SPECTRUM AWARE SELF-ORGANIZING NETWORKING IN OFDMA/LTE HETEROGENEOUS NETWORKS

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ABSTRACT

SPECTRUM AWARE SELF-ORGANIZING NETWORKING IN OFDMA/LTE HETEROGENEOUS NETWORKS

Emerging information technologies provide a large number of services which require high throughput for the users. In order to supply the data rate needed by the consumer, the evolving ecosystem of mobile technologies have been shifting from coverage to capacity era. Needs of higher capacity can be achieved by small cell approach that provides good indoor coverage for video and high speed data services. Whilst Cellular Network Architecture is shifting from Circuit-Switched mode to Packet-Switched mode, small cells have begun to adapt this evolution earlier since they use the largest packet network, “the Internet”, as a backhaul, that is why they perfectly fit in the packet oriented architecture and they are inevitable in Long Term Evolution (LTE). Deployment of small cells requires flexible and dynamic operation, administration, maintenance and provisioning schemes. Self-organization and self-optimization of network elements emerge as a necessity for network management. Hence, using Self-Organizing Networks (SON) algorithms and techniques in LTE small cells is a key issue; in this study we are going to discuss the impact of SON in performance of LTE small cells after reviewing the principles of the topic.

ÖZET

DİKEY FREKANS BÖLMELİ ÇOKLU ERİŞİM KULLANAN/UZUN DÖNEM EVRİMLİ HETEROJEN AĞLARDA TAYF FARKINDALIĞIYLA KENDİ KENDİNİ ORGANİZE EDEN AĞLAR OLUŞTURMA

Gelişen bilgi teknolojileri, yüksek işlem hacmi gerektiren birçok servis ve uygulama sağlamaktadır. Kullanıcılar tarafından gereksinim duyulan veri aktarım hızlarını karşılayabilmek için mobil teknolojilerin ekosistemi kapsama devrinden kapasite devrine geçiş yapmaktadır. Daha yüksek kapasite ihtiyaçları, video ve yüksek hızlı veri servisleri için güçlü iç mekan kapsaması sağlayan küçük hücre yaklaşımı ile karşılanabilir. Hücresel Ağ Mimarileri Devre-Anahtarlamalı yapıdan Paket-Anahtarlamalı yapılara geçerken, küçük hücreler en büyük paket ağı olan interneti kullandıkları için bu evrime daha önceden adapte olmuş haldedirler. Bu nedenle küçük hücreler paket tabanlı mimariye mükemmel uyum sağlayarak, LTE (Uzun Dönemli Evrim) için kaçınılmaz olmuşlardır. Küçük hücrelerin mobil ağlara yerşeltirilmesi esnek ve dinamik; operasyon, idare, bakım ve provizyon tasarılarına ihtiyaç duyacaktır. Ağ yönetimi için, kendi kendini optimize ve organize eden ağ elemanları bir gereksinim olarak ortaya çıkmıştır. Bu nedenle LTE küçük hücrelerde SON (kendi kendini optimize ve organize etme) algoritmaları ve tekniklerinin kullanımı, üzerinde durulması gereken önemli bir alandır. Bu çalışmada konunun bazı temellerini inceledikten sonra kendi kendine iyileşme ve düzenlenme yeteneğinin LTE küçük hücrelerin performansı üzerindeki etkisini tartışacağız.

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LIST OF ACRONYMS/ABBREVIATIONS

1G	1st Generation
2G	2nd Generation
3G	3rd Generation
4G	4th Generation
3GPP	3rd Generation Partnership Project
ABS	Almost Blank Subframe
ARQ	Automatic Repeat Request
ARIB	Association of Radio Industries and Businesses
ATIS	Alliance for Telecommunications Industry Solutions
BTS	Base Transceiver Station
BW	Bandwidth
CA	Carrier Aggregation
CAGR	Compound Annual Growth Rate
CCSA	China Communications Standards Association
CDMA	Code Division Multiple Access
CDPD	Cellular Digital Packet Data
CQI	Channel Quality Indicator
CLSM	Closed Loop Spatial Multiplexing
CoMP	Coordinated MultiPoint transmission and reception
CSG	Closed Subscriber Group
DCS	Digital Cellular Service
DL	DownLink
DSP	Digital Signal Processing
EDGE	Enhanced Data rates for GSM Evolution or Enhanced Data rates for Global Evolution
EGPRS	Enhanced GPRS
eNB	evolved/enhanced Node B
EPS	Evolved Packet System
ETSI	European Telecommunications Standards Institute

EV-DO	EVolution-Data Optimized or Data Only
EV-DV	EVolution-Data and Voice
E-UTRA	Evolved Universal Terrestrial Radio Access
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FAP	Femto Access Point
FDD	Frequency-Division Duplexing
FFR	Fractional Frequency Reuse
FDMA	Frequency Division Multiple Access
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HARQ	Hybrid Automatic Repeat Request
HeNB	Home enhanced-Node-B
HetNet	Heterogeneous Network
HFR	Hard Frequency Reuse
HII	High Interference Indicator
HSPA	High Speed Packet Access
ICI	Inter-Channel Interference
ICIC	Inter-Cell Interference Coordination
IMS	IP Multimedia Subsystem
IMT	International Mobile Telecommunications
IMT-2000	International Mobile Telecommunications for the year 2000
IMT-SC	IMT Single Carrier
ISDN	Integrated Services Digital Network
ISI	Inter-Symbol Interference
ITU	International Telecommunication Union
JT	Joint Transmission
LTE	Long Term Evolution
LTE-A	LTE-advanced
MIMO	Multiple-Input Multiple-Output
MIESM	Mutual Information based Effective SINR Mapping
MMOG	Multimedia Online Gaming

MS	Mobile Station
MU-MIMO	Multi User MIMO
NGN	Next-Generation Networks
NMS	Network Management System
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OI	Interference Overload Indicator
OTDOA	Observed Time Difference of Arrival
PCC	Primary Component Carrier
PCS	Personal Communications Service
PDCCH	Physical Downlink Control Channel
PRB	Physical Resource Block
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
PWS	Public Warning Systems
RACH	Random Access Channel
RAN	Radio Access Network
RE	Range Expansion
RNTP	Relative Narrowband Transmit Power Indicator
RRC	Radio Resource Control
RRH	Remote Radio Head
QoS	Quality of Service
SAE	System Architecture Evolution
SCC	Secondary Component Carrier
SDMA	Space-Division Multiple Access
SFR	Soft Frequency Reuse
SDO	Standards Development Organization
SFN	Single Frequency Network
SON	Self-Organizing Networks
TDD	Time-Division Duplexing
TDMA	Time Division Multiple Access

TTA	Telecommunications Technology Association
TTC	Telecommunication Technology Committee
TTI	Transmission Time Interval
UL	UpLink
UMTS	Universal Mobile Telecommunication System
UTRA	Universal Terrestrial Radio Access
WAP	Wireless Application Protocol

1. INTRODUCTION

Mobile technology has evolved remarkably over the past years and mobile broadband demand is growing at a tremendous rate, buoyed by the rise of smart-phones and vast application developer communities. This technology was first used for only communicating people by text messages or voice calls but nowadays it is more than that such as Multimedia Online Gaming (MMOG), mobile TV, Web and streaming contents. People of the modern society exploit this technology for accessing to the Internet from everywhere and most people use the mobile services and applications to facilitate their daily lives by easing their tasks with these services and applications. The world has absorbed this innovation rapidly and has quickly demonstrated that legacy networks are inadequate to meet the vigorous expectations of a modern lifestyle. The expectation from the modern cellular communication networks is it to provide high-capacity coverage over a wide area.

In 2011, mobile data traffic was eight times the size of the entire global Internet in 2000, and mobile video traffic exceeded 50% for the first time. Global mobile data traffic is expected to increase 18-fold by 2016 compared to 2011, with a forecast of growth reaching to 10.8 exabytes per month at a compound annual growth rate (CAGR) of 78% [1] as Figure 1.1 illustrates. Proliferation of advanced devices, services and applications has lead the acceleration of traffic growth and this is one of the biggest challenges facing wireless operators today, and how their network can cope with the demand under CAPEX and spectrum constraints.

Cautious estimates predict a 20 to 30-fold increase in network traffic over the next five years, far greater than the two to four times capacity improvements that communications service providers can expect from new spectrum resources and advanced technologies like long-term evolution (LTE) [2]. Network optimization, advanced cellular technologies (e.g., LTE), and data compression algorithms help, but they may not be enough on their own. Instead, operators will need to offload capacity from their macrocells onto smaller cells. Delivering cost-effective mobile broadband services while

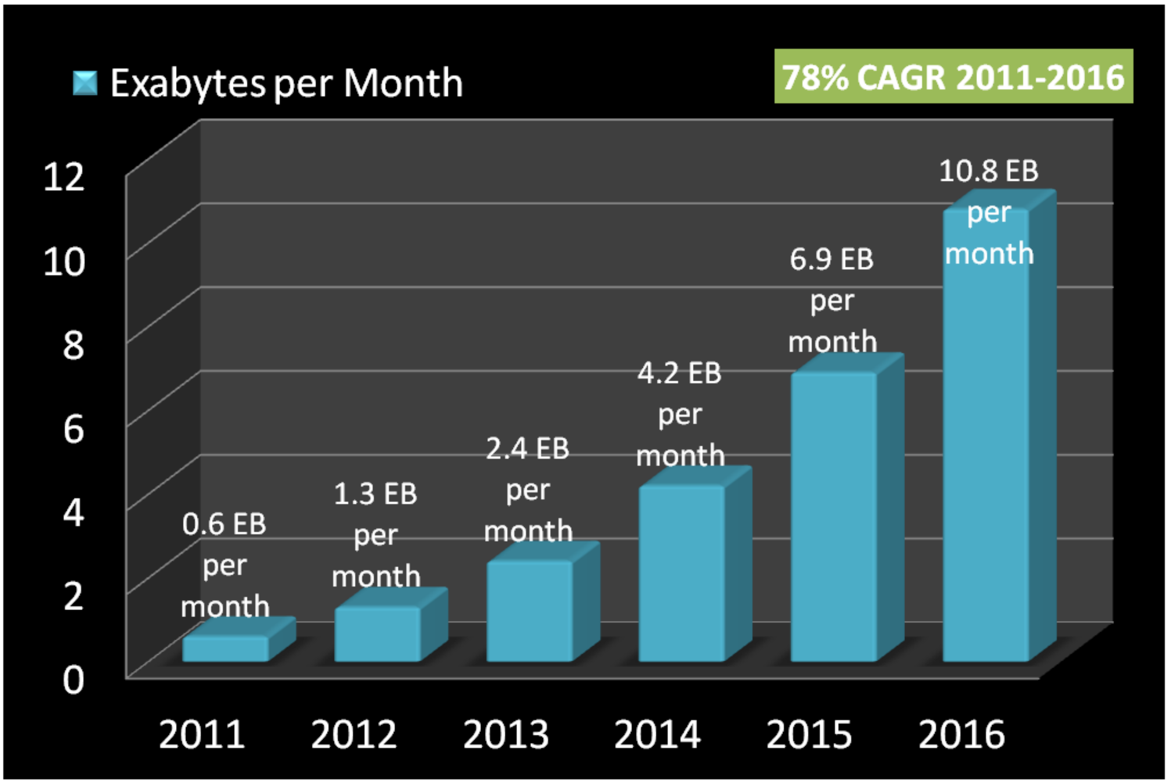


Figure 1.1. Mobile data traffic growth (Adopted from [1]).

facing this extraordinary traffic growth, means service providers must evolve their network architectures and associated operational models. Network designs, operators and their technology vendors are turning to heterogeneous network (HetNet) architectures to address the capacity crunch.

By 2016 and 2017, it is expected that 30% of Earth's population will live in less than 1% of its total land area and generate around 60% of mobile traffic [3] as depicted in Figure 1.2. According to the study from Cisco, at least 80% of the traffic are coming from indoor locations. Jaime Lluch Ladron of Telefonica expects that 95% of data traffic will come from indoor locations in a few years' time [4]. These forces drive the market and academy to focus on small cells.

According to [5] the number of LTE small cells sold (127,000) will surpass the number of LTE macrocells, forecast at 113,000, as early as 2014. There were more

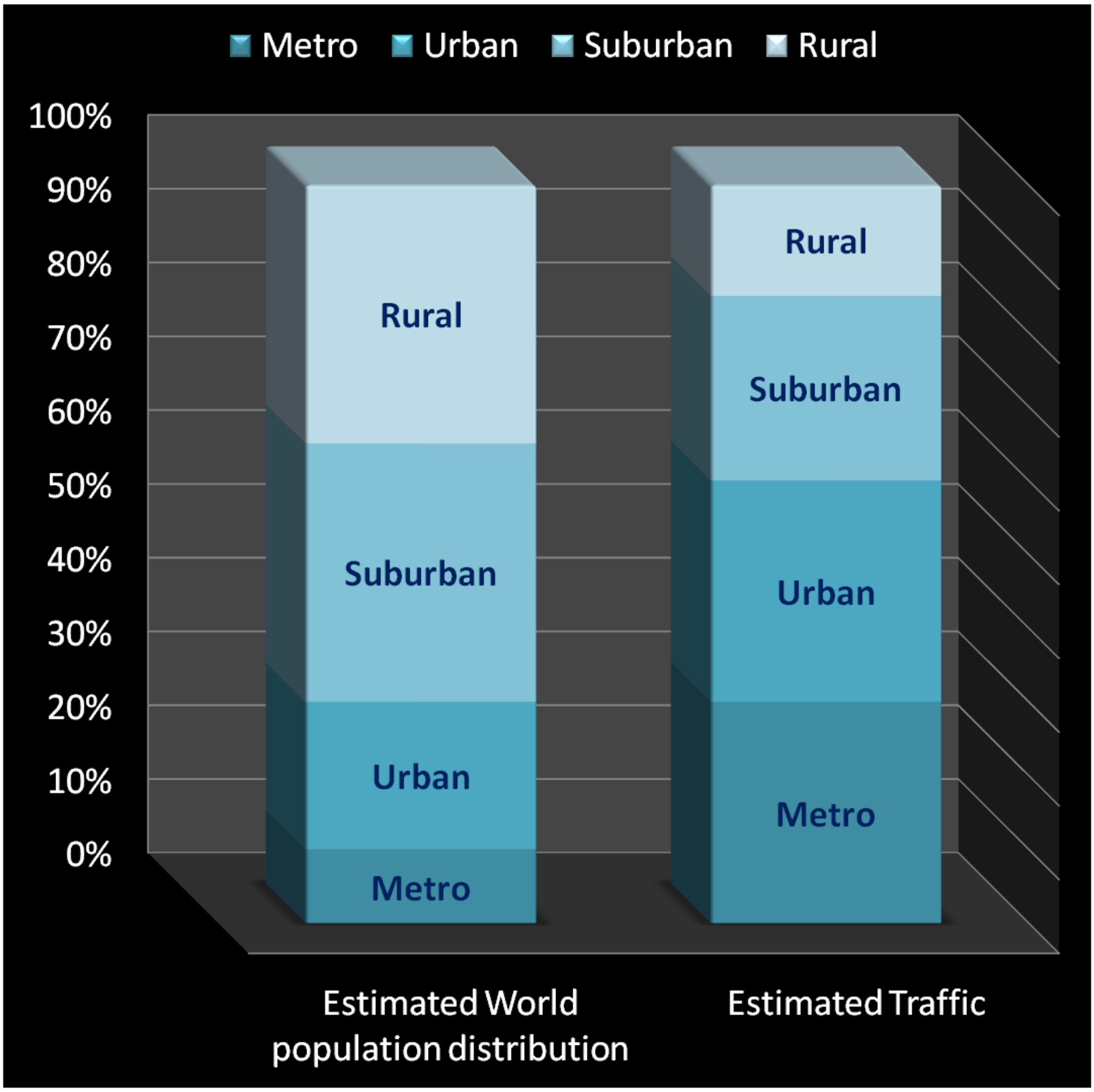


Figure 1.2. Estimated traffic per population (Adopted from [3]).

3G femtocells than 3G macrocells in June 2011 and [6] reports that there will be more femtocells than macrocells for all technologies combined, by the end of 2012. They also estimate that small cells will make up almost 90% of all base stations by 2016 while femtocells constituting the 88% of all base stations globally. A quotation [7] from Joe Madden, Principal Analyst at Mobile Experts, explains the situation, “The good old days of Tower and Power are ending”.

The problems in HetNet inevitably occur when small/low-power cells are deployed in a network consisting of large/high-power cells unless they are used effectively and efficiently since these new cells, after all, are nothing more than new sources of interference . Merely the beauty of LTE is that it divides the data and traffic channels into discrete partitions in the frequency and time domains. This feature can be leveraged to minimize interference and to maximize the combination of macrocells, picocells, and eventually femtocells. In [8] it is stated that interference can work against capacity defects if it is managed carefully, it could improve mobile network performance by 100 fold. We are here to provide a benchmark for dynamic small cell environment and provide an innovative mechanism to increase capacity of the overall network with reduced black-out region by turning interference into advantage.

1.1. Scope of the Thesis

The need for Heterogeneous Networks (HetNEts) and increasing number of small cell deployment is explained in Introduction chapter. We will present the references in the literature as the topics are discussed but we are going to provide a brief summary of investigated papers and literature review in here.

A lot of study have been conducted in the literature in order to solve the interference management problem in Heterogeneous Networks, [9] explains resource partitioning in frequency-domain and time-domain by using almost blank subframes (ABS) for Range Expansion (RE). Likewise soft-cell method is introduced without counting interference problem between smallcells into account. [10] explains advanced interference management and Slowly-Adaptive Interference Management where it goals to find a combination of transmit powers for all the transmitting base stations and user terminals — and over all the time and/or frequency resources that maximizes the total utility of the network. It states that for such an algorithm a distributed method may be more desirable compared to a central entity to compute the algorithm. In [11], Hard Frequency Reuse is applied for throughput enhancement but it harms the macro-layer capacity while it is attractive from the femtocell perspective.

In studies [12–14] interference management in HetNets is investigated. Several

ICIC methods are proposed and evaluated in [12, 15–19]. In [20–24] the ICIC and its performance for femtocell networks is analyzed, especially in [25–27] they are focused on interference management for femtocell introduced HetNets and [28] goals interference avoidance via resource scheduling in TDD underlay femtocells.

After reviewing these studies we decided to assume that all nodes in the HetNet operate on the same frequency in order to effectively utilize the spectrum. We preferred to use FFR scheme in macro-layer network since it gives more flexible spectrum choices for femtocells in order to avoid interference and it uses the frequency resources effectively for both layer. Interference Management techniques using FFR is presented in [13, 17, 25–27, 29–36].

Researched studies generally neglected intra-layer interference for HeNBs. In [37], Adaptive FFR is used to mitigate the inter-femtocell interference with a similar approach to our graph method but it needs a central management system. Other graph based approaches are presented as well in [38–40] but not for heterogeneous networks.

In this study we will propose a distributed semi-static SON method to avoid interference between macro-layer and femto-layer while considering inter-small-cell interference to optimize the overall and seperate throughput for each element of heterogeneous network, still objecting the minimal cost for implementation via preferring non-intensive X2 signalling instead of a central management entity.

1.2. Technological Background

The cellular concept was first deployed in the U.S. in 1947. The first approach used to avoid interference between cells was to assign different operating frequencies to the cells in the first cellular systems. A high frequency reuse factor which is termed as the total number of frequencies used, provides reduced interference between cells but makes poor use of the scarce and expensive spectrum resource. This cellular technique dominated for the next four decades, including the Global System for Mobile Communications (GSM), which was the first cellular system to achieve worldwide penetration, with billions of users.Figure 1.3 shows an example of a cellular network which has a frequency reuse factor of 3.

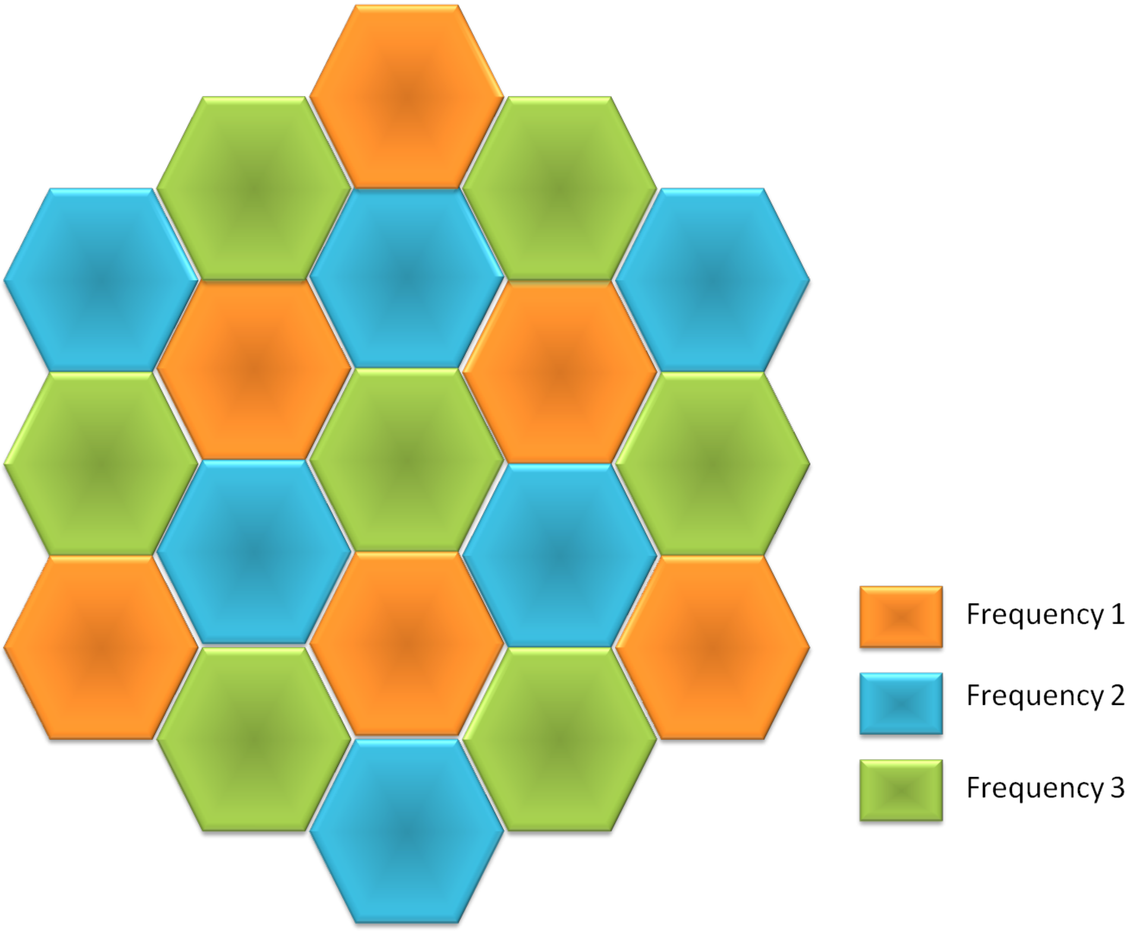


Figure 1.3. Frequency Reuse.

During the widespread deployment of the Global System for Mobile Communications (GSM), the crucial importance of network planning is appeared in relation with frequency reuse planning which was dominant in cellular concept more than 40 years. Propagation conditions are modelled in complex software tools in order to determine the optimal frequency assignments since it is not straightforward as the simple example as in Figure 1.3. In fact it is much more than that and that is why network planning emerged as a necessity in cellular techniques.

To introduce the evolution of digital wireless communication we must begin with the second generation (2G) since the first generation (1G) was analogue. While the first generation (1G) has fulfilled the basic mobile voice, the second generation (2G) has introduced capacity and coverage. This is followed by the third generation (3G), which has quest for data at higher speeds in the late 1980s and the 1990s. The 3rd Generation systems which has become dominant worldwide objecting to meet the requirements set out by the International Telecommunication Union (ITU) for the so-called IMT-2000 family was developed in the 3rd Generation Partnership Project (3GPP) and is known as the Universal Mobile Telecommunication System (UMTS). 3GPP is a partnership of six regional Standards Development Organizations (SDOs) covering Europe (ETSI), Japan (ARIB and TTC), Korea (TTA), North America (ATIS), and China (CCSA). Details can be found in [41].

In 1982 the Groupe Spéciale Mobile (GSM) was founded and was given its well-known name, the *Global System for Mobile communications (GSM)*, by ETSI since it was adopting the specification process. After the creation of 3GPP, GSM development process was transferred to 3GPP. The first version of GSM was standardized in 1991 which operates at 900 MHz by using 124 full-duplex channels [42] and offers international roaming, automatic location services, authentication, encryption on the wireless link, efficient interoperation with ISDN systems, relatively high audio quality. Further enhancements were the short message service with up to 160 alphanumeric characters, fax group 3, and data services at 9.6 kbit/s. Later versions of GSM emerged with the integration of new methods, GSM-1800 was used in the 1800 Mhz spectrum in Europe, which is known as DCS 1800, with better speech codecs and more cells having smaller range whereas in the US GSM-1900, also called PCS 1900, was operating at 1900 MHz [43].

To understand the evolution of medium access we should refer to previous technologies. Space-Division Multiple Access (SDMA) is a channel access method originated from forming parallel spatial pipes next to higher capacity pipes via spatial multiplexing and/or diversity [44], this technology is implemented in GSM by using cells with Base Transceiver Station (BTS) and each Mobile Station (MS) was assigned to a BTS. Frequency Division Multiple Access (FDMA) splits the spectrum into frequency channels so that a user can transmit and receive in one of the channels which

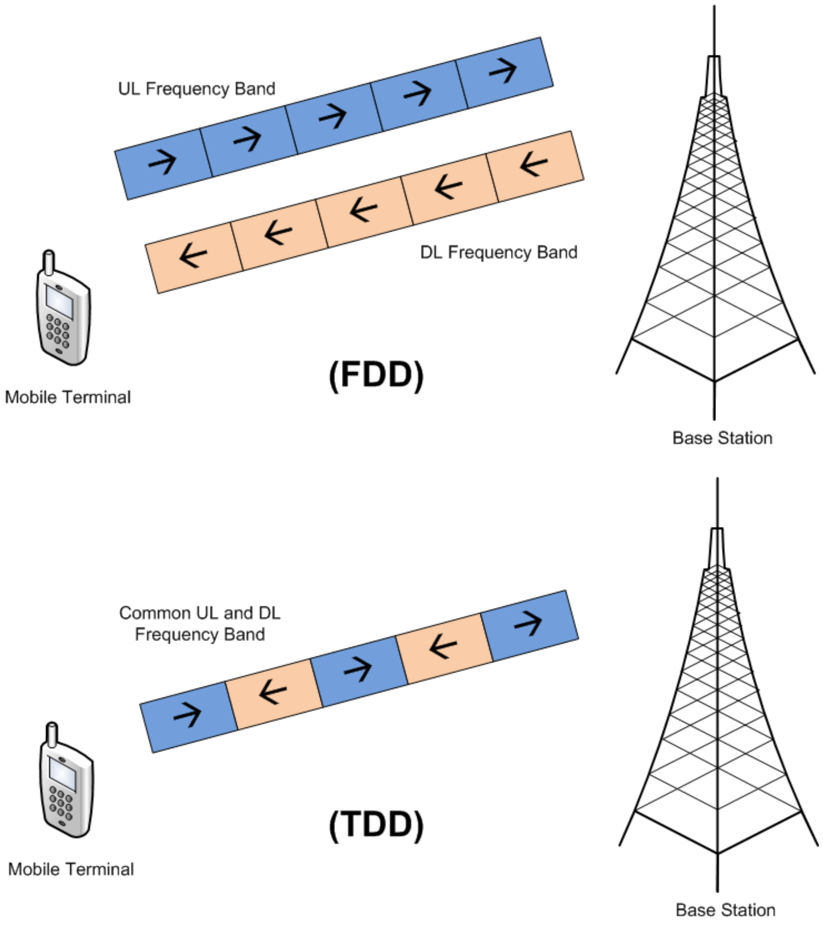


Figure 1.4. FDD and TDD usage in GSM.

it is allowed to. On the other hand, Time Division Multiple Access (TDMA) splits time component of the spectrum into slots and time slots are assigned to users, which may repeat periodically [45]. GSM employs FDMA and TDMA by combining them for media access. Frequency-division duplexing (FDD) means that the transmitter and receiver operate at different carrier frequencies and it is used to separate downlink (DL) and uplink (UL). GSM 900 used 124 full-duplex channel for FDMA, each channel was 200 kHz whereas GSM 1800 used 374 channels [43]. Figure 1.4 illustrates the usage of Frequency-Division Duplexing (FDD) and Time-Division Duplexing (TDD) in GSM uplink and downlink for channel separation.

Code Division Multiple Access (CDMA) system separates the users out by utilizing an orthogonal code per each user. Orthogonal codes are used to spread the energy of the signal over the frequency to allow multiple users to be separated at the receiver [45]. This technology had been used for military applications even before GSM but its suitability was demonstrated in 1990s when used in the American *IS-95* standards and with *cdmaOne* as the first competitor technology to TDMA in the US. CDMA can enable a frequency reuse factor of 1 to be used in cellular network planning and deployment with inter-cell interference sensitivity [41]. Most of the systems added CDMA technology to evolve and become 3G systems, this evolution over time can be summarized as follows : *General Packet Radio Service (GPRS)* introduced a packet-oriented solution with adding higher data rates to GSM. GPRS was originally standardized by ETSI in response to the earlier *Cellular Digital Packet Data (CDPD)* and *i-mode* packet-switched cellular technology of NTT DoCoMo in Japan. While Wireless Application Protocol (WAP) did not succeed in the beginning, i-mode encompassed a wider variety of Internet standards, including web access, e-mail and the packet-switched network that delivers the data. *Enhanced Data rates for GSM Evolution (EDGE)* (also known as Enhanced GPRS (EGPRS), or IMT Single Carrier (IMT-SC), or Enhanced Data rates for Global Evolution) improved data transmission rates by proposing a new modulation scheme meanwhile cdmaOne was enhanced to *cdma2000 1x* offering higher data rates.

Usage of radio technologies Universal Terrestrial Radio Access (UTRA) FDD and UTRA TDD, was easified since GPRS has already enhanced the GSM core network. Time Division Synchronous Code Division Multiple Access (TD-SCDMA) was the Chinese proposal for 3G where it has been integrated in UTRA TDD later. UMTS started by using the same core network of GSM/GPRS but adding a new radio interface.

Evolution of cdmaOne to cdma2000 technologies was backward compatible, where cdma2000 1x offers higher data rates up to 153 kbit/s. It continued to use the same 1.25 MHz channels as cdmaOne did, whereas three 1.25 MHz channels are used to fit *cdma2000 3x* into ITU's 3G frequency scheme. However cdma2000 1x continued to be enhanced as follows :

- *cdma2000 1x EV-DO (EVolution-Data Optimized, or High Data Rate (HDR), or*

Data Only) : It adds a second 1.25 Mhz channel and offers 2.4 Mbit/s peak data rates. Cdma 1x EV-DO was the first member of cdma2000 family which was accepted as a 3G system by ITU.

- *cdma2000 1x EV-DV (EVolution-Data and Voice) :* It promises 1.2 Mbit/s for mobile users and 5.2 Mbit/s for stationary users.

After the introduction of *Universal Mobile Telecommunication System (UMTS)*, new Quality of Service (QoS) requirements and consequent changes for network planning accompanied a significant shift from predominantly circuit-switched applications requiring roughly constant data rates toward packet-switched data traffic by *High-Speed Packet Access (HSPA)*. *Long-Term Evolution (LTE) of UMTS* was a radical step, in parallel with the widespread deployment and continuing enhancement of HSPA (e.g. *HSPA+*), which objects to provide a further major step forward in the provision of mobile data services and it adds new dimensions for optimization in the frequency and spatial domains, also LTE resumed the spectrally efficient frequency reuse-1 of UMTS. LTE itself is progressively evolving like UMTS did and *LTE-advanced (LTE-A)* is a 4th Generation (4G) system which is evolved from LTE and continues to evolve [41].

Figure 1.5 summarizes the evolutionary path to LTE and categorizes the systems emphasized in italic font in this section and also covers the evolution of digital wireless communication systems. Interested readers are referred to [46] for more information about each legacy system and technology.

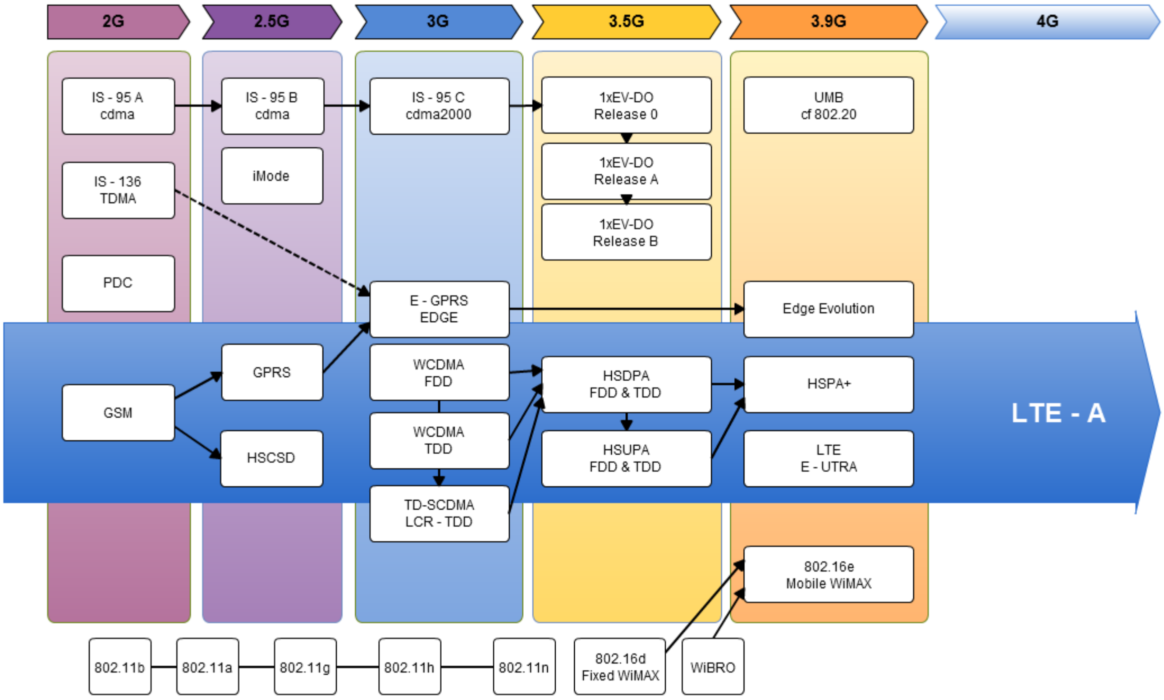


Figure 1.5. Digital Wireless Evolution.

2. LONG TERM EVOLUTION

2.1. Introduction

3GPP Long Term Evolution, usually referred to as LTE, also known as Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN), is specified in 3GPP Release 8. It is a standard for high-speed wireless data communications technology for mobile phones and data terminals and LTE is the evolution of the GSM/UMTS standards. It was defined to provide a high-data-rate, low-latency and packet-optimized system which ensures the competitiveness of GSM/EDGE and UMTS/HSPA network technologies for the future by increasing the capacity and performance using new Digital Signal Processing (DSP) and modulation techniques.

The new network architecture which is a new flatter-IP core was called System Architecture Evolution (SAE) and later it is termed as 3GPP Evolved Packet System (EPS), this core supports Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) which utilized the new OFDMA-based air interface. LTE air interface is a successor of GSM/EDGE and UMTS/HSxPA network technologies but has the ability to support bandwidths wider than 5 MHz, and EPS network architecture targeted to reduce the number of network level elements relative to High Speed Packet Access (HSPA) network in order to decrease the latency. Since LTE is designed to address higher throughput, increased base station capacity, reduced latency, and full mobility; it has set aggressive performance requirements and enhanced its IP-based Orthogonal Frequency Division Multiple Access (OFDMA) access with Multiple-Input and Multiple-Output (MIMO) and smart antennas [45]. Table 2.1 summarizes the key performance requirements for LTE Release 8.

Table 2.1. Key Performance Requirements for LTE Release 8 [47].

		Absolute requirement	Release 6 (for comparison)	Comments
Downlink	Peak transmission rate	> 100 Mbps	14.4 Mbps	LTE in 20 MHz FDD, 2 × 2 spatial multiplexing. Reference: HSDPA in 5 MHz FDD, single antenna transmission
	Peak spectral efficiency	> 5 bps/Hz	3 bps/Hz	
	Average cell spectral efficiency	> 1.6–2.1 bps/Hz/cell	0.53 bps/Hz/cell	LTE: 2 × 2 spatial multiplexing, Interference Rejection Combining (IRC) receiver . Reference: HSDPA, Rake receiver , 2 receive antennas
	Cell edge spectral efficiency	> 0.04–0.06 bps/Hz/user	0.02 bps/Hz/user	As above, 10 users assumed per cell
	Broadcast spectral efficiency	> 1 bps/Hz	N/A	Dedicated carrier for broadcast mode
Uplink	Peak transmission rate	> 50 Mbps	11 Mbps	LTE in 20 MHz FDD, single antenna transmission. Reference: HSUPA in 5 MHz FDD, single antenna transmission
	Peak spectral efficiency	> 2.5 bps/Hz	2 bps/Hz	
	Average cell spectral efficiency	> 0.66–1.0 bps/Hz/cell	0.33 bps/Hz/cell	LTE: single antenna transmission, IRC receiver. Reference: HSUPA, Rake receiver, 2 receive antennas
	Cell edge spectral efficiency	> 0.02–0.03 bps/Hz/user	0.01 bps/Hz/user	As above, 10 users assumed per cell
System	User plane latency (two way radio delay)	< 10 ms		LTE target approximately one fifth of Reference.
	Connection set-up latency	< 100 ms		Idle state → active state
	Operating bandwidth	1.4–20 MHz	5 MHz	(initial requirement started at 1.25 MHz)
	VoIP capacity	NGMN preferred target is > 60 sessions/MHz/cell		

2.2. EPS Architecture

Evolved Packet System (EPS) is the new system architecture that was proposed to cope with an all IP network that consists two layers as core network and access network. The core network is based on the Evolved Packet Core (EPC) and it is called the System Architecture Evolution (SAE). The access network is based on a Long Term Evolution (LTE) which relies on the Evolved Universal Mobile Telecommunication System Terrestrial Radio Access Network (E-UTRAN). A simple sketch of this architecture is illustrated in Figure 2.1.

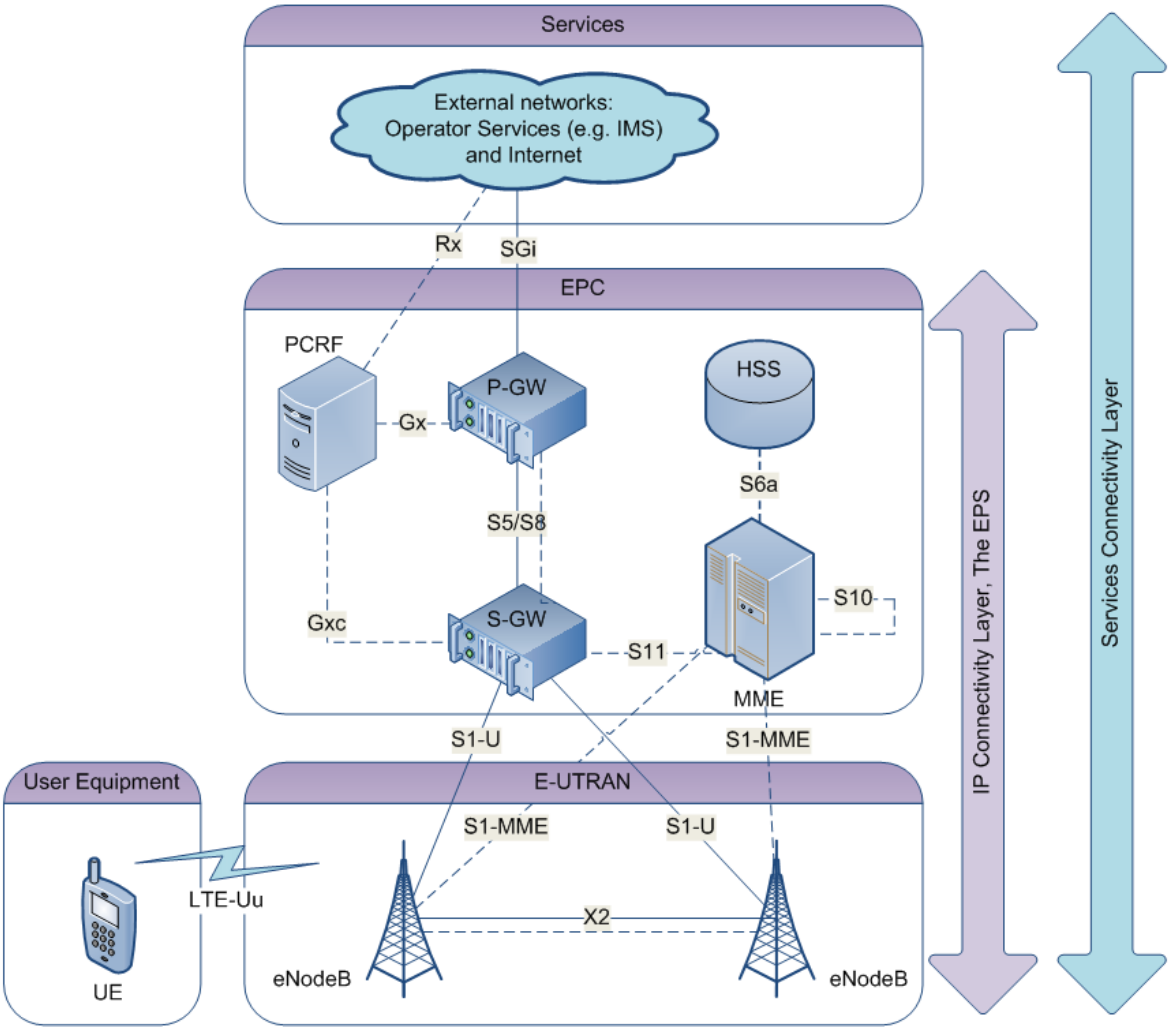


Figure 2.1. System architecture for E-UTRAN only network (Adopted from [48]).

In EPS architecture, the Radio Network Controller (RNC) was eliminated and the central control functions of the RNC are distributed between the evolved/Enhanced Node B (eNB) and the Mobility Management Entity (MME) as eNBs are able to communicate with each other using a new logical inter-eNB interface, called X2 interface. Another point that simplifies the architecture is that there is no need for soft handover since the transmission is of data only. Further details of each entity in the EPS can be found in [47–50].

2.3. Overview of Physical Layer (PHY)

As defined in [51–55] LTE PHY layer is responsible for performing the following functions:

- Error detection on the transport channel and indication to higher layers
- Forward Error Correction (FEC) encoding/decoding of the transport channel
- Hybrid ARQ soft-combining
- Rate matching
- Mapping of the coded symbols to physical channels
- Power weighting of physical channels
- Modulation and demodulation
- Frequency and time synchronization
- Radio characteristics measurements and indication to higher layers
- MIMO/transmit diversity beamforming support
- RF processing

One major change in LTE compared to its predecessor mobile technologies is the use of OFDM and MIMO techniques. Table 2.2 lists the key parameters in LTE air interface. As seen from Table 2.2 the physical layer is based on OFDMA in downlink and SC-FDMA in the uplink, both with a cyclic prefix.

OFDMA and SC-FDMA schemes exploit the use of frequency domain as a new dimension, Figure 2.2 illustrates the frequency-time representation of an OFDM Signal for 5 MHz bandwidth. Supported channel bandwidths are listed in Table 2.3 for LTE.

Note that channel bandwidth and transmission bandwidth is not the same and transmission bandwidth is defined in terms of resource blocks as seen in Figure 2.3.

There are two types of frame structure in LTE namely, Type-1, which uses both FDD and TDD duplexing, and Type-2,which uses TDD duplexing. And there are three duplexing modes such as, full duplex FDD, half duplex FDD and TDD. The

Table 2.2. LTE Key Air Interface Parameters.

Frequency Range	UMTS FDD bands and UMTS TDD bands
Modulation Schemes	**Downlink:** QPSK, 16QAM, 64QAM **Uplink:** QPSK, 16QAM, 64QAM (optional for UE)
Multiple Access	**Downlink:** OFDMA (Orthogonal Frequency Division Multiple Access) **Uplink:** SC-FDMA (Single Carrier Frequency Division Multiple Access)
MIMO technology	**Downlink:** Transmit Diversity, Spatial Multiplexing, Cyclic Delay Diversity (max. 4x4) **Uplink:** Multi User Collaborative MIMO
Peak Data Rate	**Downlink:** 150 Mbps (UE category 4, 2x2 MIMO, 20 MHz) 300 Mbps (UE category 5, 4x4 MIMO, 20 MHz) **Uplink:** 75 Mbps (20 MHz)

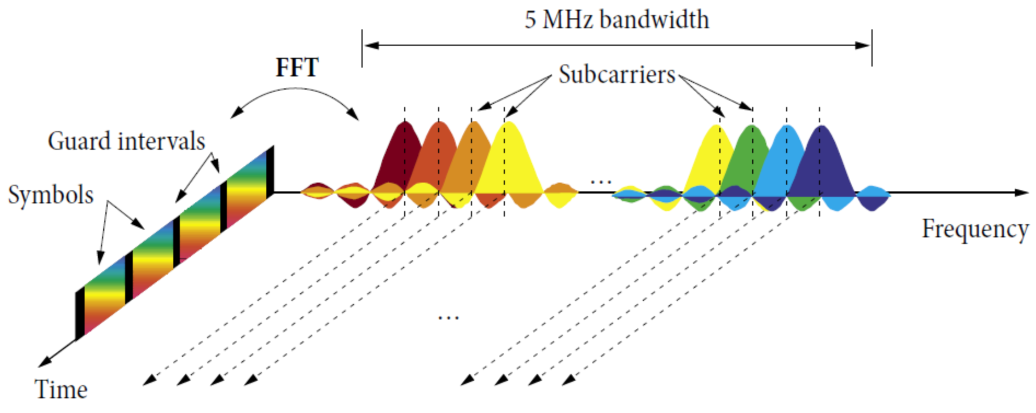


Figure 2.2. Frequency-Time Representation of an OFDM Signal [56].

basic time-frequency resource structure is presented in Figure 2.5. Moreover, Figure 2.4 shows the frame structure Type-1. A downlink radio frame is 10ms length where it consists 20 slots with 0.5ms duration for each slot. Two slots form a subframe and one resource block (RB) spans 12 subcarriers. Number of resource blocks have been

Table 2.3. LTE Channel Bandwidths.

Channel Bandwidth 1RB=180kHz	**1.4 MHz**	**3 MHz**	**5 MHz**	**10 MHz**	**15 MHz**	**20 MHz**
	6 RBs	15 RBs	25 RBs	50 RBs	75 RBs	100 RBs

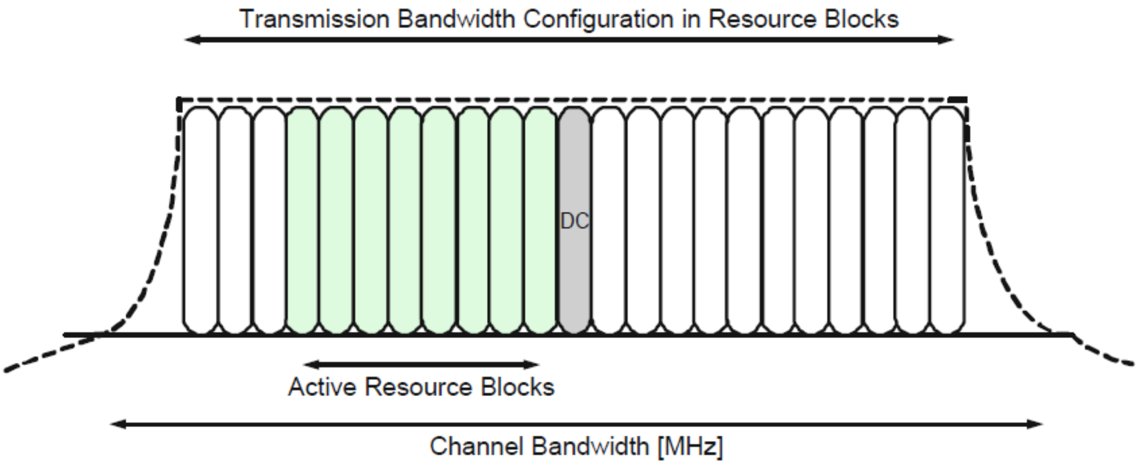


Figure 2.3. Channel Bandwidth and Transmission Bandwidth representation [45].

defined in Table 2.3 according to channel bandwidth.

Medium Access Control (MAC) layer and PHY layer interaction is modelled in Figure 2.6. Note that for downlink eNodeB is the transmitter and UE is the receiver and for the uplink the opposite is valid where UE is the transmitter and the eNodeB is the receiver. Additional information about LTE Frame and PHY layer can be found in [45, 47].

2.4. Power Control and Interference Management in LTE

Radio resource management (RRM) issues such as downlink and uplink power control, downlink and uplink scheduling, and inter-cell interference coordination (ICIC)

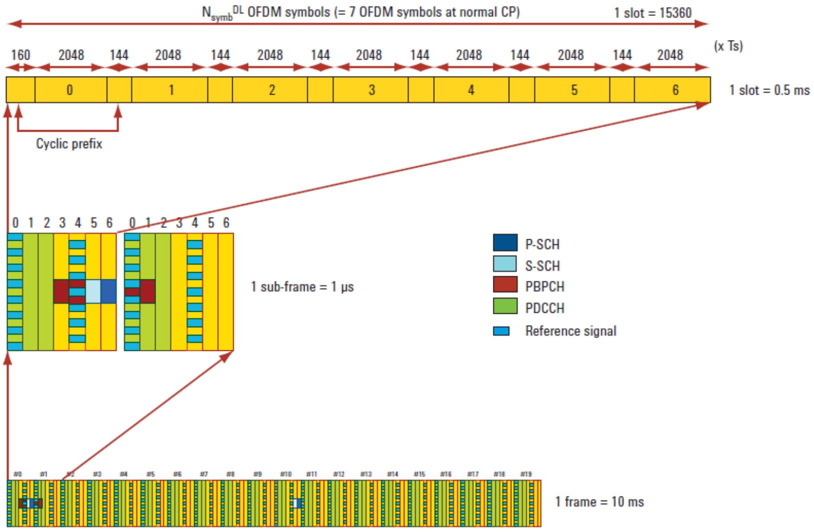


Figure 2.4. Frame structure Type-1 [57].

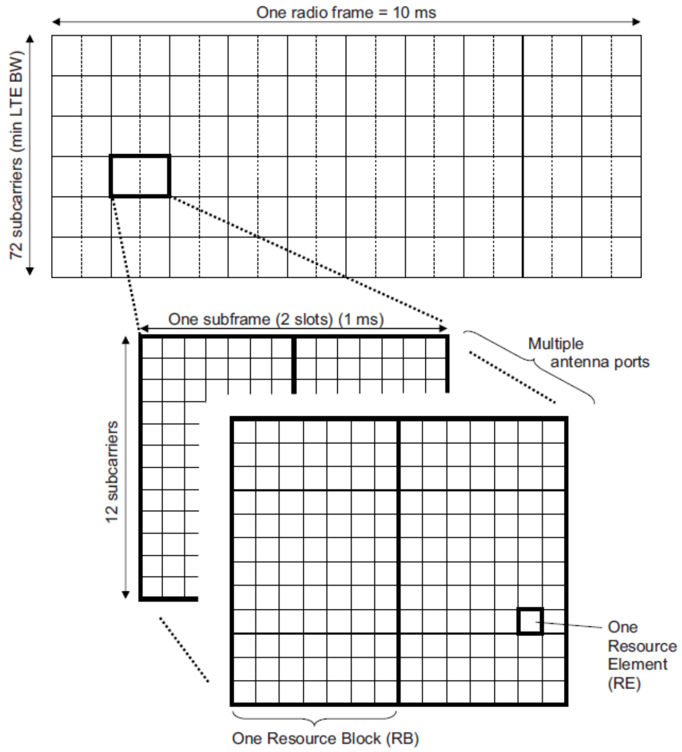


Figure 2.5. Basic time-frequency resource structure of LTE (normal cyclic prefix case) [47].

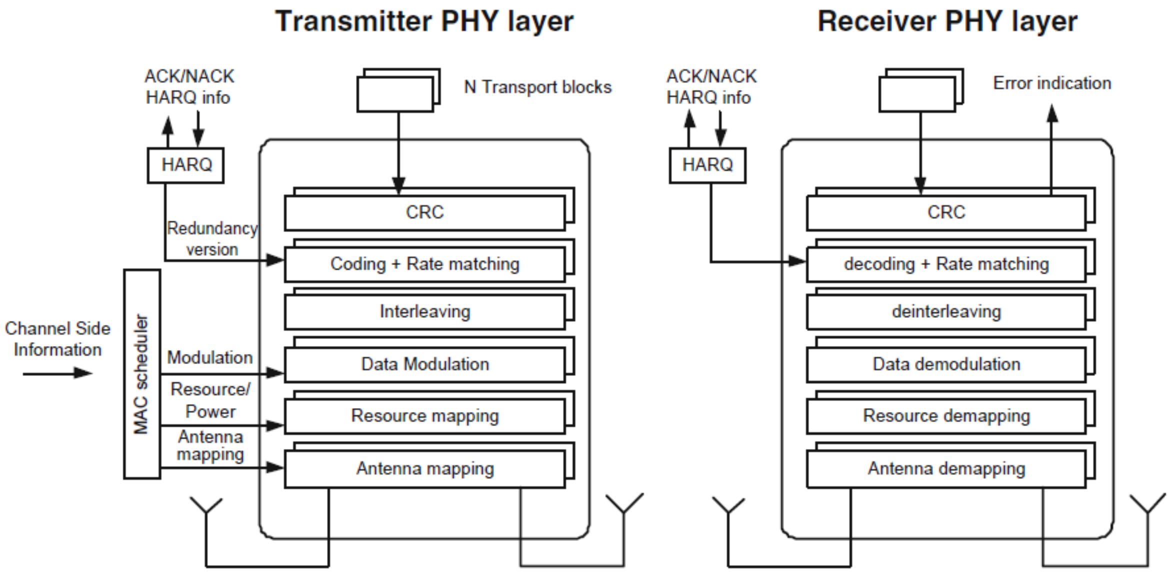


Figure 2.6. LTE Physical layer interaction [45].

is the main concern in LTE Heterogeneous Network (HetNet) deployments including macrocells, picocells, and/or femtocells. Since OFDMA is used in LTE with appropriate cyclic prefixes inter-channel interference (ICI) and inter-symbol interference (ISI) can almost completely be avoided but ICIC methods are developed in order to manage inter-cell interference. LTE Release 8 primarily rely on frequency domain scheduling and adjustment of transmit powers.

2.4.1. Uplink Power Control

Uplink power control in LTE aims to ensure that the transmit power for different uplink physical channels do not create interference to other cells. It requires and measures the information of channel properties like channel attenuation and the noise and interference level at the receiver side. The power scaling for Physical Uplink Shared Channel (PUSCH) is as follows in [54]:

$$\sum_{\forall i} w_c \cdot P_{PUSCH,c} \leq P_{TMAX} - P_{PUCCH} \tag{2.1}$$

where w_c is the power-scaling factor for PUSCH on carrier c ($w_c \leq 1$), $P_{PUSCH,c}$ is the transmit power for PUSCH on carrier c as determined by the power-control algorithm, P_{TMAX} is the maximum terminal output power and P_{PUCCH} is the transmit power for Physical Uplink Control Channel (PUCCH).

2.4.2. ICIC Related X2 Signalling

Resource partitioning schemas can be dynamically configured in LTE by means of information exchange over the X2 interface between eNodeBs. In [58] and references therein exchanged information is defined and described. Here is the list of information messages related to ICIC in Release 8 and Release 9.

Relative Narrowband Transmit Power Indicator (RNTP): The exchanged information message contains 1 bit per physical resource block (PRB) in the downlink and it indicates the PRB which will have a greater transmission power with respect to a specified threshold. As a result, neighbor eNBs can combine this information with the UEs' Channel Quality Indicator (CQI) reports and take the correct scheduling decisions immediately.

High Interference Indicator (HII): HII works similar to RNTP but for uplink transmissions. This indicator can also be used in frequency partitioning scheme in order to identify the used bands.

Interference Overload Indicator (OI): OI is sent to neighbor eNBs whose UEs are potentially causing high interference in the uplink direction and it can contain 3 types of indicator per PRB namely; high,low or medium. This message is not sent periodically but only triggered when high interference is detected in the uplink direction.

In Release 10, X2 signalling is enhanced to support more complex interference mitigation techniques such as interference coordination in time domain for heterogeneous networks. A simulation to compare the differences between Homogeneous network scenario and Heterogeneous Network scenario is presented in [59]. It also counts

Range Expansion (RE) into account which is a topic that we will not discuss in here.

2.4.3. Frequency Techniques for Inter-Cell Interference Coordination

LTE is designed to work with the frequency reuse factor of 1, but the reduction of cell-edge users' performance requires to use more complex frequency reuse mehtods. In [16,60–63] the degradation in performance of cell edge users' throughput is discussed and illustrated graphically.

According to [64], if one was only interested in maximizing the data rates that could be offered to users at the cell edge - that is, maximizing the “worst-case-user” quality - a reuse larger than one could actually be preferred. Nevertheless, some frequency reuse schemes can lead to degradation on overall system efficiency so more efficient methods are developed in order to balance the system throughput. We will discuss the advantages and disadvantages of the most important frequency reuse schemes in here.

2.4.3.1. Full Frequency Reuse. As stated previously, LTE is designed to operate in Full Frequency Reuse scheme where the transmit power is uniform over the entire bandwidth. Full Frequency Reuse implies no frequency partitioning between cells or sectors. Figure 2.7 depicts the Full Frequency Reuse configuration. Other methods can't achieve the average throughput values compared to full reuse achieved as concluded in [65], however the main disadvantage of this configuration is the significant degradation of the communication performance in cell-edges. Cell-edge users causes serious interference in the uplink to the neighboring cells while they also experience heavy interference from them.

2.4.3.2. Hard Frequency Reuse. Hard Frequency Reuse (HFR) divides the system bandwidth into a number of disjoint sub-band sets with respect to a specified reuse factor and makes neighboring cells transmit on different subbands in a way that neighboring cells don't operate in same set of frequencies. This method was generally used

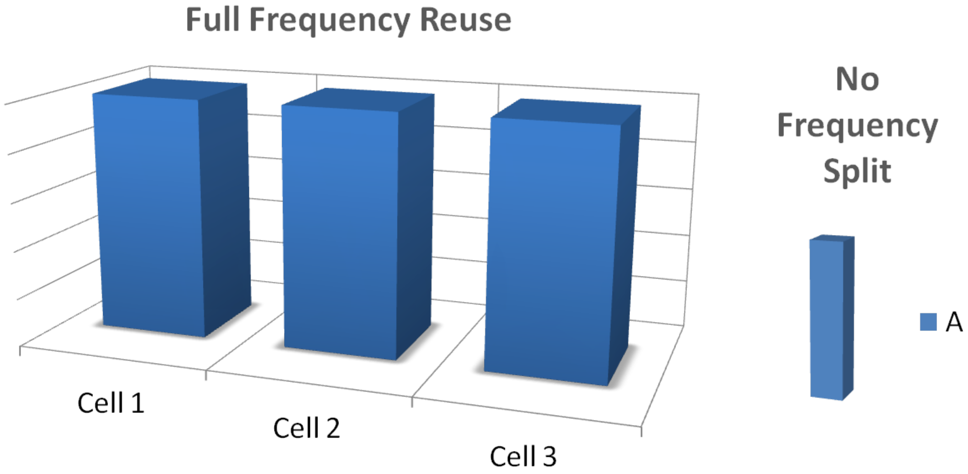


Figure 2.7. Full Frequency Reuse.

in GSM networks. The bandwidth and frequency configuration for frequency reuse factor (FRF) of 3 is illustrated in Figure 2.8. This method reduces the interference level maximally at the cell edge, notwithstanding it also reduces the spectrum efficiency by a factor near to the frequency reuse factor used and its interference advantage does not pay off in the higher rate required cases.

2.4.3.3. Fractional Frequency Reuse. Fractional Frequency Reuse (FFR) [66] combines the Hard Frequency Reuse and Full Frequency Reuse methods smartly. It splits the spectrum into an inner and outer part where a frequency reuse factor of one is applied to the center and a frequency reuse factor greater than one is applied in the edge part. The inner-part of the splitted bandwidth is used by all cells while the other part is used as in HFR and distributed differently among neighboring cells. Figure 2.9 picturizes the configuration for FFR-3. In [59] it is indicated that FFR is particularly useful for ICIC in the uplink, where severe interference situations can occur when the user is located close to a strong interferer in the neighbor cell. The impact of FFR on

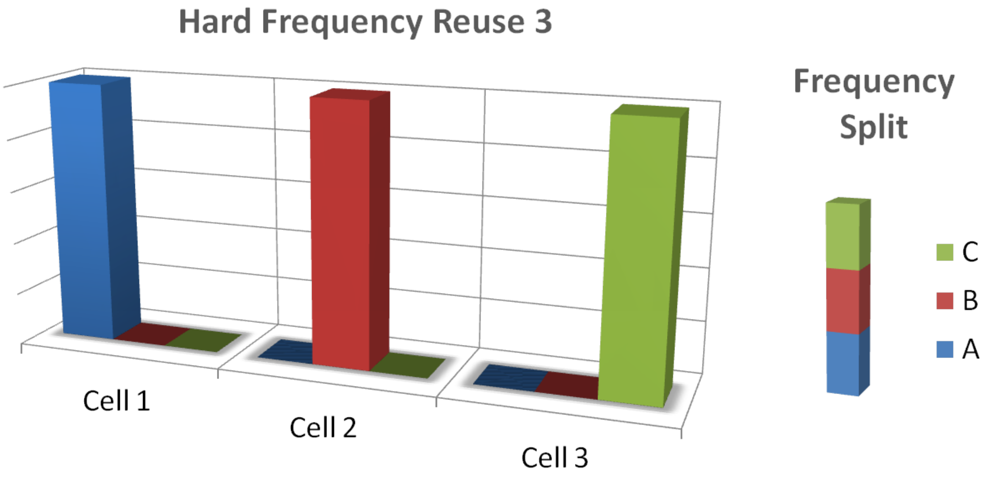


Figure 2.8. Hard Frequency Reuse.

LTE uplink performance can be found in [35]. Other interference methods using FFR can be found in [13, 17, 25–27, 29–36].

2.4.3.4. Soft Frequency Reuse. Soft Frequency Reuse (SFR) [67] method uses the whole frequency spectrum non-uniformly. Users near to eNBs are scheduled on the PRBs with a lower transmit power, while cell-edge users are restricted for the highest power level in the spectrum. Performance results for different downlink transmit power profiles is presented in [17] and optimal power masking for SFR is discussed in [65]. Figure 2.10 shows the spectrum configuration for SFR. This method is suitable for ICIC in downlink direction. [16, 68] analysis the use of SFR for uplink ICIC in LTE networks where [69] analysis the performance in LTE for downlink transmission.

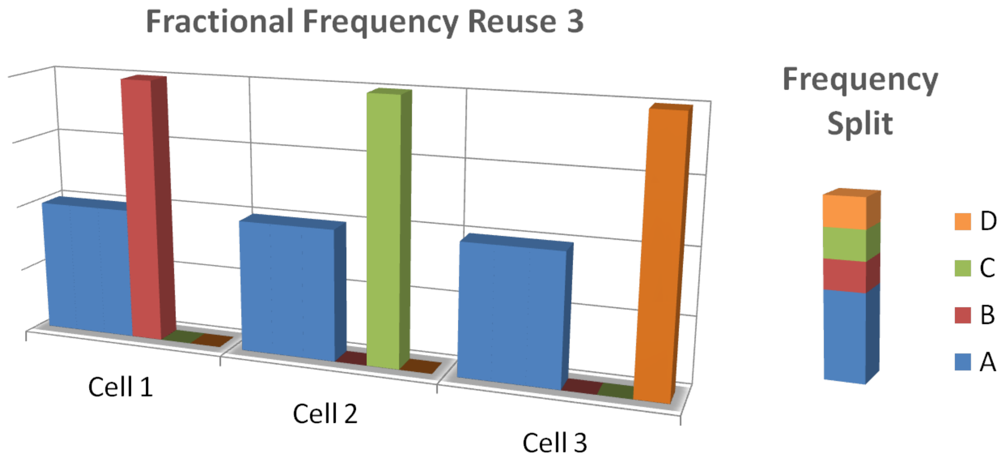


Figure 2.9. Fractional Frequency Reuse.

2.5. LTE Release 10 and Beyond: LTE-Advanced

LTE Release 8 had matured with the great contribution from industry than ever before in 3GPP by December 2007 and it is submitted to ITU-R as a member of the IMT family of radio access technologies. 3GPP continued to further develop LTE firstly by LTE second release, Release 9, and after LTE is enhanced towards LTE Release 10 which is the next giant step known as LTE-Advanced that completely fulfills the requirements set by ITU for IMT Advanced, also referred to as 4G.

LTE Release 9's priority was to ensure the suitability for different markets and deployments. Below is a list of actions in Release 9:

- Public Warning Systems (PWS) support is improved
- Enhanced accurate positioning methods introduced such as using Observed Time Difference of Arrival (OTDOA) in new reference signals in LTE downlink transmission

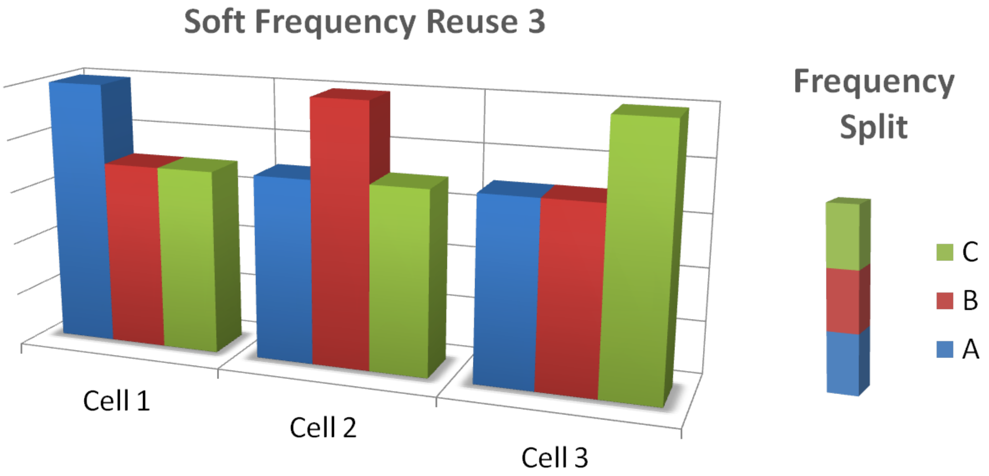


Figure 2.10. Soft Frequency Reuse.

- Enhanced Cell-ID-based techniques are also supported
- Support for a broadcast mode based on Single Frequency Network (SFN) type transmissions
- Extension of the Release 8 beamforming mode to support two orthogonal spatial layers that can be transmitted to a single user or multiple users
- Definition of new requirements for pico base stations and home base stations
- Improving support for Closed Subscriber Groups (CSG)
- Enhancement of support for self-optimization of the networks

LTE Release 10 is set to provide higher bitrates in a cost efficient way and it fully satisfies the requirements set by ITU-R for the IMT-Advanced designation [70] and even exceeds them in several aspects where 3GPP has set more demanding performance targets than those of ITU-R. Here are some of the most important features introduced in LTE-Advanced:

- Carrier aggregation, allowing the total transmission bandwidth to be increased up to 100 MHz
- Coordinated multipoint transmission and reception (CoMP)
- Downlink MIMO enhancements, targeting peak spectral efficiencies up to 30 bps/Hz
- Uplink MIMO transmission for peak spectral efficiencies greater than 7.5 bps/Hz and targeting up to 15 bps/Hz
- Enhanced inter-cell interference coordination techniques including interference coordination in time domain
- Support for relaying
- Support for heterogeneous networks and LTE self-optimizing network (SON) enhancements
- Home enhanced-node-B (HeNB) mobility enhancements
- Extended measurement reports from the terminals and minimization the need for drive tests with this support

In one early investigation which took place on 25 December 2006 with information released to the press on 9 February 2007, NTT DoCoMo detailed information about trials in which they were able to send data at speeds up to approximately 5 Gbit/s in the downlink within a 100MHz bandwidth to a mobile station moving at 10km/h. The scheme used several technologies to achieve this including variable spreading factor spread orthogonal frequency division multiplex, MIMO, and maximum likelihood detection. Details of these new 4G trials were passed to 3GPP for their consideration [71]. After the two workshops held by 3GPP in 2008 *"Requirements for Further Advancements for E-UTRA"* [72] is published at the same year in June. Table 2.4 compares the key parameters of LTE-Advanced with previous cellular technologies beginning from the UMTS. Performance targets and the technology components for LTE-A can be found in [73].

Table 2.4. Comparison of LTE-A key paramters

	WCDMA (UMTS)	**HSPA HSDPA/ HSUPA**	**HSPA+**	**LTE**	**LTE-A (IMT-A)**
Max DL speed	384 kbps	14 Mbps	28 Mbps	100 Mbps	1 Gbps
Max UL speed	128 kbps	5.7 Mbps	11 Mbps	50 Mbps	500 Mbps
Latency RTT	150 ms	100 ms	50 ms	10 ms	less than 5 ms
3GPP Release	Rel 99/4	Rel 5/6	Rel 7	Rel 8	Rel 10
Multiple Access	CDMA	CDMA	CDMA	OFDMA/ SC-FDMA	OFDMA/ SC-FDMA

2.5.1. Carrier Aggregation

Carrier Aggregation (CA) is the most essential feature of the LTE-Advanced technology. Currently, it is unlikely to improve the spectral efficiency of LTE with its widest channel bandwidth, which is 20 MHz, in order to achieve the 4G target downlink peak data rate of 1 Gbps. It is clear that more bandwidth is required to address this goal; however large portions of contiguous spectrum is practically uncommon, yet it is feasible to aggregate multiple Component Carriers (CCs), which are Release 8/9 carriers, to achieve high-bandwidth transmission. In LTE Release 10 the transmission bandwidth can be extended further, up to 100 Mhz with 40 MHz the expectation for minimum performance, by means of so-called Carrier Aggregation, where multiple component carriers, up to five 20 MHz Rel 8/9 CCs, are aggregated and jointly used for transmission to/from a single terminal. Also it can be used for both FDD and TDD.

The most straightforward method for combining carriers is to aggregate contiguous component carriers within the same operating frequency band, so called intra-band contiguous. Besides, LTE-Advanced supports fragmented spectrum for non-contiguous allocation inter-band or intra-band as depicted in Figure 2.11.

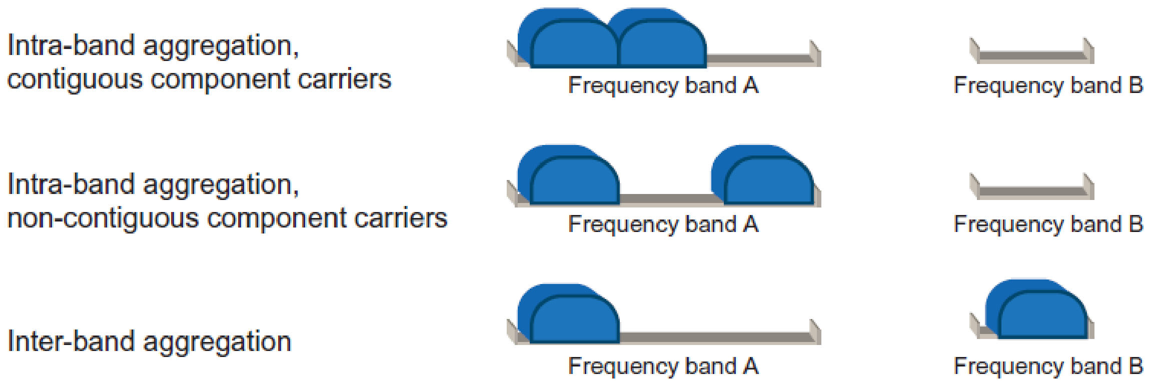


Figure 2.11. Carrier Aggregation [64].

For each CC there is a related serving cell that whose coverage may vary. This is a useful property for heterogeneous network planning as can be seen from Figure 2.12. Primary serving cell, served by the Primary Component Carrier (PCC) is responsible for the RRC connection of a UE, all other CCs are termed as Secondary Component Carrier (SCC). Note that the number of CCs in downlink and uplink do not have to be equal, Figure 2.13 illustrates the symmetricity relation of uplink and downlink in LTE where 'P' denotes the primary component carrier.

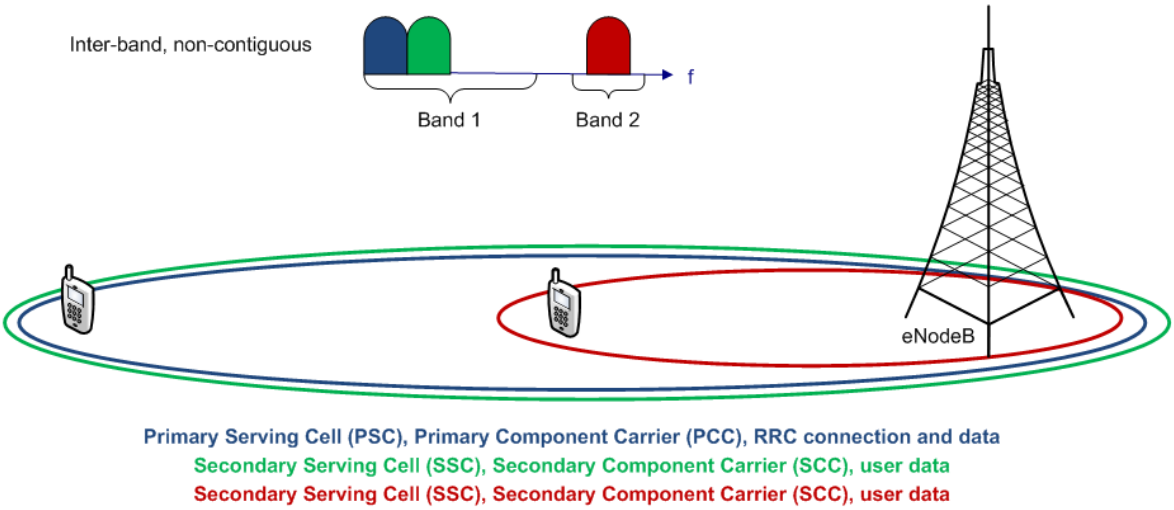


Figure 2.12. Carrier Aggregation Serving Cells (Adopted from [74]).

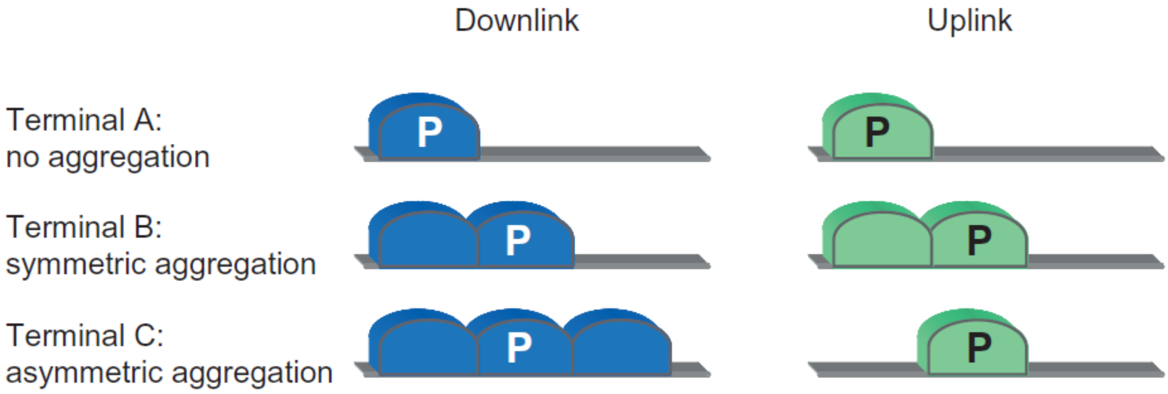
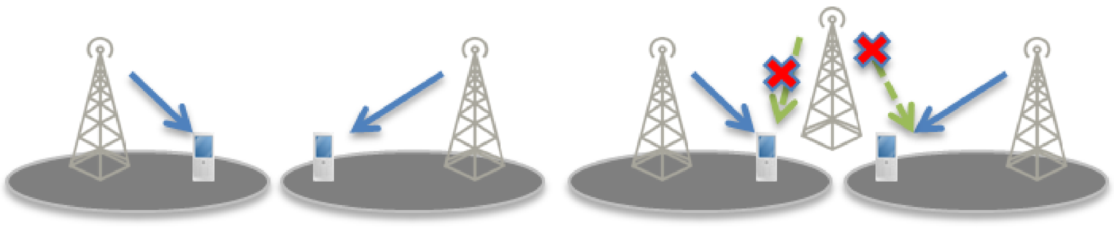


Figure 2.13. Carrier Aggregation Symmetricity Relation [64].

Selecting the primary and secondary CCs so that to reduce interference is also an important aspect, in [75, 76] good methods of selecting primary and secondary component carriers are proposed. For more information about Carrier Aggregation and details such as Cross-Carrier Scheduling, the reader is referred to [47,48,64,71,74, 77–80].

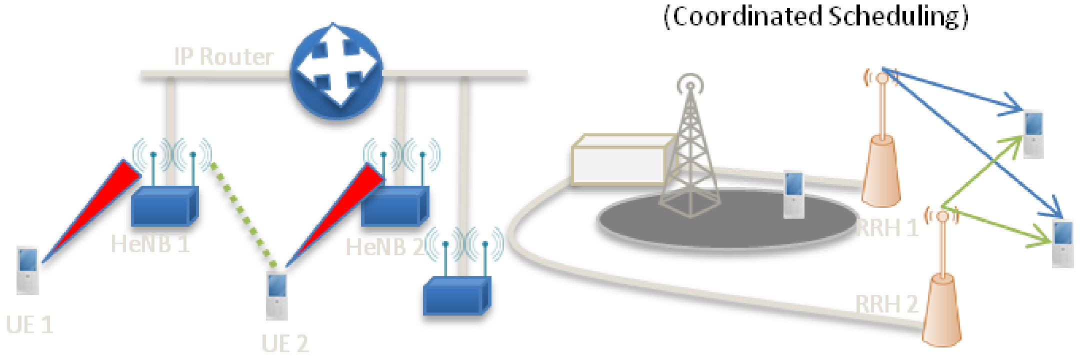
2.5.2. Coordinated Multipoint Transmission and Reception (CoMP)

With the evolution of LTE-Advanced for Release 11 and beyond a new term Coordinated Multi-Point (CoMP) transmission/reception, also called Cooperative MIMO, has gained attention which provides great benefits in heterogeneous network deployments. It refers to a range of different techniques which object to increase performance, especially at the cell edge, by dynamically coordinating the transmission and reception. Uplink cooperation is analogic to softer handover in UMTS but for multiple sites. Maximum-ratio combining and interference-rejection combining are examples of joint reception. Downlink cooperation techniques are as in Figure 2.14. While (A) denotes the traditional uncoordinated single-cell transmission, (B) denotes *coordinated scheduling* where $Cell_B$ adapts its transmission power for particular time-frequency resources in order to manage the interference on UE_A and UE_C. Likewise Inter-Cell Interference Coordination (ICIC) via partial frequency reuse is a form of coordinated scheduling and dynamic coordination of scheduling is of benefit to Home eNodeB (HeNB) closed access mode deployments.



(A) Non-cooperative Transmission

(B) Coordinated Silencing
(Coordinated Scheduling)



(C) Coordinated Beamforming

HeNB 1 forms beam to UE 1 with
transmitnulling of UE2

(D) Coherent Joint Transmission
(Multicell MIMO or Network MIMO)

Figure 2.14. Downlink Transmission Techniques [47].

A spatial dimension of ICIC is *coordinated beamforming* for multi-antenna eNodeBs. As pointed out in (C) transmit beams can be steered away from a specific UE in the region of another HeNB's coverage. In [81], it is concluded that coordinated beamforming adds little spectral efficiency improvement compared to single-cell MU-MIMO in homogeneous macrocell deployments.

Joint transmission refers to transmission of data to a terminal from several sites jointly. Coherent Joint Transmission (JT), as known as multicell MU-MIMO or network MIMO, plays a significant role in heterogeneous network deployments by multicell channel State feedback from the terminal. Case (D) of figure highlights the JT with Remote Radio Heads (RRHs), picocells can also be used instead. In [82] it is mentioned that substantial spectral improvement can be gained by using JT across a large number of eNBs, theoretically. Further information about CoMP can be found in [47, 64].

3. HETEROGENEOUS NETWORKS AND SMALL CELLS

A combined network of macrocells and small cells is generally known as *heterogeneous network (HetNet)*[1] or *multi-layered network*. Heterogeneous deployments consist of deployments with a mixture of cells with different downlink transmission power, which are macro base station deployments that typically transmit at high power overlaid with several low power nodes such as pico base stations, distributed antennas, femto base stations, and relays. They operate on (partially) the same set of frequencies and with overlapping geographical coverage. It can consist of different cell scales which range from macro to micro, pico and even femtocells. Nodes can deploy different access technologies such as WiMAX and WiFi, over both licensed and unlicensed bands. Remarkable gains in network capacity via aggressive spatial spectrum reuse and benefiting from unlicensed bands is one of the advantage of a HetNet. For instance, co-channel femtocells can supply linear gains in air interface capacity with increasing number of femto-APs in a hybrid deployment. Macro layer furnishes the coverage while the small cells are better suited for capacity infill and indoor coverage in order to eliminate coverage holes in outdoor and indoor environments and also to increase the capacity of the network. A survey on 3GPP HetNets is presented in [83].

Deploying small cells under the coverage area of a macro cell as presented in Figure 3.1 is preferable complement to a uniform densification of the macro-cell layer, in terms of cost. Third-generation cellular networks utilize three cell types: macro, micro, and pico based on their coverage area and user capacity [84]. In LTE as well as WiMAX, a fourth type is introduced to serve a single household—femtocell. These four types are defined in [41] as follows:

Macrocells: The largest cell types that cover areas in kilometers. These eNBs can serve thousands of users simultaneously. They are very expensive due to their high installation costs (cabinet, feeders, large antennas, 30–50 m towers,etc). The cells

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[1] Note that multi-RAT networks are also termed as HetNets but we refer to multi-layered networks as HetNets throughout this study.

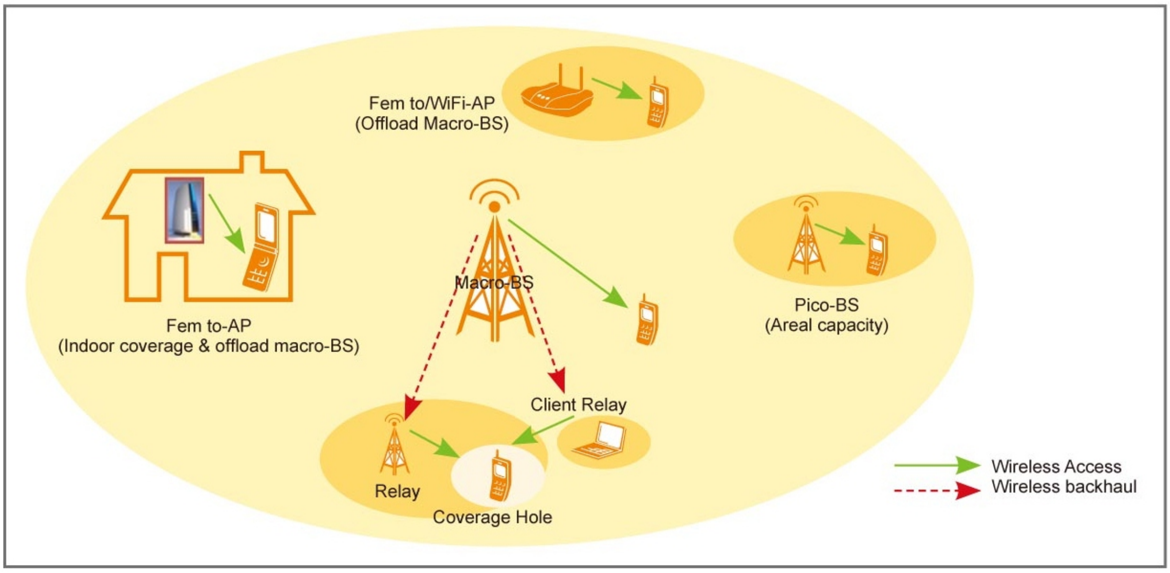


Figure 3.1. Heterogeneous Network architecture [85].

have three sectors and constitute the heart of the cellular network. Their transmitting power levels are very high (5–40 W).

Microcells: Provide a smaller coverage area than macrocells, and are added to improve coverage in dense urban areas. They serve hundreds of users and have lower installation costs than macrocells. You can find them on the roofs of buildings, and they can have three sectors as well, but without the tower structure. They transmit several watts of power.

Picocells: Used to provide enhanced coverage in an office like environment. They can serve tens of users and provide higher data rates for the covered area. The 3G networks use picocells to provide the anticipated high data rates. They have a much smaller form factor than microcells and are even cheaper. Their power levels are in the range of 20 to 30 dBm.

Femtocells: Introduced for use with 4G systems (LTE and WiMAX). They are extremely cheap and serve a single house/small office. Their serving capacity does not exceed 10 users, with power levels less than 20 dBm. A femtocell will provide very high

DL and UL data rates, and thus provide multi-Mbps per user, thus accomplishing mobile multimedia, anywhere anytime, with global mobility support, integrated wireless solution, and customized personal service (MAGIC).

Figure 3.2 renders the hierarchy of small cell types and macro cell.

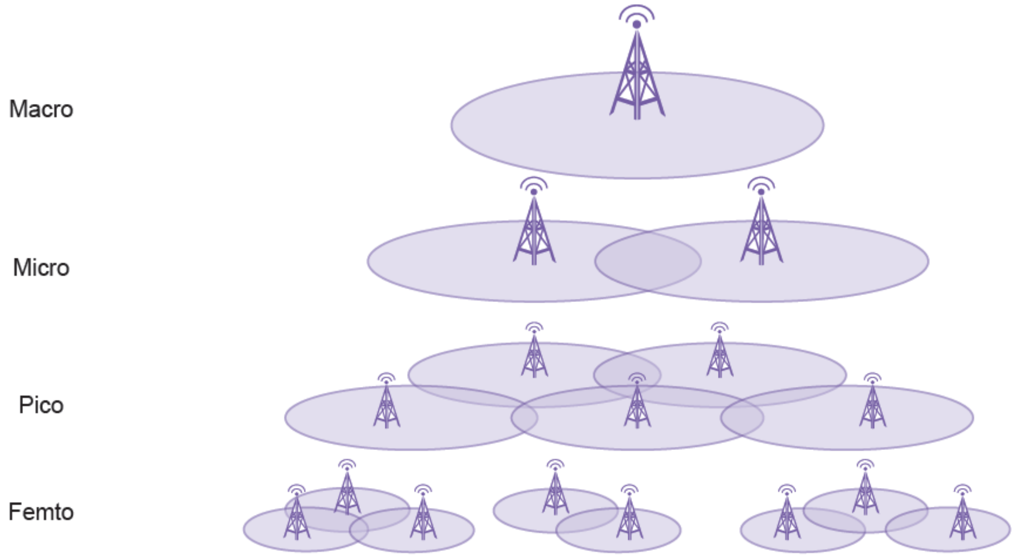


Figure 3.2. Small Cell Hierarchy.

Our study mainly focused on Home-eNodeBs (HeNBs) / femto base stations . A home-eNodeB corresponds to a small low-power base station deployed by the end-user, typically within the home, and connecting to the operator network using the end-user's wireline broadband connection as the LTE femtocell architecture is depicted in Figure 3.3.

A home-eNodeB is often associated with a so-called Closed Subscriber Group (CSG), with only users that are members of the CSG being allowed to access the home-eNodeB. Thus, users not being members of the CSG have to access the radio-access network via the overlaid macro-cell layer even when in close proximity to a home-eNodeB. Hence, this causes additional interference problems with home-eNodeB deployments, beyond those of ordinary heterogeneous network deployments. Detailed information about femtocells can be found in [41, 47, 64, 86–88].

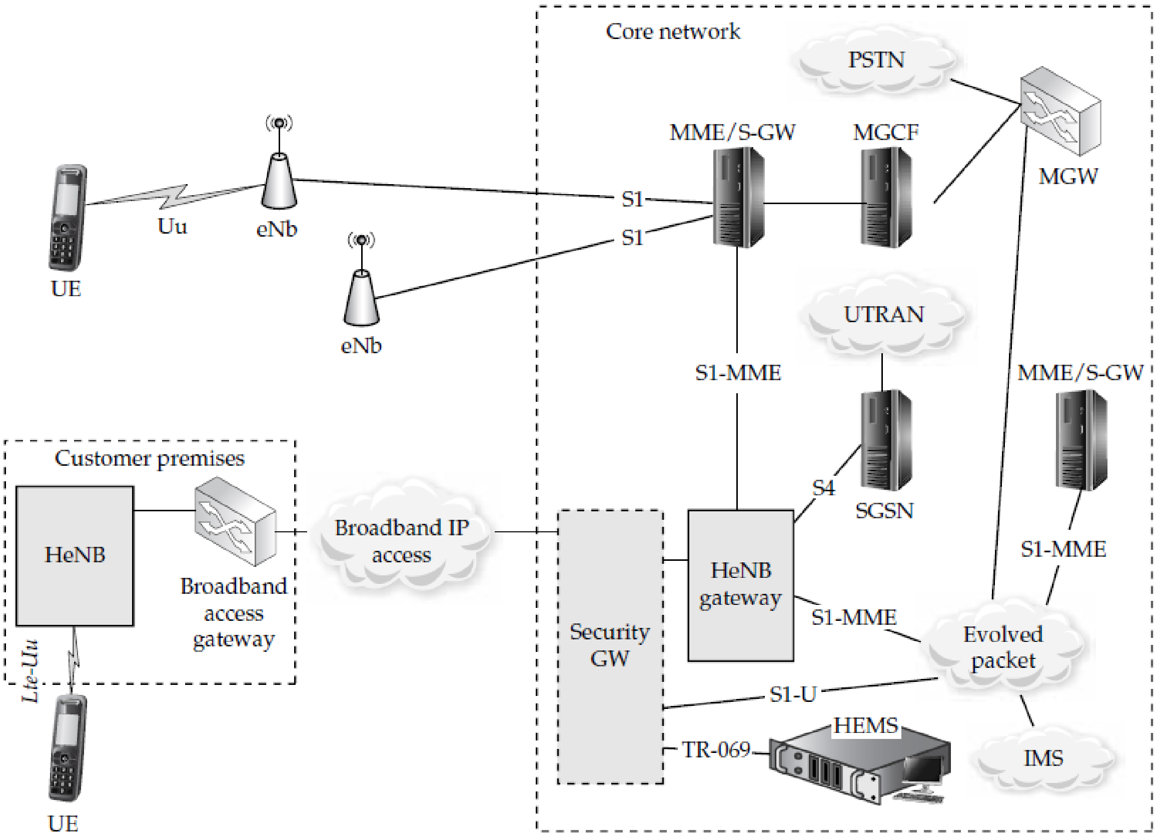


Figure 3.3. LTE Femtocell Architecture [86].

3.1. Interference Handling in HetNet

Heterogeneous deployment in GSM network have been using different sets of carrier frequencies for different cell layers, hence avoiding heavy interference between the layers. Notwithstanding for a wideband radio-access technology such as LTE, this method may lead to inefficient spectrum utilization and causes undesirable spectrum fragmentation, therefore reduction of maximum achievable data rates in each layer becomes indispensable. Additionally, in the case of HeNB with CSG there exists more interference problems as explained in Table 3.1. More scenarios about interference management in OFDMA femtocells are described in [89]. These studies claim that there is a need for femtocells to adapt interference mitigation techniques in order to handle occasional extreme cases. Thence, inter-layer and intra-layer interference coordination can address this issues effectively.

Table 3.1. Potential interference scenarios for femtocells [88].

Potential issue	**Potential impact**
Downlink power from femtocells with closed subscriber group causes interference to macrocell user	Macrocell user experiences degraded service and potential loss of service
Femtocell user at edge of femto coverage transmits at high power, causing noise rise to nearby macrocells	Macrocell users at edge of coverage experience degraded service
Macrocell user close to femtocell but far from macrocell operates at high power, causing interference and potentially receiver blocking to femtocell	Femtocell users experience degraded coverage and service
Femtocell user at edge of coverage of femtocell 1 but close to femtocell 2	User experiences degraded downlink service due to interference from femtocell 1 and transmits at high power, degrading uplink service for users of femtocell 2

4. SELF-ORGANIZING NETWORKS

4.1. The Concept of SON

Considering the extensive growth in mobile data traffic, network operators should cope with the data explosion by expanding their capacities taking the challenges into account in terms of cost and work effort with their limited budgets of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). Since Average Revenue Per User (ARPU) is decreasing due to competitive equilibrium state of the market, network operators need a smart technology in order to minimize the manual intervention and thus minimize the costs. To meet these demands and to address the challenges foreseen due to management of several RATs along with the introduction of LTE, the concept of SON appeared with the adoption of the Next Generation Mobile Networks (NGMN) alliance as a vital technology. According to [90], a SON enabled LTE network can achieve 26% net savings, with components 34% for OPEX and 21% for CAPEX, compared to an LTE network without SON.

4.1.1. SON Functions

SON functions can be divided into three categories: Self-Configuration, Self-Optimization and Self-Healing/Maintenance as topics are summarized in Figure 4.1.

4.1.1.1. Self-Configuration. This function is also referred as 'plug-and-play'. It includes auto-connectivity, security setup, auto-commisioning and dynamic radio configuration.

4.1.1.2. Self-Optimization. Following the Self-Configuration process Self-Optimizing functions starts to work in order to optimize required parameters. Self-Optimization consists of Mobility Robustness Optimization, Mobility Load Balancing and Traffic Steering, Energy Saving, Coverage and Capacity Optimization, Random Access Chan-

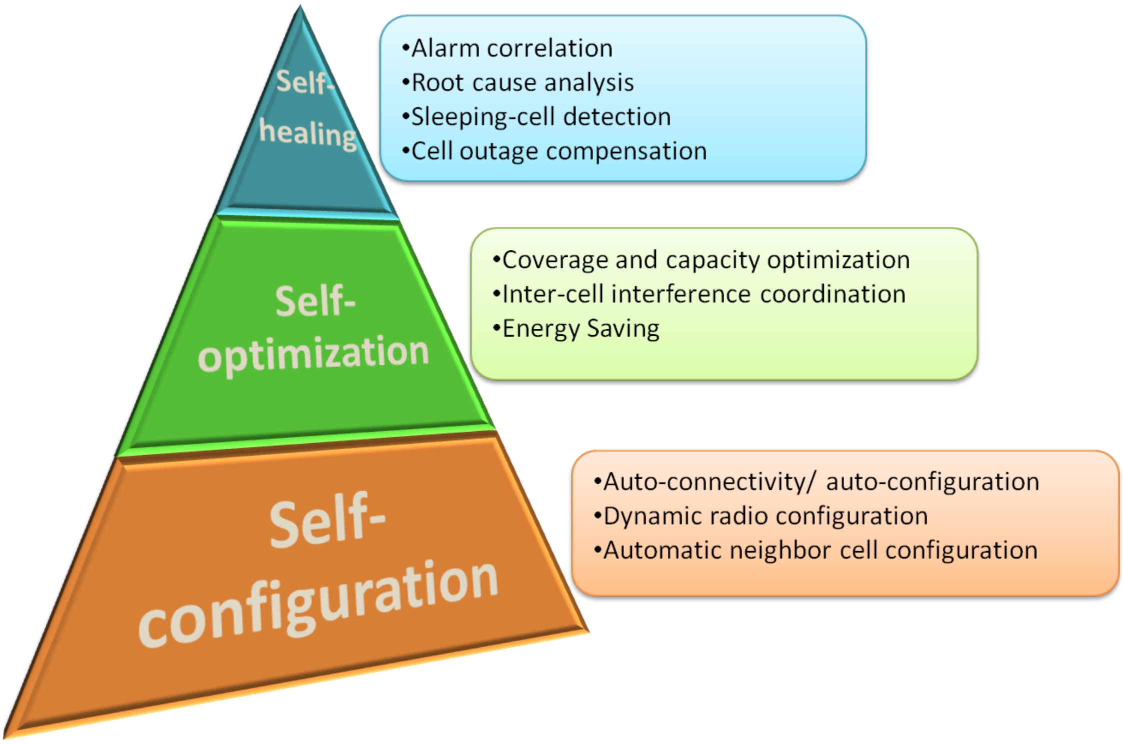


Figure 4.1. SON Use Cases (Adopted from [91]).

nel (RACH) Optimization and optimization of Radio Resource Management (RRM) parameters for inter-cell interference coordination (ICIC) and power control.

<u>4.1.1.3. Self-Healing/Maintenance.</u> Self-Maintenance is a continuous process that monitors the performance and uses continuous measurements. It comprises Cell Degradation Detection, Diagnosis and Prediction also it supports Cell Outage Compensation.

Interested reader is referred to read [91–94] for more details of SON. In this work, we will be mainly focusing on the use cases of; Coverage and Capacity Optimization (CCO), Interference Reduction and Inter-cell Interference Coordination (ICIC) as defined by 3GPP in [95].

4.2. SON in Femtocells

Femto Access Points (FAPs) are the equipments that will be installed by the end customer without an intervention from the operators, thence they need to be plug-and-play and heal themselves while considering optimization also. Some of the important SON capabilities that a femtocell should include can be listed as follows:

- FAP registration and authentication
- Network and neighborhood discovery
- Software Upgrade and Fallback
- Self Diagnostics (Hardware and Software)
- Automatic selection of the physical cell identity
- Configuration and optimization of the neighboring cell list
- Configuration and optimization of the handover parameters,
- Configuration and optimization of the RF parameters (power and frequency)

4.2.1. Optimization of Coverage and Interference in HeNB HetNet

Optimization of interference in HetNet includes three types of solutions. Power domain solutions try to utilize the interference level by adapting the transmission power of a base station whereas frequency domain solutions offer to use different frequency for interfering elements. Besides with Release 10, enhanced time domain interference management with enhanced Inter-Cell Interference Coordination (eICIC) is introduced. A survey about eICIC in LTE-A HetNets can be found in [96]. In [97], the impact of TDM ICIC and Range Expansion (RE) is tested for an LTE-A HetNet and it is concluded that TDM ICIC is very likely to boost the system performance.

As discussed previously interference mitigation between HeNB and macro layer requires more attention due to CSG. Therefore interference mitigation between HeNB and macrocell layer requires interaction between those layers. Below is a series of suggestion by NGMN [98].

4.2.1.1. UE Assisted DL Control. This is a power domain solution. In case of high interference reports from multiple UEs to macro BTS, macro BTS instructs the interfering HeNB to adjust its DL transmission power.

4.2.1.2. Fractional Frequency Reuse. As described in Section 2.4.3.3, the macrocell and femtocell can coordinate their schedulers in order to avoid co-channel interference by assigning different time/resource blocks or by reducing power in certain blocks.

4.2.1.3. Partial Co-channel Deployment. This solution requires macro base station to allocate a small subset of its available bandwidth to HeNB so that control channels are avoided to experience heavy interference. In [60] another solution is proposed to enhance LTE Cell-Edge Performance via Physical Downlink Control Channel (PDCCH) ICIC.

4.2.1.4. Noise Padding. This technique objects to avoid UL power interference between each layer and requires macro base station to send a maximum noise figure, maximum transmit power or overload indicator to femto-base station in order HeNB to temporarily increase its noise figure for mitigating bursty interference situations that harms the rate prediction and error correction mechanism of the femto-base station.

4.3. SON Architecture

In [99], three types of SON architectures are defined as Centralized, Distributed and Hybrid architecture. Figure 4.2 shows these different approaches.

The advantage of centralized architecture is that it to be more manageble however the latency, failure of single SON server and filtered information from eNodeBs are the main disadvantages of this approach. Thus a distributed approach can deal with this problems by adjusting itself and tuning the parameters autonomously, as well it can derive additional information via UE measurements or X2 signalling but the only disadvantage can be the inability to ensure the standards thus interoperability is decisive for distributed architecture.

The last approach, which is hybrid, contains both centralized and distributed functionalities. In this technique Network Management System (NMS) and eNodeB works together for execution of the SON optimization algorithm. In this study, a distributed semi-static SON approach is selected in order to minimize CAPEX and OPEX and for the ease of implementation.

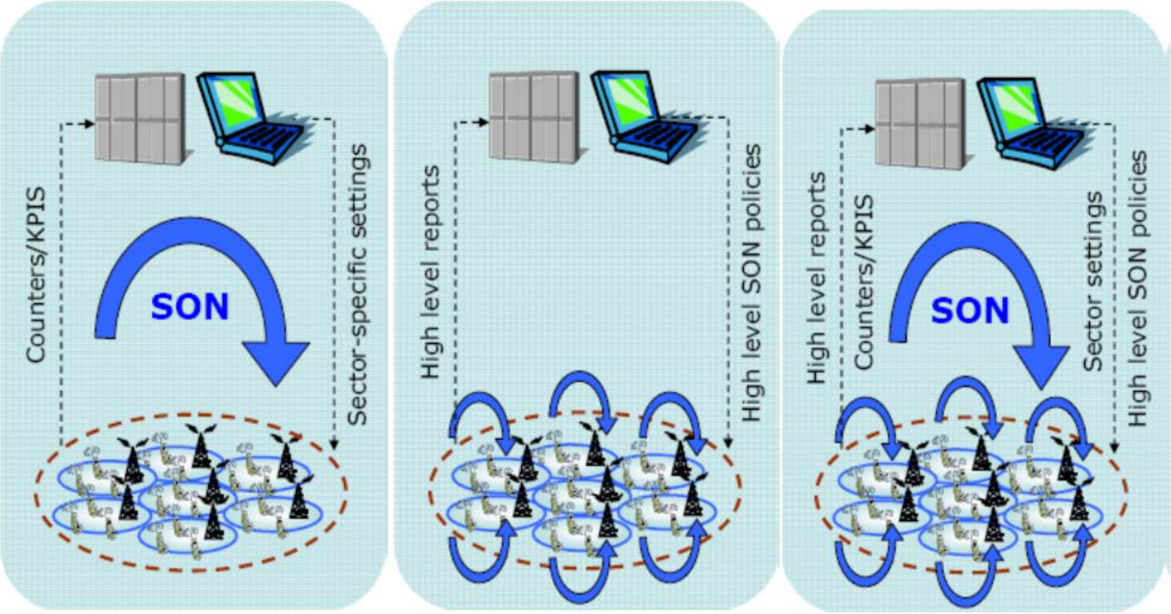


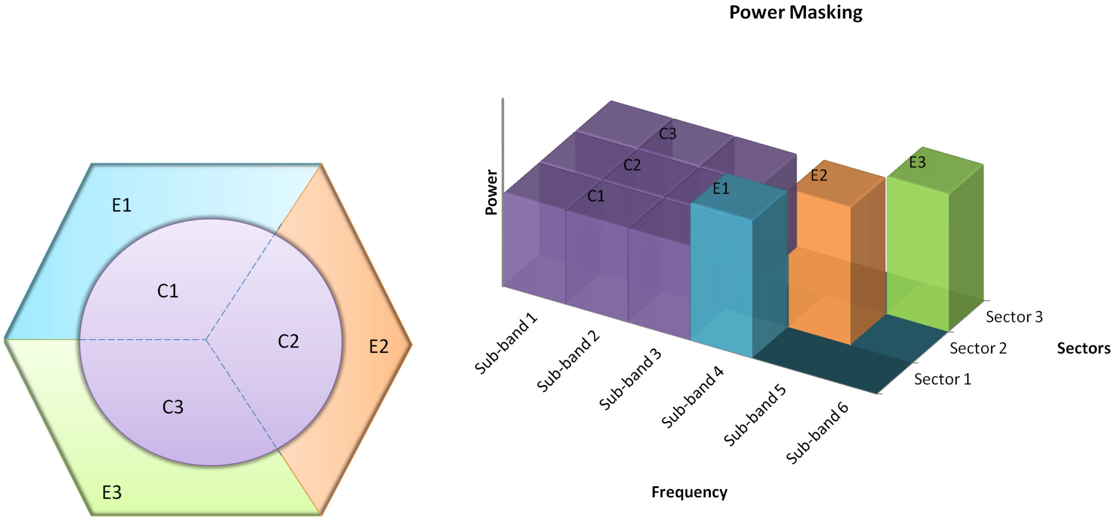
Figure 4.2. Different SON architecture approaches : Centralized (left), Distributed (center) and Hybrid (right) [98].

5. EXPERIMENTS AND RESULTS

5.1. System Model and Formulation

5.1.1. FFR-3 Scenario System Model

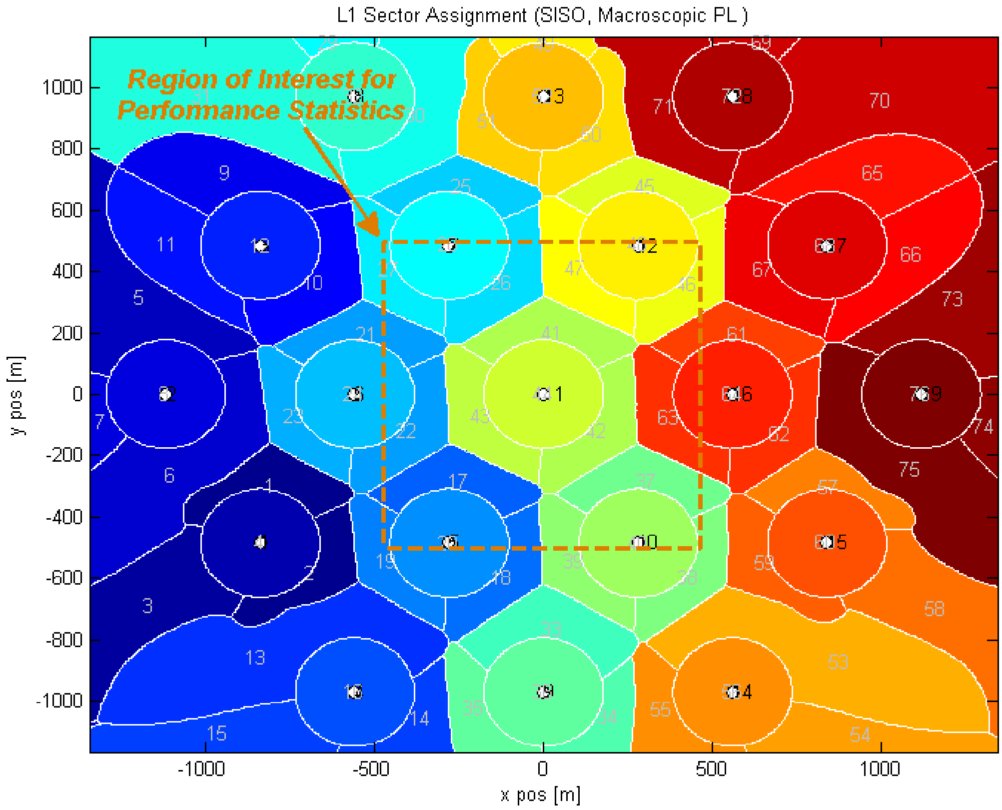
The heterogeneous network model consists of deploying femtocells in the coverage area of macrocells. Firstly, available frequency sub-bands are allocated for macrocells in an FFR-3 fashion as Figure 5.1 illustrates. Figure 5.2 shows a 2-tier (19 macrocells) network layout with the target area that will be used in performance statistics specified as a square which has an area of 1 km^2 in the middle.We will use a 1-tier (7 macrocells) scenario for capacity plots for the purpose of simplicity.



(a) Sector Assignment (b) Power Masking

Figure 5.1. Fractional Frequency Reuse with 3 sectors (FFR-3) Schema.

Figure 5.1 depicts the FFR-3 method used for each macrocell and the graph of the power masking function for each sector as in [65]. In this schema every macrocell has three sectors that is assigned to different sub-bands and an omnidirectional antenna is placed on top in order to create the center zone. Determining the radius of the center zone is a key issue in FFR technique, in [31, 36] it is analyzed that a center radius of 0.63 times the cell radius is optimal for FFR-3 schema. After setting up the macrocells, femtocells are deployed randomly in the region of interest enclosed by



Region of Interest for Performance Statistics

Figure 5.2. Macro Network Layout.

external walls around them. Channel models are reproduced as described in [100]. Macrocell propagation model for urban area is as follows:

$$PL = 40 \times (1 - 4 \times 10^{-3} \times Dhb) \times \log_{10} R \\ -18 \times \log_{10} Dhb + 21 \times \log_{10} f + 80dB \tag{5.1}$$

where Dhb is the base station antenna height in meters, measured from the average rooftop level, f is the carrier frequency in MHz and R is the eNodeB - UE separation in kilometers. In our simulation, we considered a carrier frequency of 2.14 GHz and the eNodeB antenna height of 15 meters above average rooftop level, so the pathloss equation becomes $PL = 128.8 + 37.6 \times \log_{10} R$. Additional wall penetration loss is added for modelling the indoor to outdoor pathloss as by using indoor environment in a square centered at femto location with a side-length of 12 meters assuming a 144 m^2 home for each CSG mode Femto Access Points (FAPs). Additional penetration loss of indoor environment is assumed to be 17 dB. Figure 5.3 shows the initial capacity distribution of a network when no femtocells introduced but indoor environment is modelled as little squares that results in additional loss. For femtocells, outdoor to indoor penetration included pathloss equation is $PL[dB] = 7 + 56 \times \log_{10}(d[m])$. All figures are displayed without shadow fading for clarity. Our aim is to maximize downlink capacity distribution for each layer when the femtocells are positioned randomly in the region of interest.

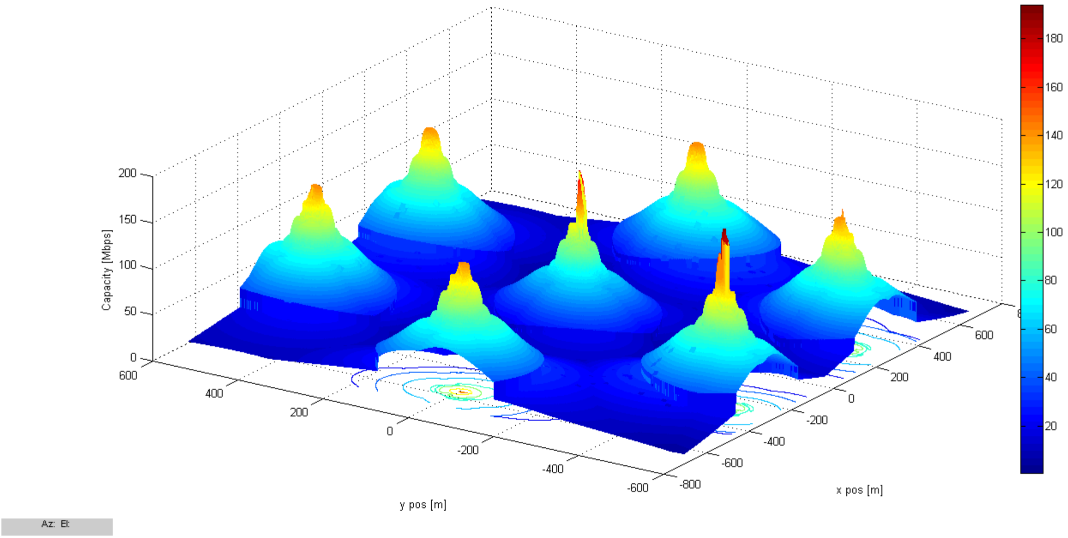


Figure 5.3. Macro-only network capacity with indoor environment.

LTE Downlink System Level Simulator [101] is modified to implement the Fractional Frequency Reuse method for macrocells and proposed SON algorithm is tested in this framework. Simulation parameters are summarized as follows in Table 5.1.

The horizontal and vertical radiation pattern of Kathrein Antenna Type 742 212 is presented in Figure 5.4.

5.1.2. Formulation

To derive a formula for the optimization problem, assume that we have N eNBs consisting N_M macro-eNodeBs and N_F Home eNodeBs (HeNBs) where $N = N_M + N_F$. Let M denotes the set of macrocell sectors and F denotes the set of femtocell sectors. We can assign an identifier number to each sector by assuming a macrocell has $\gamma + 1$ sectors where γ is the frequency reuse factor in the edge zone of FFR-γ schema and a

Table 5.1. Simulation Parameters.

Parameter	**Value**
Frequency	2.14 GHz
Bandwidth	20 MHz for LTE simulations 100 MHz aggregated for LTE-A simulations
Thermal noise density	-174 dBm/Hz
Receiver noise figure	9 dB
Inter eNodeB distance	560 m
Minimum Coupling Loss	70 dB for macrocell [100] 53 dB for femtocell [100]
Shadow fading	Lognormal, space-correlated [102] $\mu = 0, \sigma = 10$ dB
Shadow fading correlation	Inter-site = 0.5 [100]
eNB TX Power	edge sector: 43 dBm = 22 W [100] center sector: 42 dBm = 15 W
eNB Antenna Type	edge sector: KATHREIN-Werke KG [103] Antenna Type 742 212 center sector: omnidirectional
3D Antenna Radiation Pattern	interpolated by common component sum method [104]
HeNB TX Power	13 dBm = 20 mW
HeNB Antenna Type	omnidirectional

femtocell has one sector since it only has one omnidirectional antenna. Additional one in $\gamma + 1$ stands for the center zone in the macrocell.

So we have $\aleph = N_M(\gamma + 1) + N_F$ sectors which can be denoted as s_i for $i = 1, 2, \ldots, \aleph$. Let B be the set of frequency bands whose elements are determined according to the frequency division of FFR schema. Then, the achievable SINR value of a user u in sector s_i by sub-band b_k which uses sub-carriers $c_l \in b_k$ within a location in the region of interest can be calculated with the formula in Equation 5.2.

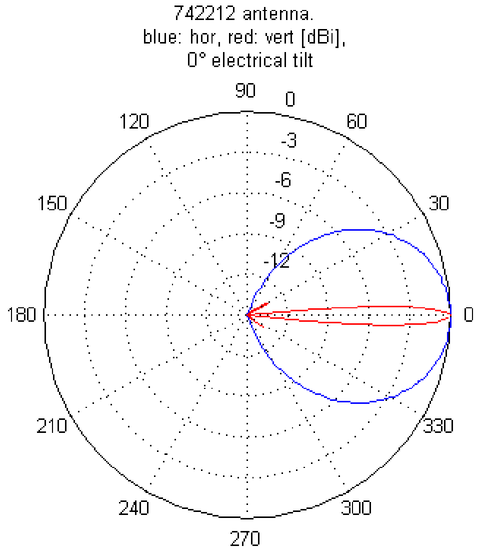


Figure 5.4. Antenna Radiation Pattern.

$$SINR_{s_i,u}^{b_k,c_l} = \frac{\Psi_{s_i}^{b_k} P_{s_i,u}^{c_l} \Lambda_{s_i,u}^{c_l}}{\sum_{\forall j \neq i} \Psi_{s_i}^{b_k} P_{s_j,u}^{c_l} \Lambda_{s_j,u}^{c_l} + N_0 \Delta f_{c_l}} \tag{5.2}$$

where $\Lambda_{s_i,u}^{c_l}$ is the experienced loss in that position including macroscopic pathloss (PL_{s_i} in dB), log-normal space correlated shadow fading (χ_a in dB) and Rayleigh fading channel loss ($|h_{s_i,u}^{c_l}|^2$) with a unit variance as in Equation 5.3.

$$\Lambda_{s_i,u}^{c_l} = 10^{-\frac{PL_{s_i}+\chi_a}{10}} \cdot |h_{s_i,u}^{c_l}|^2 \tag{5.3}$$

Other parameters in Equation 5.2 are as follows: $P_{s_i,u}^{c_l}$ is the maximum transmitted power from sector s_i to user u in sub-carrier c_l, N_o is the thermal noise density and Δf_{c_l} is the sub-carrier spacing. The coefficient $\Psi_{s_i}^{b_k}$ is the power ratio mapping between sectors and sub-bands, macrocells have no power adaptation for our proposed method so for macrocells it can be assigned as follows:

$$\Psi_{s_i}^{b_k} = \begin{cases} 1 & \text{if } s_i \text{ operates in } b_k, \\ 0 & \text{otherwise.} \end{cases} \tag{5.4}$$

For femtocells it can be used to modify the transmission power in a specific sub-band for coordinated scheduling and it can be silenced for a specific sub-band in order to manage interference by setting the coefficient to zero. So $1 \geq \Psi_{s_i}^{b_k} \geq 0$ for femtocells.

The obtainable throughput can be calculated for each location by assuming that inter-cell and inter-sector interference is modelled as a zero-mean Gaussian process whose variance equals the sum of the powers received from adjacent co-channel cells as in [24], since there are more than 400 cells in the simulation this assumption can be approved by Central Limit Theorem. We also assume that sub-carriers are uncorrelated. By modifying the Shannon capacity formula [105] the equation becomes as follows:

$$C_{\alpha,s_i,u}^{b_k} = \sum_{\forall c_l \in b_k} \alpha \cdot \Delta f_{c_l} \cdot \log_2(1 + SINR_{s_i,u}^{b_k,c_l}) \tag{5.5}$$

where α refers to signalling overhead including the multiplication of cyclic prefix ratio, reference symbol ratio and synchronization symbol ratio. Then the overall throughput can be expressed as:

$$T_{total} = \sum_{\forall s_i \in S} \sum_{\forall b_k \in B} \sum_{\forall u \in U} \Psi_{s_i}^{b_k} \Phi_{s_i}^{u} C_{\alpha,s_i,u}^{b_k} \tag{5.6}$$

where $\Phi_{s_i}^{u}$ is the scheduling between user u and sector s_i. It is scheduled and detected by maximum received SINR values. To give an example, let's say we identify each sector in Figure 5.5 like this: $E1 \rightarrow s_1, E2 \rightarrow s_2, E3 \rightarrow s_3$ and center zone $\rightarrow s_4$ and let's say we have four bands (that can be a group of sub-carriers). Assume each sector s_i operates in b_i for $i = 1, 2, 3, 4$ respectively. If a user u is located at $C3$ it will receive strongest SINRs from s_3 and s_4 so $\Phi^u_{s_i}$ will be like this:

$$\Phi^u_{s_i} = \begin{cases} 1 & i = 3, 4, \\ 0 & \text{otherwise.} \end{cases} \tag{5.7}$$

In fact, it refers that user u is served by both s_3 and s_4 due to our simulation simplification by assigning an omnidirectional antenna sector for center zone. For a user in $E1, \Phi^u_{s_i}$ will be 1 only for $i = 1$ and zero for other i^s. Femto users will have only one $\Phi^u_{s_f} = 1$ since femtocells do not use FFR method and a UE u in CSG of HeNB s_f can only be connected to that Femto Access Point in its coverage area.

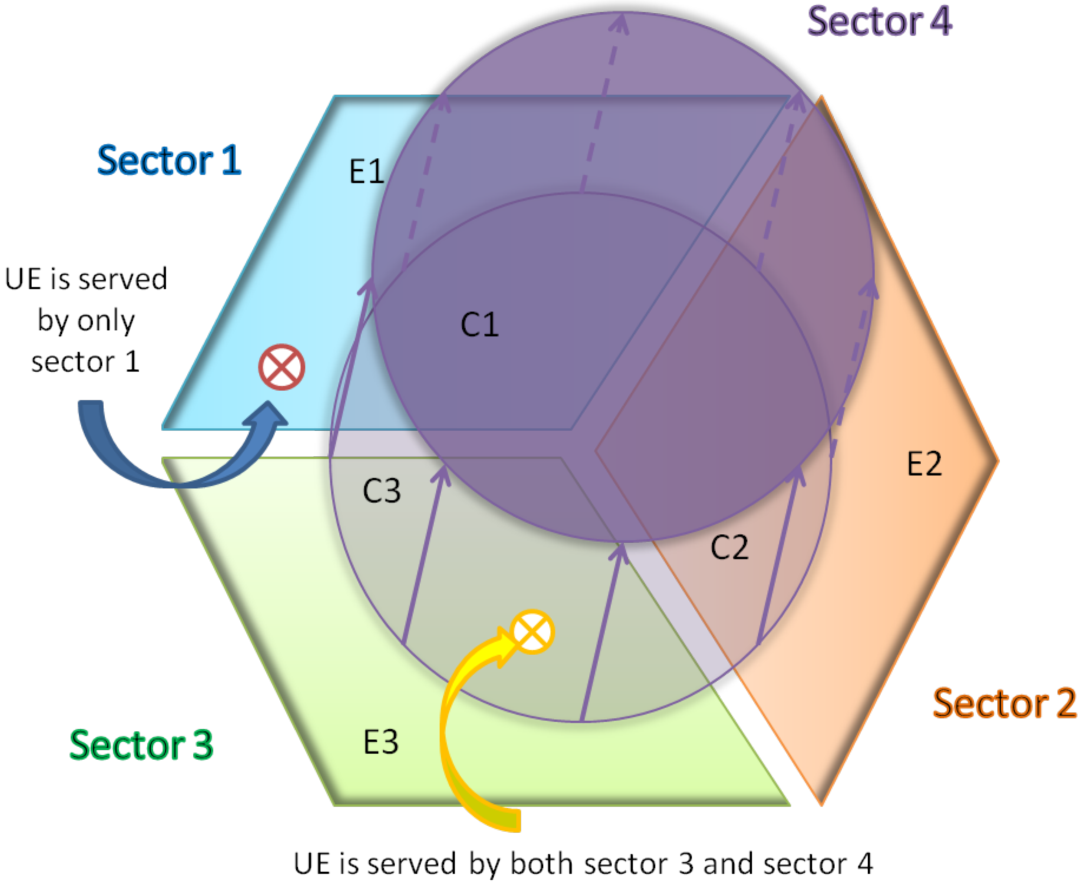


Figure 5.5. Mapping of Φ.

We can also distinguish throughputs for macrocells and femtocells with the equations below:

$$T_{macro} = \sum_{\forall s_m \in M} \sum_{\forall b_k \in B} \sum_{\forall u \in U} \Psi^{b_k}_{s_m} \Phi^{u}_{s_m} C^{b_k}_{\alpha, s_m, u} \tag{5.8}$$

$$T_{femto} = \sum_{\forall s_f \in F} \sum_{\forall b_k \in B} \sum_{\forall u \in U} \Psi^{b_k}_{s_f} \Phi^{u}_{s_f} C^{b_k}_{\alpha, s_f, u} \tag{5.9}$$

Finally, we formulate the optimization problem as,

$$\max_{\Psi^{b_k}_{s_i}} (T_{femto} + T_{macro}) \tag{5.10}$$

it can clearly be seen that our purpose is maximizing the overall and separate throughputs with respect to frequency assignment and power adaptation for each sector.

5.2. Proposed Method for Interference Management

A lot of work in the literature has focused on the interference problem between macrocells and femtocells and neglected the inter-femtocell interference. With a large number of femtocell deployment this issue arises a problem and managing both interference at the same time can leverage the overall network efficiency while significantly enhancing the throughput for femtocells.

Proposed method is defined in Figures 5.9,5.10,5.11,5.12. When a new femtocell f_{new} is introduced to the system it should first find the available bands with respect to its location as proposed in [25]. Figure 5.6 depicts the proposed allocation method for femtocells in [25] under the conditions that macrocells do apply FFR-3 scheme. With this allocation scheme, femtocells prefer sub-bands which are not used in the macrocell sub-area. In addition to this, if the femtocell stands in the center-region it also excludes the sub-band that is used by macrocell in the edge-region of current sector since the signal power received from the edge-region of macrocell is relatively strong for this femtocell. This scheme greatly avoids the interference between macrocells and femtocells but it needs to be enhanced further in order to mitigate inter-femtocell interference. Proposed method takes into account that two or more femtocells that lies in the same region of FFR-3 scheme can cause interference to each other and reduce the overall throughput of these femtocells. A graph based solution is proposed to address this issue by sharing the available sub-bands orthogonally for very close located femtocells, so-called dangerous neighbors, and adjusting the transmission power for other neighbors so that to minimize inter-femtocell interference.

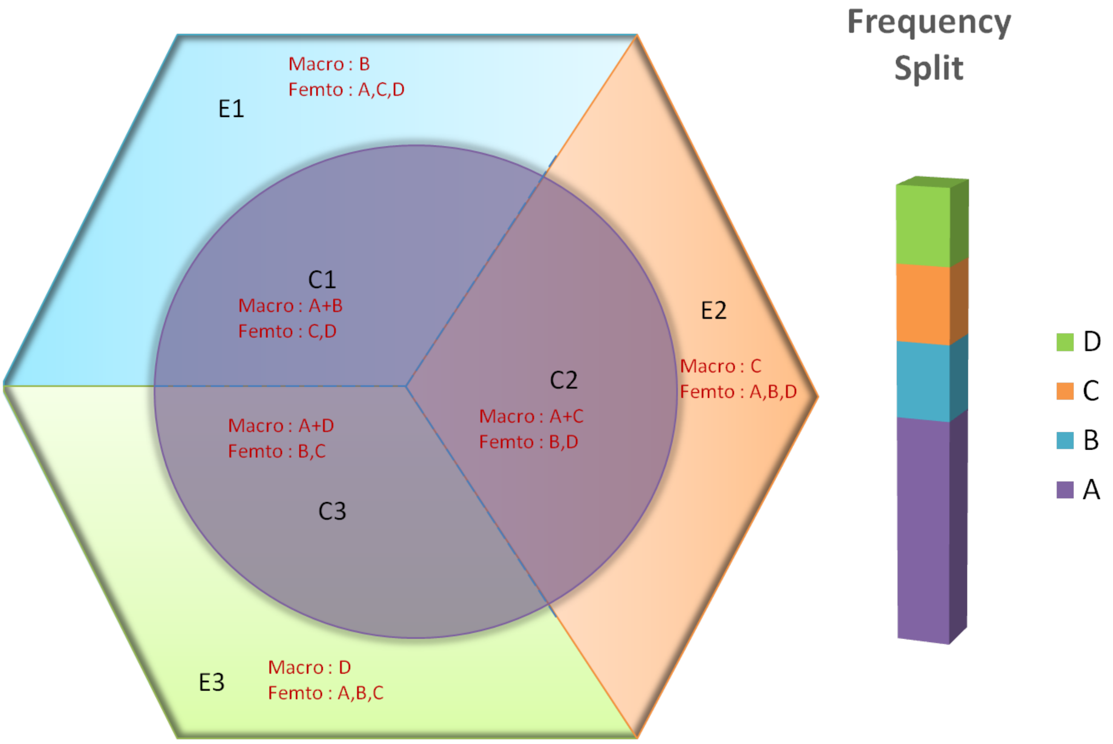


Figure 5.6. First step allocation for femtocells under FFR-3 is used for macrocell.

To understand how the Graph Based SON algorithm works a simplified example can be presented. Assume that we have 50 femtocells located in a $100m^2$ area and assume we have set the thresholds properly so that they detect a femto closer than $1m$ as near neighbor and closer than $0.5m$ as dangerous neighbor. Figure 5.7 shows the initial distribution of this example where blue circles denotes the femtocells, cyan colored lines refers to near neighborhood, red colored lines refers to dangerous neighbors and green squares for femtocells that has no neighbor. Note that the threshold values are not used in our system simulation, they are just straightforward to be used in this example in order to simplify understanding the algorithm.

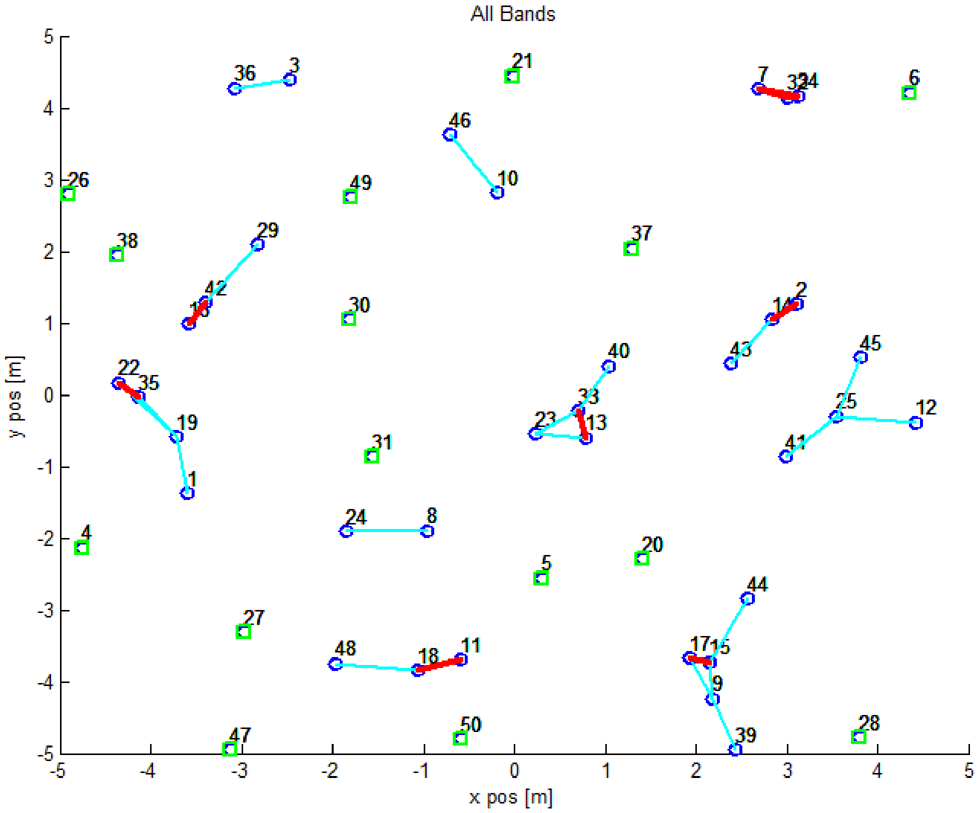


Figure 5.7. Initial femtocell distribution simulation.

Suppose we have 4 sub-bands and all femtocells use all four sub-bands initially as in Figure 5.7. We can parallelly follow the Algorithm 5.9 by assuming B_A includes these four sub-bands. Algorithm 5.11 makes sub-bands shared for dangerous neighbors. For instance femtocells numbered $\{7, 32, 34\}$ in Figure 5.7 are dangerous neighbors, another examples are the group of femtocells $\{22, 35\}$, $\{16, 42\}$, $\{18, 11\}$, $\{33, 13\}$, $\{17, 15\}$ and $\{14, 2\}$. If we apply the Algorithm 5.11 to dangerous neighbors, it divides the four sub-bands for each femtocell orthogonally so that avoid inter-femtocell interference in a big portion. Figure 5.8 shows the distribution of each femtocell in each sub-band after they are managed by GraphBasedSON algorithm. Reader can see that all dangerous neighborhood relations are cleared by the algorithm, for instance dangerous neighbors $\{7, 32, 34\}$ are shared between sub-bands so that 7 uses 1^{st} sub-band, 32 uses 4^{th} sub-band and 34 uses 2^{nd} and 3^{rd} sub-bands.

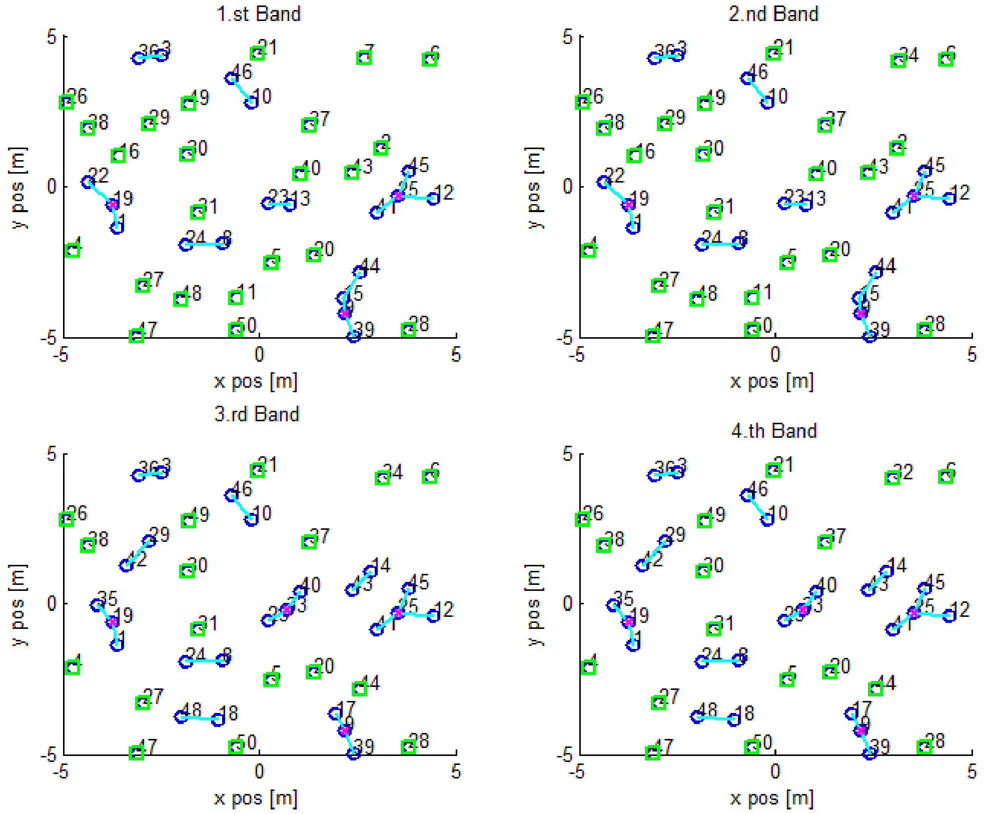


Figure 5.8. Femtocell distribution for each sub-band when they are managed by GraphBasedSON algorithm.

Further the algorithm mitigates the inter-femtocell interference by adjusting transmission powers for other neighbors, so-called near neighbors. The algorithm decides which femto is critical and should reduce its transmission power. For this, critical femto is detected as the femtocell that has more neighbors than its neighbors have. In order to give an example, reader can see the femtocells $\{41, 25, 12, 45\}$ are in Figure 5.7 or Figure 5.8 forms a group of near neighbors. Femtocell 25 has 3 neighbors and femtocells 45, 12 and 41 all have only one neighbors in this example. Thus femtocell 25 have more neighbors than all of its neighbors have, that is why femtocell 25 have a mark on it with a magenta star in Figure 5.8. So reducing the transmission power of the femtocell 25 is of benefit for femtocells 45, 12 and 41. The reduction in power ratio is as in Algorithm 5.12. Another example can be given as femtocell 19, please pay attention that critical femtocells are assigned per sub-band basis, femtocell 19 is the critical one in 1^{st} and 2^{nd} sub-bands when it has 22 and 1 as neighbors whereas in

3^{rd} and 4^{th} sub-bands it is again the critical one but it has 35 and 1 as neighbors in these bands.

One can understand the Algorithm 5.12 tries to find the most central femtocell in each neighborhood in order to manage inter-femtocell interference effectively. By reducing the transmission power of the central femtocell interference becomes avoided for more number of femtocells. If a node in the graph have the same number of neighbors with any of its neighbors than the Algorithm 5.12 compares the sum of received SINR values from the neighbors in that band, so that in terms of distances the one which have its neighbors closer is selected as the critical. Transmission power is reduced proportional to the number of neighbors for the critical femtocells, power is decreased 15% for each neighbor with a maximum limit of 60% in Algorithm 5.9. Since the GraphBasedSON algorithm is executed for each femtocell as they have set-up, criticality can change the adress by visiting neighbors, in order to avoid unnecessary power reduction the exterior neighbors increase their power in each step in that band.

By adjusting the $SINR_{\tau_1}$ threshold properly in Algorithm 5.10, deployed femtocell can understand if it is in the center-zone or edge-zone of a macrocell or one can use a similar algotihm to Algorithm 1 in [106] but a version for FFR-3. Later on, the interference management graph must be prepared for each femtocell by exchanging neighbor information. A femto access point should detect its neighbors and dangerous neighbors, which are really close located, by specified thresholds $SINR_{\tau_2}$ and $SINR_{\tau_3}$ in Algorithm 5.10. If a femtocell has prepared its neighborhood table it can exchange information between its neighbors that means the femtocell does not have to know all the femtocell locations in the system it needs only its neighbors information, so a central management system is not needed for managing the interference.

5.3. Results

Several scenarios are simulated and tested both in LTE and LTE-Advanced configurations. Results showed that proposed GraphBasedSON algorithm significantly leverages the throughput for femtocell users while not harming the macrocell throughput as

```
Procedure: GraphBasedSON($\mathbf{f_{new}}$)
$\mathbf{M} \Leftarrow$ Set of all macrocells
$\mathbf{F} \Leftarrow$ Set of all femtocells
$\mathbf{B_{\forall}} \Leftarrow$ Set of all sub-carriers in the system
SniffEnvironment($\mathbf{f_{new}}$)
$\mathbf{B_A} \Leftarrow \mathbf{B_{\forall}} \setminus \mathbf{B_M}$
for $\mathbf{b_k} \in \mathbf{B_A}$ do
    $\mathbf{\Psi^{b_k}_{f_{new}}} \Leftarrow 1$
end for
SplitAndShareBands($\mathbf{f_{new}}$)
Update neighborhood relations for each band
for $\mathbf{b_k} \in \mathbf{B_A}$ do
    FindCriticals($\mathbf{f_{new}}, \mathbf{b_k}$)
    if $\mathbf{f_{new}}$ is critical in $\mathbf{b_k}$ then
        $\mathbf{\Gamma} \Leftarrow 0.15 \times |\text{neighbors of } \mathbf{f_{new}}|$
        if $\mathbf{\Gamma} > 0.6$ then
            $\mathbf{\Gamma} \Leftarrow 0.6$
        end if
        $\mathbf{\Psi^{b_k}_{f_{new}}} \leftarrow 1 - \mathbf{\Gamma}$
        for $\mathbf{n} \in \mathbf{N_{near,b_k}}$ do
            if $\mathbf{\Psi^{b_k}_{n}} < 0.9$ then
                $\mathbf{\Psi^{b_k}_{n}} \Leftarrow \mathbf{\Psi^{b_k}_{n}} + 0.1$
            else
                $\mathbf{\Psi^{b_k}_{n}} \Leftarrow 1$
            end if
        end for
    end if
end for
```

Figure 5.9. Graph Based SON Algorithm.

```
Procedure: SniffEnvironment($\mathbf{f_{new}}$)
$\mathbf{B_M} \Leftarrow \varnothing$
for ∀ band $\mathbf{b_k}$ in $\mathbf{B_\forall}$ do
  $\mathbf{N_{near,b_k}} \Leftarrow \varnothing$
  $\mathbf{N_{danger,b_k}} \Leftarrow \varnothing$
  for ∀ sniffed sector $\mathbf{s_i}$ operates in $\mathbf{b_k}$ do
    if $\mathbf{s_i} \in \mathbf{M}$ and received SINR from $\mathbf{s_i} \geq SINR_{\tau_1}$ then
      $\mathbf{B_M} \Leftarrow \mathbf{B_M} \cup \mathbf{b_k}$
      if $\mathbf{b_k}$ is a sub-band used in center then
        Add also the edge sub-band to $\mathbf{B_M}$
      end if
    else if $\mathbf{s_i} \in \mathbf{F}$ and received SINR from $\mathbf{s_i} \geq SINR_{\tau_2}$ then
      $\mathbf{N_{near,b_k}} \Leftarrow \mathbf{N_{near,b_k}} \cup \mathbf{s_i}$
      if received SINR from $\mathbf{s_i} \geq SINR_{\tau_3}$ then
        $\mathbf{N_{danger,b_k}} \Leftarrow \mathbf{N_{danger,b_k}} \cup \mathbf{s_i}$
      end if
    end if
  end for
end for
```

Figure 5.10. Neighbor detecting and sniffing algorithm.

a result adding more to overall system efficiency. Figure 5.13 shows the throughput distribution when the interference is not managed, that means no FFR scheme is applied to macrocells and femtocells use the same spectrum with macrocells. 400 femtocells are deployed randomly to 1-tier macrocell environment that use LTE configuration. Reader can see the capacity holes if the femtocells are located near to macrocells this is because of the interference between macrocells and femtocells also we can see that near femtocells are canceling each others' throughput even if they are located far from the macrocell.

```
Procedure: SplitAndShareBands($\mathbf{f_{new}}$)
for $\mathbf{n} \in \mathbf{N_{danger}}$ do
    $\mathbf{B_{mutual}} \Leftarrow$ mutual bands used by $f_{new}$ and $n$
    if $|\mathbf{B_{mutual}}| > 1$ then
        $\mathbf{\Delta_1} \Leftarrow 1.^{st}$ to $\lceil |\mathbf{B_{mutual}}| / \mathbf{2} \rceil .^{th}$ elements of $\mathbf{B_{mutual}}$
        $\mathbf{\Delta_2} \Leftarrow \mathbf{B_{mutual}} \setminus \mathbf{\Delta_1}$
        $\mathbf{\Psi_{f_{new}}^{b_i}} \Leftarrow 1$ for $\forall i \in \mathbf{\Delta_1}$ and $\mathbf{\Psi_{f_{new}}^{b_j}} \Leftarrow 0$ for $\forall j \in \mathbf{\Delta_2}$
        $\mathbf{\Psi_{n}^{b_i}} \Leftarrow 1$ for $\forall i \in \mathbf{\Delta_2}$ and $\mathbf{\Psi_{n}^{b_j}} \Leftarrow 0$ for $\forall j \in \mathbf{\Delta_1}$
    else if $|\mathbf{B_{mutual}}| = 1$ then
        if number of bands used by $\mathbf{n} > 1$ then
            $\mathbf{\Psi_{f_{new}}^{b_i}} \Leftarrow 1$ and $\mathbf{\Psi_{n}^{b_i}} \Leftarrow 0$ for $\forall i \in \mathbf{B_{mutual}}$
        else if $|\mathbf{B_A}| > 1$ then
            $\mathbf{\Psi_{f_{new}}^{b_i}} \Leftarrow 0$ and $\mathbf{\Psi_{n}^{b_i}} \Leftarrow 1$ for $\forall i \in \mathbf{B_{mutual}}$
        else
            There is no way to share the bands, $\mathbf{\Psi_{f_{new}}^{b_i}} \Leftarrow 1$ for $\forall i \in \mathbf{B_{mutual}}$
        end if
    end if
end for
```

Figure 5.11. Band sharing algorithm.

We can conclude from Figure 5.14 that the througput for femtocells are falling down as the number of femtocells gets high, moreover the worst is, the deployment of femtocells decreases the throughput for macrocell users.

In Figure 5.15 reader can see the 3D surface plot of throughput distibution for each point when GraphBasedSON algotihm is applied and Figure 5.16 compares the average throughputs with Full Frequency Reuse scheme without SON algorithm. It can be seen that unmanaged case has relatively low throughput levels for femtocell users compared to proposed case, and it diminishes the capacity for macrocell users while proposed algorithm does not damage the throughput for macro network besides

```
Procedure: FindCriticals($\mathbf{f_{new}}, \mathbf{b_k}$)
isCritic $\Leftarrow$ true
for $\mathbf{n} \in \mathbf{N_{near,b_k}}$ do
    if $|$neighbors of $\mathbf{n}| > |$neighbors of $\mathbf{f_{new}}|$ then
        isCritic $\Leftarrow$ false
    else if $|$neighbors of $\mathbf{n}| = |$neighbors of $\mathbf{f_{new}}|$ then
        if $\sum$ received SINRs by $\mathbf{n} > \sum$ received SINRs by $\mathbf{f_{new}}$ then
            isCritic $\Leftarrow$ false
        end if
    end if
end for
```

Figure 5.12. Critical femto detection algorithm.

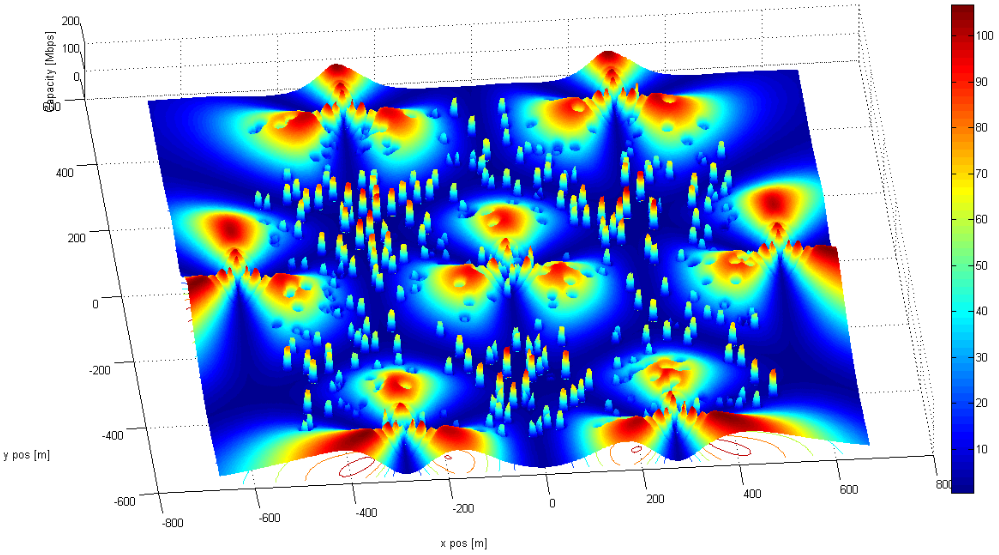


Figure 5.13. Full Frequency Reuse without SON.

proposed method lifts the throughput of overall system.

FFR-3 scheme has a higher capacity value compared to Full Frequency Reuse method when there is no femtocell introduced (starting point of the curves) since the region used for performance statistics include more cell-edge than the cell-center area

Figure 5.14. Full Frequency Reuse Throughputs.

and more importantly the distance between eNodeBs cause this situation, as discussed in [107] the cell edge performance improvement is almost linear while the degradation to the cell-center UEs is logarithmic in FFR scheme.

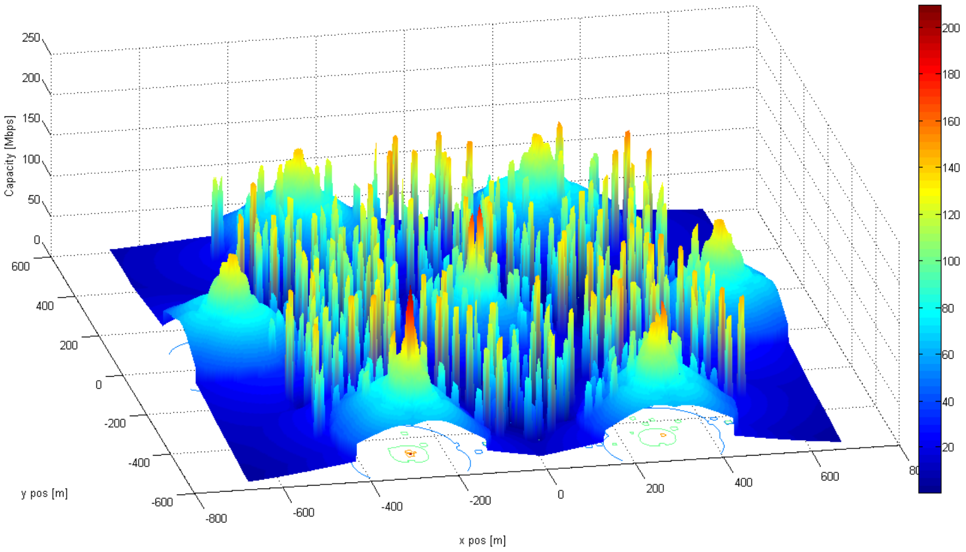


Figure 5.15. Proposed Method's Throughput Distribution in LTE.

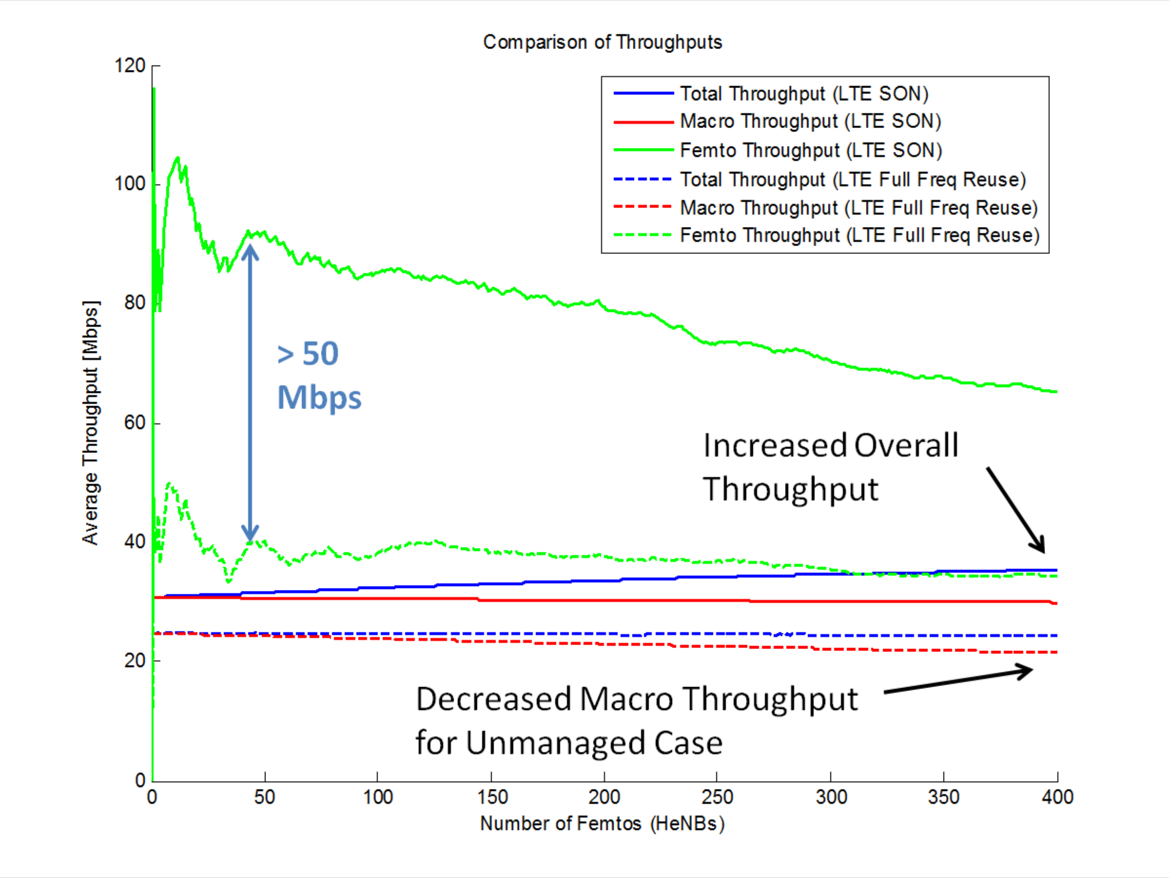


Figure 5.16. Comparison of Proposed Scheme with Unmanaged Case in LTE.

Since in LTE-Advanced we can use a wider bandwidth, management of spectrum becomes more and more important. To observe the difference of inter-femtocell interference management in FFR-3 scheme, Figure 5.17, Figure 5.18 and Figure 5.19 are presented so that Figure 5.17 illustrates the throughput in each location for FFR-3 scheme as proposed in [25] while Figure 5.18 depicts the same with the proposed method in this study. It can be hard to distinguish the difference between each Figure, hence in Figure 5.19 the difference between each method's output is presented.

It can be seen from Figure 5.20, proposed method improves the capacity for femtocell users by not impairing the macrocell throughput. It averagely provides more than 35 Mbps enhancement to femtocell users which is a noteworthy value for data-hungry applications.There is a small difference on overall system capacity and on macrocell throughput and they are marked in Figure 5.20 when 400 femtocells are introduced to the system.

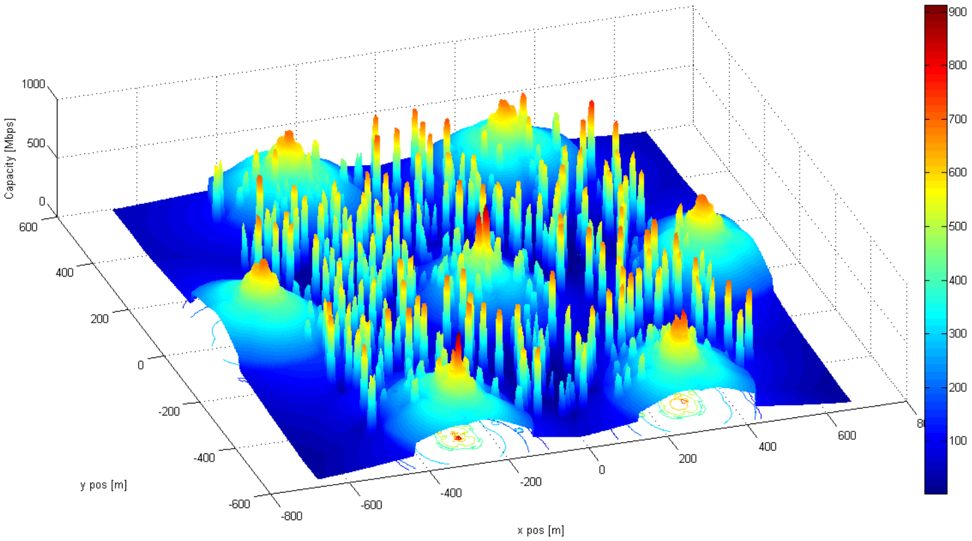


Figure 5.17. Throughput Distribution of FFR-3 scheme in LTE-Advanced.

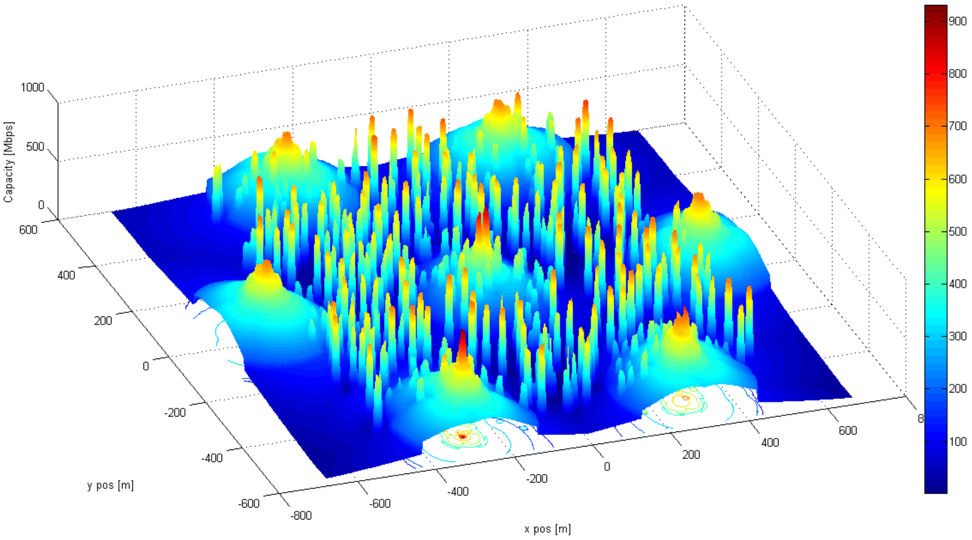


Figure 5.18. Throughput Distribution of proposed scheme in LTE-Advanced.

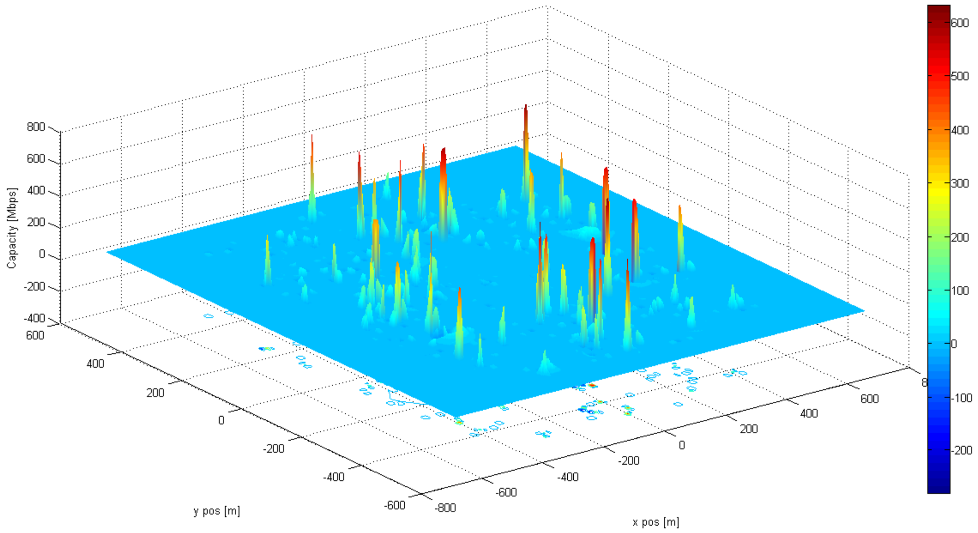


Figure 5.19. Difference in Throughput distribution.

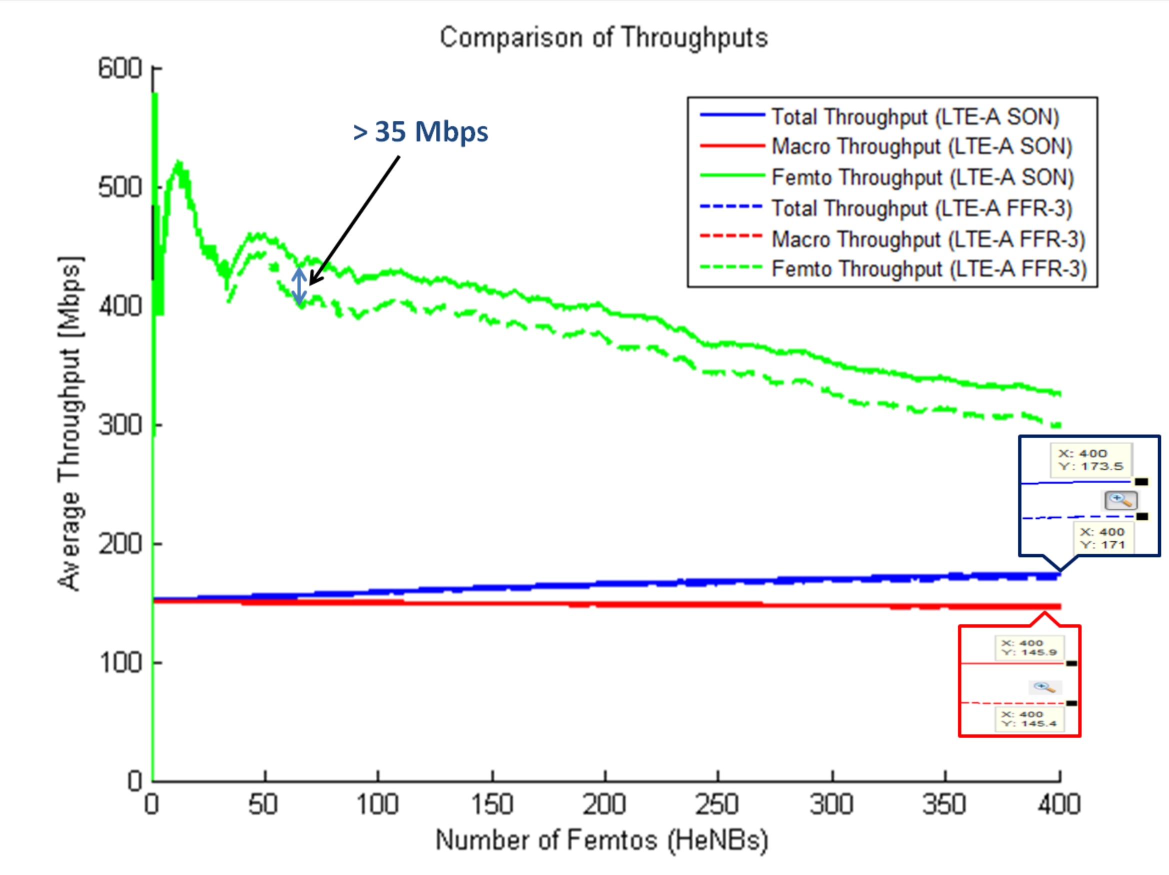


Figure 5.20. Comparison of proposed method and FFR-3 scheme in LTE-Advanced.

6. CONCLUSION AND FUTURE WORK

6.1. Conclusion

In this study, we proposed a scheme for addressing the interference management issue in Heterogeneous networks. While most of the studies in the literature has focused on interference between femtocells and macrocells, proposed method aims to provide a solution for both inter-femtocell interference management and coordination among other HetNet elements for improving the data rates for indoor users, which is significantly essential since it is statistically known that 80% of the mobile traffic used today is indoor traffic. GrahpBasedSON algorithm became superior for indoor environment compared to the state-of-art methods used when Fractional Frequency is applied for interference avoidance in Heterogeneous networks.

Another important advantage of the proposed method is that it does not add a lot of overhead in the signalling since it works at the initial deployment of a femtocell it only needs to communicate with its neighbors one time after that this femtocell will exchange its neighborhood table if a new femtocell is deployed nearer than a specified distance threshold. Last but not least, this method does not need a central management system which means another source of cost and work-force for operators.

6.2. Future Work

We hope this study makes as insight for using X2 interface, which is introduced with LTE, efficiently in order to coordinate and manage interference among Heterogeneous Network elements without needing a central system. This study can be expanded with new LTE-Advanced technologies that are introduced in Rel 10 and beyond, such as Coordinated MultiPoint (CoMP) transmission and reception especially Coherent Joint Transmission and eSON methods like time domain scheduling for interference management.

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