuration had upper hand compared to other scenarios. Technology potential for sparse deployment, CSI estimation using CRS REs with Ideal LA for dense and ultra-dense showed that usage of CSO increases the system performance at high load conditions irrespective of the scenarios. All the three heterogeneous deployments in a practical case after performing CSI optimization showed that *Nonshifted CRS* frequency planning maximized the system performance in comparison to other planning strategies. But the improvement expected after using CSO was not prominent for all the three heterogeneous deployment studied in practical case.

The recommendations or conclusions that can be derived from the observations and findings are that CSI estimation error poses severe problem for system performance, compared to contaminated channel estimates. Nonshifted CRS configuration sees highest CSI estimation error compared to other CRS frequency planning strategies. On compensating for CSI estimation error it was seen that *Nonshifted CRS* configuration gave the highest system performance improvement. We started the thesis with a problem statement, to find the CRS frequency planning best suited to improve the system performance under CSI optimization. After all the evaluations and analysis performed we can strongly conclude that *Nonshifted*

*CRS* configuration gives the best system performance in terms of mean user bitrates for LTE Rel-8 networks.

## 7.2 Future work

The proposed solution, analysis, findings and conclusion drawn, lays a solid foundation for promising work in future. The proposed solution in this thesis is brute force in nature so a more dynamic algorithm can be materialized in future based on the current study. After designing a dynamic algorithm the question still exists that how this solution can be employed in real time networks. The CSI optimization performed using ($\kappa$, $\Delta$) adjustment in this thesis is network specific, it was understood that if a UE specific ($\kappa$, $\Delta$) adjustment is performed, system performance could be further maximized. System performance maximization in terms of mean user bitrates was addressed in this thesis exclusively. This maximization problem can be even extended to cell edge user bitrate. The three heterogeneous deployments studied had specific combinations of picos and hotspots. New combinations can be formulated and studied for new findings. CSOs of 0dB and 6dB was studied, other combinations of CSOs can also be looked at in future. Apart from the scenarios considered in homogeneous and heterogeneous deployments, other scenarios can also be visualized and studied. Implementation of advance receiver algorithms like IC-CRS and analyzing the system performance maximization problem for different CRS planning can result in interesting results and eye openers. CRS introduced in LTE Rel-8 is carried on to further releases of LTE where new signals are introduced, so the dynamics of interference is even higher. This study can be a good reference to understand those dynamics.

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# List of Figures

# List of Tables

# Appendix 1.1

This appendix concentrates on performance figures of technology potential for higher file size. On using higher file size the UEs stay longer in the network to download the file. This in turn creates more interference in the network. These results stress that in spite of this new file size usage, nonshifted CRS performs better in comparison the shifted CRS configuration. Figure 65 to 68 shows average resource utilization, mean rank, mean user bitrates and cell edge user bitrates respectively for the same case mentioned.

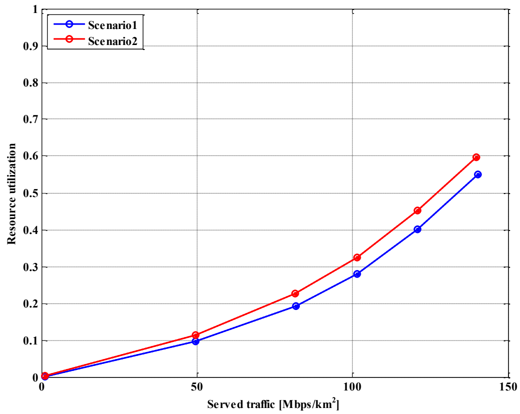


**Figure 65**: Resource utilization as a function of Served traffic for technology potential in macro-only case, higher file size

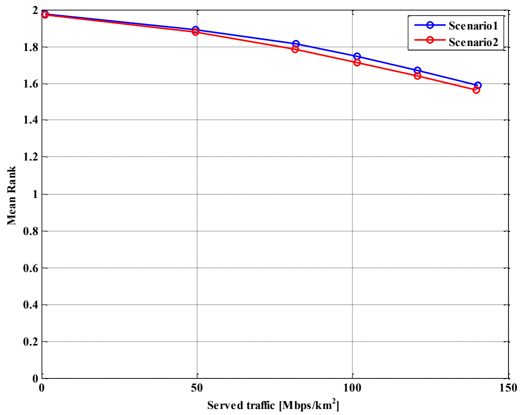


**Figure 66**: Mean rank as a function of Served traffic for technology potential in macro-only case, higher file size

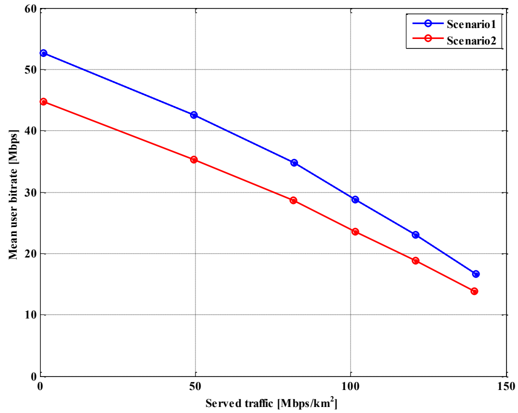


**Figure 67:** : Mean user bitrate as a function of Served traffic for technology potential in macro-only case, higher file size

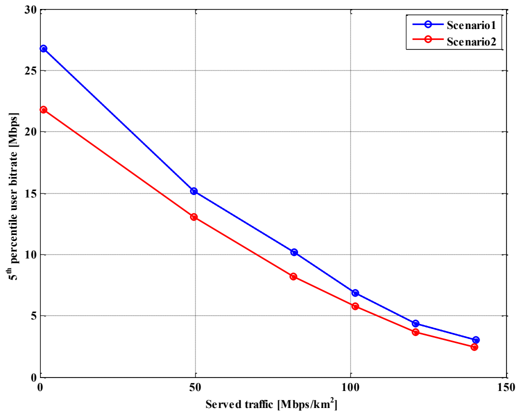


**Figure 68**: 5th percentile as a function of Served traffic for technology potential in macro-only case, higher file size

# Appendix 1.2

CSI estimation using CRS REs with Ideal LA for higher file size shows that shifted CRS has better performance in comparison to nonshifted CRS. This trend is similar to the lower file size results seen earlier for CSI estimation using CRS REs with Ideal LA case. Figures 69 to 72 showcase, average resource utilization, mean rank, mean user bitrates and cell edge user bitrates respectively for the same case.

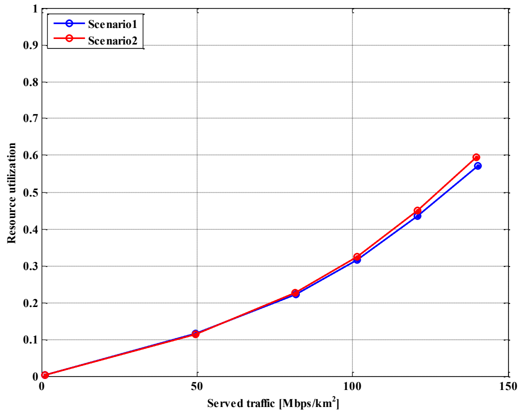


**Figure 69:** Resource utilization as a function of Served traffic for CRS based CSI with Ideal LA in macro-only case, higher file size

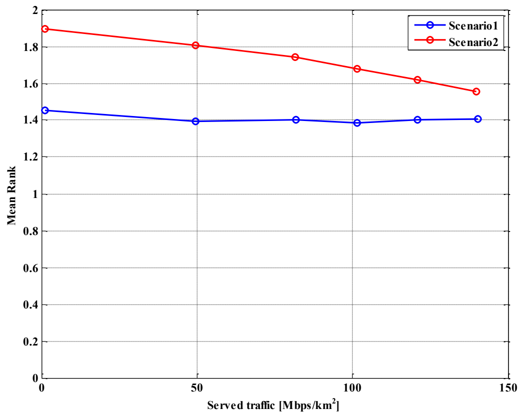


**Figure 70:** Mean Rank as a function of Served traffic for CRS based CSI with Ideal LA in macro-only case, higher file size

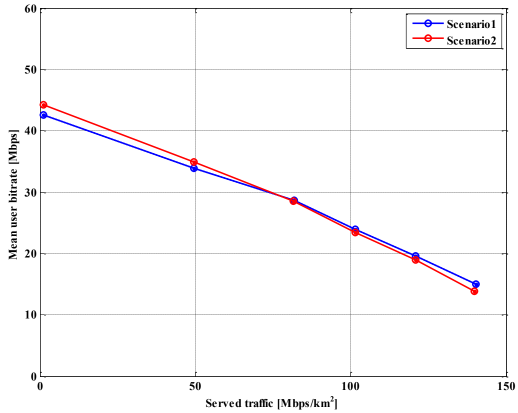


**Figure 71:** Mean user bitrate as a function of Served traffic for CRS based CSI with Ideal LA in macro-only case, higher file size

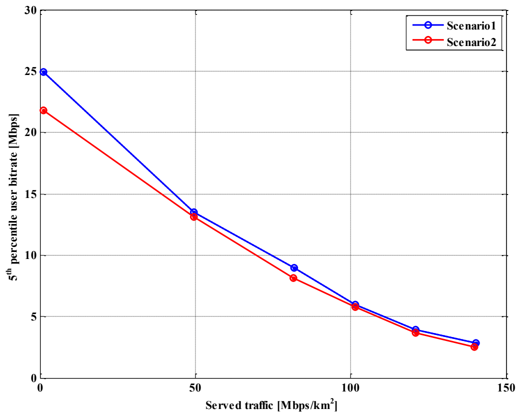


**Figure 72:** 5$^{th}$ percentile as a function of Served traffic for CRS based CSI with Ideal LA in macro-only case, higher file size

# Appendix 1.3

Result shown in figure 73 is of mean user bitrate for practical nontuned case. It is seen that shifted CRS has an upper hand compared to other scenarios. This trend can be attributed to the fact that CRS REs in scenario2 experience minimal interference at low and medium loads.

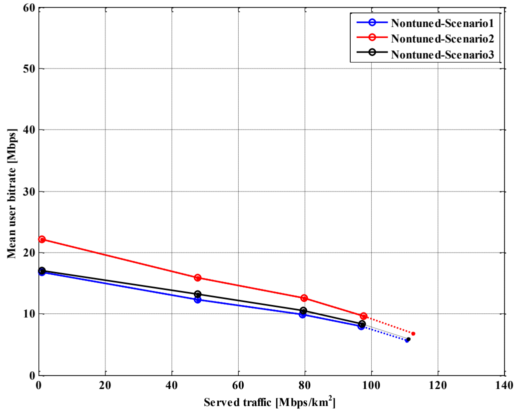


**Figure 73**: Nontuned mean user bitrate as function of served traffic for practical case in macro-only deployment

Figure 74 shows nontuned mean user bitrates comparison between scenario 1 and 2 for IRC receivers. It can be seen that usage of IRC gives an upper hand over SIRC for both scenarios.

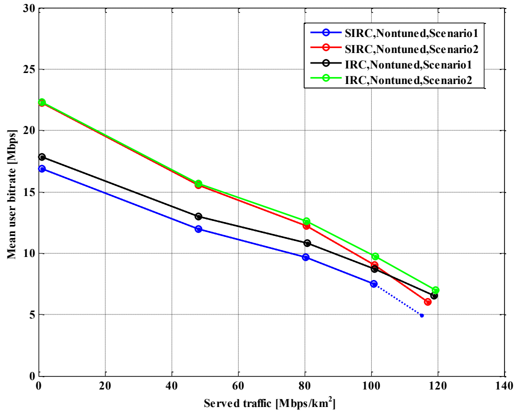


**Figure 74**: IRC vs SIRC nontuned mean user bitrate for practical case in macro-only deployment

# Appendix 2.1

The performance figures shown in this appendix concentrates on CSI estimation based on CRS REs with Ideal LA for ultra-dense deployment. The trend seen here is similar to the dense deployments where CRS REs are used for CSI estimation with Ideal LA. Figures 75 to 78 showcase, average resource utilization, mean rank, mean user bitrates and cell edge user bitrates respectively.

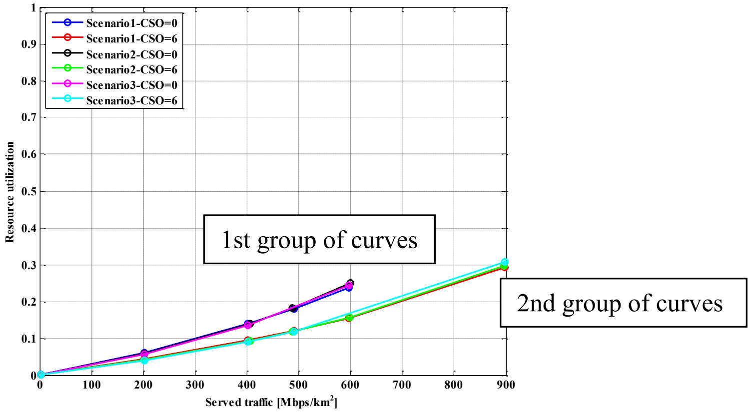


**Figure 75**: Resource utilization as a function of Served traffic for CRS based CSI estimation with Ideal LA in ultra-dense heterogeneous case

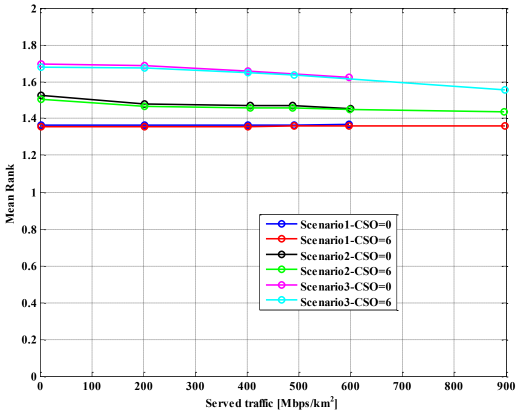


**Figure 76**: Mean rank as a function of Served traffic for CRS based CSI estimation with Ideal LA in ultra-dense heterogeneous case

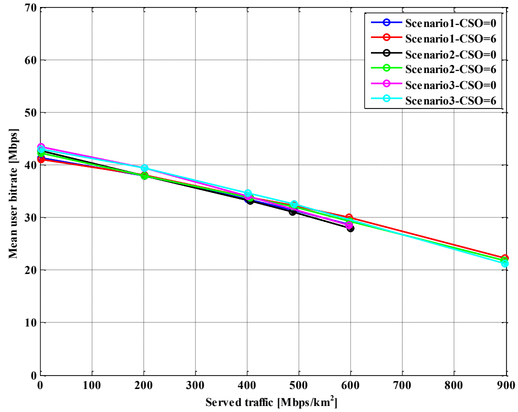


**Figure 77**: Mean user bitrate as a function of Served traffic for CRS based CSI estimation with Ideal LA in ultra-dense heterogeneous case

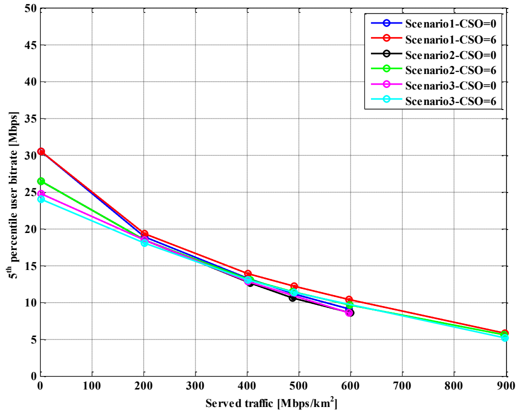


**Figure 78**: 5th percentile as a function of Served traffic for CRS based CSI estimation with Ideal LA in ultra-dense heterogeneous case

# Appendix 2.2

Results related to CSI estimation for tuned practical case for dense deployment is given below. The trends seen in this case is comparable to tuned practical sparse deployment. Figures 79 to 82 are as follows average resource utilization, mean rank, mean user bitrates and cell edge user bitrates.

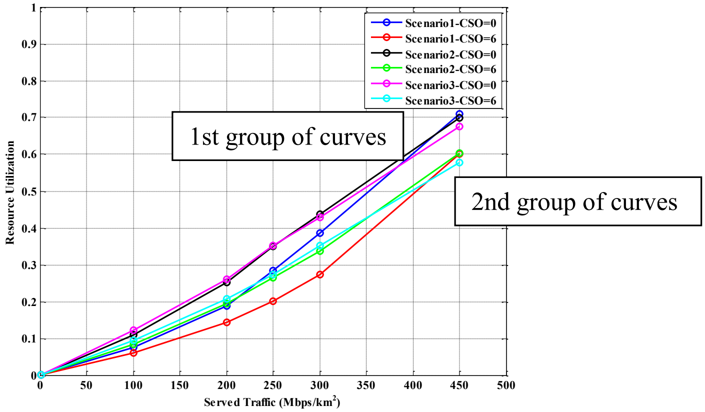


**Figure 79**: Tuned Resource utilization as function of served traffic for practical case in dense heterogeneous case

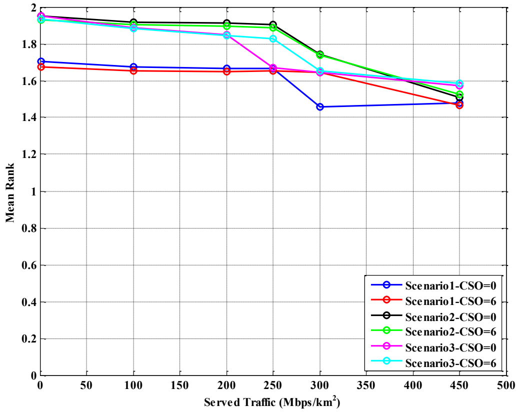


**Figure 80**: Tuned mean rank as function of served traffic for practical case in dense heterogeneous case

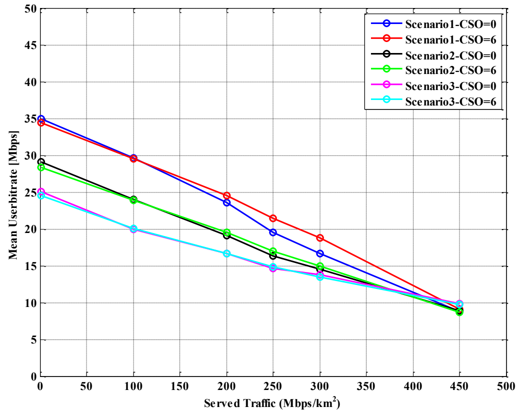


**Figure 81**: Tuned mean user bitrate as function of served traffic for practical case in dense heterogeneous case

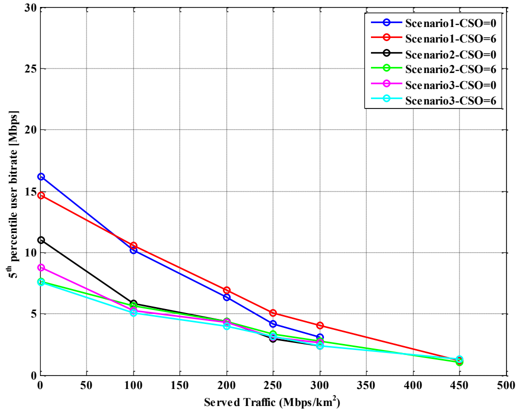


**Figure 82**: Tuned 5$^{th}$ percentile user bitrate as function of served traffic for practical case in dense heterogeneous case

# Appendix 3.1

The simulator used in this thesis is a MATLAB based in-house multi-cell radio network simulator. OFDM transmission is modeled and it supports multi-antenna transceivers. As the simulator supports OFDM and multi-antenna transceivers it can be used in evaluations of radio access systems such as 3GPP LTE and WiMax (802.16). Simulator consists of Round Robin (RR) and Proportional Fair Time (PFT) scheduler algorithms. Hybrid Automatic Repeat-reQuest (HARQ) is present in the simulator, with different soft combining process. UE receiver architectures like SIRC and IRC are available. The channel model present in the simulator is 3GPP based spatial channel models and their extensions. A link-to-system interface is implemented in the simulator to reduce the complexity and simulation time. But this reduced complexity won't compromise on the performance analysis. Homogeneous and Heterogeneous network deployments can be visualized in the simulator. This simulator has been used successfully in many of the evaluation campaigns.

http://www.eit.lth.se