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Distributed Capacity Based Multi-Channel Allocation Algorithm for Local Area Networks

Faculty of Electronics, Communications and Automation

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ABSTRACT OF THE MASTER'S THESIS

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The past decade has seen a vast growth in wireless communication, continuously fueled by the users' ever-increasing demand for higher data rates. Various technologies are constantly competing with each other, trying to establish supremacy over other concurrent technologies and desperately vying to make its own space in the field of telecommunication. With the advent of 4G systems, we are at a crucial juncture. The all-important question has become: how to provide ubiquitous coverage for all the users in the network in a cost-efficient manner while at the same time satisfy high data rates and the Quality of Service (QoS) requirements proposed by ITU-R for IMT-Advanced systems?

One technology which can provide an answer to the above question is low-power home base stations called femtocells used for local area deployments such as residences, apartment complexes, offices, business centers and outdoor hotspot scenarios. Through this work, we propose a scalable and fully distributed solution called the Distributed Capacity Based Channel Allocation Algorithm to overcome the problem of interference management and efficient system operation in a local area environment. The proposed scheme is simple yet robust and helps Home eNodeBs select the best available radio resources which minimizes interference to the neighboring nodes. Further, the scheme is subjected to various mitigating circumstances and interference-limited scenarios. The performance evaluation of the scheme is done under such conditions to ensure that it is scalable, flexible and can be considered as a practically viable option.

Through this work, we try to not just improve the throughput experienced by the average user in a cell, but also the ones at the cell-edge who suffers the most due to interference from the neighboring cells. The scheme proposed aims to be energy-efficient as well by reducing the total number of component carriers used by each HeNB without compromising the average cell throughput values.

Keywords: Dynamic Channel Allocation, Femtocells, Home eNodeB, Inter-Cell Interference, Local Area Networks, LTE-Advanced, Multi-Channel Allocation, Self-Organized Networks

Preface

This thesis work is undertaken for fulfillment of the requirements of the Master's Degree Program in Communications Engineering at Aalto University School of Electrical Engineering, Finland. The task was performed at the research premises of Nokia Research Center, Helsinki, Finland.

The thesis is organized in such a manner as to provide an incremental and graduated approach to the problem studied, so that the reader can gain an in-depth understanding of the research topic. The literature is structured as follows:

- Section 1 discusses the motivational background behind selecting this topic for research as well as defining the objectives of the study undertaken.
- Section 2 gives an idea of the background of the study done in the course of this thesis. Important features of 3GPP LTE and LTE-Advanced is presented, literature review of the current work done in the field of channel allocation is also discussed. Further work done on interference management for femtocell network is discussed as well.
- Section 3 presents an overview of the system simulator used in the study. The main scenario used for the study is presented in this section. Further, the throughput calculation methodology, scheduling algorithms, path loss model and simulation parameters are also discussed in detail.
- Section 4 gives a detailed description of the interference management algorithms proposed. First the primary channel allocation algorithm is discussed and then the distributed multi-channel allocation algorithms are discussed in detail. The Centralized channel allocation algorithms which were studied to understand the performance of distributed algorithms are also described in this section.
- Section 5 discusses in detail about the performance results of the algorithms described in Section 4. The results are presented with respect to various scenarios and detailed comparison between various schemes is made.
- Section 6 mentions the conclusions and inferences made from the studies conducted. The scope for future work is also discussed in this section.

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Finally, but with greatest regard I would like to express my gratitude and indebtedness towards my grandmother, parents and my brother for their overwhelming love and support at every step of my life. During this work, they had continuously motivated me and showered me with their invaluable warmth and encouragement. Without them this work would not have been possible.

Otaniemi, 21.02.2011

Athul Prasad.

Contents

List of Acronyms

2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
ACCS	Autonomous Component Carrier Selection
ACLR	Adjacent Channel Leakage Ratio
AP	Access Point
B3G	Beyond Third Generation
BIM	Background Interference Matrix
BS	Base Station
CDF	Cumulative Distribution Function
CMM-TA	Centralized Maximize Mean-Throughput Allocation
CMWU-TA	Centralized Maximize Worst User-Throughput Allocation
CN	Core Network
CoMP	Coordinated Multi-Point transmission and reception
CSG	Closed Subscriber Group
CSI	Channel State Information
DCBCAA	Distributed Capacity Based Channel Allocation Algorithm
DCA	Dynamic Channel Allocation
DFT	Discrete Fourier Transform
DL	Downlink
DSL	Digital Subscriber Line
eNBs	eNodeB
eNodeB	Evolved Node-B
EPC	Evolved Packet Core
E-UTRAN	Evolved-UMTS Terrestrial Radio Access Network
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
GW	Gateway
HeNB	Home eNodeB
IFFT	Inverse Fast Fourier Transform
IMT	International Mobile Telecommunications
IMT-A	International Mobile Telecommunications-Advanced
IP	Internet Protocol
ISD	Inter-Site Distance
ITU	International Telecommunications Union
ITU-R	International Telecommunications Union - Radiocommunications

LOS	Line-of-Sight
LTE	Long Term Evolution
LTE-A	Long Term Evolution - Advanced
MAC	Medium Access Control
MCL	Minimum Coupling Loss
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
MME	Mobility Management Entity
MU	Multi-User
MU-MIMO	Multi-User Multiple-Input Multiple-Output
NLOS	Non-Line-of-Sight
OFDM	Orthogonal Frequency Division Modulation
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
PDCP	Packet Data Convergence Protocol
PF	Proportional Fair
PHY	Physical Layer
QoS	Quality of Service
RF	Radio Frequency
RLC	Radio Link Control
RN	Relay Nodes
RR	Round Robin
RRM	Radio Resource Management
RRAT	Radio Resource Allocation Table
RSRP	Reference Signal Received Power
RSSI	Reference Signal Strength Indicator
RU-1	ReUse-1
S-GW	Serving Gateway
SC-FDMA	Single Carrier Frequency Division Multiple Access
SINR	Signal to Interference plus Noise Ratio
SON	Self Organized Network
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UE	User Equipment
UL	Uplink
UTRAN	UMTS Terrestrial Radio Access Network
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Inter-operability for Microwave Access
WINNER	Wireless World Initiative New Radio

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1 Introduction

1.1 Motivation

The enabling of affordable and high bandwidth mobile Internet access greatly improves the quality of experience for the users. This in turn paves way for development of new services and improving the currently available ones, which can considered to be one of the key aspects of Next Generation Mobile systems. According to the requirements defined in [2], IMT-Advanced (IMT-A) systems can support very high peak data rates up to 1 Gbps in low mobility and up to 100 Mbps in high speed environments. LTE standards which cater to features defined for Beyond 3G (B3G) Mobile systems will be further enhanced as LTE-Advanced (LTE-A) which will be submitted to the ITU-R as the candidate technical proposal for IMT-Advanced systems. Some of the main technical advantages of home base stations are discussed in [16], the financial perspective and economic viability is discussed in [19].

Considering all these factors, Home Base Stations (HeNBs) are rapidly emerging as a promising technology acting as an enabler for the future evolution of cellular wireless systems. This motivates further research into overcoming one of the key challenges faced by this technology namely Inter-Cell Interference (ICI). The main reason for interference in base stations is due to the fact that home users deploy the system without any prior network planning or careful considerations regarding where others in the neighboring area have deployed their home base stations.

One of the key features in an LTE-A system is Carrier-Aggregation which pertains to satisfying the bandwidth requirements stipulated by ITU-R for IMT-A systems. Carrier aggregation basically implies aggregation of multiple adjacent component carriers up to 100 MHz for a single User Equipment (UE) unit in order to support very high data rate transmission over a wide bandwidth. In order to enable aggregation, optimal carrier selection for each eNB becomes an interesting problem. This problem is more acute for Local Area Networks due to higher perceived deployment density of HeNBs. Optimal carrier selection in a local area deployment can solve both these challenges, of Inter-Cell Interference as well as higher throughputs with the help of extended system bandwidth.

Most of the research work already conducted in this field focusses extensively on scenarios where user-deployed cells use the same frequency band as the one used by macrocells. In such a macrocell overlay case, the capacity and coverage gains will be lost if the co-channel interference between macrocell and femtocell is not taken into consideration. However, [13, 20, 21, 23, 26, 47, 50] are some of the works which concentrate on the inter-cell interference problem from a home base station point of view. With the development of Self-Organized Networks, base stations are expected to be able to Self-Scale and Self-Adjust in an autonomous fashion. The optimal allocation of radio resources between HeNBs are dependant on mutual interference coupling between them as well as the offered traffic for each individual HeNB. The optimal allocation of component carriers can be thus considered as a highly dynamic, non-linear, non-convex, NP-Hard optimization problem.

There are two main factors which motivated the selection of this topic of research. The first factor is that there is currently limited focus in the area of inter-cell interference in dense local area deployments, hence further study in this area is bound to yield interesting results. The second factor is the fact that local area deployments are expected to see a rapid growth in the immediate future due to which key proposals are anticipated in overcoming the challenges currently being encountered, which is hoped to be achieved through this study.

1.2 Objectives

The main objective of the thesis work is to conduct a comprehensive study on inter-cell interference mitigation in a local area network. Another important objective of the work is to develop a resource allocation scheme which ensures fairness to cell-edge users who are worst affected due to the inter-cell interference without compromising much on average cell capacity. Through the interference management scheme, we try to reduce the total transmitted power consumed by the whole network by providing a resource allocation pattern which is conservative at the same time not compromising on average cell throughput. The study is done based on LTE-Advanced system specifications from a local area perspective. This work aims to develop fully distributed, scalable and autonomous channel allocation schemes with minimal information sharing between HeNBs. Since each HeNB takes decisions in an autonomous fashion, there is no need for any centralized control entity.

The decisions are made using downlink measurements taken by UEs during their normal system operation. Each HeNB gains knowledge about the system in its close neighborhood using this data. A simple yet robust Inter-Cell Interference management scheme called the Distributed Capacity Based Channel Allocation Algorithm (DCBCAA) is proposed during the course of this work. The central idea of the proposed scheme is to consider the capacity gained by an HeNB when a new carrier resource is selected, estimated with the help of data collected by UEs during their normal system operation and compare it with the capacity loss reported by all the neighboring HeNBs using the same resource. The resource is not selected if the loss exceeds the gain thereby ensuring the fairness criteria, both in terms of lower percentile as well mean user throughput. The algorithms are studied in a local area setting, in which it yields very good results in terms of system throughput performance.

2 Background

In this section, we will introduce 3GPP Long Term Evolution (LTE) and its advanced version LTE-Advanced. We will discuss the main features of both technologies, as well as present them from a local area perspective. We will also discuss in detail the channel allocation problem and some of the important contributions currently made in this field. Since inter-cell interference is one of the key challenges faced by Femtocell technology in both LTE and LTE-Advanced, we will also discuss some of the proposals currently made for overcoming this. This section tries to provide all the information required for gaining a better understanding of the future sections.

2.1 Long Term Evolution (LTE)

3GPP Long Term Evolution (LTE) is one of the latest mobile telecommunication standards which was developed with the view of enabling high data rates to mobile broadband users, enhanced service provisioning and cost reduction. This is achieved with the help of a new air interface design with bandwidths scalable from 1.4MHz to 20MHz, multiple access schemes of OFDMA (DL) and SC-FDMA (UL), more sophisticated scheduling and multi-antenna methods (MIMO), lower control plane latency, simplified network architecture, simple and cost effective operation[3, 4].

A simplified E-UTRAN architecture is as shown in Figure 1. E-UTRAN mainly consists of eNBs, providing the E-UTRA User Plane (PDCP/RLC/MAC/PHY) and control plane (RRC) protocol terminations towards the User Equipment (UE). The X2 interface is used for interconnecting the eNBs with each other. The eNBs are also connected by means of the S1 interface to the Evolved Packet Core (EPC) and more specifically to the MME (Mobility Management Entity) by means of the S1-MME and to the Serving Gateway (S-GW) by means of the S1-U. The S1 interface supports a many-to-many relation between MMEs / Serving Gateways (S-GW) and eNBs.

Some of the main design features of LTE are [4]:

- From a performance viewpoint, LTE Release 8 specifications supports peak data rates of 300Mbps in DL direction and more than 75Mbps in UL[36]. Best system performance is achieved at low mobility (0 - 15 km/h) and can support mobility rates up to 350 km/h. Reduced user-plane and control-plan latency is another key feature of LTE systems.
- From a spectrum allocation perspective, LTE systems are designed to operate on the IMT-2000 frequency band, at the same time compatible with legacy systems. LTE systems support both paired, unpaired spectrum allocations and bandwidth scalability operating on 1.25, 1.6, 2.5, 5, 10, 15 and 20MHz.

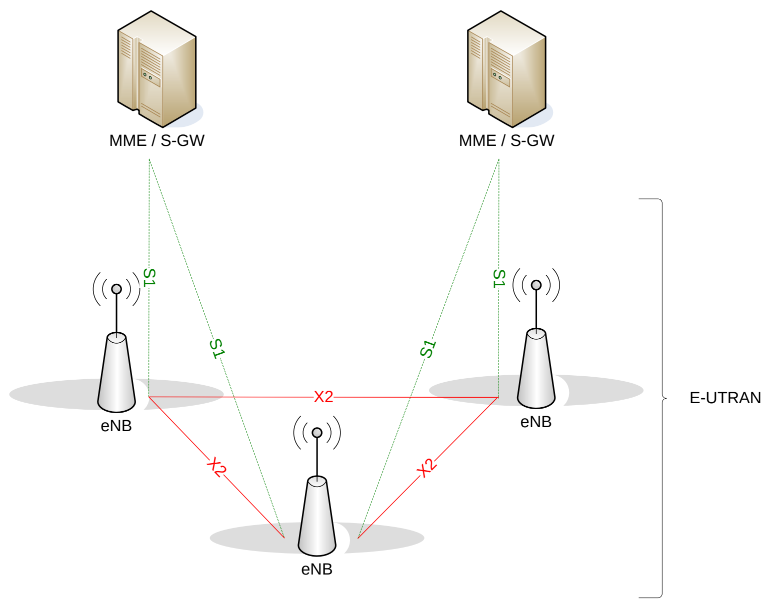

Figure 1: Overall E-UTRAN Architecture[8]

- LTE RAN is an all-IP based architecture which supports both conversational and real-time traffic. Compared to legacy systems such as WCDMA and HSPA, the LTE architecture is far more simpler with fewer network elements and interfaces which in-turn reduces network signaling. Convergence of technologies and networks is achieved with the help of a single application domain which serves customers across multiple networks and devices. LTE Base Stations (eNodeB) provide an all-in-one radio access interface between the UE and the Core Network (CN).

- LTE systems provide an enhanced Multi-Layer Multi-Vendor security paradigm which is quintessential for IP-based networks which are much more prone to security attacks. Some of the key LTE network security design considerations include strict user-operator authentication, authorization and auditing, secure data storage and network management, configuration integrity and unsolicited traffic protection.

- Some of the key cost considerations in LTE systems are reduction of network planning and maintenance costs, thereby reducing the OPEX for the operators.

There are several advantages to the technical and system design innovations made in LTE, such as the use of OFDM enables reduced downlink interference due to transmission done over orthogonal carriers. This also enables higher data rates compared to WCDMA based systems. Thus the increased spectrum efficiency combined with the operational benefits of an all-IP network brings down the cost per bit drastically. There are several other important design modifications made in LTE which help the system achieve the goals set.

With higher and higher data rates supported by the system, the deployment density also increases which in turn enables higher quality links and more spatial reuse. One of the key enabling technologies for this is Home eNodeBs or femtocells. Femtocells are low-power cellular base stations mainly aimed at indoor deployment for residential, enterprise or hot-spot settings. The user installed device communicates with the cellular network over a broadband connection such as digital subscriber line (DSL), cable modem or by using a separate RF backhaul channel. The main advantage of femtocell deployment is an excellent user experience with the help of better coverage for voice and very high data rate services[16]. Femtocells have distinct advantages in terms of providing high-speed services with very little or no expenditure from the operator side. Studies on wireless usage patterns indicate that more than 50% of voice calls and 70% of data calls originate indoors[1, 16]. The extensive and uncoordinated deployment of femtocells however, poses the important challenge of interference management. This work discusses schemes for mitigating this eventuality.

The E-UTRAN architecture with HeNB GW deployed is as shown in Figure 2. E-UTRAN architecture can deploy a Home-eNB Gateway (HeNB GW) to allow the S1 interface between the HeNB and the EPC to support a large number of HeNBs in a scalable manner. The HeNB GW serves as a concentrator for the C-Plane, specifically the S1-MME interface. The functions supported by the HeNB is the same as those supported by an eNB (with some exceptions) and the procedures run between a HeNB and the EPC is the same as those between an eNB and the EPC again with some exceptions[8].

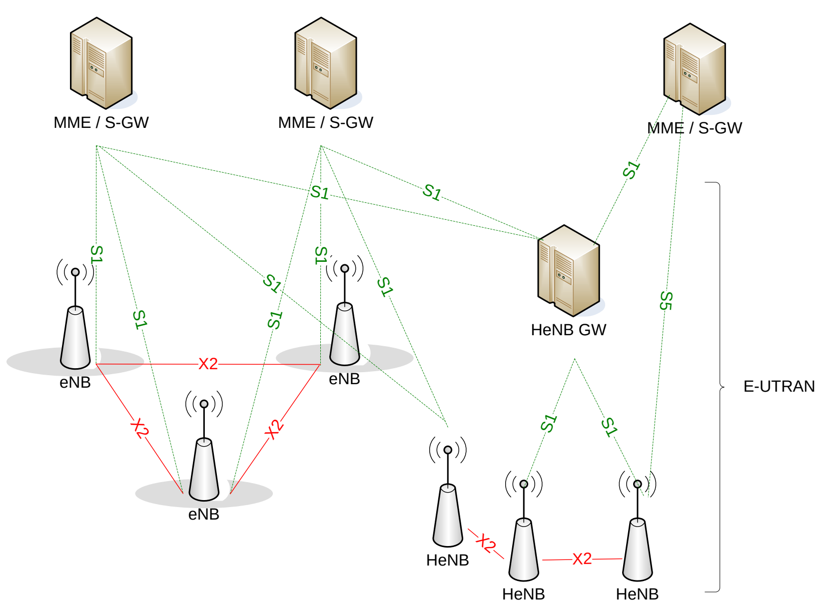

Figure 2: Overall E-UTRAN Architecture with deployed HeNB GW[8]

We have discussed about some of the design specifications of LTE and how femtocells feature in the whole picture. The advantages of using femtocells are proved beyond doubt by various studies done in this area [16, 31, 34, 28]. The main advantages include lower operational and maintenance cost, better coverage, UE-battery life improvement by virtue of smaller cells, capacity gains which all eventually lead to lesser subscriber churn. In further sections we will discuss the technical specifications of LTE-Advanced and how femtocells are affected by this. This forms the basis for further study that is done during the course of this thesis work.

2.2 LTE-Advanced

Work on LTE-Release 10 (also called LTE-Advanced or 4G) started with ITU-R calling for candidate technologies proposals for IMT-Advanced radio interface technologies[2]. The goals set for LTE-Advanced is to meet or exceed the requirements specified for IMT-A systems as well as to meet 3GPP operator requirements for the evolution of E-UTRA[36]. Some of the key features are:

- Extended and scalable System Bandwidth: System bandwidth support is extended upto 100MHz in order to support high data rate requirements for IMT-Advanced systems.

- Peak data rates of over 1Gbps in DL and upto 500Mbps for UL for low mobility environment. Peak data rates of upto 100Mbps in DL for high mobility environment.

- Backward compatibility to legacy systems: Legacy systems such as 2G, 3G and LTE systems should work in an uninterrupted manner while doing handover to LTE-A systems.

- Optimized support for new IMT bands: LTE-A systems should provide complete support for the new IMT bands.

- Latency: C-plane from Idle (with IP address allocated) to Connected in $<$ 50 ms and U-plane latency shorter than 5 ms one way in RAN taking into account 30% retransmissions (FFS).

- Cell edge user throughput requirements should be 2 times higher than that in LTE based systems.

- Average User Throughput for LTE-A systems should be at least 3 times higher than that currently supported in LTE.

- Capacity (Spectrum Efficiency) should be 3 times higher compared to LTE systems.

- Peak spectrum efficiency DL: 30 bps/Hz, UL: 15bps/Hz (using up to 64QAM modulation schemes).

- Coverage area is vastly improved for LTE-A systems. Coverage should be optimized or deployment in local areas/micro cell environments with ISD up to 1 km.

In order to satisfy the requirements for LTE-Advanced, improvements to radio interface technologies were studied with LTE Release 8 as the baseline. There are various candidate proposals for enabling these requirements. Some of the candidate proposals are:

- Component Carrier Aggregation for enabling 100MHz system bandwidth.
- Advanced MIMO options of up to 8x8 in DL and 4x4 in UL.
- Coordinated Multipoint Transmission and Reception (CoMP).
- Enhanced Relay Nodes for ubiquitous coverage and backhaul cost optimization.
- Local area optimization of air interface with the help of inter-cell interference coordination schemes such as the Autonomous Component Carrier System (ACCS) for Uncoordinated Femtocell deployment.

LTE Release 8 supports bandwidth up to 20MHz, while extended bandwidths of up to 100MHz is a requirement for LTE-Advanced systems. The proposal for enabling bandwidth extension for LTE-A systems is carrier aggregation. Using this technology multiple carriers can be aggregated to form the 100MHz system bandwidth required for the high data rates defined for IMT-A systems. Carrier aggregation is the method by which several contiguous LTE-Release 8 compatible component carriers are placed adjacent to each other on the same subcarrier grid so that simple IFFT/FFT operations are possible. This essentially makes LTE-A systems backward compatible with Release 8. In downlink it works out to be a simple extension of FFT sizes from the baseband perspective, but in uplink, since SC-FDMA is used, a separate DFT per component carrier prior to IFFT will be used for transmission[9]. If the spectrum is non-contiguous, then spectrum aggregation will be used to combine the non-contiguous spectrum to form the required larger spectrum chunk. The main advantage of spectrum aggregation is that wider total bandwidth can be obtained without a correspondingly wider contiguous spectrum. CA and SA is as depicted in Figure 3.

LTE Release 8 supports multiple-input multiple-output (MIMO) multiplexing of up to four layers in DL and MIMO multiplexing is not supported in UL. Enhanced MIMO schemes are proposed for LTE-A systems for both DL and UL. Improved Multi-User (MU) MIMO schemes are being proposed such as Cooperative MU-MIMO in DL to provide a higher degree of FD-Scheduling flexibility and better MU interference suppression by better precoding schemes and interference coordination. Closed-loop spatial multiplexing using 8-transmit antennas will be supported in DL and up to 4-transmit antennas in UL. This will be crucial to satisfy the peak spectral efficiency requirement of 30bps/Hz in DL and 15bps/Hz in UL.

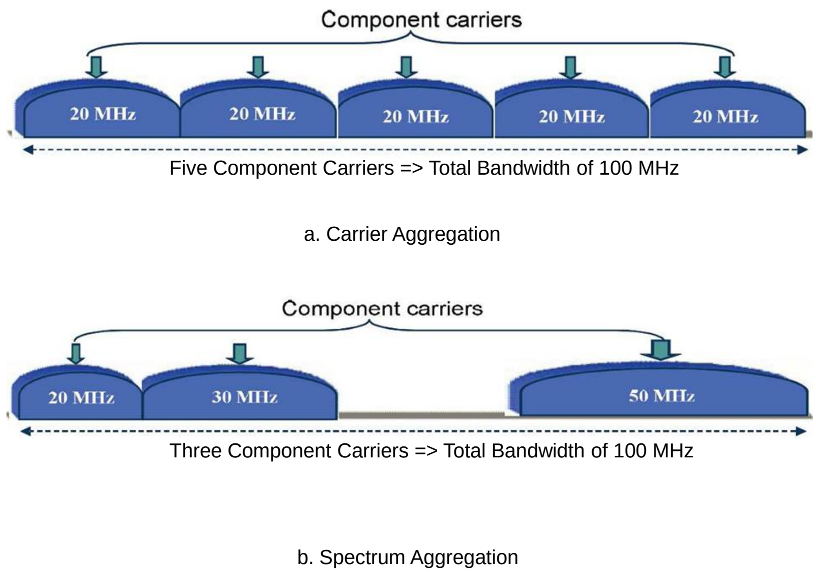

Figure 3: Carrier Aggregation and Spectrum Aggregation to achieve 100MHz Bandwidth[17])

The main limiting factor for LTE Release 8 systems was inter-cell interference due to the fact that OFDMA and SC-FDMA was used. To overcome this, for LTE-A systems, the concepts of base station coordinated scheduling, beamforming and joint transmission are an integral part of the system specifications, commonly called Cooperative MultiPoint transmission and reception (CoMP)[9]. The main challenge faced by this scheme is in terms of restricting the signaling overhead at the same time providing reasonable improvements. Another challenge is from a network perspective in terms of configuration and coordination of the cooperative cell clusters and cooperative active UEs from a UE perspective.

Enhancements on Relay Nodes (RN) is another key technology proposed for LTE-A systems. As mentioned previously, enhanced data rates require denser deployment of eNBs and the case for RNs is further strengthened by the fact that the majority of data users are indoor users. Hence, for providing high throughputs consistently across the network, transmitting nodes should be placed close to the user. Relay Nodes provide an attractive, simple, cost efficient and easy to install solution for this problem. The backhaul link from RN to macro eNB will be a radio interface and optimal positioning can enable high data rates, coverage and spectral efficiency. The backhaul link is realized by an LTE link to the eNB with the help of either an inband (same frequency band) or outband (additional frequency band).

Local area deployments such as femtocells are touted to play a significant role in cost-efficient delivery of new services for LTE-A systems such as multimedia, gaming, social networking, etc which require a high level of QoS especially for indoor users which is not possible for macro-cell networks. Since LTE-A networks are essentially self-organizing with minimal external interference, the inter-cell interference mitigation schemes also should comply with this. As we had discussed previously, as in the case of LTE systems, femtocells play a key part in enabling high data rate requirements for LTE-A systems. Another main limiting factor for local area deployments is the interference coming from macro-eNBs. In LTE-A systems, it is proposed to use separate bands for femtocells, thereby limiting the interference for densely deployed networks. But this poses additional challenge pertaining to spectrum scarcity as well.

Autonomous Component Carrier Selection

As emphasized previously, one of the main limiting factors for uncoordinated femtocell deployment is inter-cell interference. Unlike macro-eNBs which are positioned after careful planning, Reuse-1 is not a viable and optimal configuration for such local area dense deployment scenarios. Depending on the positioning of the eNBs, UEs and also on other factors such as offered traffic, etc. the optimal frequency allocation varies. One of the proposals for enabling an uncoordinated local area deployment which gives high performance is Autonomous Component Carrier Selection (ACCS)[26, 27, 36]. Depending on the channel conditions, each HeNB selects a set of carriers which causes minimal interference to neighboring HeNB users thereby providing an automatic mechanism for component carrier selection to boost average spectral efficiency and cell-edge performance.

The main principle behind the proposal is that based on the DL reference signal received power (RSRP) measurements done by UEs, the potential SINR is estimated. Since the data is collected as part of system operation over a long period of time, SINR values with a given outage probability can be calculated for all relevant neighboring cells. In this manner, HeNBs learn the environment and information regarding the same is stored in Background Interference Matrices (BIM). The data stored in this manner is used at a later point of time to make carrier selection decisions.

Also, it is proposed that HeNBs will maintain an outgoing BIM which lists all the potentially interfered HeNBs, thereby estimating how much interference is caused to the interfered cells if it decides to reuse a channel. When an HeNB tries to add a new carrier, it will use the information in the BIM and RRAT (Radio Resource Allocation Table) to understand whether the new allocation will affect any existing allocations. This makes sure that HeNBs will allocate new channels only if it does not violate the minimum SINR conditions defined for the surrounding cells.

2.3 Channel Allocation Problem in Wireless Networks

With the advent of mobile technology and with the passage of generations, the importance of Orthogonal Channel Allocation in relation to Inter-Cell RRM has been continually reducing. Comparison between random channel allocation is done with dynamic channel allocation schemes in [49] from a Code Division Multiple Access (CDMA) system perspective and it is shown that for 3G systems Randomized allocation performs better. Also, systems belonging to later generations such as LTE based on OFDMA, when deployed in a planned and coordinated manner performs well when a simple Reuse-1 is used as shown in [44]. There has been an active interest from the research community in topics such as Cognitive Radio, Self-Organized Networks which has found practical application in Local Area Optimizations on Femtocell networks in the recent past. This has lead to a renewed interest on channel allocation studies.

The trend towards ubiquitous wireless communication demands for the network to be totally devoid of any external or central dedicated control entity, in essence be totally Self-Organized[41]. This also means that the system should be able to adapt dynamically to any change in the system functioning. The network architecture of Self-Organized Networks is described in [18]. Self-Organization from a Femtocell point of view is studied in [13, 21, 43]. Some of the design paradigms of Self-Organized Networks which can be extrapolated to be used in self-organized dynamic channel allocation are[41]:

- Local behavior rules should be designed in such a manner that they achieve global properties. From a channel allocation point of view, this essentially means that, the allocations which are done through local negotiations of nodes should aim to achieve a global optima.

- To avoid conflicts between the nodes, make use of implicit coordinations instead of aiming for perfect coordination. This essentially means that instead of hoping to achieve perfect assignment (which centralized control aims to achieve), try to move towards allocations which give the best performance under the current conditions and have a new allocation when conditions change.

- Dependance on long-lived state information or statistical data should be minimized. The algorithms should not depend on data collected over a long duration which has an impact on the complexity and scalability of the system.

- Network conditions change often rapidly with the passage of time, hence protocols designed should be able to adapt to change as well.

Research in the field of Dynamic Channel Assignment was going on long before Self-Organizing mobile networks were proposed. One of the first proposals for Dynamic Channel Assignment by means of Channel Segregation to improve spectral efficiency is done in [24] whereby each cell acquires its favorite channel by learning from experience about the channel usage pattern in other cells. The problem is further studied in [25] where it is investigated in an FDMA/TDMA setup extending it to a distributed multi-coloring algorithm. In [29], a distributed online frequency assignment is proposed. The solution is presented to be an online multi-coloring algorithm. Most of the algorithms solving the distributed graph coloring or interference graph problems can be broadly classified into Greedy Local Search Algorithms and Rule-Based Reasoning and Negotiation Algorithms. They are further discussed as follows.

Greedy-Local Search Algorithms

Greedy heuristics arrives at a feasible solution in 'n' steps, where 'n' denotes the number of elements in a solution (Problem Size). At each step, an element and its value is chosen by making the most favorable choice available [35]. The main feature of pure greedy algorithms is that they arrive at a decision very quickly but tend to yield sub-optimal solutions. Local search algorithms strives to iteratively achieve a local optimum by searching for a better solution which is close to the current solution. This process is continued until no better solution is available. Greedy-Local heuristics is the process where at each step of the process, a locally optimum choice is arrived at which may or may not lead to a global optimum.

Greedy local search algorithms have been extensively discussed in literature. In [25], a greedy algorithm which is essentially a local search based on channel segregation is discussed. A distributed asynchronous spectrum sharing algorithm is proposed in [12]. Here nodes are combined into clusters and each cluster has a cluster head. These cluster heads search for low interference channels and the channel having the lowest interference is selected by the cluster heads, eventually converging into a local minima. In [39] Distributed Adaptive Channel Allocation based on a game theoretic framework is proposed. A Greedy Local search based algorithm is proposed in [38]. Cooperative and non-cooperative learning game approaches are proposed which is shown to give comparable mean throughput values. Algorithms based on Greedy and local search heuristics are proposed in [35].

A distributed graph coloring algorithm combined with an algorithm for adding and removing edges, operating on different times scales is proposed in [32]. Here distributed local search algorithms enabling plateau walks are used along with a noise strategy to avoid local minima. It is also shown that these algorithms can outperform distributed greedy local search algorithms.

Rule-Based Reasoning and Negotiation Algorithms

Rule-Based Reasoning algorithms basically use an inference engine to match the pattern in the data being processed with the pattern in the pre-defined set of rules. Inference engines is mostly implemented using software code and can process rules, cases, objects and other types of knowledge and expertise based on the facts of a particular scenario. Negotiation based algorithms accommodate a set of parameters for achieving the desirable goal and try to negotiate for a solution which is closest to the targets specified.

A distributed rule regulated spectrum sharing approach is proposed in [15] which can be considered as a Rule-Based Reasoning algorithm with no collaboration between the nodes. There is no negotiation between the nodes which is proposed to significantly reduce the signaling overhead as compared to a collaborative approach using explicit coordination and communication. Inertia-Based Distributed Channel Allocation on planar conflict graphs is studied under a graph coloring problem setting with four colors in [33]. In this work, deviations from fully-solved configurations are considered to be defects. The work concentrates proposes a methodology to remove these deviations or defects. This is done by moving them to the boundaries of the system in a direction-persistent or inertial manner, where they are more likely to vanish due to the reduced number of neighbors.

A solution for the 3-dimensional graph coloring problem using emergence engineering principles is proposed in [11] based on rule-based reasoning with no negotiations with neighboring nodes and in a self-organized manner. The spectrum allocation problem is presented as a variant to the graph coloring problem in [48] where a centralized and distributed approach is proposed. The distributed approach follows an iterative negotiation approach to arrive at the final allocation and it is shown that distributed and centralized approaches gives comparable performance with very less signaling overhead for the former approach. A negotiation based self-organization approach is proposed in [42] as well for wireless sensor networks.

There are other sub-classifications of algorithms such as iterative local search algorithms, based on number of channels assigned - single and multi-channel allocation algorithms, etc. Most of the works mentioned are on single-channel allocation, except [15, 25, 48, 26] where the problem is essentially presented as a multi-coloring one. The problem is also presented in a self-organized local area setting in [12, 38, 39]. We will discuss more about the channel allocation problem for a femtocell network in the coming section.

2.4 Interference Mitigation in Femtocells

Femtocell technology is rapidly emerging as a promising solution to the indoor coverage problem in Long Term Evolution (LTE) and LTE-Advanced networks. The various advantages of femtocell networks such as easy deployment, scalable architecture, easy upgradation to future standards, lower cost for end user, longer UE battery life, higher capacity and reduced subscriber churn have already been discussed in the previous sections. Various forecasts done on the growth of indoor mobile users[45] and correspondingly femtocell deployments are also expected to see significant growth[10] indicating that there will be a huge increase in the deployment density of indoor networks.

With the perceived huge increase in deployment density, interference from nearby macrocell and femtocell transmissions will also increase considerably. The mitigation of this interference and resultant loss in capacity poses a major challenge for femtocell technology in future wireless networks[16]. A lot of studies are going on in this area, mainly concentrating on interference management and coordination in a self-organized manner. Some of these studies will be presented in this section.

A state-of-the-art study on distributed dynamic multi-channel allocation called the Autonomous Component Carrier System (ACCS) with minimum coordination for inter-cell interference mitigation from a local area perspective can be found in [26, 27]. Here, based on downlink SINR measurements made by UEs, long term SINR statistics data is collected by HeNBs and is stored in Background Interference Matrices (BIM). This BIM is used in the decision making process to select primary and secondary component carriers.

A comprehensive study on a negotiation based Interference Coordination between femtocells in LTE-A networks with the help of Carrier Aggregation is done in [50]. A two-step interference coordination scheme is proposed to deal with interference between HeNBs in an LTE-A network. In the first step, a carrier which does not interfere or has the least interference with the neighboring HeNBs is assigned to each HeNB. In the second step, based on specified utility functions defined, more carriers are attempted to be utilized by each HeNB in order to improve the system spectral efficiency. The results show considerable improvement on average and lower percentile throughput values compared to Reuse-1.

A self-organized interference management scheme for femtocell networks investigated from TDD and FDD underlay is proposed in [20]. In the FDD case, HeNBs and macrocell use the same resources for UL and DL and an opportunistic access method is suggested. For the TDD case, coordinated and non-coordinated approaches are proposed. Results show that better performance is obtained with a TDD underlay with a coordinated approach with shared UL using FDD. A cross-tier Interference management scheme with the help of uplink power control is proposed in [30]. In this work the schemes proposed are aimed to mainly avoid uplink throughput degradation of the macrocell BS.

3 System Level Simulator

In this section, a detailed description of the actual simulation environment used to generate the performance measurements is given. The section also gives an overview of the simulator used, listing the simulation parameters defined, throughput calculation methodology and channel models used. The main aim of the study is to find an optimal channel allocation scheme for local area deployment and hence the simulations done are towards achieving that end. The simulator is used to find the performance of the wireless network studied with the help of algorithms developed and to find the impact of various factors such as channel conditions, system level parameters, etc on the performance. The generic flowchart of the operation of the dynamic system simulator for our studies, during the course of each snapshot is as shown in Figure 4.

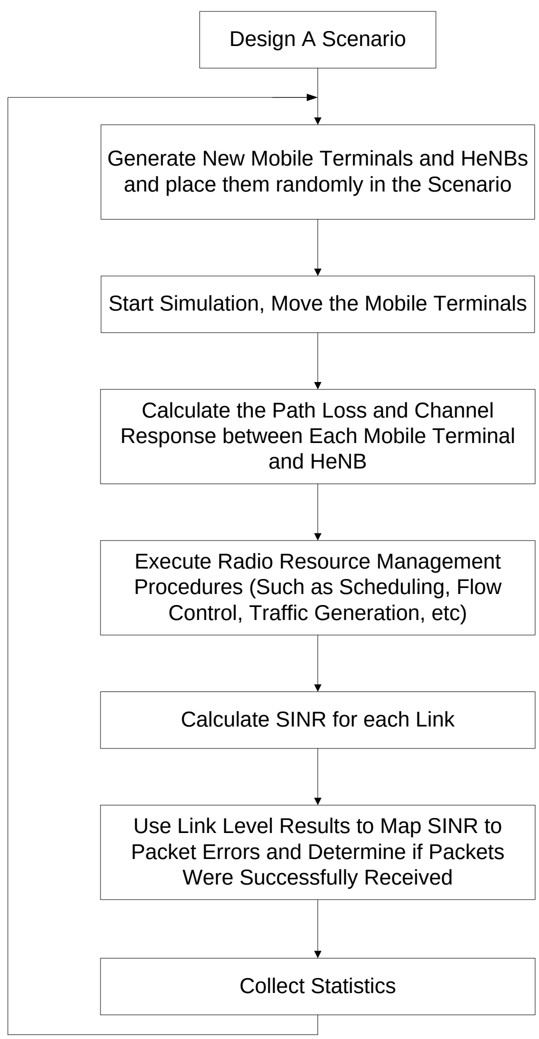

Figure 4: Flowchart of Dynamic System Simulator Operation.

3.1 Simulator Overview

The primary purpose of the system simulator is to replicate real-world scenarios in the best possible way. The simulator also enables us to determine the system level performance by aggregating the link level performances experienced by all the UEs defined in the scenario. The link to system level mapping followed is as proposed in [14]. A dynamic system simulator is utilized whereby the throughput is calculated over a set of snapshots, where each snapshot represents the period of time over which the UEs and HeNBs remain in a static state. A detailed description of the dynamic simulator can be found in [22], the difference is in the fact that handovers are not considered since we are studying a home environment with Closed Subscriber Groups (CSGs) under low mobility, which causes only a very limited amount of handovers and hence will not affect the results. In all the scenarios studied, we consider every apartment having its own Closed Subscriber Group and only UEs in the same apartment can access the HeNB in the apartment. This in turn leads to a very interesting and challenging scenario.

The scenario emulated in the simulator is a indoor layout with one HeNB in a 4-room apartment, randomly placed in any one of the rooms. There are 4 UEs uniformly distributed within each apartment in a random location. The channel, path loss and slow-fading models are based on A1-type generalized models for the frequency range 2-6 GHz developed in WINNER[46]. The scenario used is similar to the one proposed in [27], except for the fact that we have studied the performance of the algorithm in 3-floor scenarios as well. To simplify the analysis, fast fading is not considered. The single floor layout is as shown in Figure 5.As mentioned previously, a simulation is run over several snapshots at the end of which calls are dropped and UEs and HeNBs are positioned randomly again at the beginning of the next snapshot. In all scenarios, uniform user distribution of 4 users/apartment is modeled.

The traffic models considered are full-buffer model and a finite buffer with 40Mbps mean data rate. For simulations with finite buffer conditions, the traffic generator generates an average of 20 packets of 1600 bytes with inter-arrival time following geometric distribution. Antenna pattern used is omnidirectional with 0 dBi antenna gain. Scenario B4 is applied for indoor-to-outdoor propagation. We study both the full-buffer and the finite buffer conditions. The entire scenario with one building showing the sample UE random position is shown in Figure 6.

3.2 Throughput Calculation

Throughput calculation is done for the UEs and statistics data is collected over the entire duration of the snapshots. The throughput is computed with the modified Shannon formula which takes into account the Bandwidth Efficiency and SINR Efficiency of the transmission scheme [37]. The Bandwidth Efficiency factor accounts for the reduction in effective bandwidth due to Adjacent Channel Leakage

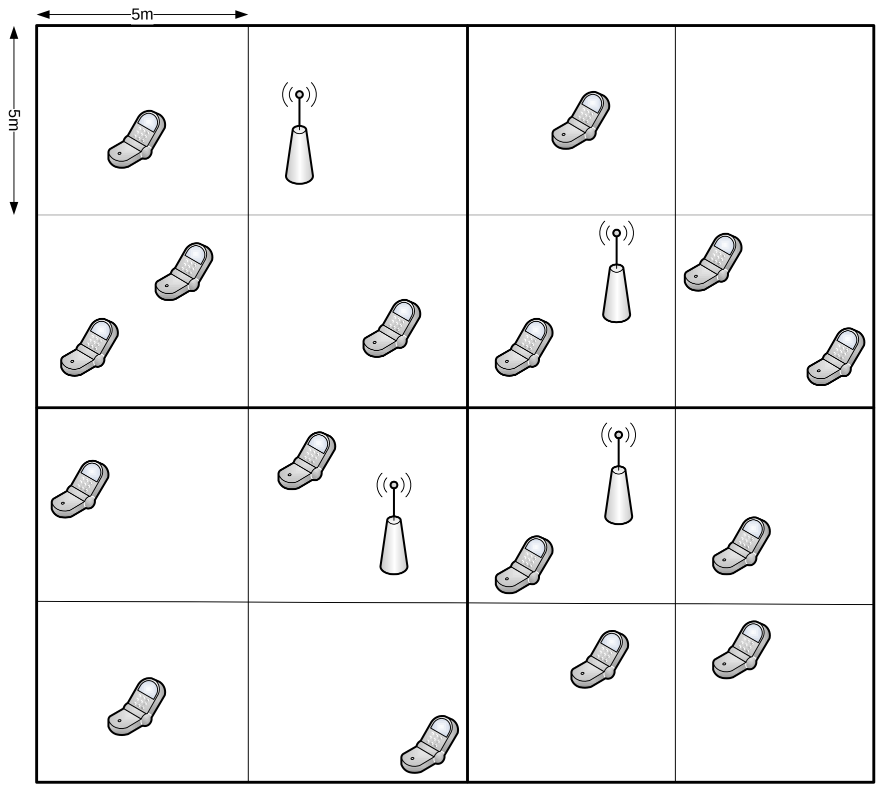

Figure 5: Single Building Layout (Randomly positioned UEs and HeNB)

Ratio (ACLR). The ACLR accounts for the unused sub-carriers and adjusts the bandwidth to meet the transmission spectrum mask requirements. The reduction in performance due to the practical codes implementation restrictions, for example limited code block length, is accounted by the SINR Efficiency factor. It also accounts for the channel estimation error.

The modified Shannon formula mentioned below is the same as the one proposed in [37].

$$Throughput[bits/s] = W * W_{\text{eff}} * \log_2(1 + SINR/SINR_{\text{eff}}) \tag{1}$$

Here the limiting SINR is 22dB, hence the above equation holds if:

$$10 * \log_{10}(SINR) < 22dB \tag{2}$$

Otherwise:

$$Throughput[bits/s] = W * W_{\text{eff}} * \log_2(1 + (10^{2.2})/SINR_{\text{eff}}) \tag{3}$$

Where

- W is the transmission bandwidth in Hz
- W_{eff} is the bandwidth efficiency

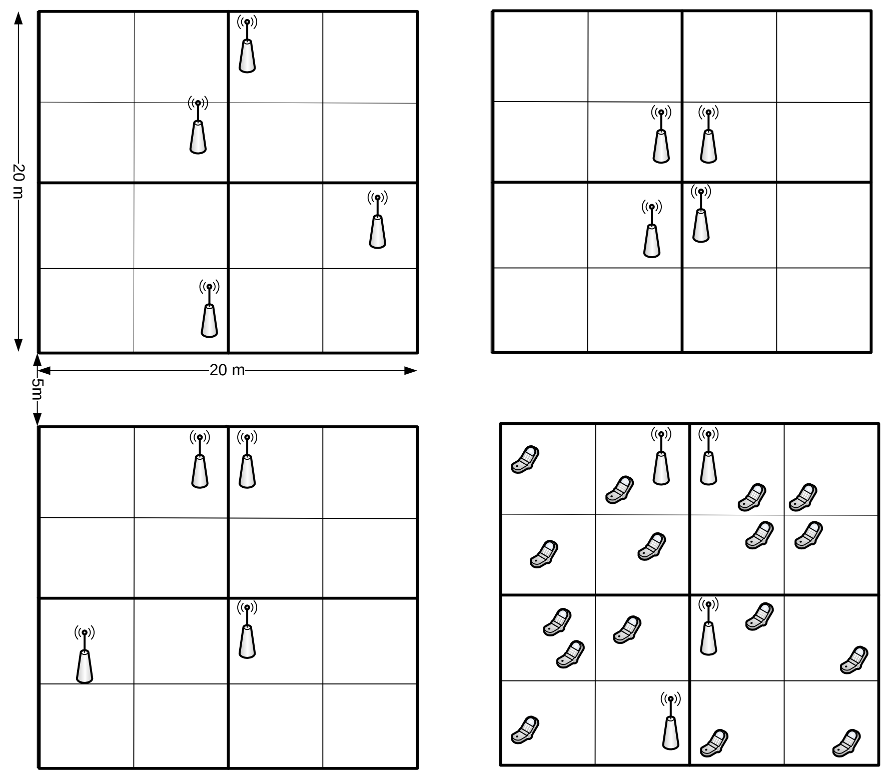

Figure 6: Indoor Scenario Layout (Randomly positioned UEs and HeNB shown in one building)

- $SINR$ is the signal to noise ratio
- $SINR_{\text{eff}}$ is the SINR efficiency

In our simulations we consider:

- Bandwidth efficiency W_{eff} as 0.56 for both Uplink and Downlink
- SINR Efficiency $SINR_{\text{eff}}$ as 2.0 for both Uplink and Downlink.

Also, the factor $W_{\text{eff}} * \log_2(1+SINR/SINR_{\text{eff}})$ in (3) represents the spectral efficiency of the transmission which is upper-bounded by the Shannon fitting, whereby SINR is limited to 22dB. Thus the peak spectral efficiency is 3.5 $b/s/Hz$ for the values given above for W_{eff}, $SINR$ and $SINR_{\text{eff}}$.

3.3 Scheduling

The scheduler used is similar to the ones described in [22, 40]. The packet scheduler is divided into time and frequency domain components. The Time Domain (TD) scheduler controls fairness between the users. It selects a particular number of UEs from the set of active UEs for Frequency Domain (FD) scheduling based

Scenario	Path Loss [dB]	Applicability Range, Antenna Height, Default Values
	Indoor Propagation (A1 Model)	
LOS	A=18.7, B=46.8, C=20	$3m < d < 100m$ $h_{\mathrm{BS}} = h_{\mathrm{MS}} = 1...2.5m$
NLOS	A=20, B=46.4, C=20, X=5n_{w}	where n_{w} is the number of walls between BS and MS
FL	For the above cases, Floor Loss (FL), if the BS and MS are in different floors $\mathrm{FL} = 17 + 4(n_{\mathrm{f}} - 1), n_{\mathrm{f}} > 0$	n_{f} is the number of floors between the BS and MS
	Indoor-to-Outdoor Propagation(B4 Model)	
NLOS	$\mathrm{PL} = PL_{\mathrm{b}} + PL_{\mathrm{tw}} + PL_{\mathrm{in}}$	$3m < d_{\mathrm{out}} + d_{\mathrm{in}} < 1000m$ h_{BS} = 10m, h_{MS} = 3(n_{Fl}-1)+1.5m

Table 1: Summary Table of Pathloss Models

on only a Round Robin (RR) scheduler criteria or a time-domain equal throughput criteria as mentioned in [22].

Our studies have been done with a Round Robin (RR) scheduler. The Frequency Domain scheduler tries to increase the spectral efficiency by using Channel State Information (CSI). It uses a Proportional Fair (PF) metric to assign Physical Resource Blocks (PRB) to UEs selected for FD scheduling.

3.4 Path Loss Models

The path loss models used in the scenario is based on WINNER II path loss models, defined for A1 (Indoor Office Scenario) and B4 (Indoor-to-Outdoor Scenario). The path loss model can be expressed as[46]:

$$PL = A \log_{10}(d[m]) + B + C \log_{10}\left(\frac{f_{\mathrm{c}}[GHz]}{5.0}\right) + X \tag{4}$$

Where:

- d is the distance between the transmitter and receiver in [m].
- f_{c} is the system frequency in [GHz].
- A includes the path loss exponent.

- B is the intercept.
- C describes the path loss dependance.
- X is an optional, environment specific term (e.g. Wall Attenuation in A1 NLOS Scenario).

The free space path loss is given by:

$$PL_{\text{free}} = 20\log_{10}(d[m]) + 46.4 + 20\log_{10}\left(\frac{f_{\text{c}}[GHz]}{5.0}\right) \tag{5}$$

The values of A, B and C is as given in Table 1.The parameters used in the table are explained as follows:

- h_{BS} and h_{MS} are Base Station and Mobile Station heights
- n_{Fl} is the floor index (ground floor has index 1)
- d_{out} is the distance between the outdoor terminal and the point on the wall that is nearest to the indoor terminal.
- d_{in} is the distance from the wall to the indoor terminal.
- and

$$PL_{\text{b}} = PL_{\text{B1}}(d_{\text{out}} + d_{\text{in}})$$

- PL_{B1} is the path loss of B1 model in [46].

$$PL_{\text{tw}} = 14 + 15(1 - \cos(\theta))^2$$

- θ is the angle between the outdoor path and the normal of the wall.

$$PL_{\text{in}} = 0.5d_{\text{in}}$$

3.5 Simulation Parameters

In this section the parameters related to the simulations conducted are listed. The parameters used are basically a subset of the ones suggested in 3GPP LTE Release 10 evaluations [5, 6, 7] as well as the ones defined in the Winner II channel and pathloss models[46].

Table 2: System Level Parameters Used

System Level Parameters		
Spectrum Allocation	5x20MHz and 3x20MHz channels	
Band Used	3.5GHz	
eNB Max Tx Power	24 dBm	
UE Max Tx Power	21 dBm	
Antenna System	UE: Omnidirectional (0dBi)	
	HeNB: Omnidirectional (0dBi)	
Minimum Coupling Loss (MCL)	50 dB	
Duplexing - TDD	DL: 50	
	UL: 50	
Propagation Model[46]		
Shadowing Standard Deviation	LOS	3dB
	NLOS	7dB
Scenario Details		
Residential	Room Size	5m x 5m
	Corridor Width	5m
	Internal Wall Attenuation	5dB
	External Wall Attenuation	10dB
	Next Floor Attenuation (For Multi-Floor Scenario)	$[17 + 4(n_f - 1), n_f > 0]$ dB
	HeNB Positioning	Random in Room, One per Apartment
Link Level Model[37]		
Bandwidth Efficiency	DL / UL	0.56
SINR Efficiency	DL / UL	2.0
User Distribution	Uniform - 4 Users/Apartment; 1 - 3 Floor Building	
Buffer Condition	Infinite Buffer / Finite Buffer	

4 Channel Allocation Schemes for Local Area Networks

In this section the various distributed capacity based channel allocation schemes are studied and will be compared to some centralized schemes which were investigated. The central idea of the distributed schemes remains the same - the comparison of an increase in estimated capacity anticipated for own cell users with the decrease in capacity of neighboring cell users. In other words, the increase in capacity is evaluated within the cell and the decrease or loss in capacity is defined by the coupling between the cells. The exact metric used for comparison varies depending on the scheme considered as described in detail below. The algorithm description for the first channel allocation (Distributed Interference Management Scheme) is also done in detail.

4.1 Distributed Interference Management Scheme

The first channel allocation is very crucial for our studies, since the capacity improvement and loss experienced by the UEs will depend heavily on the optimality of this process. The algorithm used for this is described in detail in [23]. Each HeNB selects the channel which has the maximum path loss to another HeNB using the same channel. The scheme is based on limited information sharing and no negotiation between the neighboring nodes. It is by definition an autonomous algorithm, and is closely related to a conflict-graph version of the greedy algorithms described in [12] and [38].

The algorithm aims to minimize the interference in the network which is the main limiting factor in an uncoordinated local area deployment. The HeNBs go through several iterations of carrier selection until arriving at a stable allocation. It is to be noted that at all points the Closed Subscriber Group (CSG) of the HeNBs are taken into account, since users will not connect to nodes belonging to a different CSG. CSGs make the scenario more challenging especially in terms of interference management. As concluded in [23] the algorithm does not end up in giving the best possible solution to the problem, but it performs close to Centralized channel assignment discussed in the paper.

4.2 Distributed Multi-Channel Allocation Schemes

Various distributed schemes will be discussed and they are divided broadly into Fair Distributed Allocation Schemes where a certain level of fairness was taken into account and Greedy Distributed Allocation Schemes where the HeNBs are expected to behave slightly more greedily in order to attain better mean throughputs. Similar strategies have been used for the Centralized Channel Allocation schemes which are discussed in the next section. The distributed channel allocations always begins with one channel allocated to each HeNB using the Distributed Interference Management Scheme.

4.2.1 Fair Distributed Capacity Based Channel Allocation Algorithms

In this section we are going to discuss various Distributed Channel Allocation schemes which give priority to users experiencing challenging interference conditions and try to maximize their throughput without sacrificing much of the mean throughput values. For all the schemes described, downlink measurements are done and the algorithms are optimized for downlink channel allocation.

Algorithm 1: Average Capacity Increase For Own Cell Users vs Sum Loss In Capacity Experienced By 'J' Worst Interfered Neighboring Cells

In this proposed scheme, the average increase in capacity of own cell user is compared with the loss in capacity experienced by the worst users in the 'J' worst-interfered neighboring cells. The central idea here is that when a node considers the possibility of adding a potential new channel, all the neighboring cells having the same channel currently in use will suffer from interference. Hence, if the potential loss which would be experienced by those cells are reported to the HeNB trying to add the channel, then based on the values reported and the estimated capacity gained by adding the channel the Node can make a decision whether to add the channel or not. This algorithm is abbreviated as DFJNWUC (Distributed Fair; J Neighbors; Worst User; Current channel loss) for future reference. The logic behind the naming is that it is a Distributed Fair algorithm which considers 'J' interfered Neighboring cells reporting their Worst User Current channel loss.

Consider the case where there are 'N' own cell users and 'J' neighboring user losses are taken into account. The capacity experienced by user 'n' having 'C' number of channels is given by the Shannon Fitting formula as defined in [37]:

$$C_n = \sum_{c=1}^{C} (W * W_{\text{eff}} * \log_2(1 + (SINR_{(\text{c,n})}/SINR_{\text{eff}}))) \tag{6}$$

And the capacity increase for the 'N' own cell users in HeNB '0' for channel 'c' is,

$$C_{(0,\text{c})} = (\sum_{n=1}^{N} C_{\text{n}})/N \tag{7}$$

Where

- W is the transmission bandwidth
- W_{eff} is the bandwidth efficiency
- $SINR_{(\text{c,n})}$ is the signal to noise ratio experienced by the user 'n' on channel 'c'.
- $SINR_{\text{eff}}$ is the SINR efficiency which adjusts for SINR implementation efficiency of LTE.

The capacity decrease is the loss in capacity experienced by neighboring cell users when an HeNB adds the new channel. Let the Worst Interfered Neighboring HeNBs be numbered '1','2', '3', ... , 'J'. The algorithm scans through the capacity loss experienced users belonging to neighboring HeNBs and the user experiencing the highest loss is denoted as the worst user. The loss by the worst user is then reported by the corresponding HeNB to the node trying to add the new channel and is termed henceforth as the worst loss.

Let $C_{(1,c)}$ be the capacity of the worst user in HeNB '1' having 'c' channels before assignment is done and $\ddot{C}_{(1,c)}$ the capacity after allocation. The loss in capacity can be formulated as:

$$C'_{(1,c)} = C_{(1,c)} - \ddot{C}_{(1,c)} \quad (8)$$

The first channel allocation is done as described in Section 4.1 and forms the basis for further channel allocation. Similarly the capacity loss of the next 'J' worst interfered HeNBs is calculated.

Now the HeNB is allowed to keep the channel if and only if:

$$C_{(0,c)} > C'_{(1,c)} + C'_{(2,c)} + C'_{(3,c)} + ... + C'_{(J,c)} \quad (9)$$

That is, the increase in capacity experienced by the own cell users is greater than the decrease in capacity experienced by the worst users in 'J' neighboring cells. This automatically also takes care of preventing greedy HeNBs from allocating all channels for itself and thereby creating unfavorable conditions for other cells. From a protocol view point, very little signaling is required for this scheme. The loss experienced by the neighboring interfered cells can be exchanged periodically. Consider the scenario described in Section 3.1 with four-room apartment in a building. The case where 'J' is taken as 3, i.e. 3 of the worst interfering neighbors are taken into account while the allocations are done is as shown in Figure 7.

One scheme of signaling involved as part of the allocation can be described as follows. As part of normal system operation, the UE measures and reports the interference experienced by it to the HeNB at regular intervals (e.g. Every 10s). The proposed idea is that when the HeNB node senses an increase in interference, based on the reported value and with the data it has (which is collected over a long time period), it will assume that the neighboring node is trying to add a new channel. Based on the channel in which interference has increased or the UE experiences a capacity loss, the channel newly allocated by the HeNB can be inferred. In this case HeNB '0' transmits on channel 'c' (in the illustrated case) for some time during which measurements are taken. It is assumed that HeNB keeps track of the interference value reported by the UEs over a period of time. Hence, when the UE reports the interference, and with the knowledge of transmitted power, it can estimate the SINR value and using the Shannon-Fitting formula, the capacity loss can be estimated as well. It then reports the loss in capacity experienced by the worst user to its neighboring nodes. The worst user is defined for each channel 'c'

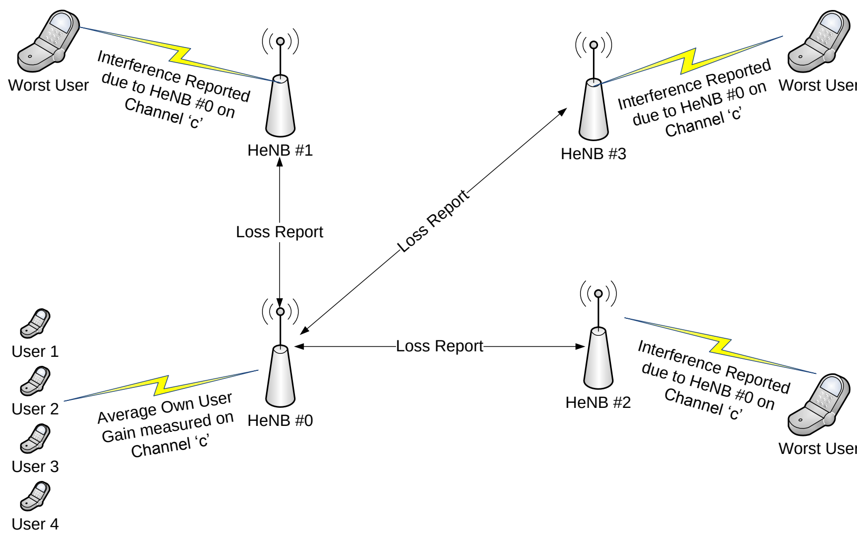

Figure 7: DFJNWUC Worst User Loss Signaling (J = 3)

and will vary from channel to channel depending on the conditions. The HeNB which is trying to add the channel then receives the message from the neighboring HeNBs. It will then compare the increase in capacity that is experienced by its own cells users with the loss in capacity reported by the neighboring HeNBs. Based on this comparison as described above, the node will decide whether to add the channel or not. If the gain is less than the loss, it will drop the channel; otherwise it will go ahead with the channel addition.

Since the previously described signaling methodology can be considered as a reactive scheme, an alternative suggestion is also put forth. The UEs measure the received signal strength of neighboring HeNBs at pre-defined time instances. Identification of neighboring HeNBs are done based on the physical cell identity. One assumption can be that the HeNBs operates on all channels at these pre-defined time instances when UEs make the measurements, so that perceived interference can be measured on all the channels. But this might give wrong estimates since when the measurements are taken, since all HeNBs transmit on all channels, the interference value could be higher than the actual value. Another assumption is that UEs measure the neighboring HeNBs on channels where the HeNBs are active and average Reference Signal Strength Indicator (RSSI) is used in the reports. Depending on the frequency selectivity of the channel response, there could be slight errors in the reported value, but it should still give a reasonably accurate estimate. The UEs then report these measurements to their HeNB and HeNBs exchange this information at regular intervals. Based on this report, HeNBs estimate the loss and gain on each channel and make channel assignment decisions.

This scheme clearly aims to improve the lower percentiles of the user throughput CDF (by taking into account the loss experienced by the worst users in each cell) as well as mean throughput (by taking into account the mean throughput gained by channel addition). Simulations were done with varying values of 'J' and it is shown that J=3 is optimal for the current setting.

Algorithm 2: Average Capacity Increase For Own Cell Users vs Sum Loss In Capacity Experienced By The Best Channel Loss Of 'K' Worst Neighboring Users Or Current Channel Loss Of The M^{th} Worst Neighboring User from the 'J' Worst Interfered Neighboring Cells

In this scheme, an HeNB keeps track of the best channel of each UE based on the SINR measurements reported by the UE over a period of time. If a neighboring HeNB is trying to add the best channel of the worst 'K' UEs, the capacity loss to the best channel after assignment is taken into account. In addition, the capacity loss of the next worse 'M' UEs on channel 'c' is evaluated. This algorithm takes into account the fact that the worst users can be scheduled on a different channel. Here it is assumed that the HeNB maintains a table of the best channel for each UEs and the SINR experienced by the UE in the best channel at all points of time. Consider the case where K = M = 2. Now, if the channel was the best channel for the worst user or the second worst user before the allocation was done, the HeNB node will report the worst user or second worst user capacity loss over the best channel before allocation and after allocation (whichever loss is greater). If the channel was not the best channel before allocation, then the loss on channel 'c' for the 2^{nd} worst user is considered. This algorithm is abbreviated as DFJNKWUB/MWUC (Distributed Fair; 'J' Neighbors; 'K' Worst Users Best channel loss / M^{th} Worst Users' Current channel loss) for future references. The logic behind the naming is that it is a Distributed Fair algorithm which considers 'J' interfered Neighboring cells, reporting the loss of 'K' Worst Users' Best channel loss or M^{th} Worst Users' Current channel loss.

Consider the case when channel 'n' is assigned to HeNB '0'. Let the average own user gain in capacity be $C_{(0,\mathrm{n})}$. Now, for the worst interfered neighboring nodes '1', '2', '3', ..., 'J' (where 'J' is the number of neighboring nodes whose losses are to be taken into account) let the capacity on the best channel for worst and second worst neighboring users estimated after the assignment be ($\hat{C}_{(\mathrm{Worst,1})}$, $\hat{C}_{(2^{\mathrm{nd}}\mathrm{Worst,1})}$); ($\hat{C}_{(\mathrm{Worst,2})}$, $\hat{C}_{(2^{\mathrm{nd}}\mathrm{Worst,2})}$); ($\hat{C}_{(\mathrm{Worst,3})}$, $\hat{C}_{(2^{\mathrm{nd}}\mathrm{Worst,3})}$); ... ; ($\hat{C}_{(\mathrm{Worst,J})}$, $\hat{C}_{(2^{\mathrm{nd}}\mathrm{Worst,J})}$). If channel 'n' was the best channel before assignment, let the capacity of worst and second worst user nodes before assignment be ($C_{(\mathrm{Worst,1})}$, $C_{(2^{\mathrm{nd}}\mathrm{Worst,1})}$); ($C_{(\mathrm{Worst,2})}$, $C_{(2^{\mathrm{nd}}\mathrm{Worst,2})}$); ($C_{(\mathrm{Worst,3})}$, $C_{(2^{\mathrm{nd}}\mathrm{Worst,3})}$); ... ; ($C_{(\mathrm{Worst,J})}$, $C_{(2^{\mathrm{nd}}\mathrm{Worst,J})}$). If the channel was the best channel for the worst and second worst user in each cell, the worst loss for HeNB 'j' (if channel 'c' is added for each of the neighboring cell) is estimated by taking:

$$C_{(\mathrm{Loss,j,c})} = Max\{(C_{(\mathrm{Worst,j})} - \hat{C}_{(\mathrm{Worst,j})}), (C_{(2^{\mathrm{nd}}\mathrm{Worst,j})} - \hat{C}_{(2^{\mathrm{nd}}\mathrm{Worst,j})})\} \tag{10}$$

But if the channel was not the best channel for the worst or second worst user, in this case the loss is calculated as:

$$C_{(\text{Loss,j,c})} = (\grave{C}_{(2^{\text{nd}}\text{Worst,j})} - \ddot{C}_{(2^{\text{nd}}\text{Worst,j})}) \tag{11}$$

Where the loss values $\grave{C}_{(2^{\text{nd}}\text{Worst,j})}$ and $\ddot{C}_{(2^{\text{nd}}\text{Worst,j})}$ are for the current channel 'c' rather than a difference between the best loss values. Finally, channel assignment is done if:

$$C_{(0,\text{c})} > (C_{(\text{Loss,1,c})} + C_{(\text{Loss,2,c})} + C_{(\text{Loss,3,c})} + ... + C_{(\text{Loss,j,c})}) \tag{12}$$

Here the working assumption is that each of the HeNB nodes maintain a table of the SINR values for each of the channels for the worst and second worst users. Hence when a new channel is added by a node, the neighboring nodes can compare the current channel capacity with the ones before the allocation was done and, depending on whether the newly added channel was the best channel for the neighboring node's UEs, the HeNBs can report back the corresponding loss values. Based on the values reported by the neighboring nodes, the HeNB which wants to add the channel can take a decision whether to add the channel or not. The difference between this

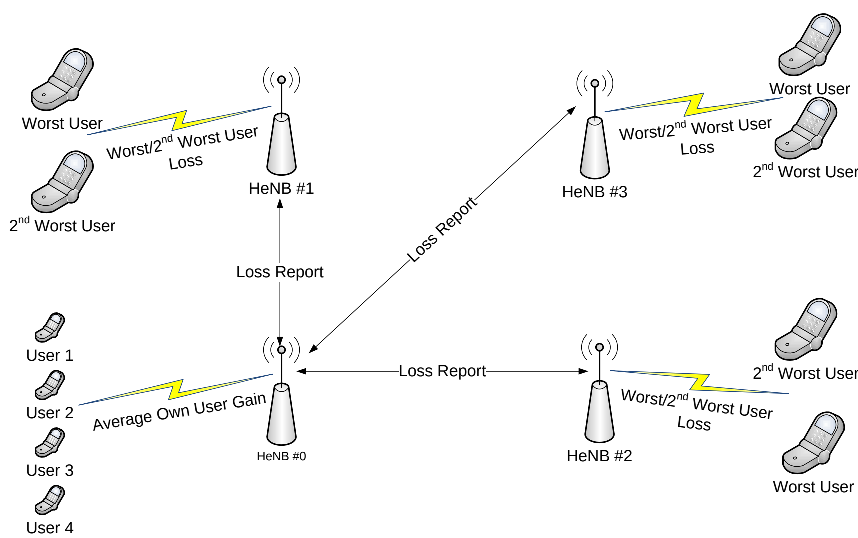

Figure 8: DFJNKWUB/MWUC Worst/2^{nd} Worst User Loss Signaling (J = 3, K = M = 2)

algorithm with the previously discussed one is that in specific scenarios the Worst User loss is not taken into account and the 2^{nd} Worst User loss is considered. Based on the results obtained this proves to be highly advantageous not only in terms of lower percentile users but also in terms of mean throughput gains. Note that detailed studies were done on the scenario mentioned in Section 3.1 where three of the worst interfering neighbors are taken into account. Based on the results, the optimal value for J, K and M are found to be 3, 2 and 2 respectively. Thus simulations are done by considering the loss reported by three of the worst interfered neighboring cells and difference between worst user loss and second worst user loss is taken into account for calculations.

Algorithm 3: Average Capacity Increase For Own Cell Users vs Worst User Best Channel loss or M^{th} Worst User Current Channel Loss from 'J' Worst Interfered Neighboring Cells

This scheme is similar to Scheme 2 (DFJNKWUB/MWUC), except for the fact that we are not considering the best channel losses for the second worst user (i.e. 'K' is always 1.). Here we compare the average own user capacity gain with the best channel loss for the worst user before and after assignment (if channel 'c' was the best channel for the node before assignment was done) or if the channel was not the best channel for the worst user, the loss due to the addition of channel 'c' for the M^{th} Worst User is considered (i.e. the capacity on channel 'c' before assignment and after assignment). This algorithm is abbreviated as DFJNWUB/MWUC (Distributed Fair; 'J' Neighbors; Worst Users Best channel loss / M^{th} Worst Users' Current channel loss) for future references. The logic behind the naming is that it is a Distributed Fair algorithm which considers 'J' interfered Neighboring cells, reporting the loss of Worst Users' Best channel loss or M^{th} Worst Users' Current channel loss.

Consider the case where M = 2. First an assignment of channel 'c' is done on the HeNB '0'. Let the average own user gain in capacity be $C_{(0,c)}$. Now, for the worst interfered neighboring nodes '1', '2', '3', ..., 'J' (where 'J' is the number of neighboring nodes whose losses are to be taken into account); let the capacity on the best channel for worst neighboring user estimated after the assignment be: $(\hat{C}_{(Worst,1)})$; $(\hat{C}_{(Worst,2)})$; $(\hat{C}_{(Worst,3)})$; ...; $(\hat{C}_{(Worst,J)})$. If channel 'c' was the best channel before assignment, let the capacity of worst user nodes before assignment be: $(C_{(Worst,1)})$; $(C_{(Worst,2)})$; $(C_{(Worst,3)})$; ...; $(C_{(Worst,J)})$. If the channel was the best channel for the worst user in each cell, the worst loss if channel 'c' is added for each of the neighboring cell 'j' is estimated by taking:

$$C_{(Loss,j,c)} = C_{(Worst,j)} - \hat{C}_{(Worst,j)} \tag{13}$$

or if channel 'n' was not the best channel for the worst user, the loss in cell 'k' before assignment:

$$C_{(Loss,j,c)} = \grave{C}_{(2^{nd}Worst,j)} - \ddot{C}_{(2^{nd}Worst,j)} \tag{14}$$

Where

- $C_{(Loss,j,n)}$ is the capacity loss
- $C_{(Worst,j)}$ is best channel loss of worst user under HeNB 'j' before assignment is done

- $\hat{C}_{(Worst,j)}$ is the best channel loss of worst user under HeNB 'j' after assignment is done
- $\grave{C}_{(2^{nd}Worst,j)}$ is the capacity of the newly added channel 'c' before assignment is done for the second worst user
- $\ddot{C}_{(2^{nd}Worst,j)}$ is the capacity of the newly added channel 'c' after assignment is done for the second worst user

Where the loss values $\grave{C}_{(2^{nd}Worst,j)}$ and $\ddot{C}_{(2^{nd}Worst,j)}$ are for the current channel 'c' rather than a difference between the best loss values. Finally, channel assignment is done if:

$$C_{(0,c)} > (C_{(Loss,1)} + C_{(Loss,2)} + C_{(Loss,3)} + ... + C_{(Loss,j)}) \tag{15}$$

Here, as in the previous case, the working assumption is that each of the HeNB nodes maintain a table of the SINR values for each of the channels for the worst and second worst users. Hence when a new channel is added by a node, the neighboring nodes can compare the current channel capacity with the ones before the allocation was done and depending on whether the newly added channel was the best channel for the neighboring node's UEs, the HeNBs can report back the corresponding loss values. Based on the values reported by the neighboring nodes, the HeNB which wants to add the channel can take a decision whether to add the channel or not. In this case also, fairness constraints are taken into account by considering the worst user loss in case the channel was the best channel for the worst user in the neighboring cell before the assignment is done as well as considering the 2^{nd} worst user in case that condition is not met. Note that detailed studies were done on the scenario mentioned in Section 3.1 with J=3 and M=2.

Algorithm 4: Worst Own Cell User Capacity Increase vs Average Capacity Loss for all the Interfered Neighboring Cell Users

This scheme takes into account the capacity gained by the user having the worst channel conditions of an HeNB on adding a new channel and compares it to the average capacity lost by all users in neighboring interfered cells. This algorithm is abbreviated as DFANWUC (Distributed Fair; All Neighbors; Worst User; Current Channel) for future references. The acronym can be elaborated as Distributed Fair algorithm, considering All Neighboring interfered cells, Worst Users' Current channel loss from each cell is considered. Let HeNB '0' be the node trying to add the new channel 'c'. Let there be 'J' neighboring nodes which are interfered by the addition of channel 'c' by HeNB '0'. Let $C_{(j,c)}$ be the average capacity of all the users served by HeNB 'j' on all 'c-1' channels before assignment is done and $\ddot{C}_{(j,c)}$ be the average capacity after the allocation is done. Also let $C_{(0,c)}$ be the estimated capacity gain by adding channel 'c' for the user with worst channel condition in HeNB '0'.

The average loss in capacity for HeNB 'j' is:

$$C'_{(j,c)} = C_{(j,c)} - \ddot{C}_{(j,c)} \tag{16}$$

The total average loss in capacity is calculated as:

$$C_{(Loss)} = (\sum_{j=1}^{J} C'_{(j,c)})/J \tag{17}$$

Finally, channel assignment is done if:

$$C_{(0,c)} > C_{(Loss)} \tag{18}$$

In this scheme, it is essential for all the nodes to keep track of the capacity values estimated for the UEs linked to it. When UEs report a reduction in capacity the nodes should be able to calculate the loss and report it to the neighboring nodes. The HeNB which is adding the channel will receive this information and will be able to compute the total average loss experienced by all the interfering cells and compare it with the capacity gained by the user with the worst channel conditions. Based on this comparison it decides whether to add the channel or drop it. The fairness constraint here is that this algorithm gives weightage to all the users having the bad channel conditions on a particular channel. Since a simple addition is done on the loss values, it effectively gives weight to the lowest loss value and hence can be greedy if there are a lot of cells which are not heavily interfered.

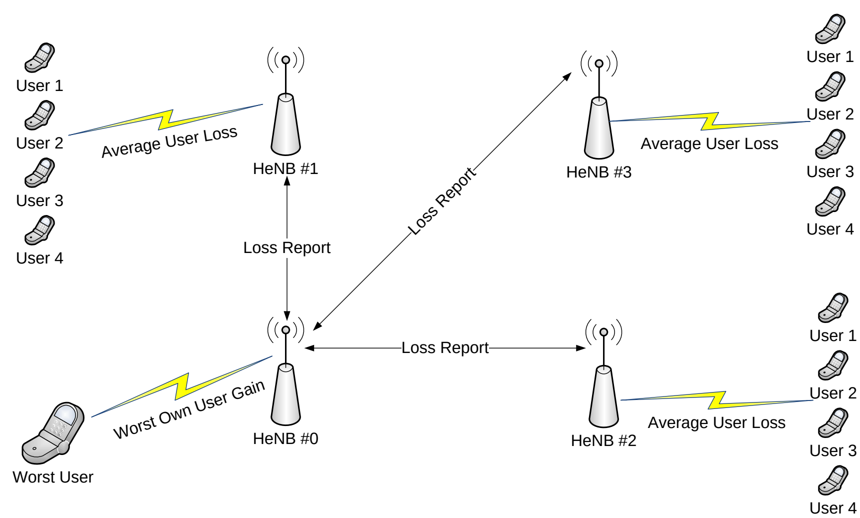

Figure 9: DFANWUC Worst Own User Gain and Neighboring Average User Loss Signaling

4.2.2 Greedy Distributed Capacity Based Channel Allocation Algorithms

In this section we will discuss greedy distributed capacity based channel allocation algorithms. As the name suggests the algorithms are comparatively greedy in choosing channels and in most cases the channel allocation comes very close to Reuse-1 (RU-1) allocation. A detailed description of algorithms are as discussed below.

Algorithm 1: Capacity Increase For Own Cell User having the Best Channel Conditions vs Loss Metrics Described in Schemes DFJNWUC to DFANWUC

The algorithms described previously can be made more greedy by taking the capacity gain for the user with best channel conditions into account while channel allocation. When this gain is compared to the losses described in DFJNWUC, DFJNKWUB/MWUC, DFJNKWUB/MWUC & DFANWUC the algorithms inherently begin to add channels more aggressively. The corresponding algorithms are abbreviated as DGJNWUC, DGJNKWUB/MWUC, DGJNKWUB/MWUC & DGANWUC (where DG represents Distributed Greedy algorithms) for future references. Due to the aggressive addition of channels, the channel allocation pattern closely resembles Reuse-1 allocation as mentioned previously and also the mean throughput performance also becomes very close to RU-1.

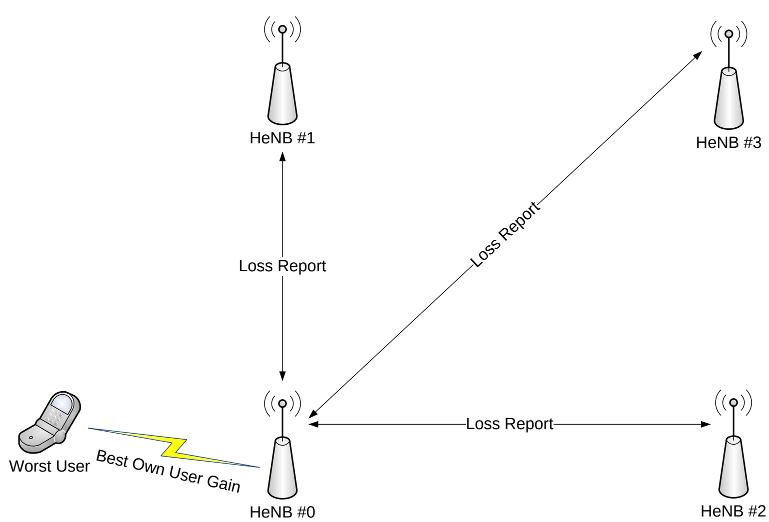

Figure 10: DGJNWUC, DGJNKWUB/MWUC, DGJNKWUB/MWUC & DGANWUC, Best Own User Gain and Corresponding Neighboring User Loss Signaling (J = 3)

These strategies, effectively cause the HeNBs to compete against each other in trying to occupy as many channels as possible, thereby increasing the mean throughput of the cell at the expense of increased outage for users in challenging interference conditions.

Algorithm 2: Average Capacity Increase For Own Cell Users vs Sum Loss In Capacity Experienced By 'J' Worst Interfered Neighboring Cells; Metric Not Considered if HeNB has less than 'L' Channels

This algorithm uses the same metric as DFJNWUC, but the metric is not considered if the HeNB has less than 'L' number of channels, where 'L' is configurable. This essentially behaves as a greedy scheme and makes sure that the HeNBs have at least 'L' number of channels. Otherwise the algorithm uses the same logic as DGJNWUC and the HeNBs keep track of the number of channels they possess and will go for those channels which do not meet the conditions until they have the requisite minimum number of channels. This scheme is useful in cases where the cells are overloaded with a large number of users and a fair scheme will noticeably affect the higher percentile user throughput as well as the mean user throughput. The algorithm is abbreviated as DGJNWUC-LC (Distributed Fair; J Neighbors; Worst User; Current channel loss; 'L' minimum Channels) for future reference. The logic behind the naming is that it is a Distributed Fair algorithm which considers 'J' interfered Neighboring cells reporting their Worst User Current channel loss, the metric is ignored if node has less than 'L' Channels.

4.3 Centralized Multi-Channel Allocation Schemes

The centralized channel allocation algorithms studied are described in this section. The studies were done to understand the performance of the distributed algorithms in terms of lower percentile and mean user throughput. From an implementation perspective centralized algorithms are very difficult to implement in practice since they grow fast in complexity and do not scale well to large networks. Further it requires a large amount of signaling. The detailed description of the algorithms developed and studied are as given below.

4.3.1 Algorithm 1: Greedy-Centralized Maximize Mean-Throughput Allocation Scheme

In this scheme, we assume that there is a centralized intelligence which does the channel allocation for all the HeNBs in the network.

The centralized intelligence goes through various combinations of allocations from 1 to 'n' number of channels for the nodes in each building and an allocation is done which provides the maximum mean throughput in the building. This study helps in comparing the mean throughput results obtained from the distributed algorithms with a possible sub-optimal allocation which provides the best possible mean throughput values. The detailed description of the algorithm is as given in Algorithm 1.

Algorithm 1 Centralized Maximize Mean-Throughput Algorithm for 5-Operational Channels; 4-Apartments/Floor Building.

```
ChComb ← [32 Unique Channel Combinations Possible Per Node]
nodeResources_m ← Reuse_1
NumCh ← SizeOf(ChComb) - 1
for bldgNum = 1 to N_Buildings do
  CapacityOld ← FindCurrentMeanUserThroughputInBldg()
  for floorNum = 1 to N_Floors do
    NodesInBldgFloor ← FindNodesInBuildingFloor()
    for i = 0 to NumCh do
      nodeResources_m[NodesInBldgFloor[0]] ← ChComb[i]
      for j = 0 to NumCh do
        nodeResources_m[NodesInBldgFloor[1]] ← ChComb[j]
        for k = 0 to NumCh do
          nodeResources_m[NodesInBldgFloor[2]] ← ChComb[k]
          for k = 0 to NumCh do
            nodeResources_m[NodesInBldgFloor[3]] ← ChComb[l]
            CapacityNew ← FindCurrentMeanUserThroughputInBldg()
            if (CapacityNew > CapacityOld) then
              bestResourceAssnmt_m ← nodeResources_m
              CapacityOld ← CapacityNew
            end if
          end for
        end for
      end for
    end for
  end for
  CapacityOld ← FindCurrentMeanUserThroughputInBldg()
end for
nodeResources_m ← bestResourceAssnmt_m
```

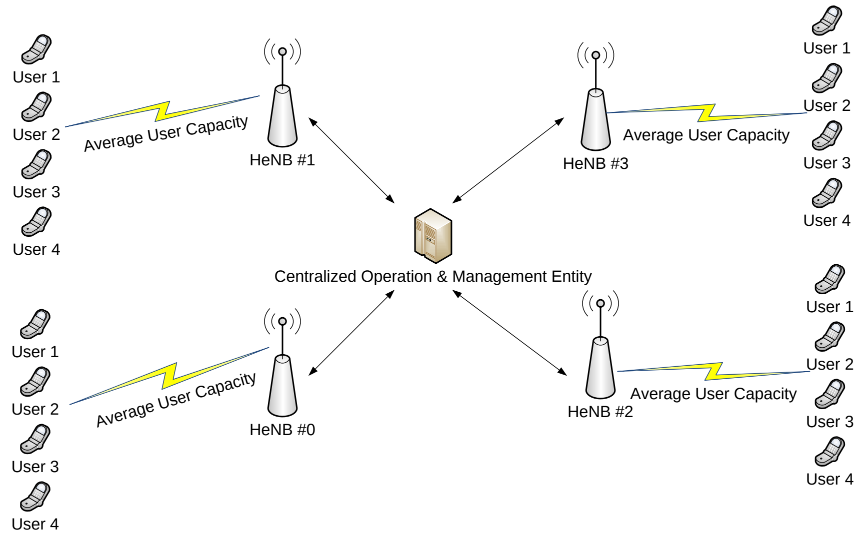

Figure 11: Centralized Maximize Mean-Throughput Network Scheme (Single Floor Layout 4 UE/Apartment)

As described above, the algorithm effectively tries to maximize the mean throughput in a building by finding an allocation among all the possible allocations which attains this goal. The algorithm described here is for a multi-floor building having four apartments per floor and total number of operational channels is assumed to be five. The allocation is done floor by floor. At each iteration the mean throughput in the building is compared to the best mean throughput value from the allocations done so far and the allocation which provides the best mean throughput is selected. This algorithm is abbreviated as CMM-TA (Centralized Maximize Mean-Throughput Allocation) for future reference.

4.3.2 Algorithm 2: Fair-Centralized Maximize Worst User-Throughput Allocation Scheme

A centralized algorithm which maximizes the throughput experienced by the user with worst channel conditions is also studied. Here the algorithm assumes the presence of a centralized intelligence which has complete knowledge of the channel conditions enjoyed by all the users and makes decisions with the use of this knowledge. Here the worst user capacity of each cell is maximized in a multi-floor scenario. The detailed description of the algorithm is as given in Algorithm 2.

This algorithm is a benchmark to compare the results obtained for the lower percentile user throughput of the distributed algorithm for the lower percentile users as compared to a near-ideal allocation which provides the best possible allocation for the lower percentile users who experience the worst channel conditions.

Algorithm 2 Centralized, Maximize Worst User-Throughput Algorithm for 5 Operational Channels; 4 Apartments/Floor Building.

```
ChComb ← [32 Unique Channel Combinations Possible Per Node]
nodeResources_m ← Reuse_1
NumCh ← SizeOf(ChComb) - 1
for bldgNum = 1 to N_Buildings do
  WorstCapacityCell0 ← FindWorstUserThroughputInCell0()
  WorstCapacityCell1 ← FindWorstUserThroughputInCell1()
  WorstCapacityCell2 ← FindWorstUserThroughputInCell2()
  WorstCapacityCell3 ← FindWorstUserThroughputInCell3()
  CapacityOld ← (WorstCapacityCell0 + WorstCapacityCell1+
  WorstCapacityCell2 + WorstCapacityCell3)
  for floorNum = 1 to N_Floors do
    NodesInBldgFloor ← FindNodesInBuildingFloor()
    for i = 0 to NumCh do
      nodeResources_m[NodesInBldgFloor[0]] ← ChComb[i]
      for j = 0 to NumCh do
        nodeResources_m[NodesInBldgFloor[1]] ← ChComb[j]
        for k = 0 to NumCh do
          nodeResources_m[NodesInBldgFloor[2]] ← ChComb[k]
          for k = 0 to NumCh do
            nodeResources_m[NodesInBldgFloor[3]] ← ChComb[l]
            WorstCapacityCell0 ← FindWorstUserThroughputInCell0()
            WorstCapacityCell1 ← FindWorstUserThroughputInCell1()
            WorstCapacityCell2 ← FindWorstUserThroughputInCell2()
            WorstCapacityCell3 ← FindWorstUserThroughputInCell3()
            CapacityNew ← (WorstCapacityCell0 + WorstCapacityCell1
            +WorstCapacityCell2 + WorstCapacityCell3)
            if (CapacityNew > CapacityOld) then
              bestResourceAssnmt_m ← nodeResources_m
              CapacityOld ← CapacityNew
            end if
          end for
        end for
      end for
    end for
  end for
  WorstCapacityCell0 ← FindWorstUserThroughputInCell0()
  WorstCapacityCell1 ← FindWorstUserThroughputInCell1()
  WorstCapacityCell2 ← FindWorstUserThroughputInCell2()
  WorstCapacityCell3 ← FindWorstUserThroughputInCell3()
  CapacityOld ← (WorstCapacityCell0 + WorstCapacityCell1+
  WorstCapacityCell2 + WorstCapacityCell3)
end for
nodeResources_m ← bestResourceAssnmt_m
```

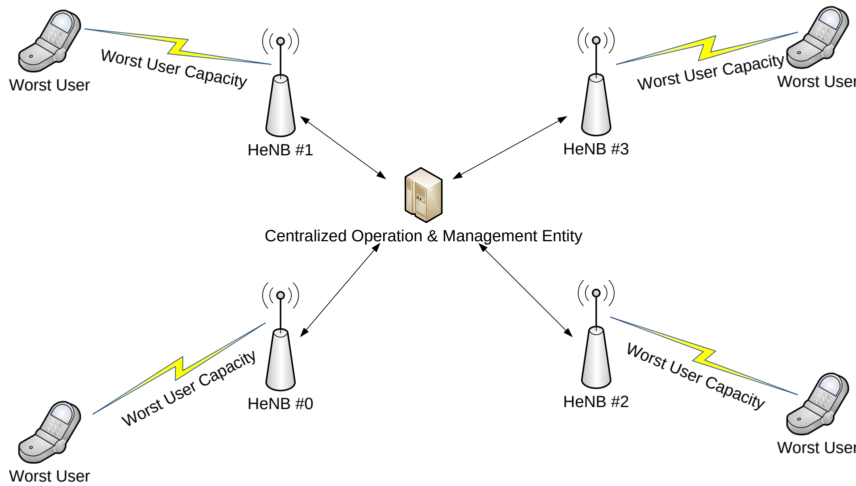

Figure 12: Centralized Maximize Worst User-Throughput Network Scheme (Single Floor Layout)

This algorithm is abbreviated as CMWU-TA (Centralized Maximize Worst User-Throughput Allocation) for future reference.

5 System Performance Analysis

Various resource allocation schemes were discussed in Section 4. This section intends to provide a holistic analysis of the results obtained by using the resource allocation schemes described and observations are drawn on the system performance improvement with the help of using those schemes. One of the main intentions of this chapter is to perform a comprehensive analysis of the result obtained in various scenarios.

In this section, the Downlink User Throughput curves for 1-Floor and 3-Floor scenarios will be studied for the different schemes for Finite and Infinite buffer conditions. SINR curves for the proposed schemes will also be discussed in detail. Various other results such as the HeNB-Resource Allocation Pattern study, results with the Proportional Fair and Round-Robin Scheduler, the impact of wall-attenuation and the flexibility of the algorithms, varying the number of neighbor losses taken into account and the number of user losses within the neighbors, etc will also be discussed.

5.1 One Floor Infinite Buffer Scenario

In this section we will discuss the results obtained for a one-floor, infinite buffer (full buffer), 5-Operation Channel scenario in terms of downlink throughput and SINR values obtained for the different channel allocation schemes mentioned in Section 4. The throughput curves are as shown in Figures 13,14 and 15. The following observations can me made from the results:

- From Figure 13 we can observe that in terms of lower percentile throughput, the distributed capacity based algorithms DF3NWUC, DF3N2WUB/2WUC and DF3NWUB/2WUC perform really well and the performance is comparable to the centralized worst user throughput maximization algorithm CMWUTA. It can also be observed that these algorithms provide better lower percentile throughputs compared to Reuse-1 for at least 50% of users experiencing bad channel conditions (for DF3NWUC) and close to 60% of users for DF3N2WUB/2WUC and DF3NWUB/2WUC.

- The steps seen in remarkably strongly in DF3NWUC and slightly more smoother in other distributed capacity based algorithms is due to the difference in channel allocation for various access points. For example, some HeNBs are allotted all the 5-Operational Channels and hence they experience the highest possible user-throughput forms one step, similarly the HeNBs with 4-Operational Channels occupy the next lower step and so on.

- It can also be observed from figure 14 that as expected, greedy algorithms perform only slightly better compared to Reuse-1 and DGANWUC performs slightly worse than Reuse-1. The Greedy-Centralized maximize mean throughput allocation scheme performs slightly better than Reuse-1 in terms of mean throughput with the help of better performance at higher percentiles.

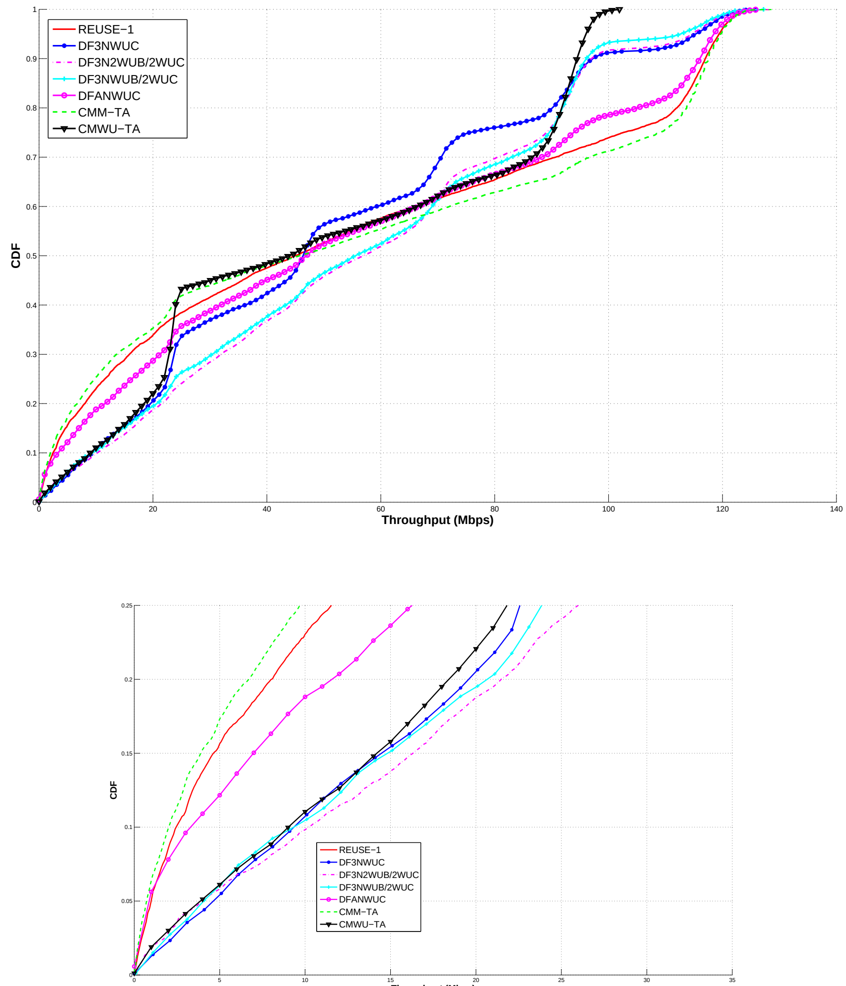

Figure 13: Downlink Throughput Curves, Fair & Centralized Algorithms (Single Floor Layout, Infinite Buffer Scenario)

- Figure 15 shows that Greedy algorithms DG3N2WUB/2WUC and DG3NWUB/ 2WUC gives better performance in lower percentiles as compared to Reuse-1 and other greedy algorithms.

The SINR curves are as shown in Figure 16 and the following inferences are made from the same:

- Except for DGANWUC, all the other algorithms are giving better SINR performance compared to Reuse-1.

- Since excessive focus is given for the worst user in a cell, the centralized maximize worst user-throughput algorithm (CMWU-TA) gives the best SINR performance compared to other algorithms. DF3NWUC gives comparable

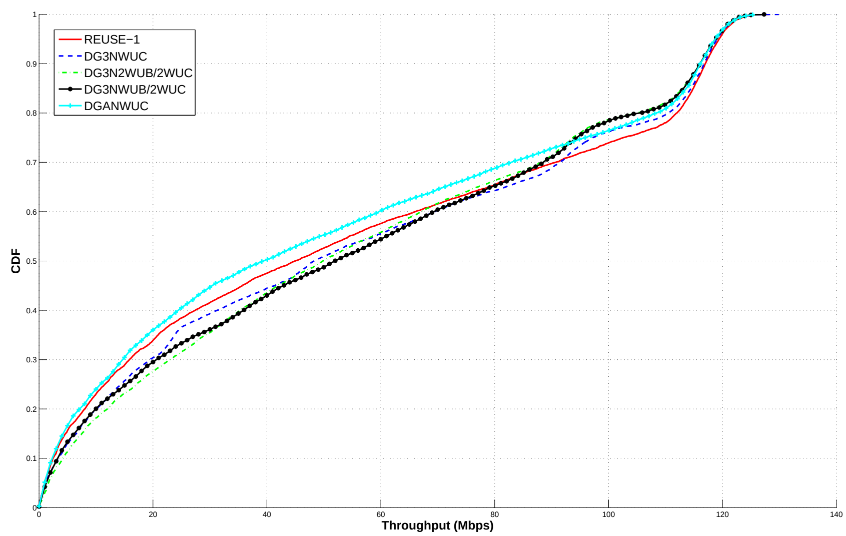

Figure 14: Downlink Throughput Curves, Greedy Algorithms (Single Floor Layout, Infinite Buffer Scenario)

performance to CMWU-TA in terms of the SINR values experienced by the users and performs remarkably well compared to DF3N2WUB/2WUC and DF3NWUB/2WUC.

- DFANWUC, DG3NWUC, DG3N2WUB/2WUC, DG3NWUB/2WUC and CMM-TA give very close performance in terms of the SINR values experienced by the users.

- The detailed 5^{th} percentile and Mean Throughput values are as given in Figures 18 and 17 respectively.

- As shown in Figures 18 and 17, DF3NWUC gives excellent 5^{th} percentile gains (4.7 times Reuse-1 value) without much loss (around 6% increase to Reuse-1) in mean throughput values.

- DF3N2WUB/2WUC and 3 gives 4 times the 5^{th} percentile throughput value as compared to Reuse-1 with slight gains in mean throughput values (3-4% increase compared to Reuse-1).

- CMM-TA performs marginally better than Reuse-1 (2% Mean Throughput increase) and the reason for only a marginal increase is due to the fact that since the mean throughput maximization occurs per building the final allocation is not the optimal allocation, but only a near-optimal one since the change in allocation in the one building affects the optimal allocation in the neighboring buildings. CMWU-TA gives 4 times the 5^{th} percentile throughput of Reuse-1.

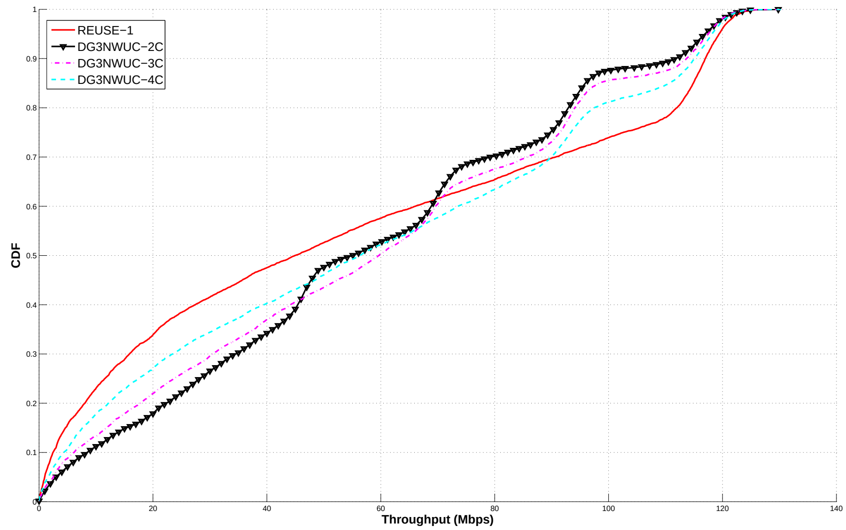

Figure 15: Downlink Throughput Curves, DG3NWUC-LC Greedy Algorithm with L=2,3,4 (Single Floor Layout, Infinite Buffer Scenario)

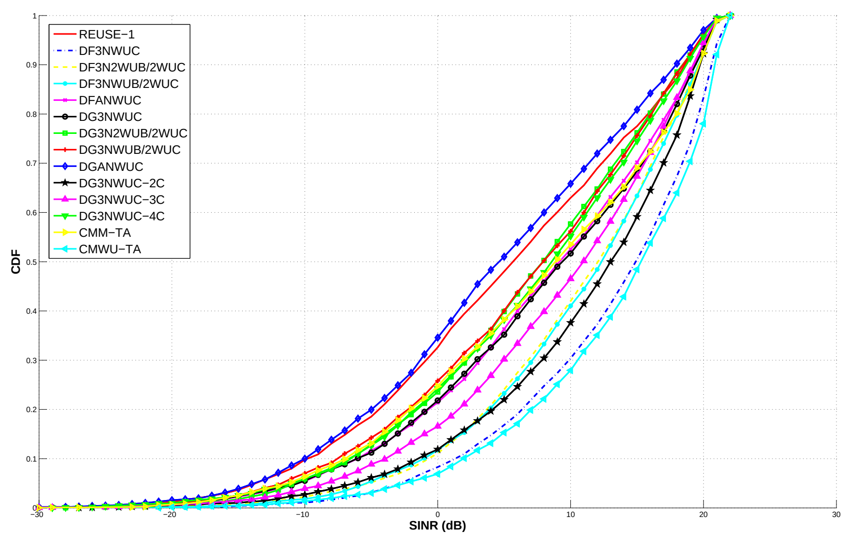

Figure 16: Downlink SINR Curves (Single Floor Layout, Infinite Buffer)

- DG3NWUC, DG3N2WUB/2WUC, DG3NWUB/2WUC & DG3NWUC-LC with (L=2,3,4) give better throughput values as compared to Reuse-1 and marginally better 5^{th} percentile throughput values as well. DG3NWUC-LC with L=2,3 and 4 gives more than 5% mean throughput gains, with excellent 5^{th} percentile throughput values as well (3, 2.5 and 1.7 times Reuse-1).

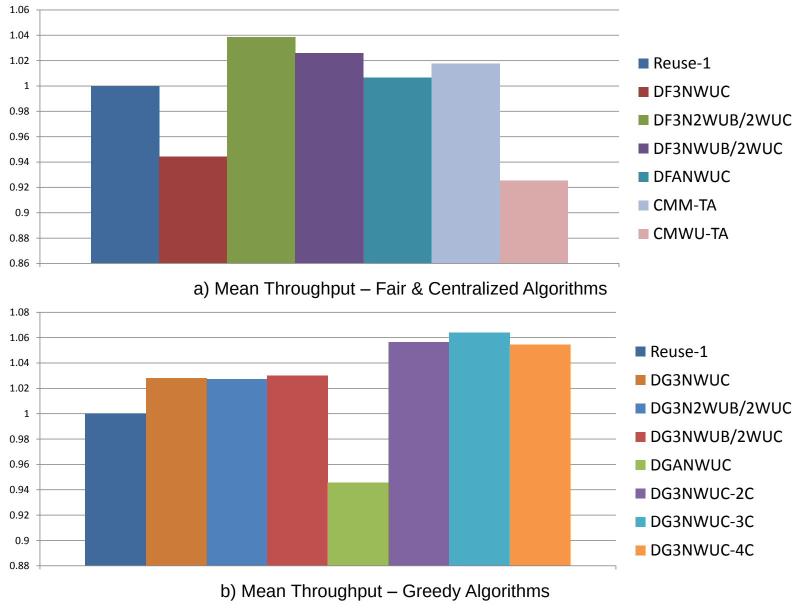

Figure 17: Normalized Mean Throughput values for One Floor Infinite Buffer

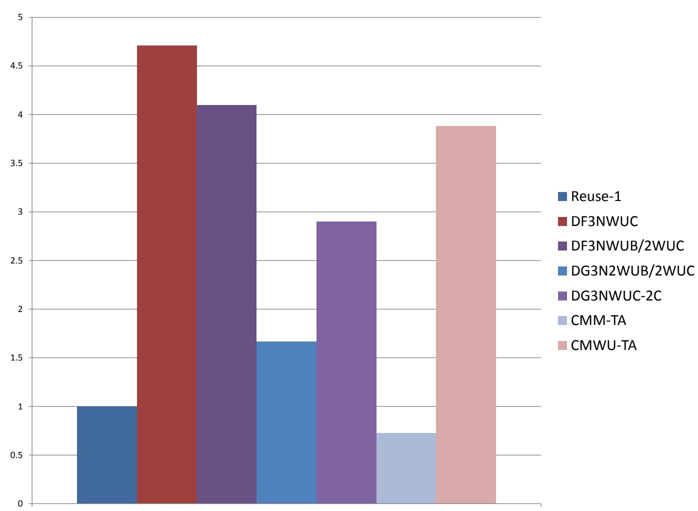

Figure 18: Normalized 5^{th} Percentile Throughput values for One Floor Infinite Buffer

- SINR values of DG3NWUC-LC(L=2 and 3) are comparable to the fair algorithms DF3N2WUB/2WUC & DF3NWUB/2WUC, with N=2 even performing slightly better than the fair algorithms. DG3NWUC-LC(L=4) performs similar to the other greedy algorithms such as DG3NWUC, DG3N2WUB/2WUC & DG3NWUB/2WUC.
- The number of channel distributed for HeNBs is as given is Figure 19.

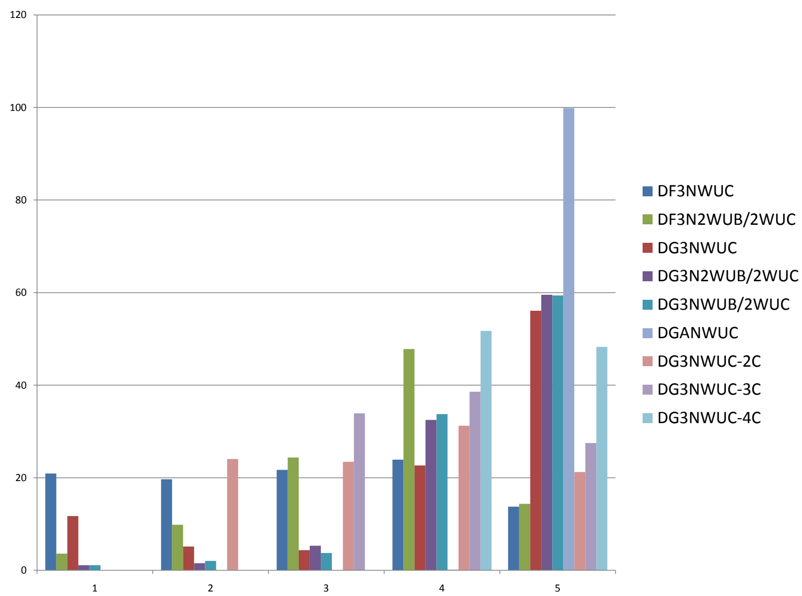

Figure 19: HeNB-No. of Channels Distribution for One Floor Infinite Buffer

5.2 One Floor Finite Buffer Scenario with Mean Data Rate of 40Mbps

In this section we will discuss the performance results for the algorithms by using finite buffer conditions and data is transmitted with a mean data rate of 40Mbps. As done in the previous section we will consider the downlink throughtput and SINR values obtained. The throughput curves are as shown in Figure 20 and 21.

The following observations can be made from the results:

- All the algorithms considered are giving better lower percentile throughput as compared to Reuse-1.
- Since DG3NWUC, DG3N2WUB/2WUC, DG3NWUB/2WUC & DGANWUC are giving similar results as in the previous case, the results are not presented here.
- From Figure 20, we can observe that DF3N2WUB/2WUC & DF3NWUB/2WUC performs remarkably well under finite buffer conditions in terms of lower percentile throughputs and mean throughput values. As can be observed from Figures 23 and 24, mean throughput is increased by more than 20% for both the algorithms and 5^{th} percentile throughput is more than 7 times the Reuse-1 values. Since these two algorithms essentially make sure that the best channel for the worst or 2^{nd} Worst UEs is not lost and results clearly indicate that this logic yields high gains on the parameters considered.
- DF3NWUC gives 5.5 times Reuse-1 5^{th} percentile throughput with a 12% gain in mean throughput value, whereas DFANWUC performs the worst among the

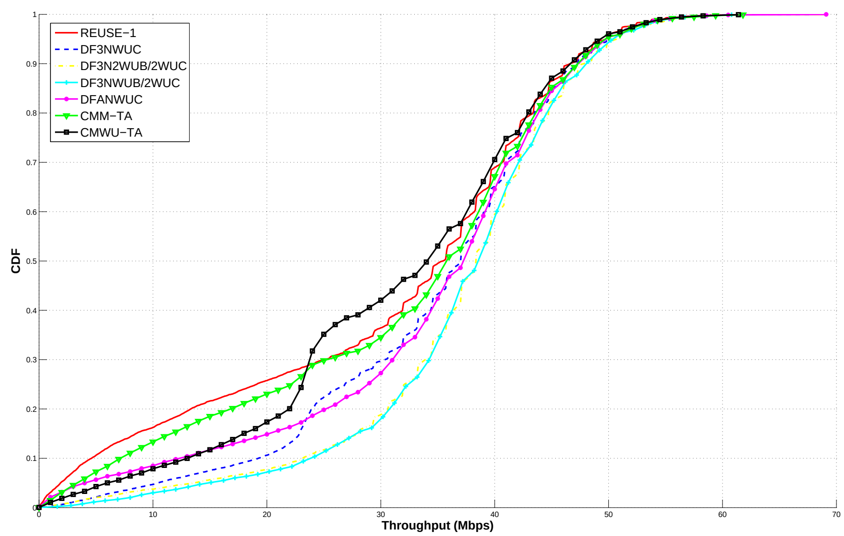

Figure 20: Downlink Throughput Curves (Fair & Centralized Algorithms, Single Floor Layout, Finite Buffer Scenario, 40Mbps Mean Data Rate)

distributed algorithms with 11% gain in mean throughput and 2.2 times 5^{th} percentile value. When comparing the results of DF3NWUC and DG3NWUC-LC (L=2,3,4), it is evident that in real-time scenarios where full-buffer conditions do not exist, being too restrictive might not yield the desired results.

- Figure 21 shows that DG3NWUC-LC performs well for L = 2, 3 and 4 which is reflected in the throughput comparison graphs as well. This shows that for finite buffer conditions, essentially restricting HeNBs to just one channel might not prove advantageous in terms of improving mean and lower percentile throughput values. A restrictive greedy algorithm like DG3NWUC-LC will yield better results under such conditions.

- Centralized algorithms CMM-TA and CMWU-TA is getting locally optimized allocations and hence are not performing as well as the distributed algorithms. But they are yielding results better than Reuse-1 allocation.

- Another observation regarding the greedy algorithm is that the mean throughput value for N = 2 is slightly better than N = 3 which again performs better than N = 4. Hence it can be inferred that in a non-limiting case, having too many channels essentially does not yield better mean throughput values, as shown by the Reuse-1 result, which is considerably worse compared to the relative values for the infinite buffer case.

The SINR curves are as shown in Figure 22 and the following inferences are made from the same:

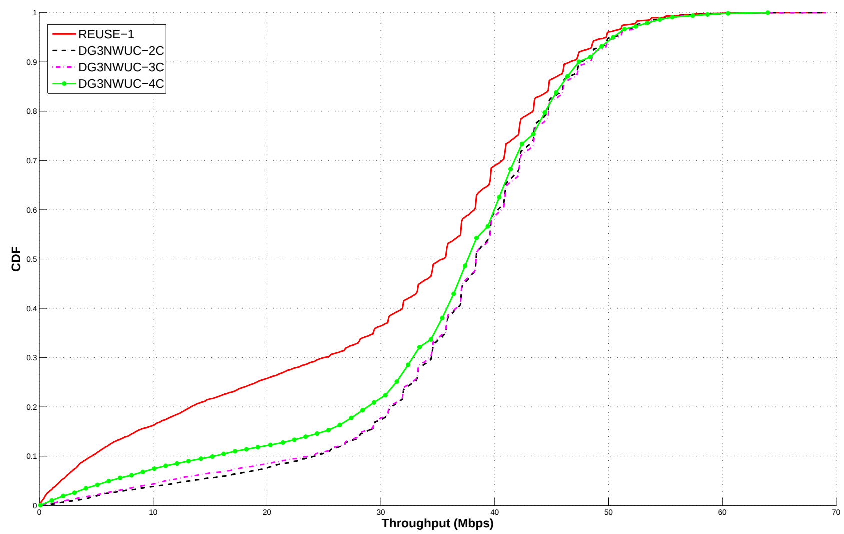

Figure 21: Downlink Throughput Curves (Greedy Algorithm DG3NWUC-LC (L=2,3,4), Single Floor Layout, Finite Buffer Scenario, 40Mbps Mean Data Rate)

- The SINR curves are similar to the infinite buffer scenario. The main difference is that with the allocation due finite buffer conditions, all the algorithms both centralized and distributed are giving better SINR performance as compared to Reuse-1. As was the case previously, CMWU-TA and DF3NWUC give the best SINR distribution for the UEs.

- Since the allocation of DG3NWUC-LC with L = 4 is very similar to Reuse-1 (except the fact that close to 50% of the HeNBs have only 4 channels), the SINR curves of Reuse-1 and DG3NWUC-4C are close.

- DG3NWUC-LC with L = 2, DF3N2WUB/2WUC & DF3NWUB/2WUC also yields really good SINR distribution for the end-users.

The channel distribution for HeNBs is described in Figure 25 and some interesting observations can be made regarding the channel allocation pattern of distributed algorithms in this scenario.

- One key observation is that DF3NWUC, DF3N2WUB/2WUC & DF3NWUB/2WUC utilizes considerably less number of channels as compared to Reuse-1 and still is able to give really good performance for lower percentile users and in terms of mean throughput. For example, with DF3NWUC allocation less than 12% of HeNBs have all the available 5 channels allocated and 21% of HeNBs have only 1 channel allocated. This again establishes that under non-full buffer conditions a conservative allocation can yield very good results.

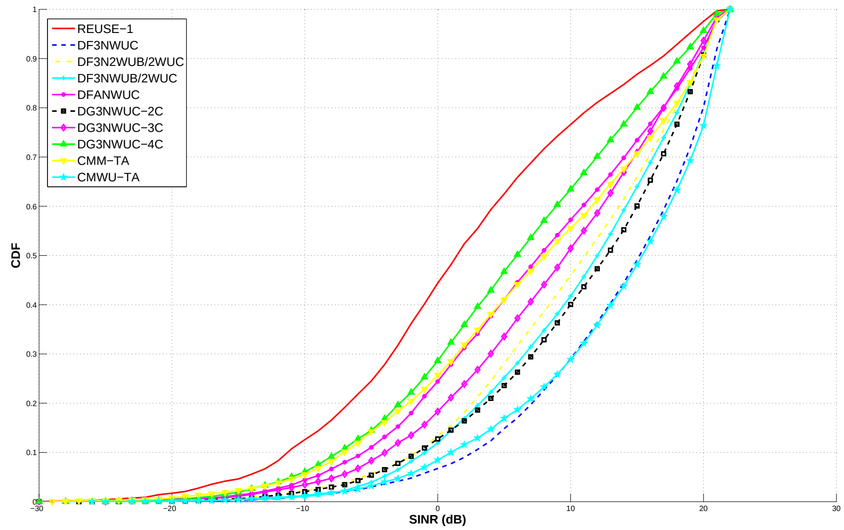

Figure 22: Downlink SINR Curves (Single Floor Layout, Finite Buffer Scenario, 40Mbps Mean Data Rate)

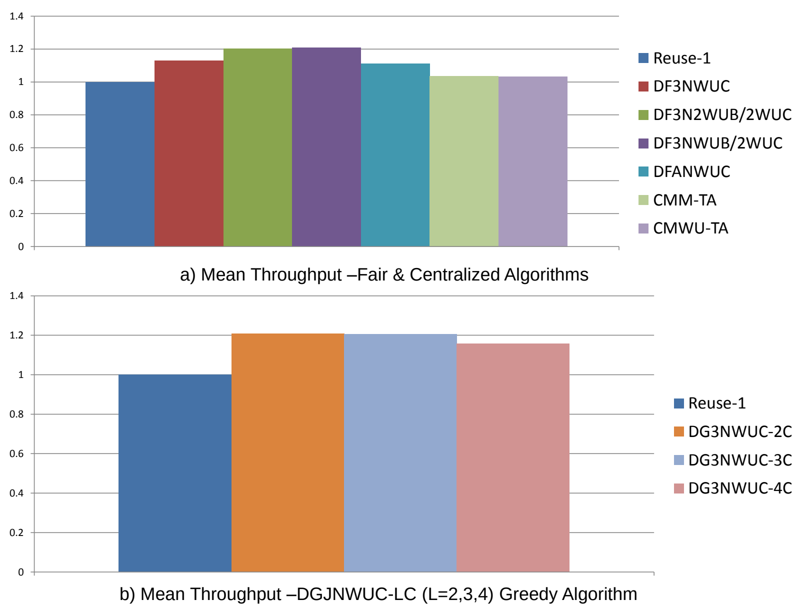

Figure 23: Normalized Mean Throughput values for One Floor Finite Buffer Scenario

- DF3N2WUB/2WUC & DF3NWUB/2WUC are slightly less conservative with close to 50% of HeNBs allocated with 4 channels and around 14% with all 5 channels, hence yielding very good overall performance in terms of mean throughput values and lower percentile throughputs.

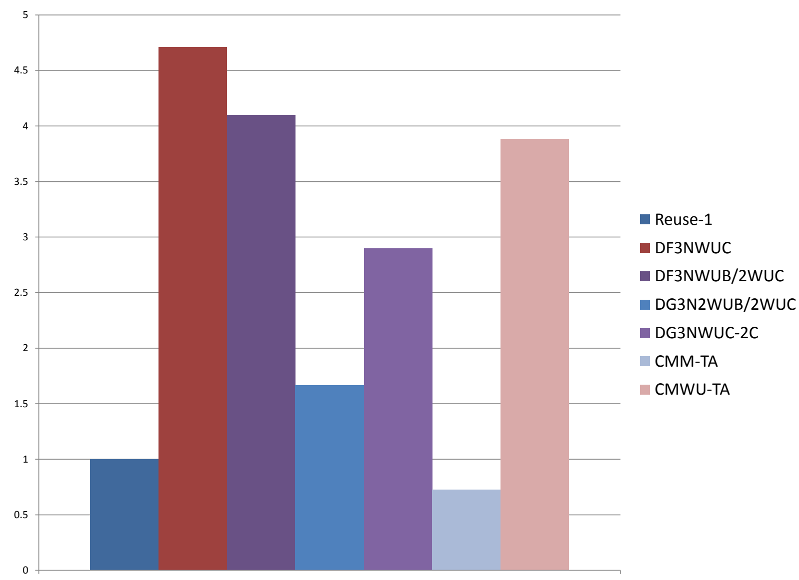

Figure 24: Normalized 5^{th} Percentile Throughput values for One Floor Finite Buffer Scenario

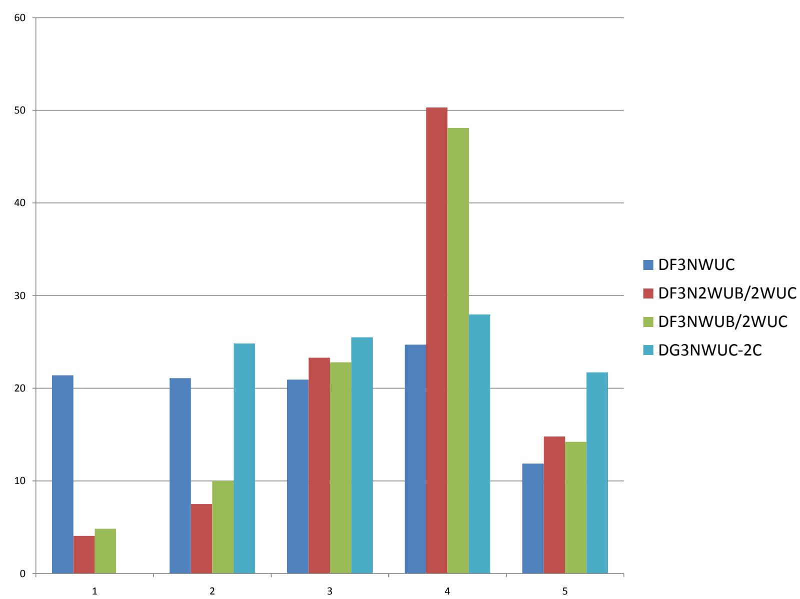

Figure 25: HeNB-No. of Channels Distribution For One Floor Finite Buffer Scenario

- DG3NWUC-LC with L=2 which yields the best results under the circumstances has slightly less conservative allocation with more than 50% of HeNBs having 2 and 3 channels further strengthens the previous observation.

5.3 Three-Floor Infinite Buffer Scenario

The one-floor scenario was further expanded to a three floor building and the algorithms were tested in such a scenario explicitly to establish the durability of the algorithm under heavy interference conditions. A three floor scenario is far more challenging compared to a single floor layout since there are multiple levels where HeNBs are present, hence increasing the interference experienced by the UEs. This section discusses mainly the downlink throughput and SINR results obtained from this scenario.The throughput and SINR curves are as shown in Figures 26, 27 and 28 respectively.

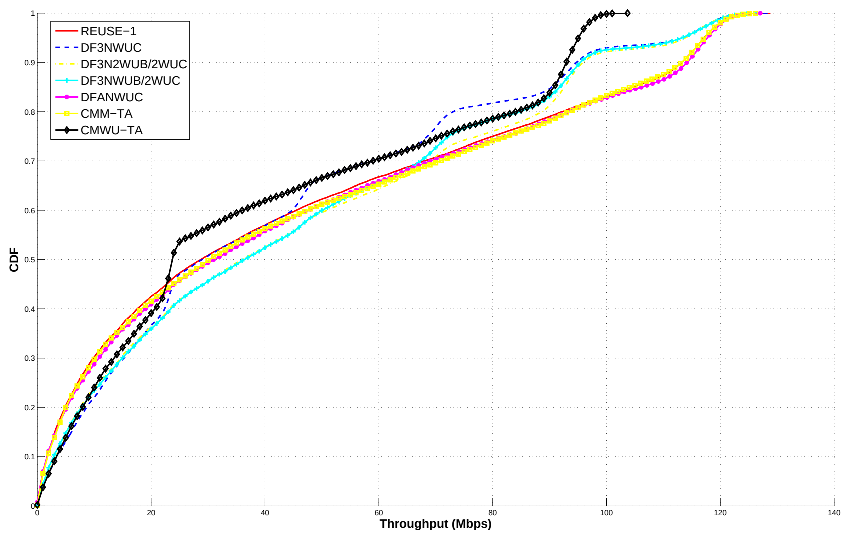

Figure 26: Downlink Throughput Curves (Fair & Centralized Algorithms, Three Floor Layout, Infinite Buffer Scenario)

The gains expected in this scenario is not as high as from the previous ones since there is a lot of interference in the network, Reuse-1 already gives quite good performance under such mitigating circumstances. From the throughput and SINR curves, the normalized mean and 5^{th} percentile throughput values are computed and are shown in Figures 29 and 30. The channel allocation pattern is also computed for the different allocation schemes and can be referred to from Figure 31. From all these figures we can make the following observations:

- Even though the gains are not as high as in a single floor layout the relative gains remains similar compared to previous scenarios. This helps in establishing the durability of the algorithms under study when exposed to mitigating circumstances.

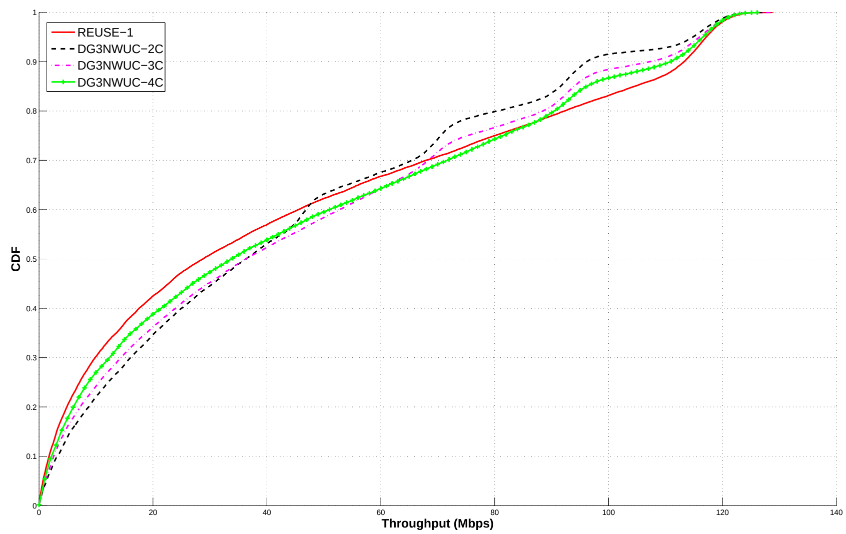

Figure 27: Downlink Throughput Curves (Greedy Algorithm DG3NWUC-LC (L=2,3,4),Three Floor Layout, Infinite Buffer Scenario)

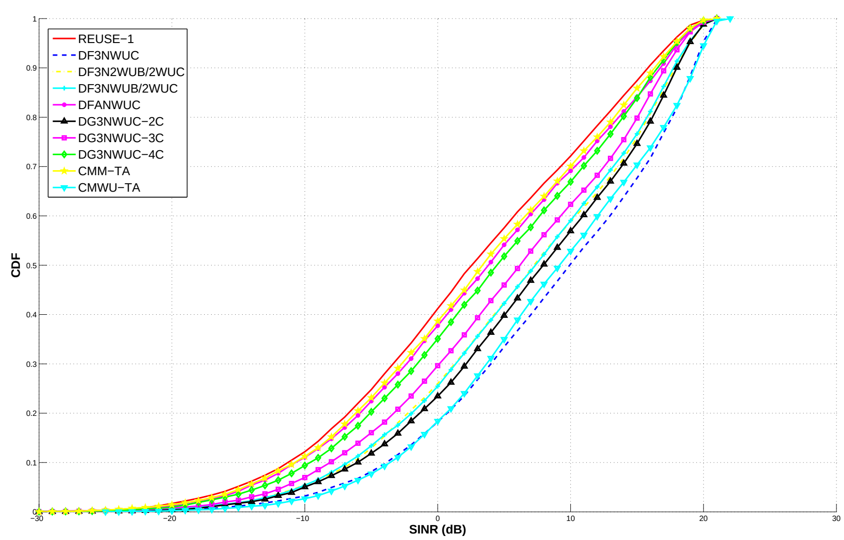

Figure 28: Downlink SINR Curves (Three Floor Layout, Infinite Buffer Scenario)

- All the algorithms whose results are presented perform marginally better in terms of lower percentile throughput except DFANWUC which performs slightly worse in lower percentiles (12% less 5^{th} percentile throughput) but gives mean throughput close to Reuse-1.

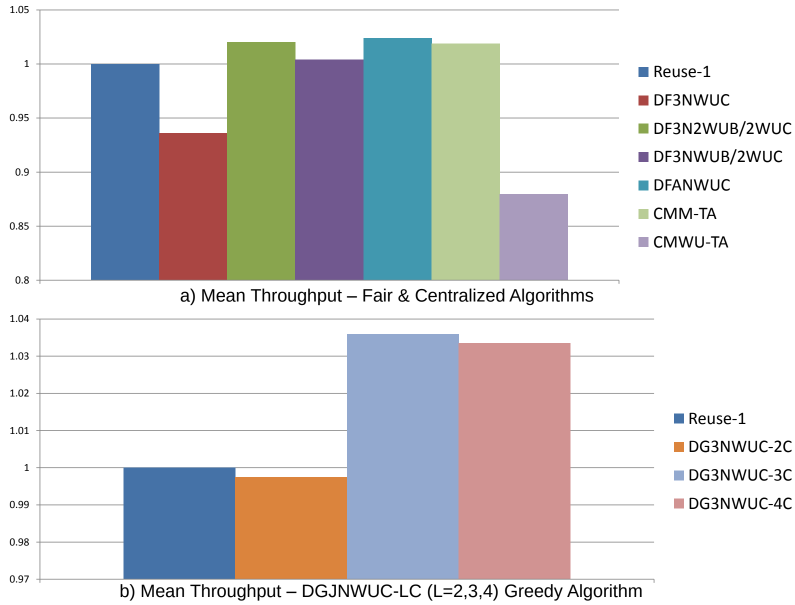

Figure 29: Normalized Mean Throughput values for Three Floor Layout, Infinite Buffer

- From Figure 26, we can observe that DF3NWUC gives the same 5^{th} percentile throughput as CMWU-TA (2 times Reuse-1 5^{th} percentile throughput) but with less loss in mean throughput compared to CMWU-TA (6% loss in mean throughput compared to Reuse-1). The same performance in reflected in the SINR curves as well. The channel allocation pattern shows that due to heavy interference the algorithm goes for slightly more conservative allocations with 22% of the HeNBs having just 1 channel allocated and around 13% of the HeNBs having all 5 channels allotted. But this also shows that even with such a conservative allocation, without much loss in average throughput compared to Reuse-1, the algorithm still gives good lower percentile user throughputs.

- DF3N2WUB/2WUC & DF3NWUB/2WUC perform extremely similarly in terms of average throughput compared to Reuse-1 and still give 1.7 times the 5^{th} percentile throughput. The channel allocation pattern is similar to previous cases with more than 41% of the HeNBs having 4 channels allocated. Even though the algorithm is slightly more greedy compared to DF3NWUC, the same is achieved without much loss to the lower percentile users. The SINR curves of these two are overlapping as well indicating similar interference levels with both allocations.

- From Figure 27, we can observe that DG3NWUC-LC with L=2 performs slightly better than DF3NWUC with 1.8 times 5^{th} percentile throughput and no loss in average throughput value. This is also consistent with the previous results and it can be stated that having more channels with the conservative constraint applied yields better lower percentile results with not much loss in

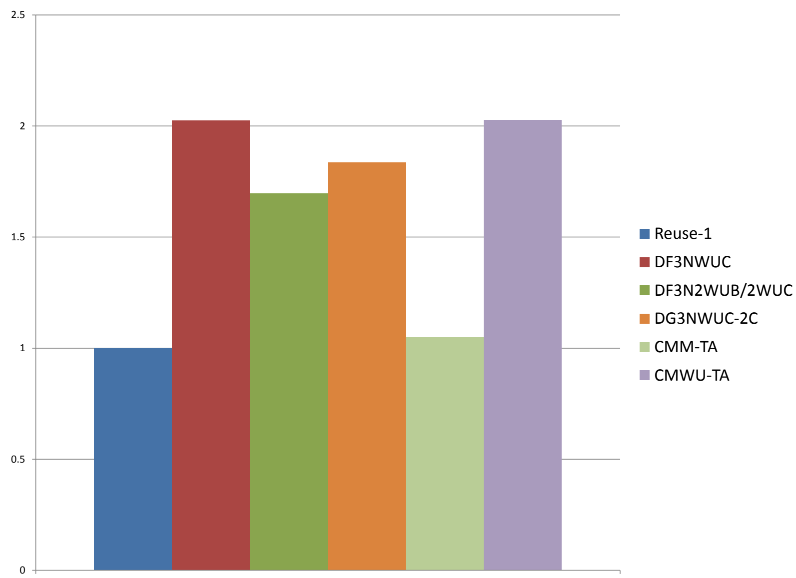

Figure 30: Normalized 5^{th} Percentile Throughput values for Three Floor Layout, Infinite Buffer

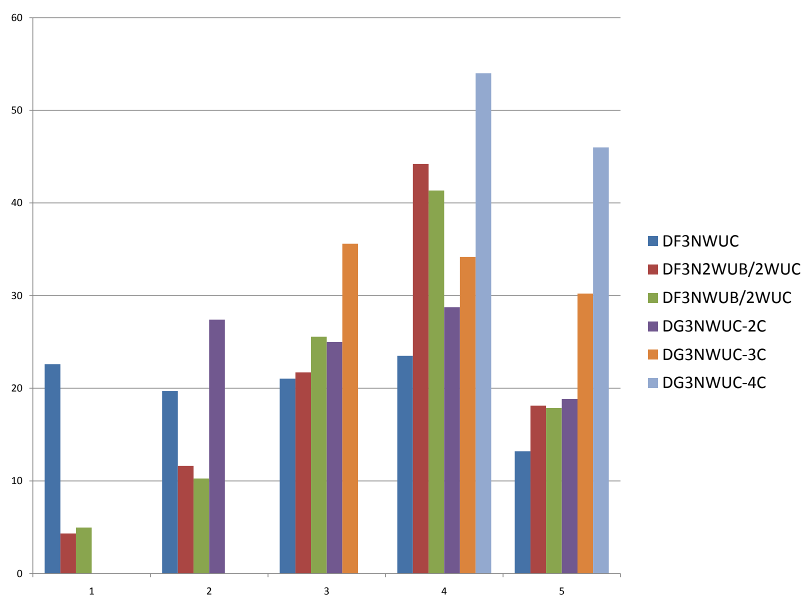

Figure 31: HeNB-No. of Channels Distribution for Three-Floor Infinite Buffer

other indices such as the average throughput experienced by all the users in the network.

- When DG3NWUC-LC is made more greedy with L = 3 and 4 it gives better mean throughput values but suffers in lower percentile throughput (1.6

and 1.3 times Reuse-1 5^{th} percentile throughput). SINR distribution is also slightly worse-off compared to L=2, since more channels inherently imply more interference to neighboring HeNBs.

5.4 One-Floor Infinite Buffer Three-Operational Channel Scenario

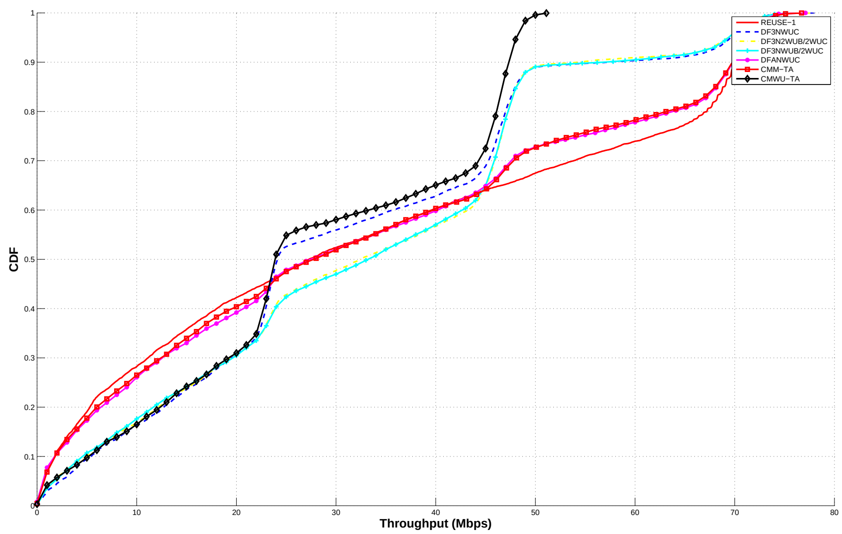

Figure 32: Downlink Throughput Curves (Fair & Centralized Algorithms, One Floor Layout, Infinite Buffer, 3 Operational Channels Scenario)

In this section we discuss a scenario similar to the one described in Section 5.1 except for the fact that we are considering only 3 x 20MHz Operational channels. Here we try to reduce the degrees of freedom available to the algorithms for channel allocation and study the impact of the same in the throughput performance. The SINR and throughput curves for this scenario is as shown in Figures 33 and 32 respectively. The 5^{th} Percentile and Mean Throughput values normalized to Reuse-1 for all the algorithms are synthesized from Figure 32 are presented in Figures 34 and 35 respectively. Also, the channel allocation pattern for this study can be observed from Figure 36. We have excluded the study of Greedy algorithms since with such low degree of freedom available they tend to follow Reuse-1 allocation and studying the results for the same does not add much value to this study.

Some of the observations and conclusions we can draw from this experiment are:

- From Figure 32 and 34, we can note that in terms of lower percentile throughput values, DF3NWUC gives the best 5^{th} Percentile throughput among the

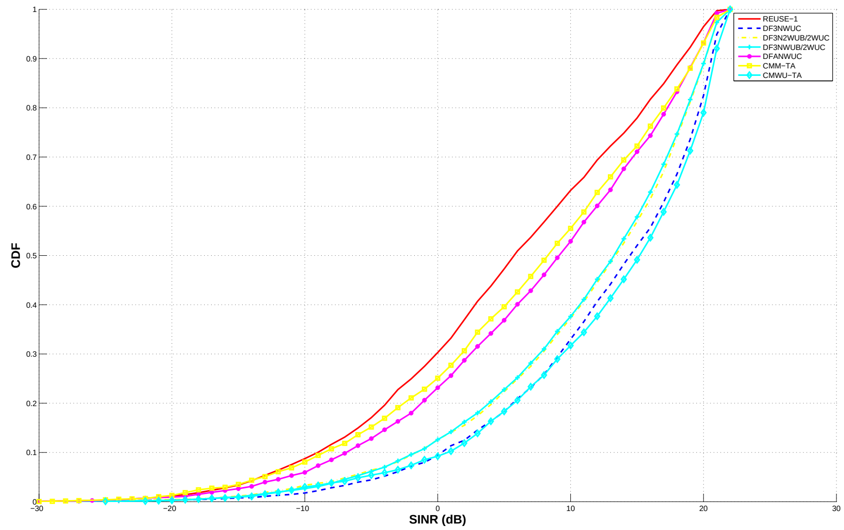

Figure 33: Downlink SINR Curves (One Floor Layout, Infinite Buffer, 3 Operational Channels Scenario)

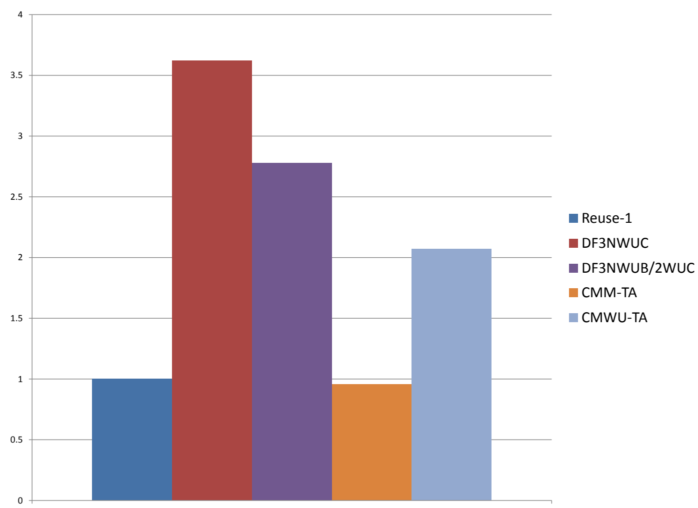

Figure 34: Normalized 5^{th} Percentile Throughput values for One Floor; Infinite Buffer; 3 Operational Channels

algorithms studied. It gives 3.6 times the 5^{th} Percentile throughput of Reuse-1 with only 7% loss in average throughput. In terms of channel allocation, 85% of the HeNBs have only 1 or 2 Channels allotted which means that the total carrier power required by DF3NWUC is 42% less than that for Reuse-1. This is one of the key benefits of the proposed distributed algorithms.

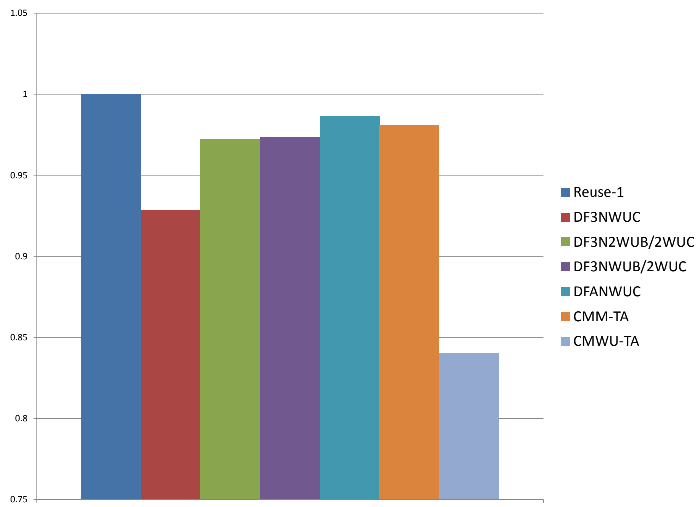

Figure 35: Normalized Mean Throughput values for One Floor; Infinite Buffer; 3 Operational Channels

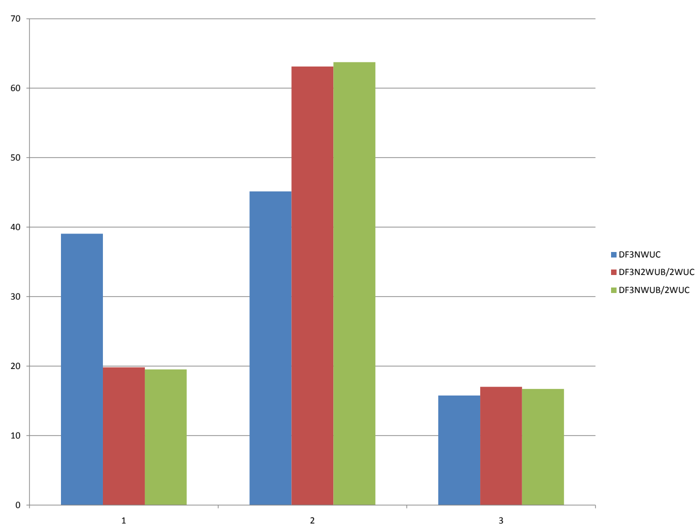

Figure 36: HeNB-No. of Channels Distribution for One Floor; Infinite Buffer; 3 Operational Channels

- The SINR curves (Figure 33) show similar results as in previous cases with DF3N2WUB/2WUC & DF3NWUB/2WUC giving similar results, DF3NWUC yielding results similar to CMWU-TA and all the algorithms studied giving better SINR performance compared to Reuse-1.

- The throughput curves of DF3N2WUB/2WUC & DF3NWUB/2WUC are also close with DF3N2WUB/2WUC giving 2.5 times and DF3NWUB/2WUC giving 2.7 times the Reuse-1 5^{th} Percentile throughput with less than 3% loss in Average Throughput. With this allocation algorithm, close to 64% of the HeNBs have 2 channels allotted to it.

- These results shows that the distributed algorithms proves to be extremely effective in challenging scenarios, even with lesser degrees of freedom available by means of a lesser number of operational channels with each HeNB.

5.5 One-Floor Infinite Buffer 5-Operational Channels with Round-Robin Scheduler

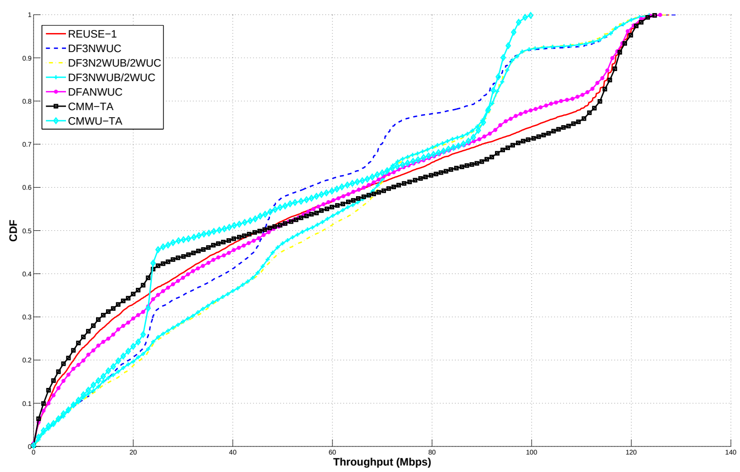

Figure 37: Downlink Throughput Curves (Fair & Centralized Algorithms, One Floor Layout, Infinite Buffer, 5 Operational Channels Scenario) with Round Robin Scheduler

In this section, we will conduct a performance analysis on the algorithms while using a Round-Robin scheduler instead of the Proportional Fair Scheduler used in the previous sections. This section is intended to see if the working of the scheduler in any way aids the results and helps in establishing that the distributed algorithms are essentially independent of the scheduler used.

The Downlink Throughput and SINR curves for this scenario are as shown in Figures 37, 38 and 39 respectively. Based on the curves, we have also computed the 5^{th} Percentile and Mean Throughput values normalized to Reuse-1 and the same is shown in Figures 40 and 41 for a more detailed understanding of the results. Also, as done in the previous sections, the channel allocation distribution pattern for HeNBs done by various allocation schemes are contained in Figure 42.

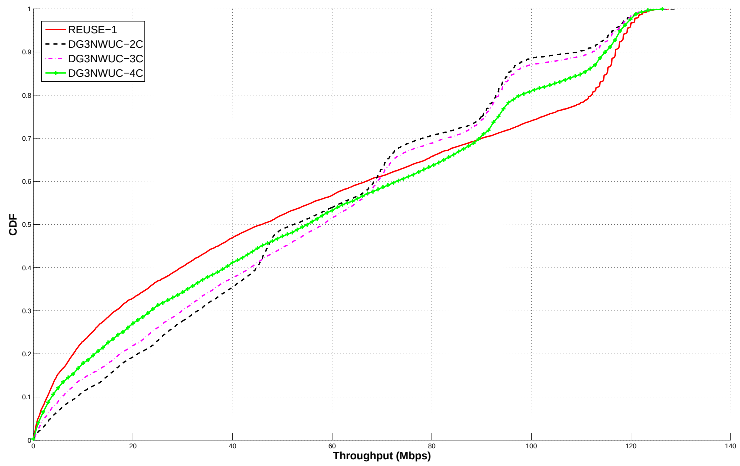

Figure 38: Downlink Throughput Curves (DG3NWUC-LC Greedy Algorithm (L=2,3,4), One Floor Layout, Infinite Buffer, 5 Operational Channels Scenario) with Round Robin Scheduler

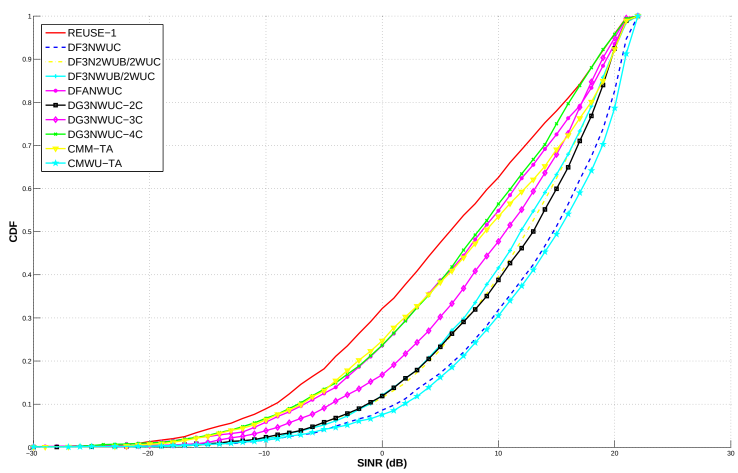

Figure 39: Downlink SINR Curves (One Floor Layout, Infinite Buffer, 5 Operational Channels Scenario) with Round Robin Scheduler

Some of the observations made from the curves as follows:

- From figures 37 and 38, we can observe that in general, Fair Algorithms - DF3NWUC, DF3N2WUB/2WUC & DF3NWUB/2WUC and Greedy Algorithm DG3NWUC-LC with L=2,3 and 4 are giving good gains both for lower percentile users and mean users.

- From figure 40 and 41 we can note that, similar to the previous scenarios,

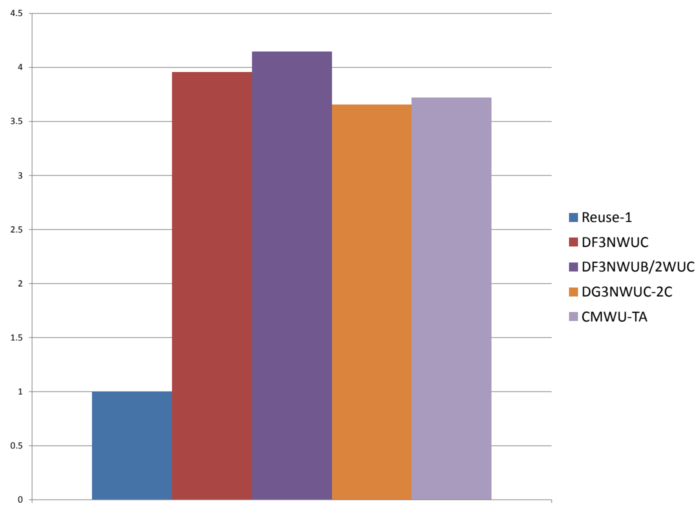

Figure 40: Normalized 5^{th} Percentile Throughput values for One Floor Infinite Buffer with Round-Robin Scheduler

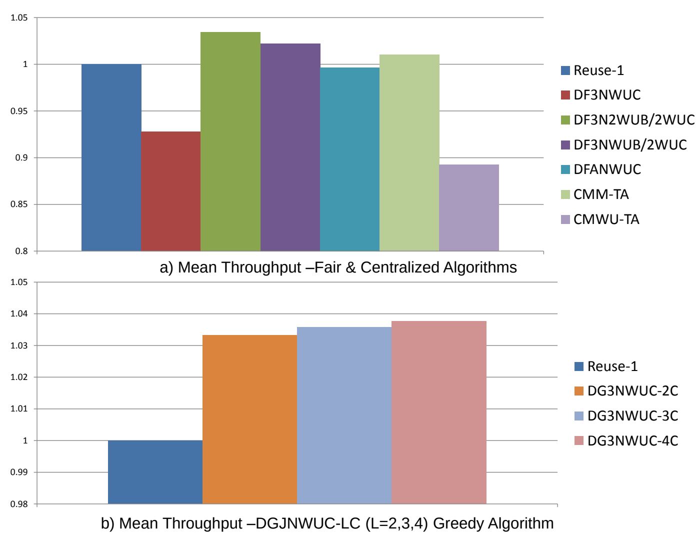

Figure 41: Normalized Mean Throughput values for One Floor Infinite Buffer with Round-Robin Scheduler

DF3NWUC gives results similar to CMWU-TA with close to 4 times the 5^{th} Percentile Throughput of Reuse-1 with only 7% loss in Mean Throughput value. The SINR curves of the both are overlapping as well. Also, 65% of the HeNBs have 3 or less channels allocated which goes to show that even with a conservative channel allocation excellent results can be obtained.

- DF3NWUB/2WUC performs slightly better than DF3N2WUB/2WUC with no loss in throughput for the mean user and 4 times the 5^{th} Percentile User

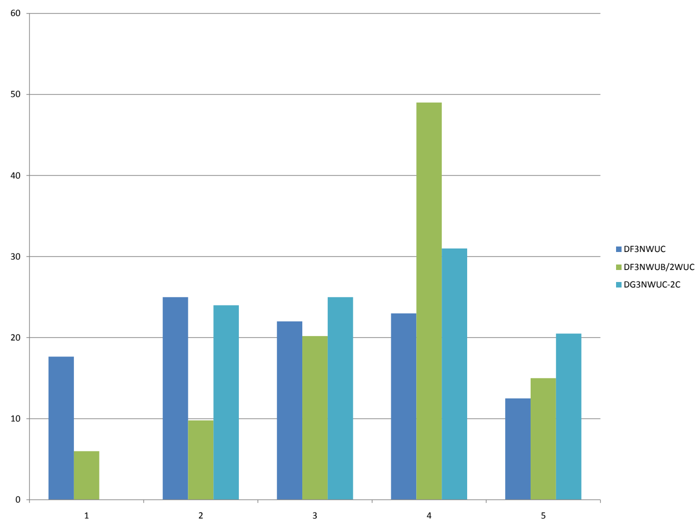

Figure 42: HeNB-No. of Channels Distribution for One Floor Infinite Buffer with Round-Robin Scheduler

Throughput compared to Reuse-1. Here close to 70% of the HeNBs are allotted 3 to 4 Channels which indicates a slightly more greedy allocation pattern, but it is reflected in a 2-3% gain in Mean Throughput value.

- DFANWUC performs consistently worse in all the scenarios studied in terms of lower percentile user gains. The behavior is close to Reuse-1 with similar Mean Throughput values in both allocations.

- DG3NWUC-LC with L=2 gives 3.7 times the gain for 5^{th} Percentile Users with a slight increase (3%) in Average User Throughput. DG3NWUC-LC with L=3 performs slightly better than with L=4 in terms of 5^{th} Percentile Throughput with a similar Average User Throughput.

5.6 One-Floor/Three-Floor Infinite Buffer with DFJNWUC, Varying Number of Neighbors (J)

In this section we study the results with DFJNWUC using a varying number of neighbors taken into account while doing the channel allocation. This is done to study whether the three-Neighbors chosen for previous experiments is an optimal value or not. First let us consider the One-Floor scenario. Here we are considering the DFJNWUC Algorithm with J = 2, 3 and 4 Neighbors whose losses are taken into account. In the current scenario we are limiting the maximum number to 4 since above that the loss values are negligible and no impact is made on the channel allocation. The throughput and SINR curves for the same is shown in Figure 43. The computed values of normalized 5^{th} Percentile and Mean Throughput values are shown in Figure 44.

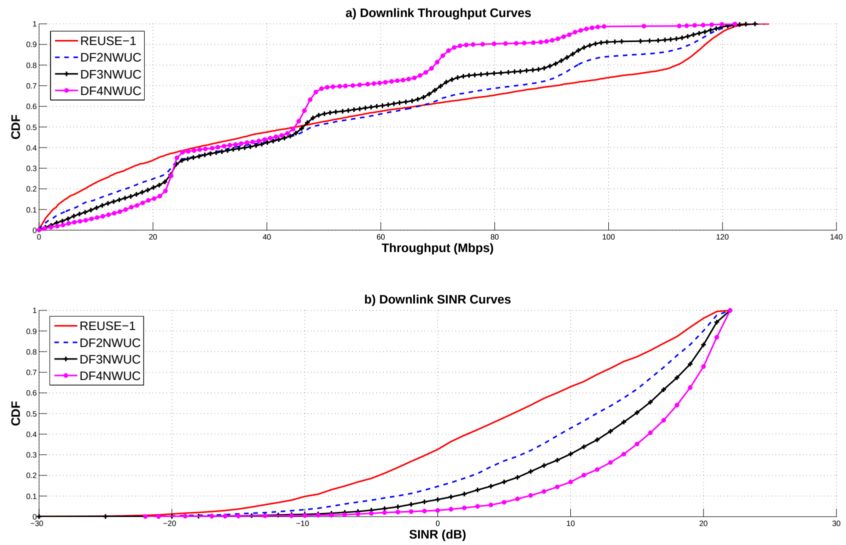

Figure 43: Downlink Throughput and SINR Curves (One Floor Layout, Infinite Buffer, 5 Operational Channels Scenario)

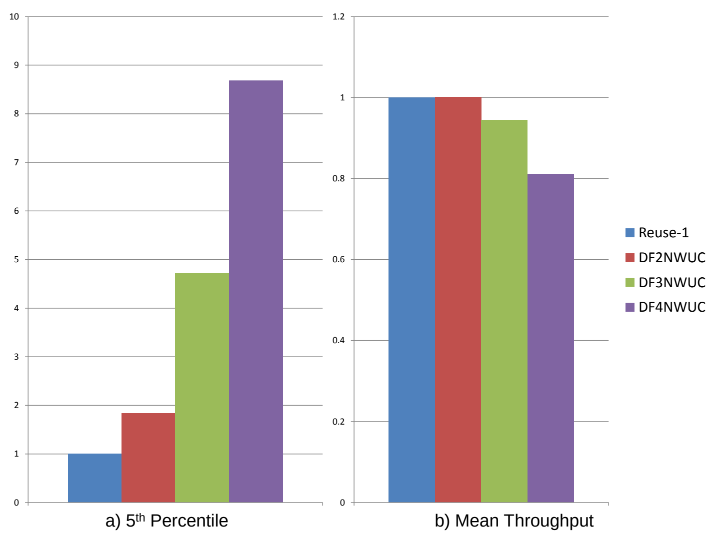

Figure 44: Normalized 5^{th} Percentile and Mean Throughput values for One-Floor, DFJNWUC Algorithm with Varying Number of Neighbors (J=2,3,4)

From the figures 43 and 44 the following observations are made:

- As the number of neighbors increases, the lower percentile user gains increases whereas the average user throughput decreases. This is due to the fact that the algorithm becomes more and more conservative giving excessive focus to interfered users from the neighboring cells.

- When only 2 neighbors are considered, the 5^{th} Percentile Throughput becomes 1.8 times the Reuse-1 value and the Mean Throughput value remains the same.

- Subsequently for 3 and 4 Neighbors the 5^{th} Percentile Throughput value increases to 4.7 and 8.7 respectively whereas the Average Throughputs are reduced by 6% and 19% respectively. As stated previously the allocation becomes more and more conservative with more HeNBs allotted 1-2 Channels.

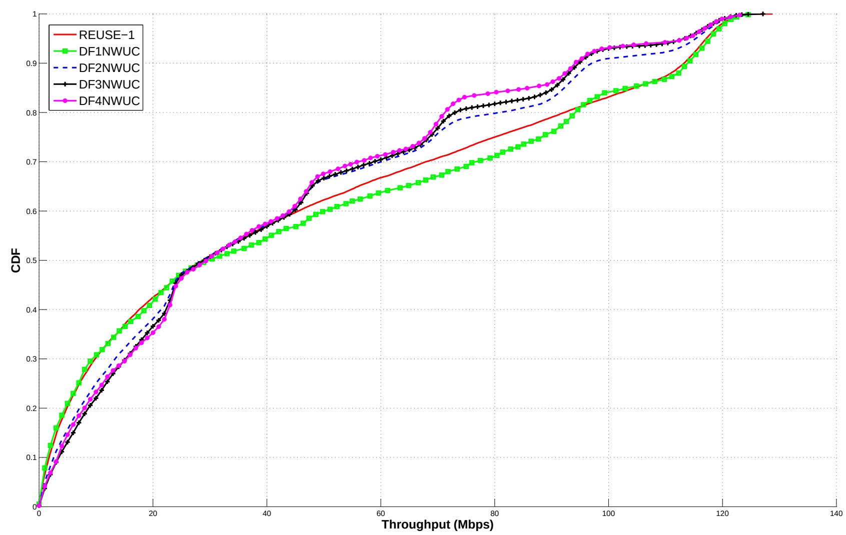

Figure 45: Downlink Throughput Curves (Three Floor Layout, Infinite Buffer, 5 Operational Channels Scenario)

For the Three-Floor Scenario, we consider DFJNWUC algorithm with J=1,2,3,4. Thus we consider the Worst User capacity loss on the newly added channel for ‘J’ number of neighbors, where neighbors can be from any of the floors in the scenario. Here as in the previous case, values of $J > 4$ does not yield much difference in the curves compared to the J=4 case. The Throughput and SINR CDF curves are shown in Figures 45 and 46 respectively. The normalized mean throughput and 5^{th} Percentile values are as shown Figure 47. Some of the observations that can be drawn are:

- The SINR performance observed from figure 46 remains close for J=2,3 and 4 which is reflected in the throughput curves as well. Also, SINR curve of J=1 and Reuse-1 is also close which reflected in the throughput curve as well.

- From Figure 47 and 44, we can note that the trend remains the same for normalized 5^{th} Percentile throughputs for One-Floor and Three-Floor until J=3. We can notice a slight decrease in the 5^{th} Percentile value for the J=4 case.

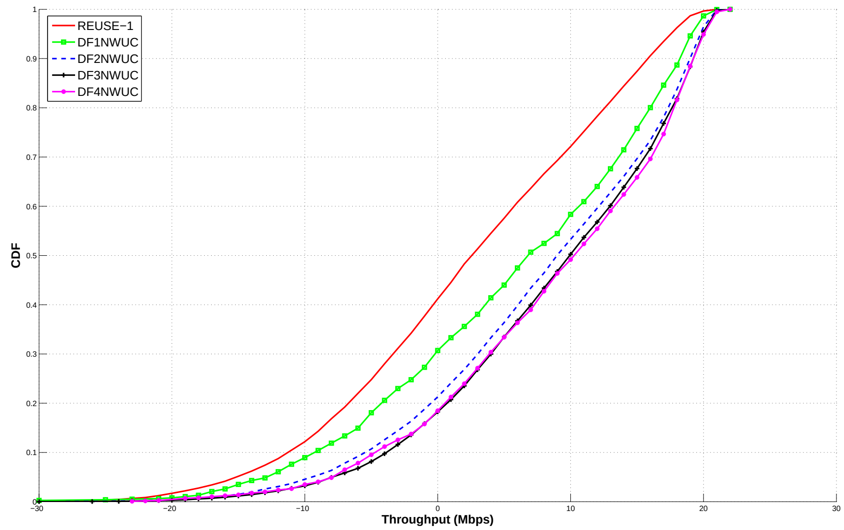

Figure 46: Downlink SINR Curves (Three Floor Layout, Infinite Buffer, 5 Operational Channels Scenario)

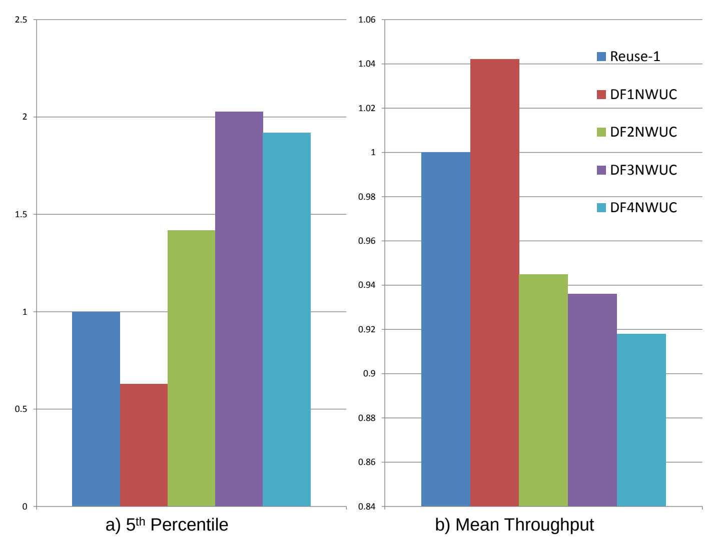

Figure 47: Normalized 5^{th} Percentile and Mean Throughput values for Three-Floor, DFJNWUC Algorithm with Varying Number of Neighbors (J=1,2,3,4)

- One of the main conclusion we can draw from the results is that due to the heavy interference conditions, coordination does not yield significant gains in such a scenario.

- Even in the three-floor scenario, considering the loss for 3-neighbors provides the optimal trade-off between lower percentile throughput gains and mean throughput values relative to Reuse-1.

From the studies done in this section, we can conclude that J=3 i.e. coordination between three of the worst interfered neighbors gives the best performance for lower percentile users when we take into account the possible trade-off between 5^{th} Percentile and the mean throughput values.

5.7 One-Floor Infinite Buffer with Varying Wall Attenuation Values

In this section we study the impact of changing the wall attenuation on the system performance for the Fair Distributed Algorithms.

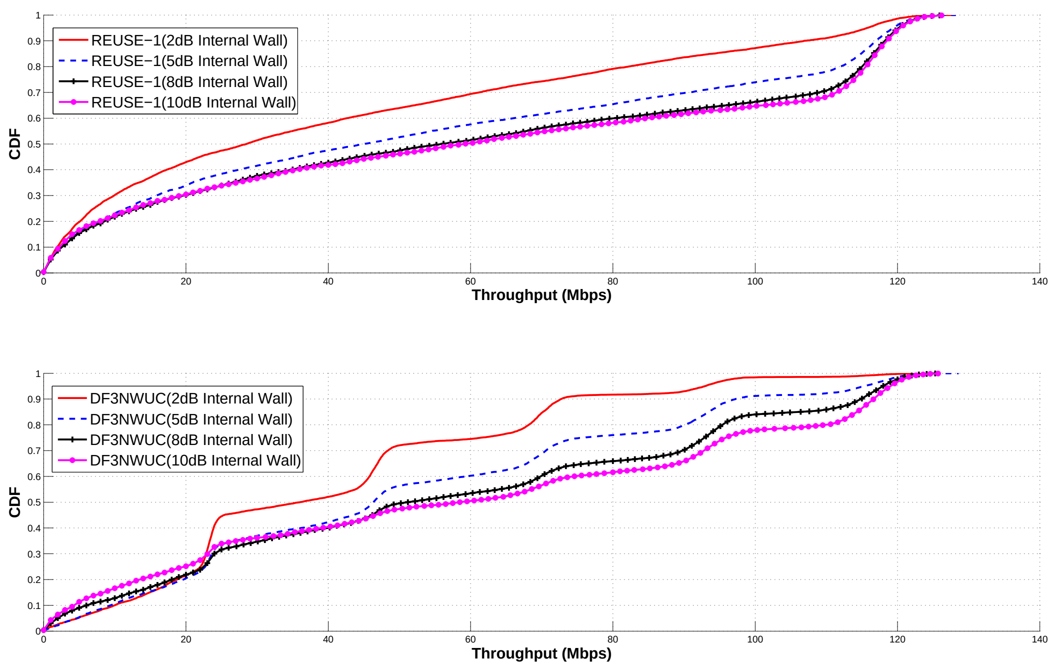

Figure 48: Downlink Throughput Curves-Varying Wall Attenuation (One Floor Layout, Infinite Buffer Scenario)

Here we subject the fair distributed algorithm to a changing internal wall attenuation and see whether the system performance is degrading under such circumstances. We consider 5-Operational channels with Proportional Fair scheduler for this study, Single Floor Layout described in Section 3.1 is used. The internal wall attenuation takes values of 2dB, 5dB, 8dB and 10dB.

The algorithms used in this study are DF3NWUC, DF3N2WUB/2WUC, DF3NWUB/2WUC & DFANWUC of which the results of DF3NWUC is presented in this sec-

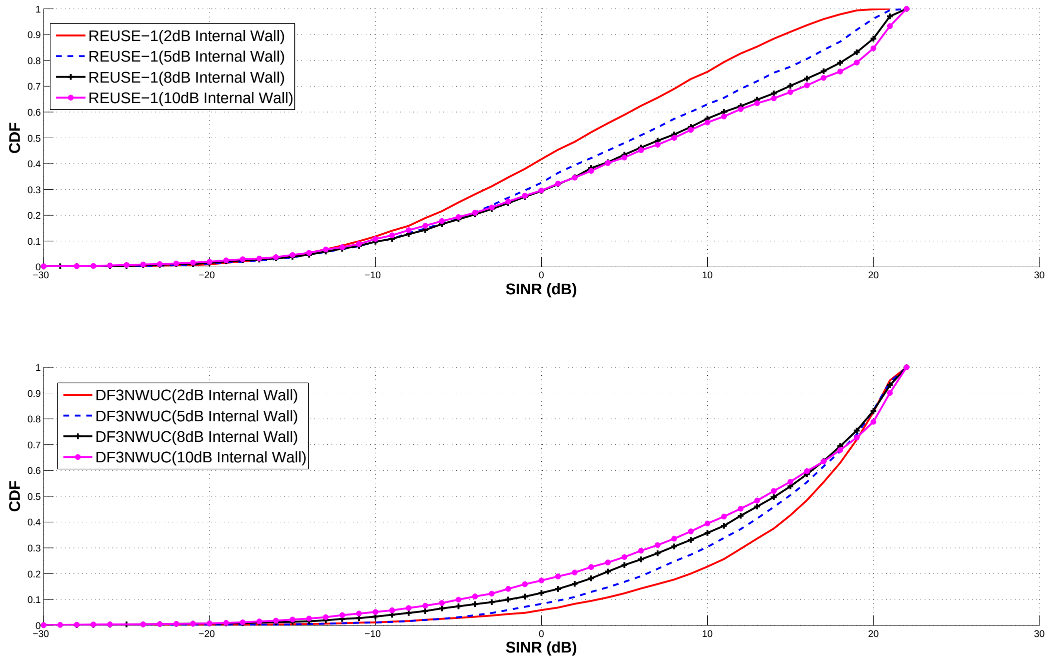

Figure 49: Downlink SINR Curves-Varying Wall Attenuation (One Floor Layout, Infinite Buffer Scenario)

tion. The throughput and SINR curves for DF3NWUC are as shown in Figures 48 and 49 respectively. Since the pattern of the result is similar, only DF3NWUC is presented here and the remaining curves are presented in the appendix section for reference. Corresponding curves for DF3N2WUB/2WUC are Figures 51, 52; for DF3NWUB/2WUC are Figures 53, 54; and for DFANWUC are Figures 55 and 56.

Some of the interesting observations that can be made from the curves are as follows:

- The algorithms give consistently good performance for lower percentile users even when the wall attenuation is varied. But the relative gains are lowered as the wall attenuation increases. The reason behind this is the fact that as the wall attenuation increases the apartments get better and better isolation from neighboring interfering HeNBs. In such a scenario Reuse-1 itself gives considerably good gain and Distributed algorithm tries to match it.

- As the wall attenuation is increased, the distributed fair algorithms become more and more greedy due to the better isolation from interfering HeNBs as mentioned previously. This is another reason why the 5^{th} Percentile Throughput gains are lowered, but still the relative mean throughput remains almost

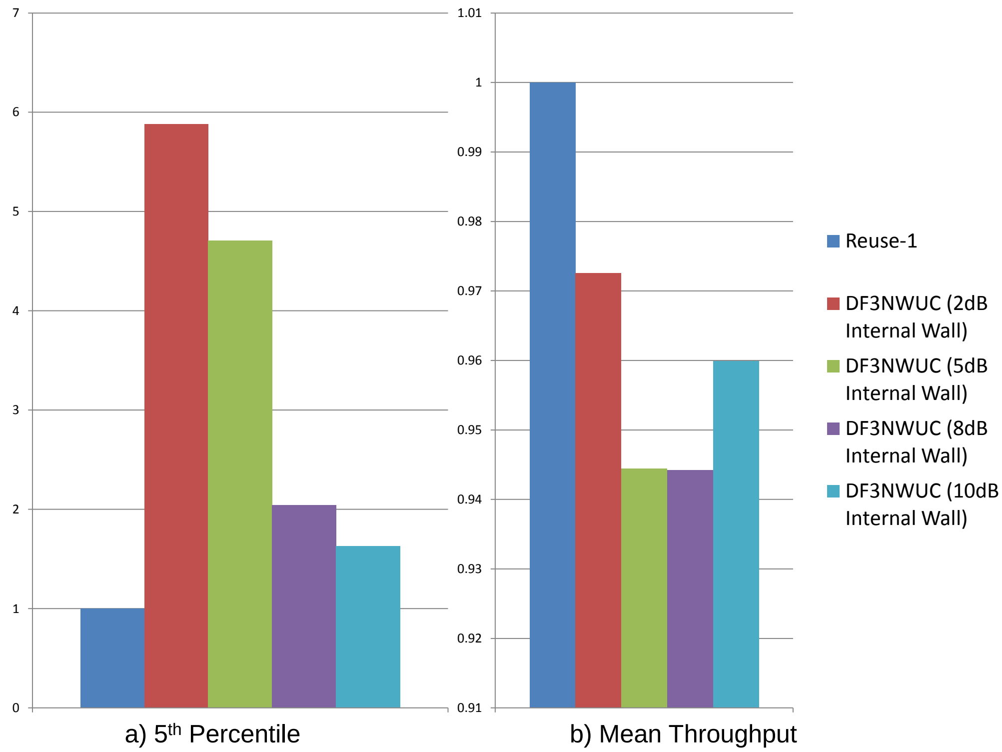

Figure 50: Normalized 5^{th} Percentile and Mean Throughput values for DF3NWUC Algorithm with Varying Wall Attenuation

constant (3-4% loss compared to Reuse-1) even though there is a considerable increase in the absolute values.

- With the increase in wall attenuation, we can observe from the SINR curves that the interference in the network is lowered for Reuse-1 allocation and it increases for the distributed algorithms (except for DFANWUC since it tends to follow the Reuse-1 allocation pattern). This is also perhaps due to better isolation being available, but we can note that the SINR values for distributed algorithms with Wall Attenuation = 10dB are still better than all the Reuse-1 cases.

- The results of this test further helps in verifying the scenario independence of the distributed algorithms.

6 Conclusions and Future Work

6.1 Conclusions

The work done during this thesis mainly investigates the performance of LTE-A Local Area Networks with respect to various channel allocation schemes and aims to establish that in a multi-channel environment, there are allocations available in a distributed manner which provide better performance than Reuse-1. Specific insights into the system performance improvements obtained with the help of the schemes described in Section 4 aew provided in detail in Section 5. The main intentions of the performance analysis undertaken is to establish the performance gains that can be obtained by using the Distributed Capacity Based Channel Allocation Algorithms in terms of lower percentile and mean throughputs as well to evaluate whether the algorithms are essentially scenario independent. We have also shown that the algorithms are essentially scheduler independent as well.

From the results obtained, the general pattern of performance of the allocation algorithms remains essentially the same. With the fair allocation algorithms, we can observe that even while maintaining a conservative channel allocation it is possible to achieve good lower percentile throughput gains relative to Reuse-1 without any compromise in the mean throughput values. A major part of the study concentrated on channel allocation under full-buffer conditions with 5-Operational Channels which gives the algorithms a considerable degree of freedom in terms of allocating mutually exclusive channels to heavily interfering HeNBs. But as it was shown that the algorithms give good 5^{th} Percentile Throughput gains even under a 3-Operational Channel scenario. This further strengthens the case for the proposed schemes to be a flexible and practically viable option. With the help of the 3-Floor Building, we try to subject the algorithm to a heavy interference scenario. The lowering of relative gains under such a heavy interference condition is graceful and along the expected lines since in such a scenario Reuse-1 tends to give good throughput performance and hence normalized values will be lower.

Comparison With Concurrent Work

Another major conclusion that can be drawn is with respect to comparison with the Autonomous Component Carrier Selection (ACCS) scheme described in [26] and [27]. The work done during this thesis work is similar to the ACCS in terms of both being a multi-channel allocation problem for local area networks as well as the similarities in scenarios used for study. The results that can be compared are the ones described in Section 5.1 and the 'extended scenario' described in [26]. The difference between the two schemes exists mainly in values used for spectral efficiency and antenna gains. We can note that the ACCS gives 4 times the 5^{th} Percentile Throughput of Reuse-1 allocation with almost the same Average Throughput value. Some of the best performing algorithms in comparison to ACCS are mentioned in this section.

Under similar conditions, DFJNWUC (with J=3) gives 4.7 times the 5^{th} Percentile Throughput of Reuse-1 allocation with less than 6% loss in Average Throughput. DF3N2WUB/2WUC & DF3NWUB/2WUC gives 4 times the 5^{th} Percentile Throughput of Reuse-1 allocation with a slight gain (3-4%) in the Average Throughput as compared to Reuse-1. Also, the distributed greedy algorithm DG3NWUC-LC with L=2 and 3 gives close to 3 times the 5^{th} Percentile Throughput of Reuse-1 allocation with a gain (around 6%) in the Average Throughput compared to Reuse-1. The algorithms proposed are quite simple and scalable and the gains remain quite similar in all the single-floor layout scenarios.

Another work in the area of interference coordination from a Femtocell perspective is proposed in [50]. The usage of a different scenario makes a direct comparison of results not possible. But the essence of the idea is similar and in terms of results the work done in [50] is also shown to give good lower percentile and mean throughput values (almost doubling of 5^{th} Percentile Throughput compared to Reuse-1 for OFP+AFR(Type B) without any loss in average cell throughput).

Based on the analysis of the results we can conclude that we can achieve significant gains for the lower percentile users with the help of Distributed Capacity Based Channel Allocation schemes with nearly uncompromised average throughput. The algorithms are fairly simple, minimal messaging is required between HeNBs and they are fast in terms of the time taken for arriving at the allocations. The lack of any hard-coded thresholds based on which channel allocation should be done is an added advantage. We can also conclude that the schemes are not only a viable alternative to Reuse-1 but also to existing multi-channel allocation schemes for local area networks.

6.2 Future Work

Due to the constraints on the duration of this Masters' thesis work, we have concentrated mainly on the downlink performance based on allocations done using downlink measurements. Future work on this area would essentially entail detailed study on extending the allocations to uplink as well. Also, current studies are limited to local area network using Femtocells. The feasibility of the algorithms when used with a macro-cell overlay would be a natural progression in this area of research. Ideally the proposed algorithms should be independent of the TDD or FDD schemes used, but simulations could be done in the future on FDD to ensure the same.

The scenarios used currently are static in terms of user positioning during a snapshot. Study of the effectiveness of the algorithms in a dynamic environment would be an interesting area as well. This would typically involve environments where HeNBs are activated/deactivated (i.e. neighbors keep changing) with the passage of time as well as UEs moving from one room to another. This would mean additional logic for channel deallocation as well as allocation.

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Appendix

Throughput and SINR Curves for Distributed-Fair Algorithms with Varying Internal Wall Attenuation

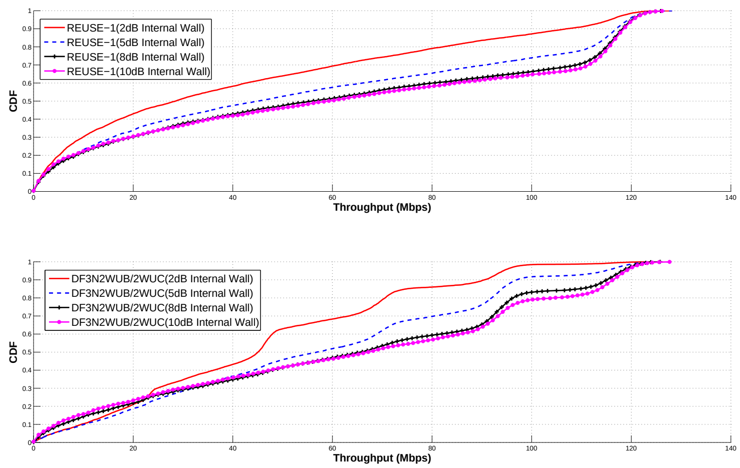

Figure 51: Downlink Throughput Curves for DF3N2WUB/2WUC (One Floor Layout, Infinite Buffer, Varying Wall Attenuation Scenario)

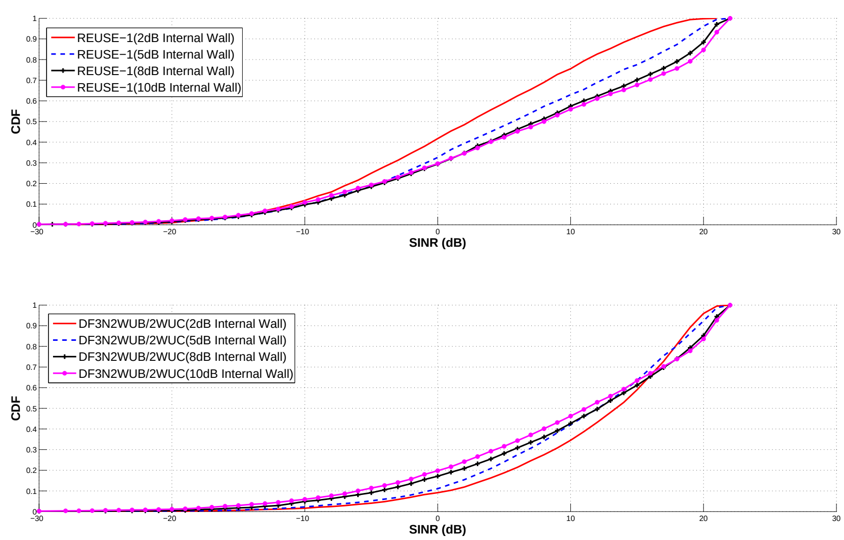

Figure 52: Downlink SINR Curves for DF3N2WUB/2WUC (One Floor Layout, Infinite Buffer, Varying Wall Attenuation Scenario)

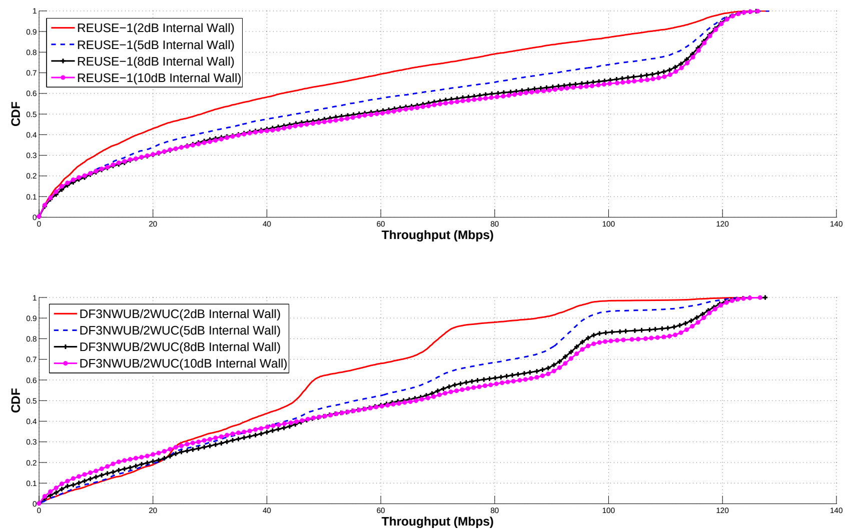

Figure 53: Downlink Throughput Curves for DF3NWUB/2WUC (One Floor Layout, Infinite Buffer, Varying Wall Attenuation Scenario)

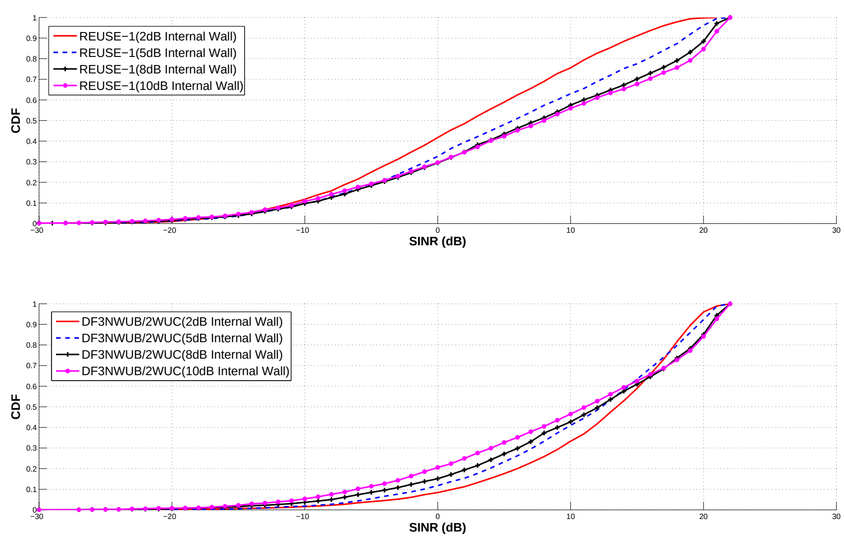

Figure 54: Downlink SINR Curves for DF3NWUB/2WUC (One Floor Layout, Infinite Buffer, Varying Wall Attenuation Scenario)

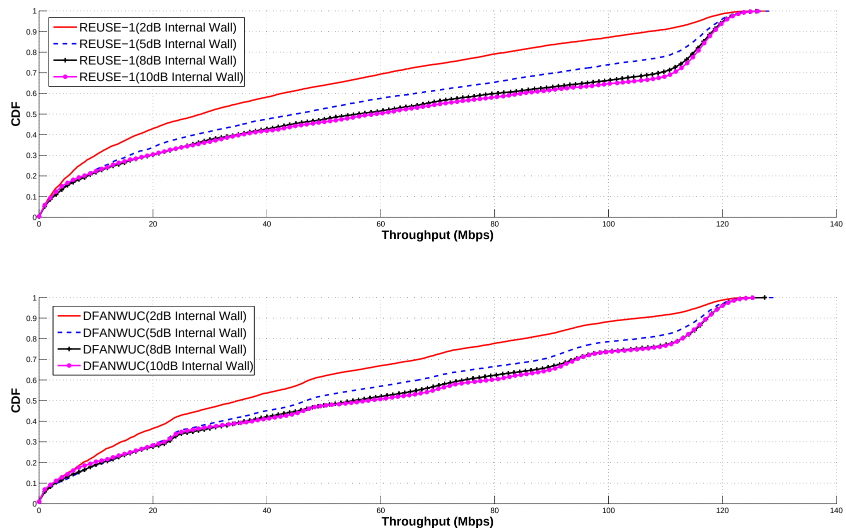

Figure 55: Downlink Throughput Curves for DFANWUC (One Floor Layout, Infinite Buffer, Varying Wall Attenuation Scenario)

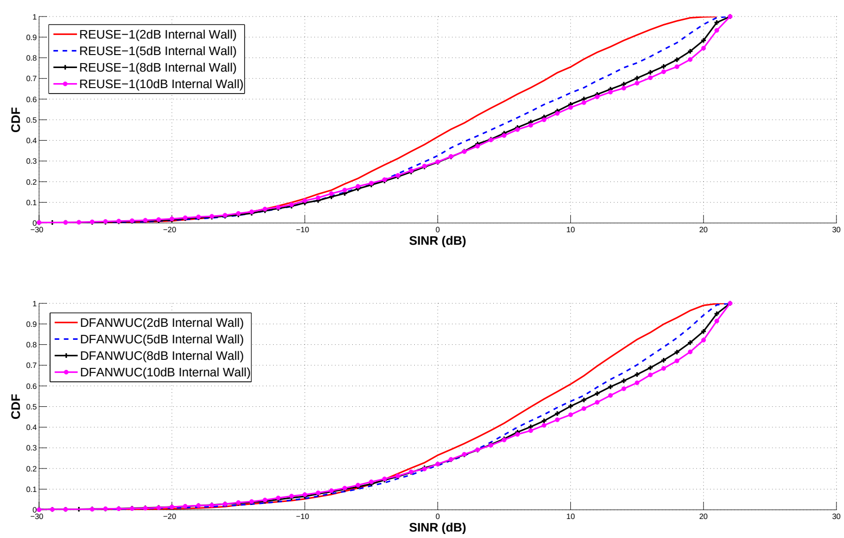

Figure 56: Downlink SINR Curves for DFANWUC (One Floor Layout, Infinite Buffer, Varying Wall Attenuation Scenario)