POLITECNICO DI MILANO

Facoltà di Ingegneria dell’Informazione

Corso di Laurea Specialistica in Ingegneria delle Telecomunicazioni

Cross Layer Scheduling Algorithm with Advanced Multi Antenna Support for 4G LTE Systems

Relatore: Prof. Maurizio MAGARINI

Correlatore: Dr. Lorenzo GALATI GIORDANO

Tesi di Laurea di:

Davide CASSONE

Matricola n. 751013

Anno Accademico 2011–2012

didicate la tesi a chi volete... potete anche non farlo ovviamente

Ringraziamenti

…

inserite la vostra sigla, di solito si usa quella dopo i riconoscimenti che ancora una volta non sono obbligatori

Abstract

Long-Term Evolution (LTE) is the next step forward in cellular 3G services. The recent increase of mobile data usage and emergence of new applications such as mobile TV, Web 2.0, streaming contents have motivated the 3rd Generation Partnership Project (3GPP) to work on LTE. The UMTS Long Term Evolution (LTE) is one of the promising solutions for the next generation broadband wireless access systems. In order to support high data rate with low latency, LTE simplifies network architecture and uses orthogonal frequency division multiple access (OFDMA) for downlink transmission technology.

LTE system performance largely depends on the high efficiency of MAC packet scheduler. This thesis has the purpose to develop a cross-layer technique that operates in frequency, time and spatial domain, exploiting the advantages of multi-user diversity and multi-antenna transmission modes supported by the LTE 3GPP standard. The implemented algorithm has been firstly developed for the single antenna scheme and lately adapted, with a geometric reshaping of the input parameter matrix, to all the other transmission modes. In this way, the scheduling procedure does apply as it is always in a single antenna scheme allowing the utilization of standard one-antenna algorithms. A complete LTE system level simulator has been developed in order to test the performance of the proposed solution, and an exhaustive number of simulations have been obtained with different propagation scenarios, speed of the users, distance from the base station.

Sommario

Il presente lavoro di tesi analizza e sviluppa un innovativo algoritmo di scheduling degli utenti per sistemi a larga banda 4G LTE. La particolare implementazione adottata ha permesso l'evoluzione degli algoritmi di scheduling dal caso singola antenna al caso multi-antenna, senza alterare in alcun modo la struttura degli algoritmi stessi.
Le prestazioni di tale algoritmo, denominato Smalloc (Smart Allocation) sono state valutate attraverso lo sviluppo di un simulatore al cui interno sono stati implementati anche altri algoritmi di scheduling giá noti in letteratura come Round Robin, Max Rate e Propotional Fair. Gli algoritmi di schedulazione degli utenti e allocazione delle risorse radio testati, utilizzano inoltre un approccio cross-layer, cioé operante a cavallo tra il livello fisico (PHY) e il livello di accesso (MAC), con particolare attenzione alle richieste di qualitá di servizio dei vari utenti. Per approccio cross-layer si intende la "schedulazione" e l'allocazione degli utenti nelle varie frequenze in modo congiunto; l'algoritmo di scheduling prende in considerazione il "feedback" degli utenti riguardo la qualitá del canale e la sua priorita' di trasmissione per elaborare la decisione su quale radiomobile ha un maggior vantaggio a trasmettere sulle risorse frequenziali prese in considerazione.
In un sistema classico, al contrario, gli utenti vengono prima schedulati nel dominio del tempo, determinando quale richiesta di servizio, tra quelle attive, deve essere allocata in quel determinato istante di tempo e quali nei successi, creando una lista di prioritá; successivamente gli utenti schedulati

saranno allocati sulle varie frequenze a seconda della metrica dell'algoritmo utilizzato. Con l'approccio cross-layer viene sfruttata maggiormente la diversitá multi-utente riuscendo ad ottenere prestazioni migliori in termini di bit rate totale (throughput per cella). Lo sviluppo del simulatore e di tutti gli algortimi implementati si é basato sullo standard di radiocomunicazione LTE (Long Term Evolution). LTE é l'evoluzione dei sistemi di telecomunicazioni di terza generazione ed é sviluppata per rispondere alle nuove e sempre piú esigenti richieste del mercato delle telecomunicazioni. Lo sviluppo di nuovi servizi a valore aggiunto e la diffusione di dispositivi mobili evoluti (smartphone, tablet etc.) ha rivoluzionato il concetto stesso di cellulare. Non piú terminale dedicato solo alle chiamate vocali, ma un dispositivo in grado di fornire una vasta gamma di servizi aggiuntivi. Per soddisfare le richieste degli utenti sono indispensabili architetture e protocolli di rete evoluti in grado di sfruttare al meglio le banda di frequenze disponibili per la comunicazione. LTE si presenta come una valida soluzione per traghettare gli operatori mobili fino alla quarta generazione della telefonia mobile. LTE é in grado di supportare alti data-rate con picchi, in presenza di antenne multiple al ricevitore e al trasmettitore, di 75Mbit/s in uplink e 300Mbit/s in downlink e con una larghezza di banda scalabile da 1,25MHz a 20MHz. In contrasto con i modelli a connessione di circuito caratteristici delle reti precedenti, in cui le comunicazioni dati a pacchetto venivano trattati da nodi dedicati, LTE é stata progettata per supportare unicamente servizi a connessione di pacchetto. Tutti i dati, anche quelli voce, viaggiano su protocolli TCP/IP e le connessione tra il terminale mobile e le reti esterne é di tipo IP. L'unificazione di tutti i protocolli di rete é una delle maggiori innovazioni introdotte da LTE che permette di ridurre costi e latenze. LTE Fornisce agli utenti connessioni con diverse qualitá di servizio (QoS). A ciascun flusso informativo é associata una specifica classe di QoS e il flusso IP con la sua specifica classe costituisce un bearer. La rete é in grado di gestire contemporaneamente piú bearers di uno stesso utente: ad esempio durante una comunicazione vocale (VoiP), un utente potrebbe accedere ad sito web, o scaricare un file tramite il protocollo FTP. I pacchetti FTP saranno associati a classe best-effort mentre quelli relativi alla chiamata VoiP avranno bisogno di una QoS piú elevata. Le rete é strutturata in modo da gestire efficacemente le diverse QoS garantendo al tempo stesso sicurezza e privacy degli utenti e delle loro informazioni.

Un'altra miglioria apportata é l'utilizzo di piú antenne sia in trasmissione che in ricezione, ossia l'LTE nasce in sostanza come un sistema MIMO (Multiple Input Multiple Output). Uno dei principali problemi dei sistemi di comunicazioni radio é relativo alla presenza di cammini multipli del segnale dovuti alla riflessione del segnale su palazzi o oggetti dislocati tra trasmettitore e ricevitore (fading da multi-path). Il MIMO permette di trarre giovamento dal multipath, andando a parallelizzare diversi cammini tra di loro indipendenti. Quando si usa il sistema MIMO é necessario utilizzare piú antenne per permettere di distinguere i segnali che provengono da percorsi diversi. Mentre é facile aggiungere antenne sulle stazioni radio base, lo stesso non si puó dire sul terminale dove le dimensioni limitano il numero di antenne che é possibile installare.

All'interno dello standard LTE esistono aspetti non specificati che pertanto danno libertá di implementazione ai costruttori di apparati. Tra questi vi sono gli algoritmi di scheduling.

Il lavoro di tesi é stato svolto presso l'azienda Azcom Technology ed ha portato alla realizzazione in linguaggio MATLAB di uno scheduler in cui gli algoritmi implementati operano anche nel caso multi-antenna.

É stato testato uno scenario a singola cella, nessuna interferenza da parte di altre celle e trasmissione in downlink. Sono stati raggruppati gli utenti nelle due principali categorie previste dallo standard LTE, utenti GBR e utenti non-GBR. GBR sta per Guaranteed Bit Rate, ossia un terminale GBR é un utente sensibile ai ritardi e come dice l'acronimo, richiede un certo bit rate minimo garantito. A differenza degli utenti GBR, i non-GBR non sono sensibili a ritardo e di conseguenza richiedono prioritá inferiore. Gli utenti GBR sono identificati da terminali che effettuano ad esempio chiamate VoIP, video chiamate in alta definizione, ecc. All'interno di tale scenario sono stati testati i diversi modi di trasmissione previsti dallo standard LTE per i vari algoritmi di scheduling sviluppati. Il contributo innovativo del lavoro di tesi é stato quello di sviluppare una tecnica che da' la possibilitá al MAC scheduler di operare con i vari modi di trasmissione previsti dallo standard LTE (Transmit diversity, MIMO closed loop, MIMO open loop) utilizzando algoritmi di scheduling sviluppati per il caso singola antenna, senza cambiare la struttura interna di quest'ultimi e quindi senza aggiungere ulteriore complessitá computazionale.

Contents

1 LTE UMTS Long Term Evolution 1

1.1 Overview 2

1.2 Architecture 4

1.2.1 User Equipment (UE) 6

1.2.2 The access network 8

1.2.3 The core network 9

1.3 Protocol Architetture 12

1.3.1 Logical Channels and Transport Channels 14

1.3.2 Scheduling 15

1.3.3 Physical Layer 15

1.4 LTE basic concepts 17

1.4.1 OFDM overview 19

1.4.2 OFDMA in the downlink 20

1.4.3 SC-FDMA in the uplink 21

1.4.4 LTE Generic Frame Structure 22

2 LTE Layer 2 and Scheduling techniques 25

2.1 Layer 2 structure 25

2.2 MAC layer 27

2.2.1 MAC Functions 27

2.3 Scheduling Techniques 32

2.3.1 The multi-user resource allocation problem 35
2.3.2 Overview of scheduling algorithms for OFDM systems 38
2.4 Scheduling Algorithm for OFDMA systems 39
2.5 Scheduling algorithm for LTE systems 41
2.6 Mimo Downlink Scheduling in LTE 42

3 Benefits of MIMO Technology in LTE 43
3.1 Introduction 43
3.2 MIMO signal model 45
3.2.1 Mapping the symbols to the transmitted signal 46
3.3 LTE Downlink Transmission Modes 46
3.3.1 Closed versus Open Loop Operations 52
3.4 MIMO in Practice 53
3.4.1 Transmission Mode in the simulator 53

4 Smalloc: from single to multi antenna solutions 59
4.1 Smart allocation algorithm 60
4.2 From single antenna to multiple antenna solution 63
4.2.1 Algorithm inputs adaptation 64

5 Simulation Scheme 68
5.1 3GPP Spacial Channel Model Extended (SCME) 68
5.2 Architecture of LTE MAC-PS MIMO Simulator 71

6 Numerical Results 75
6.1 Smalloc performance in different transmission mode 75

Bibliografia 85

List of Figures

1.1 System architecture for E-UTRAN only network. 6
1.2 Functional split between eNB and MME/GW. 7
1.3 Overall E-UTRAN architecture. 9
1.4 LTE Protocol Architetture. 13
1.5 Downlink Channel Mapping. 16
1.6 Uplink Channel Mapping. 16
1.7 Multipath caused by reflections. 18
1.8 Example of OFDM signal. 19
1.9 Lte time-domain frame structure. 23
1.10 The LTE physical time-frequency resource. 24

2.1 Downlink layer 2 structure. 26
2.2 Uplink layer 2 structure. 27
2.3 SNR-CQI mapping model [2]. 30

3.1 MIMO system with N transmit antennas and M receive antennas. 45
3.2 Diminishing returns of throughput gains from increased SNR. 48
3.3 Multiple Antenna Access Schemes. 50
3.4 Antenna Selection transmission scheme. 55
3.5 Trasnmit Diversity transmission scheme. 55
3.6 Spatial Multiplexing transmission scheme. 56

3.7 Closed-Loop MIMO Channel. 57

4.1 Smalloc algorithm diagram. 63
4.2 Antenna Selection adaptation scheme. 66
4.3 Spatial Multiplexing adaptation scheme. 67

5.1 Example of Simulation Scenario. 69
5.2 Simulation Chain. 70
5.3 Generation of H matrices. 70
5.4 H matrix structure. 71
5.5 Example of new model simulator. 73
5.6 Generation of CQI matrices. 74
5.7 Example of Cross Layer Packet Scheduler 74

6.1 Urban-Macro: achieved bit rate versus different number of users RB constraints in Single Antenna case. 77
6.2 Urban-Macro, achieved bit rate for each user for different algorithms in Single Antenna case. 77
6.3 Urban-Micro, achieved bit rate for each user for different algorithms in Single Antenna case. 78
6.4 Urban-Macro, achieved bit rate versus different number of users RB constraints in Transmit Diversity case. 78
6.5 Urban-Marco: Smalloc performance in Closed-Loop Spatial Mult. with different distance between antenna element at BS. 79
6.6 Urban-Macro: achieved bit rate versus different number of users RB constraints in Closed-Loop Spatial Mult. case. . . . 80
6.7 Urban-Macro:Smalloc performance in Open-Loop Spatial Mult. with different distance between antenna element at BS. . . . 80
6.8 Urban-Macro: achieved bit rate versus different number of users RB constraints in Open-Loop Spatial Mult. case. 81
6.9 Smalloc performance in different transmission mode. 81

6.10 Transmission mode performance at difference distance from BS. 82

List of Tables

1.1 LTE (FDD) downlink and uplink peak data rates. 4

2.1 CQI table. 31

5.1 SINR interval vs CQI value. 72

6.1 Parameters scenario. 76

Elenco dei listati

Elenco delle abbreviazioni

Chapter 1

LTE UMTS Long Term Evolution

Before describing the system overview it is useful to explain some of the terminology surrounding LTE since the history and naming of the technology is not intuitive. The term LTE is actually a project name of the Third Generation Partnership Project (3GPP). The Goal of the project, which started in November 2004, was to determine the long-term evolution of 3GPP's Universal Mobile Telephone System (UMTS). UMTS was also a 3GPP project that studied several candidate technologies before choosing Wide-band Code Division Multiple Access (W-CDMA) for the Radio Access Network (RAN). The term UMTS and W-CDMA are now interchangeable, although that was not the case before the technology was selected.

The project name LTE is described as an evolution of UMTS although LTE and UMTS actually have very little in common. The UMTS RAN has two major components: (1) the UMTS Terrestrial Radio Access (UTRA), which is the air interface including the User Equipment(UE) or mobile phone, and (2) the UMTS Terrestrial Radio Access Network (UTRAN), which includes the Radio Network Controller (RNC) and the base station, which is also known as the Node B (NB).

Because LTE is the evolution of UMTS, LTE's equivalent components are thus named Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN). These are the formal terms used to describe the RAN. The system, however, is more than just the RAN since there is also a parallel 3GPP project called System Architecture Evolution (SAE), which is defining a new all-IP packet-only Core Network (CN) known as the Evolved Packet Core (EPC). The combination of the EPC and the evolved RAN (E-UTRA plus E-UTRAN) is the Evolved Packet System (EPS). Depending on the context, any of the terms LTE, E-UTRA, E-UTRAN, SAE, EPC and EPS may get used to describe some or all of the system. Although EPS is the only correct term for the overall system, the name of the system will often be written as LTE/SAE or even simply LTE.

1.1 Overview

Long-Term Evolution (LTE) is the next step forward in cellular 3G services. The recent increase of mobile data usage and emergence of new applications such as mobile TV, Web 2.0, streaming contents have motivated the 3rd Generation Partnership Project (3GPP) to work on LTE.
LTE, whose radio access is called Evolved UMTS Terrestrial Radio Access Network (E-UTRAN), is expected to substantially improve end-user throughputs, sector capacity and reduce user plane latency, bringing significantly improved user experience with full mobility. With the emergence of Internet Protocol (IP) as the protocol of choice for carrying all types of traffic, LTE is scheduled to provide support for IP-based traffic with end-to-end Quality of service (QoS). Voice traffic will be supported mainly as Voice over IP (VoIP) enabling better integration with other multimedia services.
LTE has been set aggressive performance requirements that rely on physi-

cal layer technologies, such as, Orthogonal Frequency Division Multiplexing (OFDM) and Multiple-Input Multiple-Output (MIMO) systems, Smart Antennas to achieve these targets. The main objectives of LTE are to minimize the system and User Equipment (UE) complexities, allow flexible spectrum deployment in existing or new frequency spectrum and to enable co-existence with other 3GPP Radio Access Technologies (RATs).
LTE aims to achieve the following:

- Increased downlink and uplink peak data rates, as shown in Table 1.1 . Note that the downlink is specified for single input single output (SISO) and multiple input multiple output (MIMO) antenna configurations at a fixed 64QAM modulation format.
- Scalable channel bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz in both the uplink and the downlink.
- Spectral efficiency improvements over High Speed Packet Access (HSPA) of three to four times in the downlink and two to three times in the uplink.
- High coverage, cell sizes of $5 - 100$ Km with slight degradation after 30 km.
- Sub-5 ms latency for small IP packets.
- Performance optimized for low mobile speeds from 0 to 15 Km/h, supported with high performance from 15 to 120 km/h; functional support from 120 to 350 Km/h, under consideration for 350 to 500 Km/h.
- Co-existence with legacy standards while evolving toward an all-IP network.

The key features of LTE are:

FDD downlink (QAM)	Antenna Configuration		
	SISO	2x2 MIMO	4x4 MIMO
Peak data rate Mbps	100	172.8	326.4
FDD downlink (Single Antenna)	Modulation depth		
	QPSK	16QAM	64QAM
Peak data rate Mbps	50	57.6	86.4

Table 1.1: LTE (FDD) downlink and uplink peak data rates.

- Multiple access scheme:
  - DL: OFDMA with Cyclic Prefix
  - UL: Single Carrier FDMA (SC-FDMA) with Cyclic Prefix
- Adaptive modulation and coding
- Advanced MIMO spatial multiplexing techniques
  - (2 or 4)x(2 or 4) downlink and uplink supported
  - Multi-user MIMO also supported
- Support for both FDD and TDD
- H-ARQ, mobility support, rate control, security

1.2 Architecture

LTE has been designed to support only packet-switched services, in contrast to the circuit-switched model of previous cellular systems. It aims to provide seamless Internet Protocol (IP) connectivity between User Equipment (UE) and the Packet Data Network (PDN), without any disruption to the end users' applications during mobility.

Figure 1.1 describes the architecture and network elements in the architecture configuration where only the E-UTRAN AN is involved. The logical nodes and connections shown in this figure represent the basic system architecture configuration. These elements and functions are needed in all cases when E-UTRAN is involved.

The high level architectural domains are functionally equivalent to those in the existing 3GPP systems. The new architectural development is limited to Radio Access and Core Networks, the E-UTRAN and the EPC respectively. UE and Services domains remain architecturally intact, but functional evolution has also continued in those areas.

UE, E-UTRAN and EPC together represent the Internet Protocol (IP) Connectivity Layer. This part of the system is also called the Evolved Packet System (EPS). The main function of this layer is to provide IP based connectivity, and it is highly optimized for that purpose only. All services will be offered on top of IP, and circuit switched nodes and interfaces seen in earlier 3GPP architectures are not present in E-UTRAN and EPC at all.

The development in E-UTRAN is concentrated on one node, the evolved Node B (eNodeB). All radio functionality is collapsed there. The eNodeB is the termination point for all radio related protocols. As a network, E-UTRAN is simply a mesh of eNodeBs connected to neighbouring eNodeBs with the X2 interface.

The element called SAE GW represents the combination of the two gateways, Serving Gateway (S-GW) and Packet Data Network Gateway (P-GW) defined for the UP handling in EPC. Implementing them together as the SAE GW represents one possible deployment scenario, but the standards define the interface between them, and all operations have also been specified for when they are separate.

Each of these network elements is interconnected by means of interfaces that are standardized in order to allow multi-vendor interoperability. This gives network operators the possibility to source different network elements from different vendors. In fact, network operators may choose in

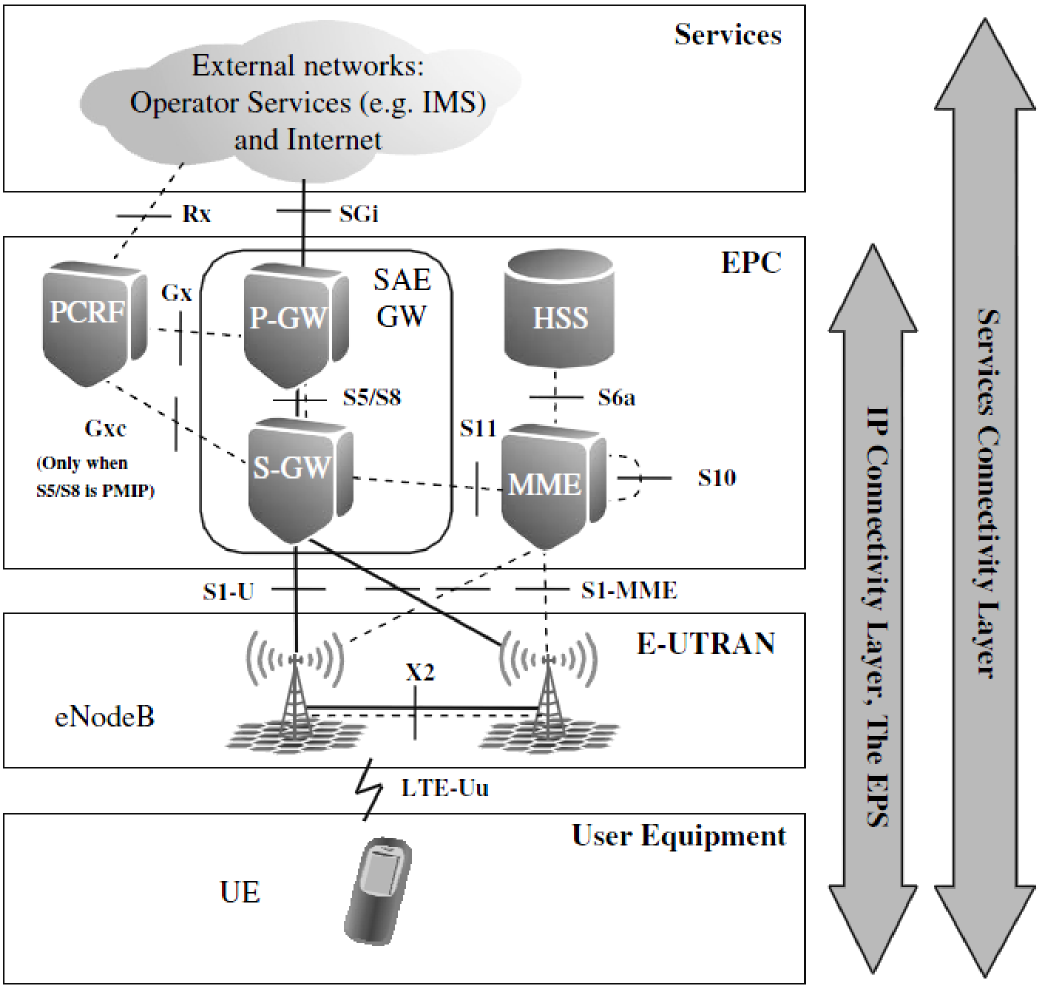

Figure 1.1: System architecture for E-UTRAN only network.

their physical implementations to split or merge these logical network elements depending on commercial considerations. The functional split between the eNB and MME/GW is shown in Figure 1.2

1.2.1 User Equipment (UE)

UE is the device that the end user uses for communication. Typically it is a hand held device such as a smart phone. UE also contains the Universal Subscriber Identity Module (USIM) that is a separate module from the rest

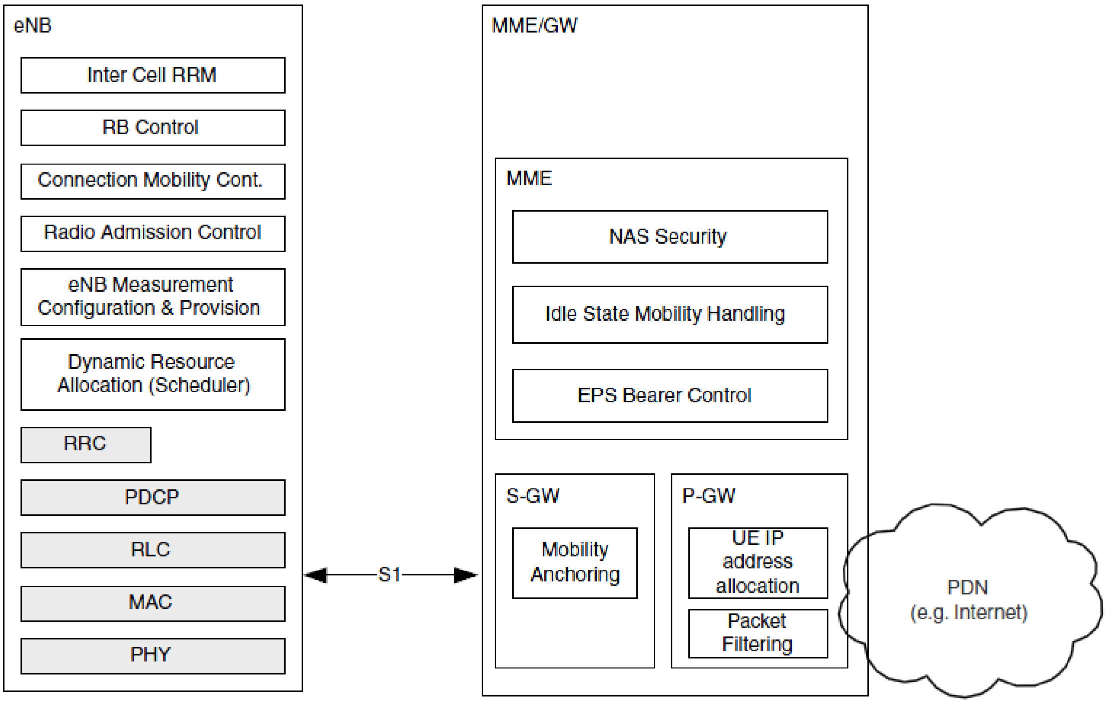

Figure 1.2: Functional split between eNB and MME/GW.

of the UE, which is often called the Terminal Equipment (TE). USIM is an application placed into a removable smart card called the Universal Integrated Circuit Card (UICC). USIM is used to identify and authenticate the user and to derive security keys for protecting the radio interface transmission. Functionally the UE is a platform for communication applications, which signal with the network for setting up, maintaining and removing the communication links the end user needs. This includes mobility management functions such as handover and reporting the terminals location, and in these the UE performs as instructed by the network. Maybe most importantly, the UE provides the user interface to the end user so that applications such as a VoIP client can be used to set up a voice call.

1.2.2 The access network

The Access Network of LTE, E-UTRAN, simply consists of a network of eNodeBs, as illustrated in Figure 1.3. A key difference between UTRAN and E-UTRAN is the absence of a centralized radio network controller, this allows tight interaction between the different protocol layers of the radio access network, thus reducing latency and improving efficiency. For these reasons, LTE does not support soft handover because there is no need for a centralized data-combining function in the network. What were once centrally-coordinated functions are now distributed into the eNBs and the X2 interfaces between them. The eNodeBs are normally interconnected with each other by means of an interface known as "X" and to the EPC by means of the S1 interface-more specifically, eNodeB and MME are interfaced by S1-MME while eNodeB and S-GW by S1-U. The protocols which run between the eNodeB and the UE are known as the "AS protocol".

The eNB is responsible for many functions including:

- *Radio Resource Management (RRM)* - It controls the usage of the radio interface, which includes, for example, allocating resources based on requests, prioritizing and scheduling traffic according to required Quality of Service (QoS), and constant monitoring of the resource usage situation.
- *Header Compression* - It compresses the IP packet headers to ensure efficient use of the radio interface, this avoids significant overhead, especially for small packet such as VoIP.
- *Security* - All data sent over the radio interface is encrypted.
- *Connectivity to the EPC* - This signals toward MME and the bearer path toward the S-GW.

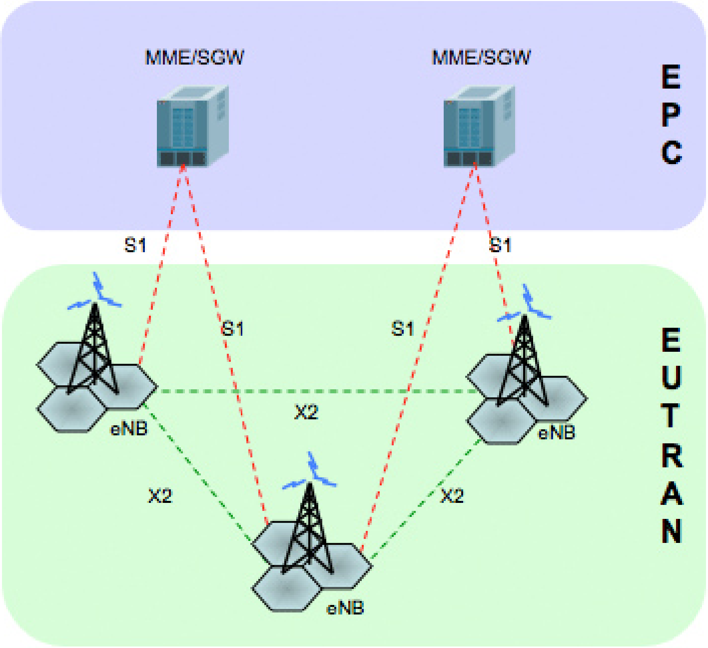

Figure 1.3: Overall E-UTRAN architecture.

In addition, the eNodeB has an important role in Mobility Management (MM). The eNodeB controls and analyses radio signal level measurements carried out by the UE, makes similar measurements itself, and based on those makes decisions to handover UEs between cells. This includes exchanging handover signalling between other eNodeBs and the MME. When a new UE activates under eNodeB and requests connection to the network, the eNodeB is also responsible for routing this request to the MME that previously served that UE, or selecting a new MME, if a route to the previous MME is not available or routing information is absent.

1.2.3 The core network

The core network, called EPC in SAE, is responsible for establishment of the bearers and the overall control of the UE. The main EPC logical nodes are:

- PDN Gateway (P-GW)
- Serving Gateway (S-GW)
- Mobility Management Entity (MME)

Packet Data Network Gateway (P-GW, also often abbreviated as PDN-GW) is the edge router between the EPS and external packet data networks. It is the highest level mobility anchor in the system, and usually it acts as the IP point of attachment for the UE. Typically the P-GW allocates the IP address to the UE, and the UE uses that to communicate with other IP hosts in external networks, e.g. the Internet. It is also possible that the external PDN to which the UE is connected allocates the address that is to be used by the UE, and the P-GW tunnels all traffic to that network.

The Serving Gateway transfers all user IP packets, which serves as the local mobility anchor for the data bearers when the UE moves between eNodeBs. It also retains the information about the bearers when the UE is in the idle state and temporarily buffers downlink data while the MME initiates paging of the UE to re-establish the bearers. In addition, the SGW performs some administrative functions in the visited network such as collecting information for charging (for example, the volume of data sent to or received from the user) and lawful interception. It also serves as the mobility anchor for inter-working with other 3GPP technologies such as general packet radio service (GPRS) and UMTS.

Mobility Management Entity (MME) is the main control element in the EPC. It is the control node that processes the signaling between the UE and the CN. The protocols running between the UE and the CN are known as the Non Access Stratum (NAS) protocols. The following lists the main MME functions in the basic System Architecture Configuration:

- *Authentication and Security*: When a UE registers to the network for the first time, the MME initiates the authentication. This includes the establishment of the connection and security between the network and UE and is handled by the connection or mobility manage-ment layer in the NAS protocol layer.
- *Mobility Management*: The MME keeps track of the location of all UEs in its service area.
- *Managing Subscription Profile and Service Connectivity*: At the time of a UE registering to the network, the MME will be responsible for retrieving its subscription profile from the home network. The MME will store this information for the duration it is serving the UE.

EPC also includes, in addition to these nodes, other logical nodes and functions such as the Home Subscriber Server (HSS) and the Policy Control and Charging Rules Function (PCRF).Multimedia applications control such as VoIP is provided by the IP Multimedia Subsystem (IMS), which is considered to be outside the EPS itself.

The Policy Control and Charging Rules Function is responsible for policy control decision-making, as well as for controlling the flow-based charging functionalities in the Policy Control Enforcement Function (PCEF), which resides in the P-GW. The PCRF provides the QoS authorization which decides how a certain data flow will be treated in the PCEF and ensures that this is in accordance with the user's subscription profile.

The Home Subscriber Server contains users' SAE subscription data such as the EPS-subscribed QoS profile and any access restrictions for roaming. It also contains information about the PDNs to which the user can connect. This could be in the form of an access point name (APN) or a PDN address which indicates subscribed IP address. In addition the HSS holds dynamic information such as the identity of the MME to which the user is currently registered or attached. Finally, the HSS may also integrate the authentication center (AUC), which generates the vectors for authentication and security keys.

It should be noted that the nodes discussed above are logical nodes. In an actual physical implementation, several of them may very well be combined. For example, the MME, P-GW, and S-GW could very well be combined into a single physical node.

1.3 Protocol Architetture

A general overview of the LTE (userplane) protocol architecture for the downlink is illustrated in Figure 1.4. The different protocol entities of the radio-access network are summarized below:

- *Packet Data Convergence Protocol (PDCP)*: performs IP header compression to reduce the number of bits to transmit over the radio interface. PDCP is also responsible for ciphering and, for the control plane, integrity protection of the transmitted data, as well as in-sequence delivery and duplicate removal for handover. At the receiver side, the PDCP protocol performs the corresponding deciphering and decompression operations. There is one PDCP entity per radio bearer configured for a terminal.
- *Radio-Link Control (RLC)*: is responsible for segmentation/concatenation, retransmission handling, duplicate detection, and in-sequence delivery to higher layers. The RLC provides services to the PDCP in the form of radio bearers. There is one RLC entity per radio bearer configured for a terminal.
- *Medium-Access Control (MAC)*: handles multiplexing of logical channels, hybrid-ARQ retransmissions, and uplink and downlink schedul-

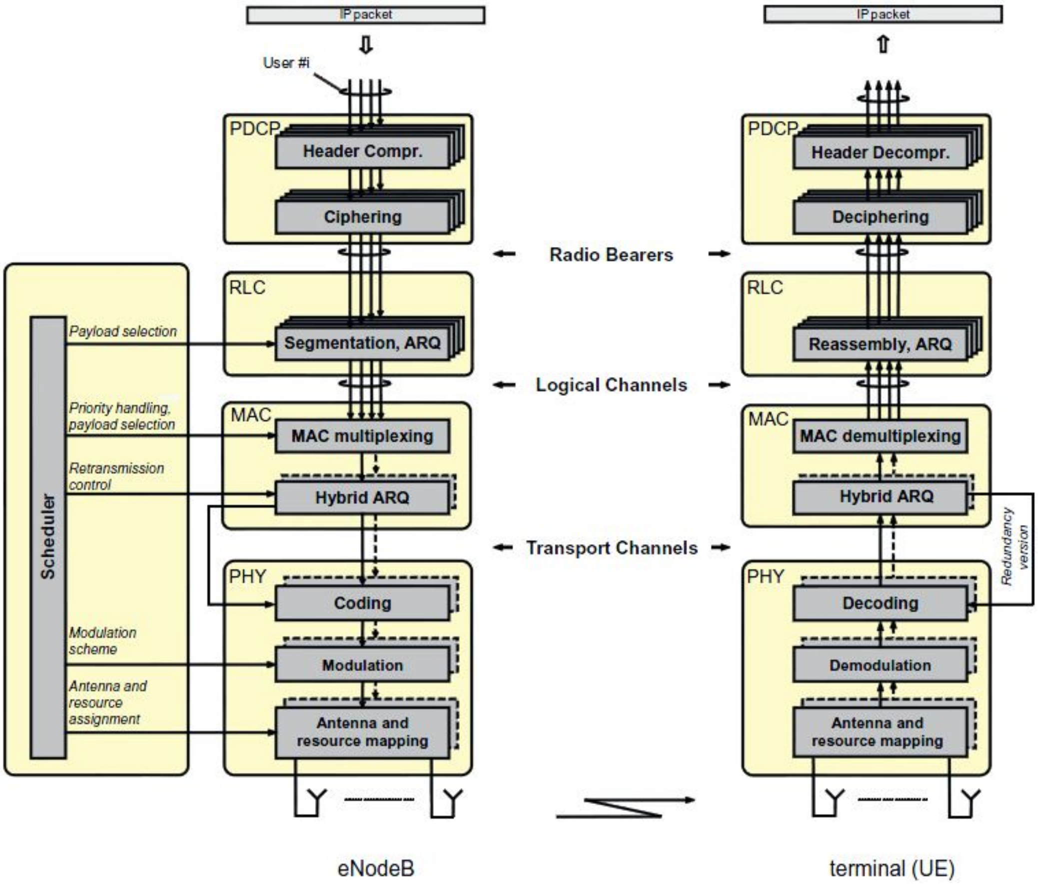

Figure 1.4: LTE Protocol Architetture.

ing. The scheduling functionality is located in the eNodeB for both uplink and downlink. The hybrid-ARQ protocol part is present in both the transmitting and receiving ends of the MAC protocol. The MAC provides services to the RLC in the form of logical channels.

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

1.3.1 Logical Channels and Transport Channels

The MAC provides services to the RLC in the form of logical channels. A logical channel is defined by the type of information it carries and is generally classified as a control channel, used for transmission of control and configuration information necessary for operating an LTE system, or as a traffic channel, used for the user data. The set of logical-channel types specified for LTE includes:Broadcast Control Channel (BCCH), Paging Control Channel (PCCH), Common Control Channel (CCCH), Dedicated Control Channel (DCCH), Multicast Control Channel (MCCH), Dedicated Traffic Channel (DTCH), Multicast Traffic Channel (MTCH).

From the physical layer, the MAC layer uses services in the form of transport channels. A transport channel is defined by how and with what characteristics the information is transmitted over the radio interface. Data on a transport channel is organized into transport blocks. In each Transmission Time Interval (TTI), at most one transport block of dynamic size is transmitted over the radio interface to/from a terminal in the absence of spatial multiplexing. In the case of spatial multiplexing (MIMO), there can be up to two transport blocks per TTI.

Associated with each transport block is a Transport Format (TF), specifying how the transport block is to be transmitted over the radio interface. The transport format includes information about the transport-block size, the modulation-and-coding scheme, and the antenna mapping. By varying the transport format, the MAC layer can thus realize different data rates. Rate control is therefore also known as transport-format selection.

The following transport-channel types are defined for LTE: Broadcast Channel (BCH), Paging Channel (PCH), Downlink Shared Channel (DL-SCH), Multicast Channel (MCH), Uplink Shared Channel (UL-SCH).

1.3.2 Scheduling

One of the basic principles of LTE radio access is shared-channel transmission that is, time-frequency resources are dynamically shared between users. The scheduler is part of the MAC layer (although often better viewed as a separate entity as illustrated in Figure 1.4) and controls the assignment of uplink and downlink resources in terms of so-called resource-block pairs. Resource blocks correspond to a time-frequency unit of 1 ms times 180 kHz.

The basic operation of the scheduler is so-called dynamic scheduling, where the eNodeB in each 1 ms interval takes a scheduling decision and sends scheduling information to the selected set of terminals. However, there is also a possibility for semi-persistent scheduling where a semi-static scheduling pattern is signaled in advance to reduce the control-signaling overhead. Coordination of scheduling decisions across multiple cells residing in different eNodeBs is supported using signaling over the X2 interface.

Uplink and downlink scheduling are separated in LTE, and uplink and downlink scheduling decisions can be taken independently of each other.

Since scheduling techniques are the core of this thesis work, they will be analyzed more in details in the next chapters.

1.3.3 Physical Layer

The physical layer is responsible for coding, physical-layer hybrid-ARQ processing, modulation, multi-antenna processing, and mapping of the signal to the appropriate physical time-frequency resources. It also handles mapping of transport channels to physical channels, as shown in Figures 1.5 and 1.6.

In addition to the physical channels with a corresponding transport channel, there are also physical channels without a corresponding trans-

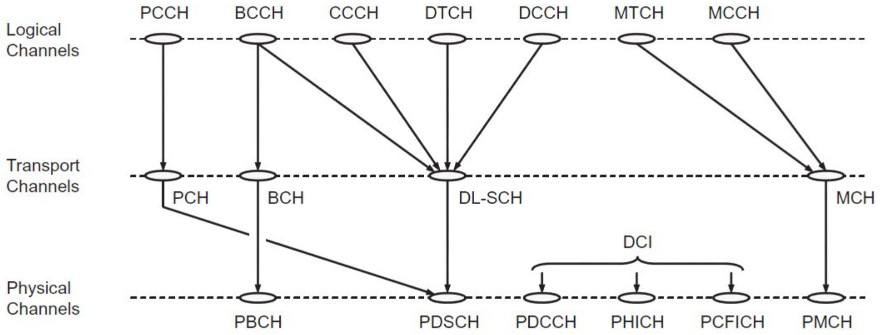

Figure 1.5: Downlink Channel Mapping.

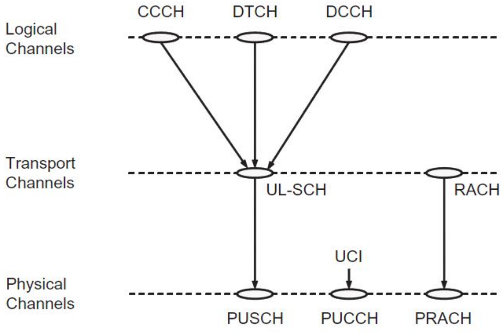

Figure 1.6: Uplink Channel Mapping.

port channel. These channels, known as L1/L2 control channels, are used for downlink control information (DCI), providing the terminal with the necessary information for proper reception and decoding of the downlink data transmission, and uplink control information (UCI) used for providing the scheduler and the hybrid-ARQ protocol with information about the situation at the terminal.

The physical-channel types defined in LTE include the following: Physical Downlink Shared Channel (PDSCH), Physical Broadcast Channel (PBCH), Physical Multicast Channel (PMCH), Physical Downlink Control Channel (PDCCH), Physical Hybrid-ARQ Indicator Channel (PHICH), Physical Control Format Indicator Channel (PCFICH), Physical Uplink Shared Channel (PUSCH), Physical Uplink Control Channel (PUCCH).

Besides physical channels, there are signals embedded in the downlink and uplink physical layer, which do not carry information from higher layers. The physical signals defined in the LTE specifications are:

- *Reference signal*: It is defined in both downlink and uplink for channel estimation that enables coherent demodulation and for channel quality measurement to assist user scheduling. There are three different reference signals in the downlink and two in the uplink, respectively:
  - Cell-specific reference signals, associated with non-MBSFN transmission.
  - MBSFN reference signals, associated with MBSFN transmission.
  - UE-specific reference signals.
  - Demodulation reference signal, associated with transmission of PUSCH or PUCCH.
  - Sounding reference signal, to support uplink channel-dependent scheduling.
- *Synchronization signal*: It is split into a primary and a secondary synchronization signal, and is only defined in the downlink to enable acquisition of symbol timing and the precise frequency of the downlink signal.

1.4 LTE basic concepts

The multiple access schemes that uses LTE are OFDMA with Cyclic Prefix (CP) in DL and Single Carrier FDMA (SC-FDMA) with CP in UL. OFDM/OFDMA have been selected by 3GPP because of its robustness to multipath propagation in wide-band channels, inherent support for frequency diversity and easiness integration with MIMO antenna schemes. As shown

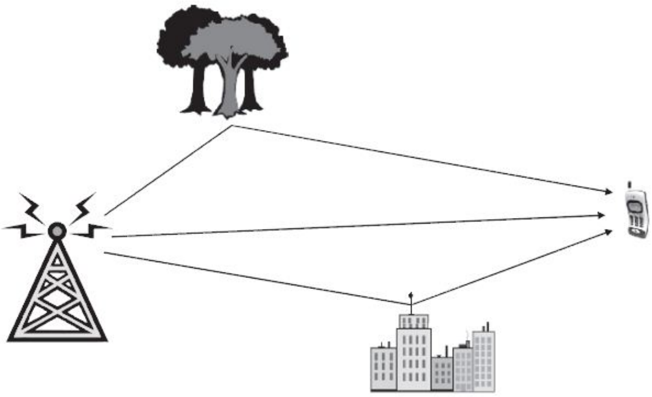

Figure 1.7: Multipath caused by reflections.

in Figure 1.7 at the receiver, there is typically (but not always) a line-of-sight path and ,in addition, there are many others paths caused by signal reflection off vehicles, buildings and other obstructions. Signal traveling along these paths are shifted in time by an amount corresponding to the differences in the distance traveled along each path. Inside each subcarrier Adaptive Modulation and Coding (AMC) is applied with three modulation schemes (QPSK, 16QAM and 64QAM) and variablecode rates. LTE performs link adaptation via AMC (explicit adaptation) and HARQ (implicit adaptation toerrors) in a fast pace (each 2 slots, or 1 ms) providing data quickly and reliably using minimal resources.The addition of AMC and HARQ process allows to minimize the turnaround time and maximize the data throughput of the system. The LTE specifications inherit all the frequency bands defined for UMTS and add more bands and describe both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) to separate uplink and donwlink traffic

1.4.1 OFDM overview

OFDMA is a multi-user OFDM that allows multiple access on the same channel, in this way it can accommodate many users in the same channel at the same time. The OFDM systems help to manage inter-symbol interference (ISI) much easier. The technique allows to carry data using a large number of closely spaced orthogonal sub-carrier signals. The data is divided into several parallel data streams or channels, one for each sub-carrier. Each sub-carrier is modulated with a conventional modulation scheme, such as QPSK, QAM, 64QAM or possible higher orders depending on signal quality, at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes in the same bandwidth.
The idea behind the analog implementation of OFDM can be extended to the digital domain by using the discrete Fourier Transform (DFT) and its counterpart, the inverse discrete Fourier Transform (IDFT). These mathematical operations are widely used for transforming data between the time-domain and frequency-domain. These transforms are interesting from the OFDM perspective because they can be viewed as mapping data onto orthogonal sub-carriers, shown in Figure 1.8. For example, the IDFT is used to take in frequency-domain data and convert it to time-domain data. In order to perform that operation, the IDFT correlates the frequency-domain

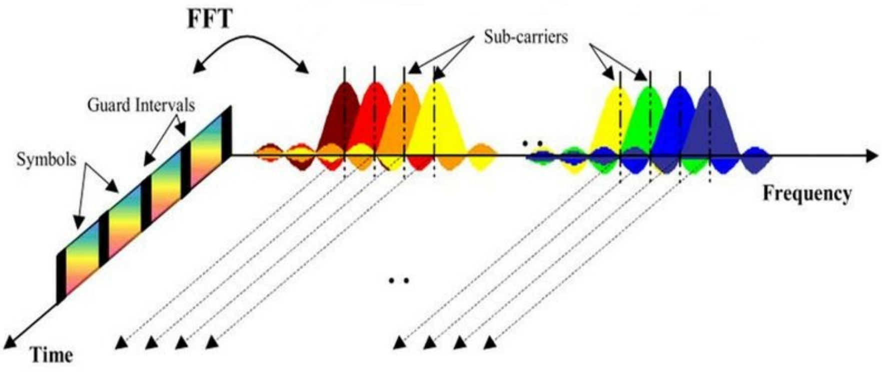

Figure 1.8: Example of OFDM signal.

input data with its orthogonal basis functions, which are sinusoids at certain frequencies. This correlation is equivalent to mapping the input data onto the sinusoidal basis functions. Each OFDM symbol is therefore a linear combination of the instantaneous signals on each of the sub-carriers in the channel. Because data is transmitted in parallel rather than serially, OFDM symbols are generally much longer than symbols on single carrier systems of equivalent data rate.

To eliminate ISI,each sent OFDM symbol is preceded by a cyclic prefix (CP). The duration of the CP is determined by the highest anticipated degree of delay spread for the targeted application. When transmitted signals arrive at the receiver by two paths of differing length, they are staggered in time. Within the CP, it is possible to have distortion from the preceding symbol.

1.4.2 OFDMA in the downlink

The OFDM signal used in LTE comprises a maximum of 2048 different subcarriers having a spacing of 15 kHz. Although it is mandatory for the mobiles to have capability to be able to receive all 2048 sub-carriers, not all need to be transmitted by the base station which only needs to be able to support the transmission of 72 sub-carriers. In this way all mobiles will be able to talk to any base station. Within the OFDM signal it is possible to choose between three types of modulation:

- **QPSK** - 2 bits per symbol
- **16-QAM** - 4 bits per symbol
- **64-QAM** - 6 bits per symbol

The exact format is chosen depending upon the prevailing conditions. The lower forms of modulation, (QPSK) do not require such a large signal to noise ratio but are not able to send the data as fast. Only when there is a sufficient signal to noise ratio can the higher order modulation format be used.

1.4.3 SC-FDMA in the uplink

For the LTE uplink, a different concept is used for the access technique. Although still using a form of OFDMA technology, the implementation is called Single Carrier Frequency Division Multiple Access (SC-FDMA). One of the key parameters that affects all mobiles is that of battery life. Even though battery performance is improving all the time, it is still necessary to ensure that the mobiles use as little battery power as possible. With the RF power amplifier that transmits the radio frequency signal via the antenna to the base station being the highest power item within the mobile, it is necessary that it operates in as efficient mode as possible. This can be significantly affected by the form of radio frequency modulation and signal format. Signals that have a high peak to average ratio and require linear amplification do not lend themselves to the use of efficient RF power amplifiers. As a result it is necessary to employ a mode of transmission that has as near a constant power level when operating. Unfortunately OFDM has a high peak to average ratio. While this is not a problem for the base station where power is not a particular problem, it is unacceptable for the mobile. As a result, LTE uses a modulation scheme known as SC-FDMA - Single Carrier Frequency Division Multiplex which is a hybrid format. This combines the low peak to average ratio offered by single-carrier systems with the multipath interference resilience and flexible sub-carrier frequency allocation that OFDM provides. Furthermore, multipath distortion is handled in the same manner as in OFDM systems (removal CP, conversion to the frequency domain, then apply the channel correction on a sub-carrier-by-sub-carrier basis).

1.4.4 LTE Generic Frame Structure

The LTE OFDM subcarrier spacing equals 15 kHz for both downlink and uplink. The selection of the subcarrier spacing in an OFDM-based system needs to carefully balance overhead from the cyclic prefix against sensitivity to Doppler spread/shift and other types of frequency errors and inaccuracies. The choice of 15 kHz for the LTE subcarrier spacing was found to offer a good balance between these two constraints. Assuming an FFT-based transmitter/receiver implementation, 15 kHz subcarrier spacing corresponds to a sampling rate $f_s = 15000 * NFFT$, where NFFT is the FFT size. It is important to understand though that the LTE specifications do not in any way mandate the use of FFT-based transmitter/receiver implementations and even less so a particular FFT size or sampling rate. Nevertheless, FFT-based implementations of OFDM are common practice and an FFT size of 2048, with a corresponding sampling rate of 30.72 MHz, with a bandwidth of 20 MHz.

In the time domain, LTE transmission $T_{\mathtt{slot}} = 0.5$ ms, with each slot consisting of a number of OFDM symbols including cyclic prefix. The 15 kHz LTE subcarrier spacing corresponds to a useful symbol time $T_u = 2048 * Ts$ or approximately $66.7\mu s$. The overall OFDM symbol time is then the sum of the useful symbol time and the cyclic-prefix length TCP. As illustrated in Figure 1.9, LTE defines two cyclic-prefix lengths, the normal cyclic prefix and an extended cyclic prefix, corresponding to seven and six OFDM symbols per slot respectively.

A *resource element*, consisting of one subcarrier during one OFDM symbol, is the smallest physical resource in LTE. Furthermore, as illustrated in Figure 1.10, resource elements are grouped into resource blocks, where each resource block consists of 12 consecutive subcarriers in the frequency domain and one 0.5 ms slot in the time domain. Each resource block thus consists of $7 * 12 = 84$. resource elements in the case of a normal cyclic

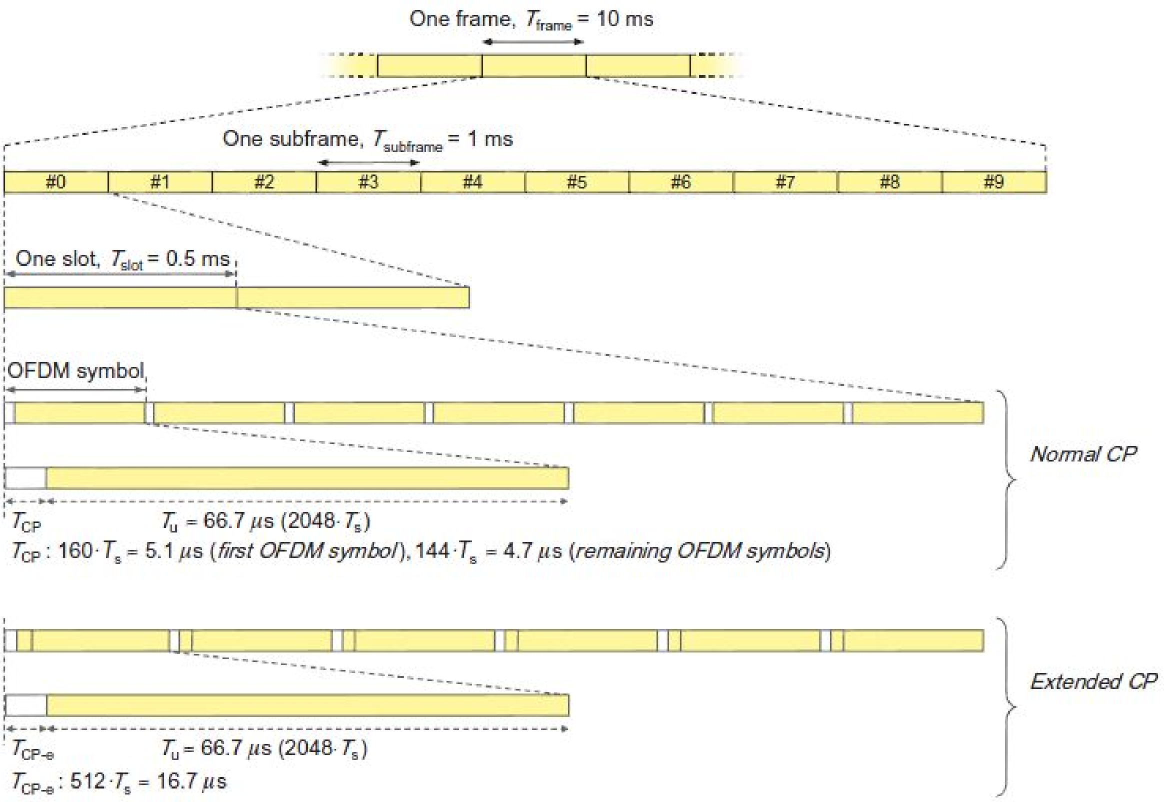

Figure 1.9: Lte time-domain frame structure.

prefix and $6 * 12 = 72$ resource elements in the case of an extended cyclic prefix.

Although resource blocks are defined over one slot, the basic time-domain unit for dynamic scheduling in LTE is one subframe, consisting of two consecutive slots. The reason for defining the resource blocks over one slot is that distributed downlink transmission and uplink frequency hopping are defined on a slot or resource-block basis. The minimum scheduling unit, consisting of two time-consecutive resource blocks within one subframe (one resource block per slot), can be referred to as a resource-block pair.

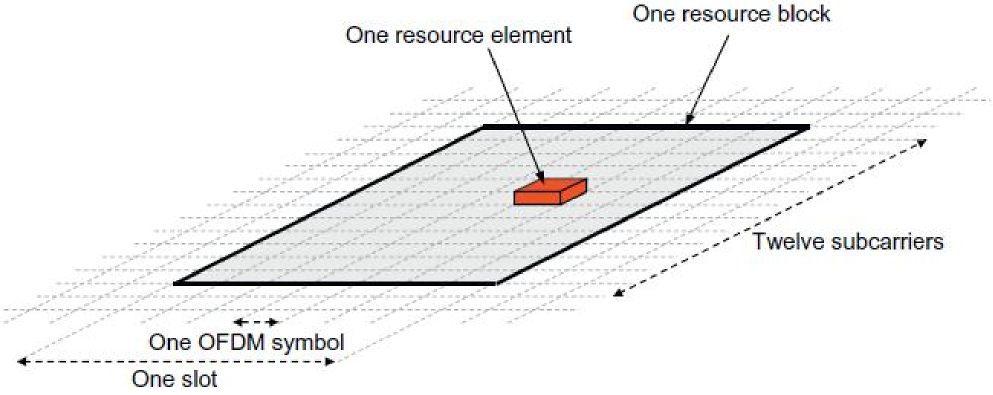

Figure 1.10: The LTE physical time-frequency resource.

Chapter 2

LTE Layer 2 and Scheduling techniques

2.1 Layer 2 structure

The layer 2 of LTE is composed of three sub-layers namely Medium Access Control (MAC), Radio Link Control (RLC), and Packet Data Convergence Protocol (PDCP) as shown in Figure 2.1 and 2.2 respectively for the downlink and the uplink. The service access point (SAP) between the physical (PHY) layer and the MAC sub-layer provides the transport channels while the SAP between the MAC and RLC sub-layers provides the logical channels. The MAC sub-layer performs multiplexing of logical channels on to the transport channels.

The difference between downlink and uplink structures is that in the downlink, the MAC sublayer also handles the priority among UEs in addition to priority handling among the logical channels of a single UE.

The Packet Data Convergence Protocol (PDCP) layer processes Radio Resource Control (RRC) messages in the control plane and Internet Protocol (IP) packets in the user plane. Depending on the radio bearer, the main functions of the PDCP layer are header compression, security (integrity

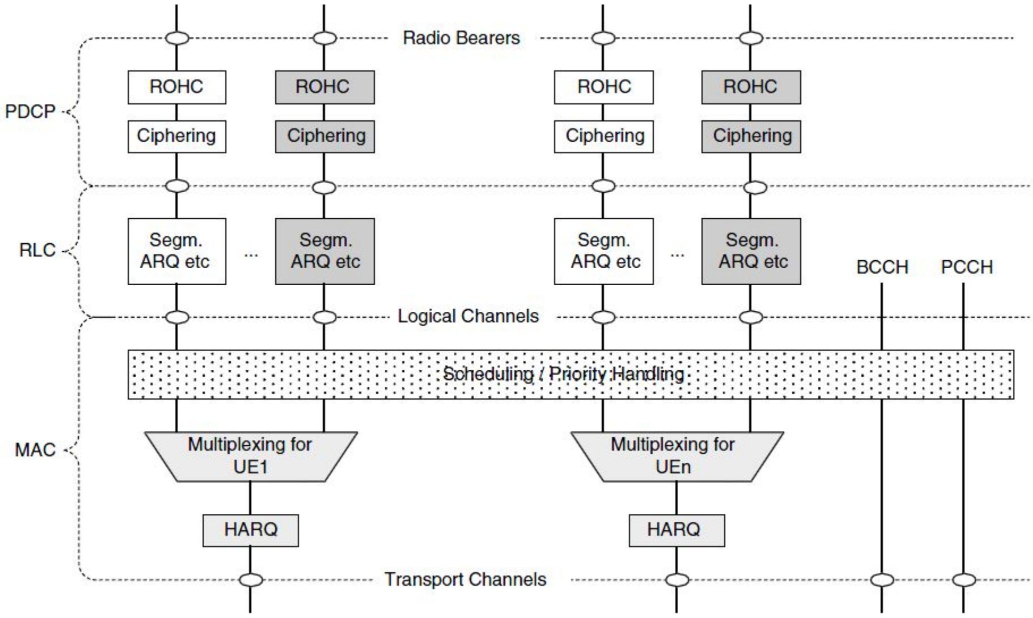

Figure 2.1: Downlink layer 2 structure.

protection and ciphering), and support for reordering and retransmission during handover. There is one PDCP entity per radio bearer.

Header compression is important because VoIP is a critical application for LTE. Because there is no more circuit switching in LTE, all voice signals must be carried over IP and there is a need for efficiency.

The main functions of the RLC layer are segmentation and reassembly of upper layer packets in order to adapt them to the size which can actually be transmitted over the radio interface. RLC performs segmentation and reassembly in three modes: *transparent mode* (TM), *acknowledged mode* (AM) and *un-acknowledged mode* (UM). These are used by different radio bearers for different purposes.

For radio bearers which need error-free transmission, the RLC layer also performs retransmission to recover from packet losses. Additionally, the RLC layer performs reordering to compensate for out-of-order reception due to Hybrid Automatic Repeat reQuest (HARQ) operation in the layer

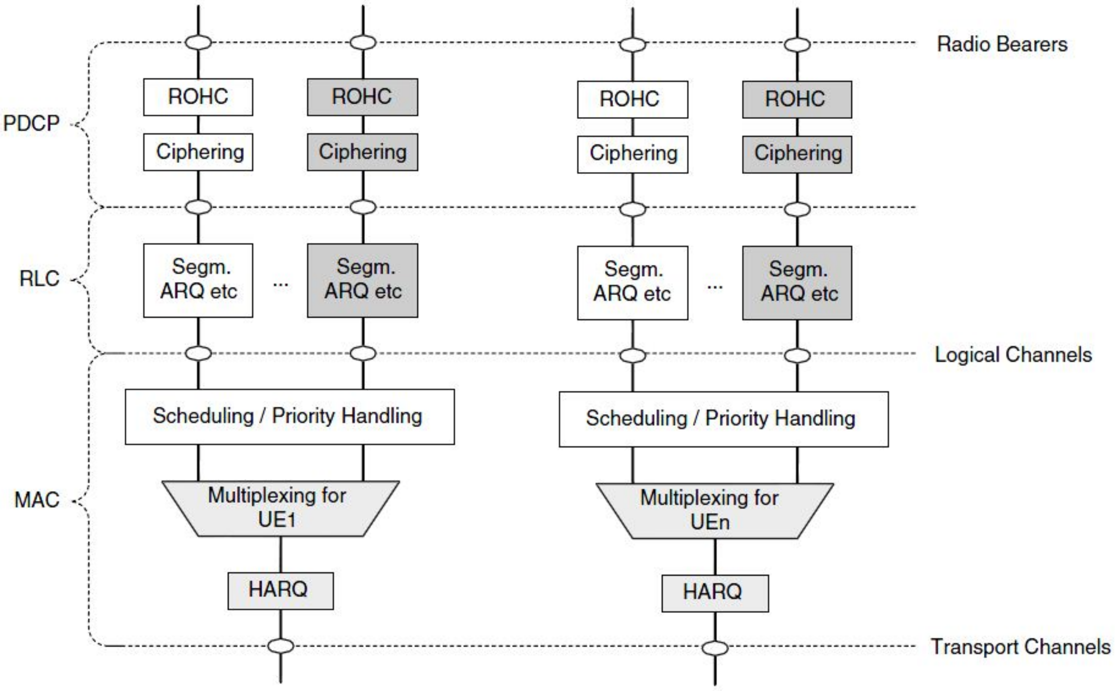

Figure 2.2: Uplink layer 2 structure.

below. There is one RLC entity per radio bearer.

2.2 MAC layer

MAC is the lowest sub-layer in the Layer 2 of the LTE. The MAC layer handles logical-channel multiplexing, hybrid-ARQ retransmissions, and uplink and downlink scheduling. It is also responsible for multiplexing/demultiplexing data across multiple component carriers when carrier aggregation is used.

2.2.1 MAC Functions

Priority Handling

Priority handling is one of the main functions supported by the MAC layer.

Priority handling refers to the process which selects the packets fromthe different waiting queues to be submitted to the underlying physical layer for transmission on the radio interface.

HARQ

The principle of hybrid ARQ is to buffer blocks that were not received correctly and consequently combine the buffered data with retransmissions. The actual method of doing soft combining depends on the HARQ combining scheme selected.

Basically, two type of combining can be used: *Chase Combining* (CC) or *Incremental Redundancy* (IR). The first one retransmits the same packets which are transmitted before, while IR retransmits new redundancy bits from the channel encoder. When IR is selected, instead of sending simple repeats of the coded data packets, in each subsequent transmission of the packet new information is sent. In this way, the decoder combines all transmissions and can decode the packet at a lower code rate.

Random Access Procedure

Control of the random access procedure is an important part of the MAC layer functionality in LTE. The random access procedure is usedto request an initial access, as part of handover, or to re-establish uplink synchronization.

The Random Access Channel (RACH) is used in that procedure.

Timing Alignment

Timing Alignment is an important function of the MAC layer because it ensures that a UE's uplink transmissions arrive in the eNodeB without overlapping with the transmissions from other UEs. Time alignment of the uplink transmissions is achieved by applying a timing advance at the UE transmitter, relative to the received downlink timing. The main role of this is to counteract differing propagation delays between different UEs.

Scheduling

The eNodeB MAC sublayer is responsible for scheduling transmissions over the LTE air interface in both the downlink and uplink directions. The eNodeB MAC sublayer contains the MAC Scheduler. The MAC Scheduler runs the scheduling algorithms which determine what gets sent when and to/by whom. The MAC Scheduler is responsible for implementing the QoS characteristics assigned to radio bearers.

The key to achieve optimal performance of base station is dynamically scheduling limited resources like power and bandwidth to offer the best service for terminals with the lowest cost. For scheduling based on OFDMA, it balances maximum throughput and fairness by scheduling time slots, sub-channels, modulation scheme and power with frequency diversity and multiuser diversity. Frequency diversity is done by utilizing the fact that each sub-channel suffers different attenuation in different time and frequency, due to shadowing, fast fading, multi-path and so on.

In a similar way, multiuser diversity is obtained by opportunistic user scheduling, since different users locate different places leading to different channel gains of an identical sub-channel for different users. By analyzing CSI (channel state information), base station recognizes variation of time, frequency, space and adjusts scheduling to keep optimal performance.

In order to follow variation of channel conditions, scheduling should be done within the coherent time, so it requires that allocation algorithms must be fast, especially time varying channel. As mentioned in previous chapter, PRB is formed from 12 consecutive sub-carriers in the frequency domain and seven or six consecutive symbols in the time domain. The smallest resource unit which is allowed to be assigned to one terminal is

Schedule Block (SB) constituted by two successive PRBs. The fastest scheduling is required to be done within 1ms according to the symbol length of SB. After scheduling, scheduling map will be sent to all terminals. Individual terminal only decodes received data in certain particular time and frequency based on scheduling map.

An important parameter to allocate radio resources to the UEs is the Channel Quality Indicator (CQI) feedback. Channel Quality Indicator is 5 bit information which an active UE sends as feedback to the eNodeB at regular interval. UE reports CQI value to eNodeB via two methods: periodically by using physical uplink control channel (PUCCH) or physical uplink shared channel (PUSCH) and a-periodically by using PUSCH channels.

The terminal reports the measured CQI to the BS by mapping the measured SNR. In the LTE simulator, the mapping of the SNR to the CQI for a BLER of 0.1 is approximated through a linear function as shown in the Figure 2.3. In the 3GPP Technical specification 36.213 reference [1], CQIs index are specified. The index ranges up to 15. Each numbered index relates to a modulation scheme and an equivalent channel coding rate. UE can choose an appropriate CQI value related to a set of Block Error Rate (BLER) thresholds. These values are listed in Table 2.1.

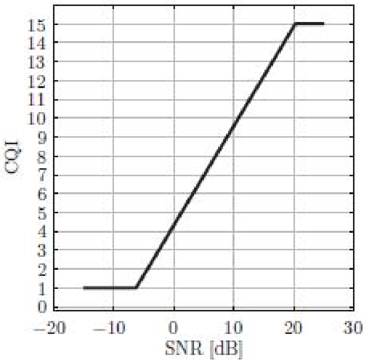

Figure 2.3: SNR-CQI mapping model [2].

Table 2.1 displays an implementation of three modulation schemes in-

CQI index	Modulation	Code rate	bits per symbols
0	No Transmission	-	-
1	QPSK	0.076	0.1523
2	QPSK	0.12	0.2394
3	QPSK	0.19	0.3770
4	QPSK	0.3	0.6016
5	QPSK	0.44	0.8770
6	QPSK	0.59	1.1758
7	16QAM	0.37	1.4766
8	16QAM	0.48	1.9141
9	16QAM	0.6	2.4063
10	64QAM	0.45	2.7305
11	64QAM	0.55	3.3223
12	64QAM	0.65	3.9023
13	64QAM	0.75	4.5234
14	64QAM	0.85	5.1152
15	64QAM	0.93	5.5547

Table 2.1: CQI table.

cluding QPSK, 16QAM and 64QAM. The use of higher order modulation such like 16QAM and 64QAM provides the possibility for higher bandwidth utilization and subsequently higher data rate, within a particular bandwidth. Higher order modulation schemes achieve higher data rates by using alternative signaling modulation alphabet been extended and thus allowing for more bits of information to be communicated per modulation symbol.

The overall system performance in the downlink is based on how efficient the scheduler is. In LTE downlink the flexibility of allocating available resource block on the physical layer is an inherent function of a user diversity system that depends on the various techniques adopted by the scheduling algorithm. These techniques are evaluated on the basis of quality of service requirement of a user, and in terms of the maximum benefit the system can derive from it using metrics of fairness, system throughput and most especially service level agreement.

Although the scheduling strategy is implementation specific and not specified by 3GPP, the overall goal of most scheduler is satisfy the system and users requirement. A good scheduling algorithm therefore has two main objectives: first to maximize the throughput and second to achieve fairness between users. To achieve this goal, there are many algorithms developed for wireless system, such as maximum rate scheduling, round robin (RR), best CQI, proportional fair (PF) and Smart allocation (Smalloc).

2.3 Scheduling Techniques

This section provides an overview of scheduling techniques that have been proposed for OFDMA (especially LTE) wireless network to support the provision of guaranteed QoS and a briefing of the state of the art of these techniques.

In the modern communication system there are a growing number of mobile applications with different QoS requirements. For these reasons, the network has to be able to support different levels of service with different throughput, delay, loss rate or delay jitter. The aim of the future wireless communication systems is to ensure the different QoS requirements.

As mentioned in Chapter 1, OFDM is based on the concept of multi-carrier transmission. The entire channel is divided into N narrow-band sub-channels, the data rate is split into N sub-streams of lower data rate, each sub-stream is modulated into N OFDM symbols and transmitted on N orthogonal sub-carriers simultaneously. Each transmission block has approximately a constant channel gain thanks to the low bandwidth of the sub-channels in order to be robust to frequency selective fading. OFDM sub-channels can be allocated dynamically among multiple users, providing an extra degree of freedom in multi-user scheduling. In addition, due to the diversity of such systems (in frequency, time, and space), the modulation type and the transmit power per sub-channel can be adapted in order to increase spectral efficiency.

In a multi-user OFDM system, diversity can be exploited by dynamically assigning different sets of sub-carriers to different terminals. OFDMA system, which adopts OFDM modulation, combines the TDMA and FDMA schemes. The time domain is segmented into (groups of) OFDM symbols and each symbol is segmented into sub-carriers. The number of sub-carriers which are allocated to a single transmitter vary according to the transmitter's needs. The transmission rate on those carriers is set to meet the transmitter's needs and capabilities. For these reasons, OFDM has become the workhorse for broadband wireless applications and has been adopted by current and future standards including IEEE 802.16/WiMAX and 3GPP LTE.

In the time domain, the scheduler chooses the candidate user to transmit then the allocator decides the modulation and coding scheme and power to be allocated for the user. Instead, in a OFDM system scheduling and resources allocation can be made in the same time; in fact the words scheduled and allocated are often used with the same meaning.

As we will see later, several algorithms provide a classic approach in the OFDM systems; it means that the algorithm creates a list of users to be scheduled first then it allocates resources to them; other algorithms schedule all users and allocate resources to them in the same time according to a criteria without a priority list. This is called joint approach.

OFDM offers more degrees of freedom to allocate resources across (i.e., tone allocation in the frequency domain). This enables exploiting both multi-user diversity and frequency diversity at a finner granularity, but also increases the complexity of the optimization. Due to this finer granularity, it is possible to increase significantly the throughput of the system.

The problem of resource allocation in an OFDMA system with N sub-carriers and K users is to determine the elements of matrix, called resource allocation matrix, $\mathbf{C} = [c_{k,n}]_{KxN}$ specifying which sub-carrier should be assigned to which user and vector $\mathbf{p} = [p_n]_{Nx1}$ specifying how much power should be allocated to each sub-carrier. The theorem proved in [3] showing that the data rate of a multi-user OFDM system is maximized when each sub-carrier is assigned to only one user that has the best channel gain for that sub-carrier.

Many dynamic resources allocation algorithms and optimization techniques have been proposed to manage the future services that continue to evolve; it is very important that these techniques are able to provide high bit rates as possible with various quality requirements. In a OFDM system each sub-carrier can have a different modulation scheme which provides a trade-of between spectral efficiency and BER. If a fixed modulation scheme is adopted in a OFDM system then it tries to maintain acceptable performance when the channel quality is poor. Using a fixed modulation, it can not be possible to increase the modulation when a channel gain of a sub-carrier improves; in this manner, it would maximize the overall spectral efficiency. On the other hand, adaptive modulation requires an accurate channel estimates at the receiver; if the channel changed faster than it can be estimated, adaptive modulation would perform poorly. Furthermore, overhead information needs to be updated regularly and exchanged so that transmitter and receiver know what modulation is being used. Two crucial issues in resource allocation for wireless communication systems are efficiency and fairness. A definition for spectral efficiency is the data rate per unit bandwidth; a user's spectral efficiency is calculated by dividing the total bandwidth throughput by the user's total bandwidth. If a system provides the highest throughput then it does not take into account the fairness among the users. There is a trade-of between efficiency and fairness in wireless resource allocation. In [4], the definition of fairness is to allocate the resources to the users so that all the users achieve the same data rate. A fairness index is defined in [5] as a rate proportional constraints with the maximum value of 1 to be the fairest case in which all users would achieve the same data rate.

2.3.1 The multi-user resource allocation problem

In this section we focus on Resource Allocation standardized by 3GPP. The main design challenge for the signaling of frequency domain resource allocations is to find a good compromise between signaling overhead and flexibility. The simplest way to indicate a resource allocation is to use a bitmap in which each bit indicates a Physical Resource Block (PRB) but in the case of more than 10 PRBs, the MAC scheduler would have to use more than 10 bits to indicate the allocated PRBs, if the system bandwidth has less than 10 PRBs then it is possible to use a single bit to indicate a PRB. The methods provided by 3GPP to save bits are:Resource Allocation Type 0, Resource Allocation Type 1, Resource Allocation Type 2.

In [6], general form of the sub-carrier and power allocation problem are presented.

The data rate achieved by a k-th user in bits/s in a multi-user OFDM system with K users and N sub-carriers is the following:

$$R_k = \frac{B}{N} \sum_{n=1}^{N} \rho_{k,n} \log_2(1 + \gamma_{k,n}) \tag{2.1}$$

where B is the total bandwidth of the system and $\rho_{k,n}$ is the assignment index; when $\rho_{k,n}$ is 1, it means that the n-th sub-carrier is allocated to k-th user, $\rho_{k,n}$ is 0 otherwise. $\frac{B}{N} = \frac{1}{T}$ is the bandwidth of each channel, T is the OFDM symbol duration. $\gamma_{k,n}$ is the SNR of the n-th sub-carrier for the k-th user, its expression is the following:

$$\gamma_{k,n} = p_{k,n} H_{k,n} = \frac{p_{k,n} h_{k,n}^2}{N_0 \frac{B}{N}} \tag{2.2}$$

where $p_{k,n}$ is the power allocated for user k in sub-channel n, $h_{k,n}$ is the channel gain and $H_{k,n}$ denotes the channel-to-noise ratio for user k in sub-channel n while $N_0 \frac{B}{N}$ is the noise power on each sub-carrier where N_0 is the power spectral density of AWGN channel. Equation 2.1 indicates the achieved data rate in a zero margin system. The total data rate R_T of a zero margin system is given by:

$$R_T = \frac{B}{N} \sum_{k=1}^{K} \sum_{n=1}^{N} \rho_{k,n} \log_2(1 + \gamma_{k,n}) \tag{2.3}$$

The following is the general form of the sub-carrier and power allocation problem with relative constraints that a scheduler should follow:

$$
\begin{aligned}
& Objective: \\
& \max_{\rho_{k,n}, p_{k,n}} R_T = \frac{B}{N} \sum_{k=1}^{K} \sum_{n=1}^{N} \rho_{k,n} log_2(1 + \frac{p_{k,n} h_{k,n}^2}{N_0 \frac{B}{N}}) \\
& or \\
& \min_{\rho_{k,n}, p_{k,n}} P_T = \sum_{k=1}^{K} \sum_{n=1}^{N} \rho_{k,n} p_{k,n} \\
& subjectto: \\
& \text{C1}: \rho_{k,n} \in 0, 1, \forall k, n \\
& \text{C2}: \sum_{k=1}^{K} \rho_{k,n} = 1, \forall n \\
& \text{C3}: p_{k,n} \geqslant 0, \forall n \\
& \text{C4}: \sum_{k=1}^{K} \sum_{n=1}^{N} \rho_{k,n} p_{k,n} \leqslant P_{total} \\
& \text{C5 : User Rate Requirements.}
\end{aligned}
\tag{2.4}
$$

The first two constraints ensure that each sub-carrier is allocated to only one user. The third and fourth constraints indicate that the power allocated to the users must not be larger than the total power. The fifth provides the fixed or variable rate required by the users. In relation to objectives and constraints, each algorithm belongs to a different class; in each class, the problem is formulated and the optimal solution is derived using different optimization techniques. As the optimal solutions have a high computational complexity, it is adopted a solution that can be applied in real time applications, a sub-optimal solution.

2.3.2 Overview of scheduling algorithms for OFDM systems

Over the last years many of works were published about scheduling in multi-carrier based systems. As it can be read in literature, resource allocation schemes can be divided in two main classes: Margin Adaptive (MA) and Rate Adaptive (RA).
The margin adaptive allocation has the object of minimizing the total transmit power while providing each user with its required quality of service. The object of rate adaptive allocation is to maximize the total data rate of the system taking into account the constraint on the total transmit power.

Round Robin scheduling Round Robin (RR) is a non-channel aware-scheduling algorithm, it belongs to fixed algorithm class. It is one of the fundamental and widely used scheduling algorithms. Its running process is very simple and easy to implement. Round robin algorithm uses a principle of sharing resources on an equal time slots basis and does not consider the channel quality information from participating user equipments Each active UE in a cell have equal access to resources and services at equal amount of time slots hence round robin algorithm is not a channel-dependent scheduling algorithm.

Max Rate As a channel dependant scheduling, Max Rate takes advantage of multiuser diversity to carry out maximum system throughput. First, scheduler analyzes CSI from terminals to obtain data rate of an identical sub-channel for different terminals. Then scheduler assigns this sub-channel to the terminal which can achieve the highest data rate in this sub-channel based on SNR. The Max Rate can be described as:

$$i = \underset{k}{argmax} R_{k,n}(t) \tag{2.5}$$

$R_{k,n}(t)$ is the data rate of terminal k for one sub-channel n in time slot t.

Max-Rate algorithm causes starving terminals while it obtains maximum throughout. Terminals in bad channel conditions are never considered by scheduler, so it is not a fair algorithm.

Propotional Fair Proportional Fair is a compromise between Maximum Rate and Round Robin [7].It pursues the maximum rate, and meanwhile assure that none of terminals is starving. The terminals are ranked according to the priority function. Then scheduler assigns resources to terminal with highest priority. Repeat the last two steps until all the resources are used up or all the resources requirements of terminals are satisfied. The priority function is following:

$$i = \underset{k}{argmax} \frac{R_{k,n}(m)}{\overline{R_k(m)}} \tag{2.6}$$

$R_{k,n}(m)$ is the estimation of supported data rate of terminal k for the resource block n. $\overline{R_k(m)}$ is the average data rate of terminal k over a windows in the past.

T_{PF} is the windows size of average throughput and can be adjusted to maintain fairness. Normally T_{PF} should be limited in a reasonable range so that terminals cannot notice the quality variation of the channels.

$$\overline{R_k(m+1)} = \begin{cases} (1 - \frac{1}{T_{PF}})\overline{R_k(m)} + \frac{1}{T_{PF}} R_{k,n}(m) & \text{if user } k \text{ is selected,} \\ (1 - \frac{1}{T_{PF}})\overline{R_k(m)} & \text{if user } k \text{ is not selected.} \end{cases}$$

2.4 Scheduling Algorithm for OFDMA systems

As mentioned above, OFDM access (OFDMA) is based on OFDM and inherits its immunity to inter-symbol interference (ISI) and frequency selective fading [8]; OFDMA is more flexible than time-division (TDM) and frequency-division (FDM) multiplexing because it provides two dimensional time-frequency resources allocation. Thanks to its flexibility, many packet scheduling and resource allocation algorithms for OFDMA wireless networks are studied.

In [9], the authors exploit the advantages of two-dimensional mapping of incoming allocation requests. They define a cost model and constraints which depends on the spacial shape of the two-dimensional allocation; since the arising problem shown by the authors is NP-hard, run-time efficient heuristic solutions are provided, they take into account the QoS and OFDMA related constraints.

The novel approach provided in [10] includes a development of jointly optimal sub-carrier, power and rate allocation for weighted sum-average-rate maximization, a formulation and derivation of the optimal resource allocation for maximizing the utility of average user rates and a development of the stochastic resource allocation schemes.

In [11], a formulation of continuous and discrete ergodic weighted sum rate maximization is presented and algorithms based on a dual optimization framework that solve the OFDMA ergodic rate maximization problem with low complexity is derived.

The proposed method in [12] is also featured as a low-complexity algorithm that involves not only adaptive modulation, but also adaptive multi-access control and cell selection.

In [13], a joint sub-carrier and power allocation for channel and queue-aware scheduling is proposed. The provided approach is to combine sub-carrier and power allocation by optimizing a user's power allocation immediately after the user has been allocated a sub-carrier.

2.5 Scheduling algorithm for LTE systems

As mentioned in [14], the proposed algorithm schedules the users first, then it allocates the candidate users on the sub-channels. Two aspects for this approach are reported; first of all, it can be possible to control the signaling overhead limiting the number of multiplexed users. Limiting the number of users it can help to control the complexity of the frequency domain scheduler. In the time domain, the authors divide the users in two sets, SET1 and SET2. Target Bit Rate (TBR) users belong to SET1 and all the other users belong to SET2. In the first set, a RR scheduler is used to sort the users while in the second set a PF scheduler is adopted.
In [15], Maximum Throughput (MT) algorithm is used in time and frequency domain; MT is the best algorithm to maximize the cell average throughput, but it is the worst in the cell edge.
In [16], the authors provide an adaptive PF scheduling algorithm in the time domain; it provides a fairness increase of about 20% and a throughput decrease of about 3% only.
Instead, the performance of several joint time-frequency schedulers is investigated in [17]; simulation results show that joint time-frequency schedulers achieve significantly superior performance compared to conventional time domain scheduler. The authors studied the performance of FD_MAX (Maximum scheduling in the frequency domain), FD_PF (Proportional Fair in the frequency domain), TD_PF (PF in the time domain), FD_RR (Round Robin in the frequency domain) and introduced their algorithm called Dynamic Allocation (FD_DA) in the frequency domain. FD_DA allocates each user in the best sub-channels; it returns better performance than TD_PF when the number of users is bigger than 17. Morevoer, it gives good performance in terms of scheduled users in each sub-frame.

2.6 Mimo Downlink Scheduling in LTE

An important enhancement applied to mobile communications systems is the use of multiple antennas at the transmitter and/or the receiver, which is a technique known as MIMO. The group of antennas can be used to increase data rates for a given transmission reliability or to improve system performance for a given data rate.

In chapter 3 it will be discussed in detail the benefits of MIMO technology and it will be listed the different transmission modes provided by standard LTE. In the second part of chapter 3 we will analyze the assumptions made for the different transmission modes in order to calculate the SINR values in the MAC scheduler simulator.

An LTE BS (eNodeB) is expected to select and switch transmission characteristics of this MIMO modes based on channel quality feedback: CQI, PMI and RI reported by mobile. In [18], [19], [20] different downlink transmission mode selection algorithm is presented.

Very few works in the literature explains how to evolve a single antenna scheduling algorithm to a multi antenna scheduling algorithm and the purpose of this thesis work is to introduce an innovative technique that has been used to evolve the simulator from single antenna case to multiple antenna case.

In chapter 4 this technique will be explained and also evaluated with a new scheduling and resources allocation algorithm.

Chapter 3

Benefits of MIMO Technology in LTE

3.1 Introduction

Multiple-input Multiple-output (MIMO) technology constitutes a breakthrough in the design of wireless communication systems, and is already at the core of several wireless standards. The introduction of the spatial dimension (provided by the multiple antennas at the transmitter and the receiver) delivers significant performance enhancements in terms of data transmission rate and transmission reliability with respect to conventional single-antenna wireless systems. Hence, the design of MIMO systems has been traditionally posed under two different perspectives: either the increase of the data transmission rate through spatial multiplexing or the improvement of the system reliability through the increased antenna diversity.

Depending on the availability of multiple antennas at the transmitter and/or the receiver, such techniques are classified as Single-Input Multiple-Output (SIMO), Multiple-Input Single-Output (MISO) or MIMO.

MIMO channels provide a number of advantages over conventional SISO channels such as the array gain, the diversity gain, and the multiplexing gain. While the array and diversity gains are not exclusive of MIMO channels and also exist in single-input multiple-output (SIMO) and multiple-input single-output (MISO) channels, the multiplexing gain is a unique characteristic of MIMO channels. These gains are described in brief below.

Array Gain

Array gain denotes the improvement in receive signal-to-noise ratio (SNR) that results from a coherent combining effect of the information signals. The coherent combining may be realized through spatial processing at the receive antenna array and/or spatial pre-processing at the transmit antenna array. Formally, the array gain characterizes the horizontal shift of the error probability versus transmitted or received power curve (in a log-log scale), due to the gain in SNR.

Spatial Diversity Gain

Diversity gain is the improvement in link reliability obtained by receiving replicas of the information signal through (ideally independent) fading links. With an increasing number of independent copies, the probability that at least one of the signals is not experiencing a deep fade increases, thereby improving the quality and reliability of reception. A MIMO channel with n_T transmit and n_R receive antennas offers potentially $n_T * n_R$ independently fading links and, hence, a spatial diversity order of $n_T * n_R$.

Spatial Multiplexing Gain

MIMO systems offer a linear increase in data rate through spatial multiplexing, transmitting multiple, independent data streams within the bandwidth of operation. Under suitable channel conditions, such as rich scattering in the environment, the receiver can separate the data streams. Furthermore, each data stream experiences at least the same channel quality that would be experienced by a SISO system, effectively enhancing the capacity by a multiplicative factor equal to the number of substreams. In general, the number of data streams that can be reliably supported by a MIMO channel coincides with the minimum of the number of transmit antennas n_T and the number of receive antennas n_R, $\min\{n_T, n_R\}$.

3.2 MIMO signal model

Let **Y** be a matrix of size $N * T$ denoting the set of (possibly precoded) signals being transmitted from N distinct antennas over T symbol durations. Thus the n^{th} row of Y corresponds to the signal emitted from the n^{th} transmit antenna. Let **H** denote the $M * N$ channel matrix modeling the propagation effects from each of the N transmit antennas to any one of M receive antennas, over an arbitrary subcarrier whose index is omitted here for simplicity. We assume **H** to be invariant over T symbol durations. The matrix channel is represented by way of example in Figure 3.1. Then the $M * T$ signal R received over T symbol durations over this subcarrier can

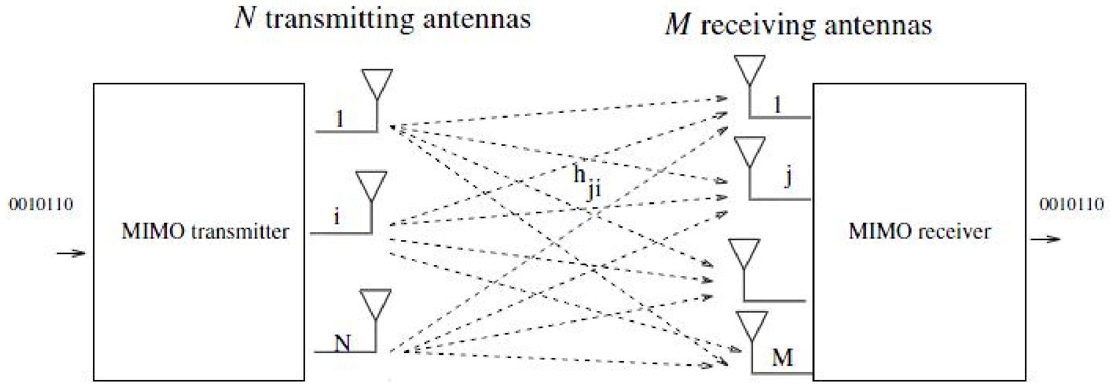

Figure 3.1: MIMO system with N transmit antennas and M receive antennas.

be conveniently written as:

$$\mathbf{R} = \mathbf{H} * \mathbf{Y} + \mathbf{N} \tag{3.1}$$

where **N** is the additive noise matrix of dimension $M * T$ over all M receiving antennas. We will use $\mathbf{h}_i$ to denote the i^{th} column of **H**, which will be referred to as the receive spatial signature of (i.e. corresponding to) the i^{th} transmitting antenna. Likewise, the j^{th} row of **H** can be termed the transmit spatial signature of the j^{th} receiving antenna.

3.2.1 Mapping the symbols to the transmitted signal

Let $\mathbf{X} = (x_1, x_2, ..., x_p)$ be a group of P QAM symbols to be sent to the receiver over the T symbol durations. Thus these symbols must be mapped to the transmitted signal **Y** before launching into the air. The choice of this mapping function $\mathbf{X} \longrightarrow \mathbf{Y}(\mathbf{X})$ determines which one out of several possible MIMO transmission methods results, each yielding a different combination of the diversity, array and multiplexing gains. Meanwhile, the so-called spatial rate of the chosen MIMO transmission method is given by the ratio $\frac{P}{T}$.

Note that, in the most general case, the considered transmit (or receive) antennas may be attached to a single transmitting (or receiving) device (base station or UE), or distributed over different devices. The symbols in $(x_1, x_2, ..., x_p)$ may also correspond to the data of one or possibly multiple users, giving rise to the so-called single-user MIMO or multi-user MIMO models.

3.3 LTE Downlink Transmission Modes

This section discusses the basic MIMO features and techniques available in LTE downlink operations. Because network conditions and UE capabilities can vary greatly, MIMO systems must be highly flexible in order to maximize gains in throughput. Since each eNodeB can be configured differently in terms of how it adapts transmissions in real time, it is important to understand the key transmission modes available in LTE, as well as the conditions under which they are most useful. Network operators can then compare scanning receiver measurements to UE-reported data logged by the network to determine if the eNodeB is effectively adapting transmissions to the RF environment.

As a radio frequency (RF) signal passes from Tx to Rx, it gradually weakens, while interference from other RF signals also reduces SNR. In addition, in crowded environments, the RF signal frequently encounters objects which will alter its path or degrade the signal. Multiple-antenna systems can compensate for some of the loss of SNR due to multi-path conditions by combining signals that have different fading characteristics, since the path from each antenna will be slightly different. SIMO and MISO systems achieve SNR gain by combining signals that take multiple paths to the Tx and Rx in a constructive manner, taking the best piece of each signal.

MIMO can work as a combination of SIMO and MISO techniques, resulting in even greater SNR gains, further boosting coverage and data rates. However, when SNR is high, additional throughput gains are minimal, and there is little benefit from further boosting SNR as shown in Figure 3.2. To achieve throughput gains where SNR is already very high, LTE uses a MIMO technique called spatial multiplexing. In spatial multiplexing, each Tx sends a different data stream to multiple Rx. These data streams are then reconstructed separately by the UE. It may seem counterintuitive that two signals sent at the same time and frequency within the same sector can result in increased throughput rather than interference. However, spatial multiplexing can be compared to conventional spectrum re-use, where signals are transmitted in the same frequency in different cells. With spatial

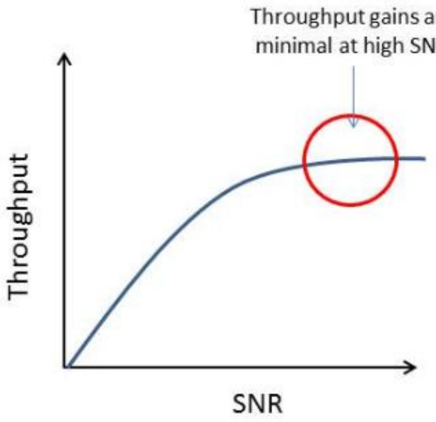

Figure 3.2: Diminishing returns of throughput gains from increased SNR.

multiplexing, the signals, instead of occupying a completely different cell, occupy different space-time in the same cell. Good multi-path conditions create the signal orthogonality that effectively turns a single cell into multiple cells with respect to the amount of data that can be sent on a particular frequency band.

In addition to good multi-path conditions, spatial multiplexing depends on high SNR to produce large throughput gains. In spatial multiplexing, even though multiple data streams are transmitted, the total power of the transmission remains the same. Essentially, spatial multiplexing distributes the total SNR between these multiple data streams, each of which has a lower power level. The result is that each data stream contains a lower SNR than would be possible with a single data stream. However, because there are diminishing returns for additional SNR when SNR is already high, each of the multiple data streams may be capable of transmitting nearly as much data as a single stream.

The increased data capacity that results from sharing SNR between multiple data streams means that, while spatial multiplexing may be used to encode the same data differently and boost SNR of the recombined data streams, it can also be used to send completely different data through each

Tx. In LTE, each set of data sent through the antennas in a spatial multiplexing operation is called a layer. The rank is equal to the number of layers in an LTE spatial multiplexing transmission. Under ideal conditions, each layer of a spatial multiplexing transmission will contain as much data as a single-Tx LTE transmission. The result is that spatial multiplexing can theoretically multiply throughput by the transmission rank.

This multiplicative effect on throughput means that MIMO technology is essential for achieving the full benefits of LTE. With the 2x2 (2 Tx and 2 Rx) antenna configuration expected to be deployed initially, effective use of MIMO could nearly double throughput both for individual users and for each cell as a whole. However, these throughput gains depend on three factors: maximizing rich scattering conditions within a cell, configuring the eNodeB to properly match MIMO settings to real-world conditions, and ensuring that UEs can take full advantage of the multi-path conditions that are present. Scanning receivers that can provide accurate real-world measurements of multi-path conditions and potential throughput are essential tools for evaluating the performance of all three of these factors. With these measurements, mobile operators can maximize the data rates and reliability of LTE networks, resulting in a premium return on their LTE equipment investments while improving customer satisfaction.

Seven MIMO modes for the downlink path are defines in LTE.

Mode 1 - Single-antenna port; Port 0

This is analogous to most current wireless system where a single data stream (code word) is transmitted on one antenna and received by either one (SISO: Single Input Single Output) or more antennas (SIMO: Single Input Multiple Output; receive diversity). Figure 3.3 shows the different antenna access schemes in modern wireless communication networks.

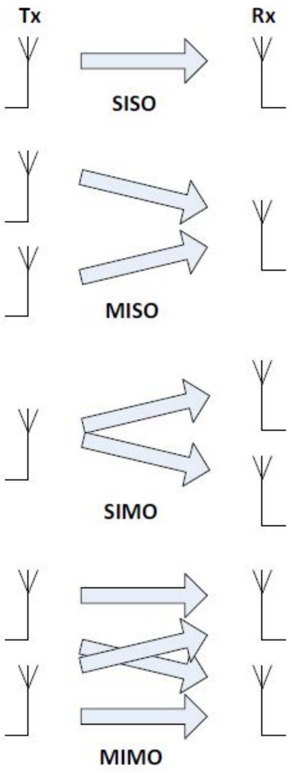

Figure 3.3: Multiple Antenna Access Schemes.

Mode 2 - Transmit diversity

This mode involves the transmission of the same information stream on multiple antennas (LTE supports the option of two or four antennas).
The purpose of spatial diversity is to make the transmission more robust. There is no increase in the data rate. This mode uses redundant data on different paths.

Mode 3 - Open loop spatial multiplexing (OL-SM)

In this case, two information streams (two code words) are transmitted over two or more antennas (up to 4 in LTE). There is no explicit feedback from the user equipment (UE), although a "Transmit Rank Indicator" (TRI) transmitted by the UE is used by the base station to select the number of spatial layers. As multiple code words are transmitter, OL-SM provides much better peak throughput than transmit diversity. It is also simpler to implement and is considered to be one of the main modes of MIMO to be implemented in LTE system.

Mode 4 - Closed loop spatial multiplexing (CL-SM)

Similar to OL-SM, two information streams are transmitted over two code words from N antennas (up to 4). The difference is "Pre-coding Matrix Indicator" (PMI) which is feedback from the handset to the base station. This feedback mechanism allows the transmitter to pre-code the data to optimize transmission over the wireless channel so the signal at the receiver can be easily separated into the original streams. This mode is expected to be highest performing mode of MIMO in LTE.

Mode 5 - Multi-User MIMO

This mode is similar to CL-SM, but the information streams are targeted at different terminals. Hence, multiple users share the same resources. While each user experiences the same data rate, the overall network data rate is improved. The number of users is limited by the number of spatial layers.

Mode 6 - Closed loop Rank 1 with pre-coding

This case represent the scenario when a single code word transmitted over a single spatial layer.

Mode 7 - Single antenna port

This is a beamforming mode where a single code word is transmitted over a single spatial layer. A dedicated reference signal forms an additional antenna port and allows transmission from more than 4 antennas. The terminal estimates the channel quality from the common reference signals on antennas 1-4. Linear antenna arrays are expected to be used for this mode.

3.3.1 Closed versus Open Loop Operations

LTE's four SU-MIMO modes include two open loop modes (Transmit Diversity and Open-Loop Spatial Multiplexing) and two closed loop modes (Rank-1 Closed-Loop Spatial Multiplexing and Closed-Loop Spatial Multiplexing). Open loop and closed loop modes differ in the level of detail and frequency with which channel conditions are reported by the UE. In turn, the eNodeB relies on detailed and timely information from the UE in order to apply the best antenna and data-processing techniques for the existing channel conditions. Depending on the UE's data-processing speed as well as the quality of its connection to the eNodeB in both uplink and downlink, LTE will operate in either closed loop or open loop mode. The eNodeB communicates with a UE in open loop when the UE is moving too fast to provide a detailed report on channel conditions in time for the eNodeB to select the precoding matrix. Other factors, such as UE processing speed or uplink data capacity (which may also be affected by UE specifications), may result in open loop operations even when the UE is moving relatively slowly. The UE's capabilities are therefore crucial for achieving the best results from particular multi-path conditions.

In open loop operations, the eNodeB receives minimal information from the UE: a **Rank Indicator (RI)**, the number of layers that can be supported under the current channel conditions and modulation scheme; and a **Channel Quality Indicator (CQI)**, a summary of the channel conditions under the current transmission mode, roughly corresponding to SNR. The eNodeB then uses the CQI to select the correct modulation and coding scheme for the channel conditions. Combined with this modulation and coding scheme, CQI can also be converted into an expected throughput.

In closed loop operations, the UE analyzes the channel conditions of each

Tx, including the multipath conditions. The UE provides an RI as well as a **Precoding Matrix Indicator (PMI)**, which determines the optimum precoding matrix for the current channel conditions. Finally, the UE provides a CQI given the RI and PMI, rather than basing CQI on the current operation mode. This allows the eNodeB to quickly and effectively adapt the transmission to channel conditions. Closed loop operations are particularly important for spatial multiplexing, where MIMO offers the greatest throughput gains.

3.4 MIMO in Practice

These modes are designed to take the best advantage of different channel and multipath conditions and eNodeB antenna configurations, as well as differences in UE capabilities and mobility. A key characteristics of MIMO channel is that its performance depends on a number of factors such as the state of the wireless channel (low vs. high scattering), the signal quality (as measured by SNR), the speed of the mobile terminal, and the correlation of the received signals at the receiver antennas, where low correlation indicates signal orthogonality. Therefore, certain MIMO modes will be more effective than others depending on these critical factor. This open the door widely for different type of practical implementation of MIMO.

3.4.1 Transmission Mode in the simulator

Depending on the type of transmission mode selected, it is necessary to calculate the hypothetical SINR value, for each RB seen in reception by each MS (Mobile Station). From SINR value the CQI is calculated, the result is the feedback that the MS sends to the BS (Base Station). With this feedback,

and based on the type of scheduling algorithm selected at the BS side, the allocation of resources is carried out for the respective users.
Below we will analyze the assumptions made for the various transmission mode in order to calculate the SINR values.

Single Antenna In that case the number of antennas at the base station is equal to the number of antennas at ms. The SINR values is calculated as:

$$SINR(f) = \frac{G_{BS} * G_{MS} * (\frac{P_{tx_{BS}}}{N_{carrier}}) * |H(f)|^2}{N + I} \tag{3.2}$$

Where G_{BS} and G_{MS} are rispectively the BS gain and MS gain, $P_{tx_{BS}}$ is the power in transmission, $N_{carrier}$ is the number of carrier, N is the noise, I is the interference and the channel matrix H(f) is a three-dimension matrix ($size(H(f)) = [RB, users, Tsim]$).

Antenna Selection Is a MISO case, where at the BS there are two antennas while at the MS there is one antenna, like shown in figure 3.4.
In that case there are two possible link in each TTI and so there are two differet channel matrix. The SINR values are calculated like in (3.2) the difference is the channel matrix dimension. H(f) is a four-dimension matrix ($size(H(f)) = [RB, user, Tsim, N]$).

Transmit Diversity Is a MISO case, where at the BS there are two antennas N_t, while at the MS there is one antenna, like shown in figure 3.4. In that case the BS transmit the same data, whit the same mcs in both antennas.
As shown in [21], transmit diversity can achieve diversity gains within 0.1

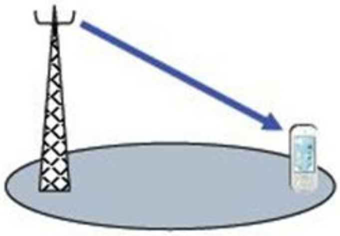

Figure 3.4: Antenna Selection transmission scheme.

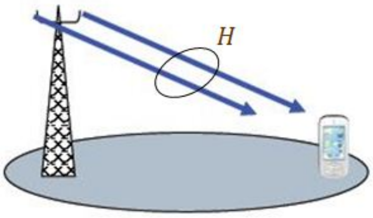

Figure 3.5: Trasnmit Diversity transmission scheme.

dB of receive diversity.

SINR is calculate using $\tilde{H}(f)$ which is combination of $H_1(f)$ and $H_2(f)$.

$$SINR(f) = \frac{G_{BS} * G_{MS} * (\frac{P_{tx_{BS}}/N_t}{N_{carrier}}) * |\tilde{H}(f)|^2}{N + I} \tag{3.3}$$

Where we consider [22],

$$|\tilde{H}(f)|^2 = |H_1(f)|^2 + |H_2(f)|^2 \tag{3.4}$$

Closed Loop Spatial Multiplexing (CLSM) The closed-loop technique provides the highest possible throughput in LTE, but requires reliable CSIT (Channel State Information at Transmitter) feedback in the form of the PMI. Hence, it is best suited to case of low to medium UE mobility with medium to high SNR.

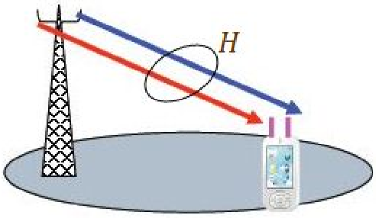

Figure 3.6: Spatial Multiplexing transmission scheme.

It is well-know that, for the case where the channel is perfectly know at the transmitter, the optimal spatial multiplexing scheme is Singular Value Decomposition (SVD) precoding, which spatially decomposes the MIMO channel into mutually orthogonal virtual channels onto which independently coded data streams are transmitted.
The time-invariant channel is described by:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w} \tag{3.5}$$

The channel matrix **H** is deterministic and assumed to be constant at all times and known to both the transmitter and the receiver. Here, h_{ij} is the channel gain from transmit antenna j to receive antenna i. There is a total power constraint, P, on the signals from the transmit antennas. In the notation of matrices, the matrix **H** has a singular value decomposition (SVD):

$$\mathbf{H} = \mathbf{U}\Lambda\, V^{*} \tag{3.6}$$

Where **U** and **V** are (rotation) unitary matrices [1] and Λ is a rectangular matrix whose diagonal elements are non-negative real numbers and whose off-diagonal elements are zero. If we define:

$$\tilde{\mathbf{x}} :=\ V^{*}\mathbf{x} \tag{3.7}$$

---

[1] Recall that a unitary matrix **U** satisfies $U^{*}\mathbf{U} = \mathbf{U}U^{*} = \mathbf{I}$.

$$\tilde{\mathbf{y}} := U^{*}\mathbf{y} \tag{3.8}$$

$$\tilde{\mathbf{w}} := U^{*}\mathbf{w} \tag{3.9}$$

then we can rewrite the channel (3.5) as:

$$\tilde{\mathbf{y}} = \Lambda\tilde{\mathbf{x}} + \tilde{\mathbf{w}} \tag{3.10}$$

Where $\tilde{\mathbf{w}}$ has the same distribution as $\mathbf{w}$ and $||\tilde{\mathbf{x}}||^2 = ||\mathbf{x}||^2$. Thus, the energy is preserved and we have an equivalent representation as a parallel Gaussian channel:

$$\tilde{\mathbf{y}}_i = \lambda_i\tilde{\mathbf{x}}_i + \tilde{\mathbf{w}}_i \tag{3.11}$$

The equivalence is summarized in Figure 3.7.

We consider a system with N_t transmit and N_r receive antennas, denoted $N_t \times N_r$. The number of spatial layers available for transmission $N_l \in \{1...min\{N_t, N_r\}\}$. We can consider Λ as channel matrix and the SINR is calculated as:

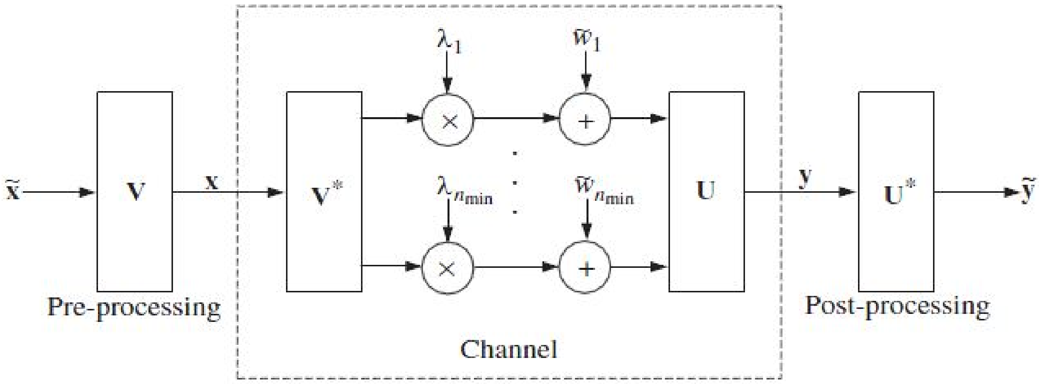

Figure 3.7: Closed-Loop MIMO Channel.

$$\mathrm{SINR}(f) = \frac{G_{BS} * G_{MS} * (\frac{P_{tx_{BS}}/N_t}{N_{carrier}}) * |\Lambda|^2}{N + I} \tag{3.12}$$

Open Loop Spatial Multiplexing (OLSM) The open-loop technique does not require PMI feedback, and so is particularly suited to the case of high UE velocity where the CSI feedback achievable with reasonably low overhead would be unreliable. In that case we assume a Linear Detection MMSE [23]. We consider a system with N_t transmit and N_r receive antennas, denoted $N_t \times N_r$. The number of spatial layers available for transmission $N_l \in \{1...min\{N_t, N_r\}\}$. The post detection SINR of the $l - th$ detector output which can serve as a signal quality indicator can be computed by:

$$\mathrm{SINR}_l(f) = \frac{\sigma_x^2}{\sigma_n^2} \frac{1}{[(\tilde{\mathbf{H}}^H \tilde{\mathbf{H}} + \frac{\sigma_x^2}{\sigma_n^2} \mathbf{I}_{N_l})^{-1}]_{l,l}} - 1 \tag{3.13}$$

where σ_n^2 is the noise power, while the signal power $\sigma_x^2 = G_{BS} * G_{MS} * (\frac{P_{tx_{BS}}/N_t}{N_{carrier}})$.

Chapter 4

Smart Allocation Algorithms: from single-antenna to multi-antenna solutions

In this chapter our attention is focused on the innovative technique that has been used to extend the scheduling tecniques to the MIMO case.
Starting from a single antenna configuration, scheduling algorithms have been developed considering only multi-user diversity. The case with multi-antenna considers the multi-antenna diversity, in addition to the multi-user diversity, so it introduces an extra degree of freedom. In order to take into account this additional degree of freedom, changes have been introduced in the simulation chain and in the scheduling algorithm in the less invasive way as possible, adapting the input matrix to the new configuration.
The innovative solution, which will be explained in detail in the following paragraphs, reshapes the inputs of the different scheduling algorithms so that these algorithms can work in the same way for the selected transmission mode.
The innovative solution will be evaluated with a new smart allocation al-

gorithm that will be introduced below. The power allocation is not considered.

4.1 Smart allocation algorithm

As will be more clear later, with the proposed solutions, a complete view of the channel situation is given to the scheduler. An intelligent allocation algorithm can allocate resources optimally, so a new scheduling and resources allocation algorithm, called Smalloc, is evaluted.
In [24],[25],[26],[27],[28],[29], scheduling and resources allocation algorithms have been studied under the assumption that all the active users request the same QoS, i.e. same priority.
The innovative part introduced in this algorithm is to take into account two different classes of services and priorities, to be scheduled and allocated in the frequency jointly (cross layer approach).
In our scenario we consider two different classes of services:

- ***Minimum Guaranteed Bit Rate (GBR) bearers:*** it can be used for real time application such as VoIP. For this type of users, the resources are permanently allocated at bearer establishment/modification. Bit rates higher than the GBR may be allowed for a GBR bearer if resources are available.

- ***Non-GBR bearers:*** it does not guarantee any particular bit rate, it can be used for non-real time applications such as web browsing or FTP transfer. No bandwidth resources are allocated permanently to these bearers.

In the literature, only few articles, based on scheduling and resources allocation algorithms for LTE systems, focus on the distinction between GBR and non-GBR users.

In [30], the authors provide a QoS class identifier-aware scheduling algorithm. The incoming packets are categorized upon their priority order. The highest MAC QoS classes represent the GBR bearers. The TD scheduler creates two candidate lists; GBR users belong to the first list and non-GBR users belong to the second list, the priorities of non-GBR are based on a PF scheduler. The FD scheduler starts with the GBR candidate list provided by the TD scheduler. The FD scheduler allocates one sub-channel with the highest SINR value; the PRB allocation is done iteratively. At the end of each iteration, the scheduler checks if data rate for that particular bearer is satisfied; if it satisfies the data rate, the bearer is removed from the candidate list.

In [31], the authors consider GBR and non-GBR users without any distinction in the time domain but the proposed algorithm assigns a higher weight to the data packets belonging to the GBR users. The numerical results show that the proposed algorithm achieves higher capacity than a fixed algorithm and approximately the same as the proportional fair approach, where fixed and fair allocation algorithm do not provide any priority for GBR services over non-GBR.

Smalloc

As in [30], the proposed algorithm schedules the GBRs first, but, unlike the cited articles, the proposed algorithm has the objective to allocate the GBR users taking into account the future allocation of the non-GBRs. It means that the chosen allocations for the GBRs will not leave the worst resources to the non-GBRs. Although the algorithm takes into account the future allocation of the non-GBRs, it needs to underline that the algorithm satisfies the GBR QoS requirements.

Let N_{GBR} and $N_{non-GBR}$ be the number of GBR and non-GBR users respectively. $CQI_{j,n}^{GBR}$ and $CQI_{k,n}^{non-GBR}$ are the CQI value of j-th GBR user and k-th non-GBR user respectively on the n-th sub-channel. S is the set of the sub-channels where $n \in S, (1 \leqslant n \leqslant Nsch)$ and G the set of GBR users where $GBR_j \in G(1 \leqslant j \leqslant N_{GBR})$. Let A be the GBR matrix allocation where each element of the matrix $a_{j,n}$ is 1 if the n-th sub-channel is allocated to the j-th GBR user.

1. Calculate $M_n = max_k(CQI_{k,n}^{non-GBR}), \forall n 1 \leqslant n \leqslant N_s ch$.
2. Create the Ratio matrix R where the element $r_{j,n} = \frac{CQI_{j,n}^{GBR}}{M_n}$ is the ratio related to the j-th GBR on the n-th sub-channel.
3. **a)** While G $\neq \varnothing$

   b)

$$a_{j^*,n^*} = \begin{cases} 1 & \text{if } r_{j^*,n^*} = max_{j,n}(r_{j,n}) \\ 0 & \text{otherwise} \end{cases}$$

   c) $\{S\} - n^*$.

   d) If GBR_{j^*} is satisfied then $G = G - GBR_{j^*}$

   e) If S $\neq \varnothing$ then keep going to allocate the GBRs

   f) end While.
4. If S $\neq \varnothing$ then allocate non-GBRs users

Non-GBR users are allocated using Proportional Fairness algorithm in the frequency domain, described in the previous chapter, every 5 TTIs and in the other TTIs, we use Max Rate algorithm that allocates only the best users. Choosing the highest ratio value $r_{j,n} \in R$, the algorithm allocates the GBRs in that n-th sub-channel in which $max_k CQI_{k,n}^{non-GBR} \forall k(1 \leqslant k \leqslant N_{non-GBR})$, is a low value.
Figure 4.1 shows the described algorithm.

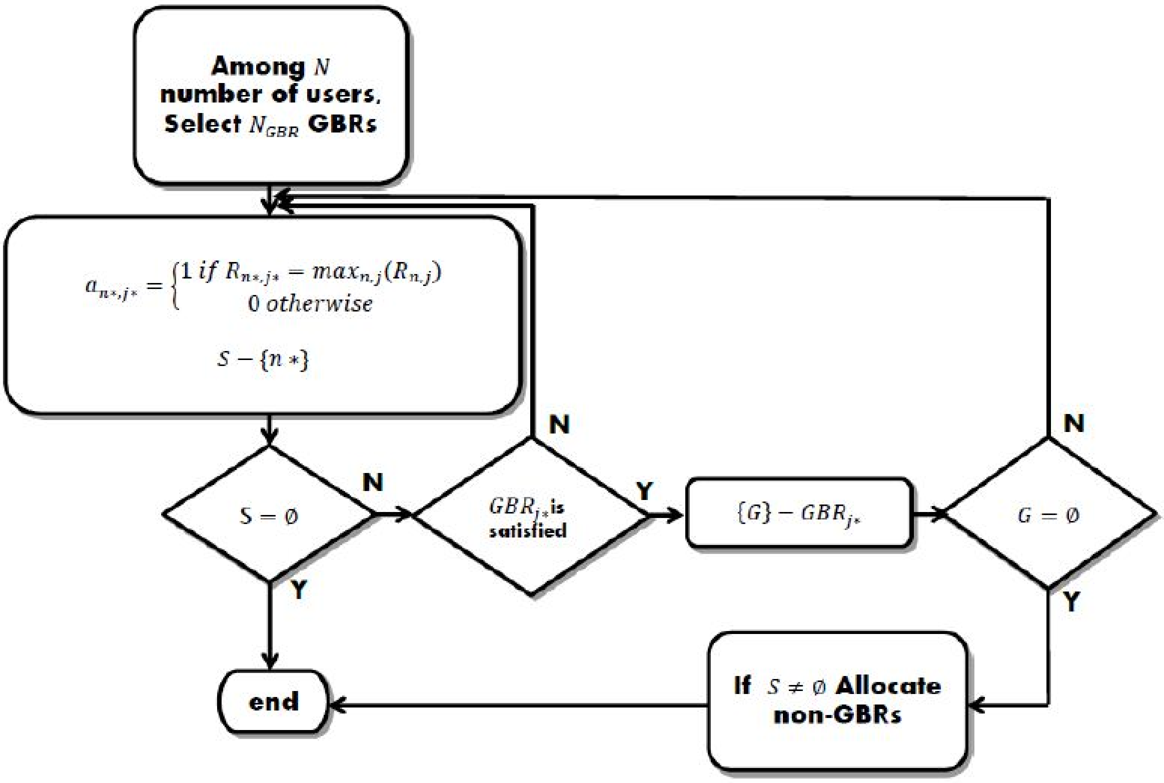

Figure 4.1: Smalloc algorithm diagram.

4.2 From single antenna to multiple antenna solution

In order to extend the scheduler from the single antenna case to the multi-antenna case, approaches were various.

A first approach could be to change the internal structure of the scheduling algorithms, so that they consider the additional degree of freedom given by multiple antenna. This didn't seem a good solution because it increases simulation time as well as scheduler complexity, becoming an additional dimension where to perform the allocation on top of frequency and time domain.

Another approach could be to run the scheduling algorithms several times for the different antennas, but this would not allow to fully exploit the spatial diversity of the active users.

The innovative developed solution consists to adapt the algorithms inputs in a suitable way, according to the transmission mode. This, as it will be more clear further on, allows to exploit in an optimal way the multi-antenna diversity in addition to multi-user diversity, without increasing the complexity of the algorithm.

4.2.1 Algorithm inputs adaptation

Scheduling algorithms inputs should be adapted, so that the scheduling algorithms work in a transparent way to the transmission mode. Such algorithms are independent from the transmission mode selected.

During the transmission of a certain amount of data between a base station and a user, depending on the channel conditions, the transmission mode can be changed without requiring any structural modification of the scheduling algorithms so without increasing the complexity of the scheduler. Being able to choose the transmission mode according to the status of the channel, the transmission system is more flexible and returns better performance.

Before going on with the explanation of how algorithms inputs are adapted in function of the transmission mode, it can be useful to explain how the scheduling algorithms works in the single antenna case. In this case, the scheduling algorithms take as input a teo dimensional matrix (CQI matrix), where along the lines are indicated the RB, while along the columns are indicated the users.

In the MIMO case, CQI matrix has the addition of a third dimension, given by the number of antennas. In order to not alter the structure of the scheduling algorithms, the information, contained in the third dimension, has been moved in a two-dimension bigger matrix.

The structure of the two-dimensions matrix depends on the transmission mode selected:

Transmit Diversity, the scheduler works as in the case of single antenna because the input matrix is two-dimension though transmitting on two antennas. In this case, as mentioned in chapter 3, the transmission is carried out on both antennas with the same MCS (modulation and coding scheme). The matrix size in input to the algorithms is already correct for this particular configuratio.

For having benefit from Transmit diversity, the two antennas should be as uncorrelated as possible and this is obtained by spacing the antennas on the BS side conveniently (typically more than 2 times the wave length).

Antenna Selection,in this case the scheduling algorithm should make the choice among the available antennas in transmission in each RB.

What we have done, is to compare the two antennas values and choose the best one, namely passing from a 3D matrix to a 2D matrix as it is shown in figure 4.2 for two antennas at BS and 4 users with only a receiving antenna. In this operation, the GBR (Guaranteed Bit Rate) users are separated from the non-GBR users, because the GBR users have the priority in the allocation procedure.

This solution has been adopted inasmuch the scheduling algorithms for each RB (represented by the rows of CQI matrix) select the user (represented by the columns of CQI matrix) to be allocated at each iteration according to their specific metrics; so expanding the two-dimension matrix as described above, the scheduling algorithm can select for each RB which user have to be allocate on which antenna. It has to be highlighted the constraint that only one user can be allocated to a RB.

This kind of solution gives the scheduler a complete view of the situation, the state of all user in each antenna, by taking advantage of the multi-antenna diversity, in addition to multi-user diversity.

Higher benefit are provided when the two antennas are uncorrelated and

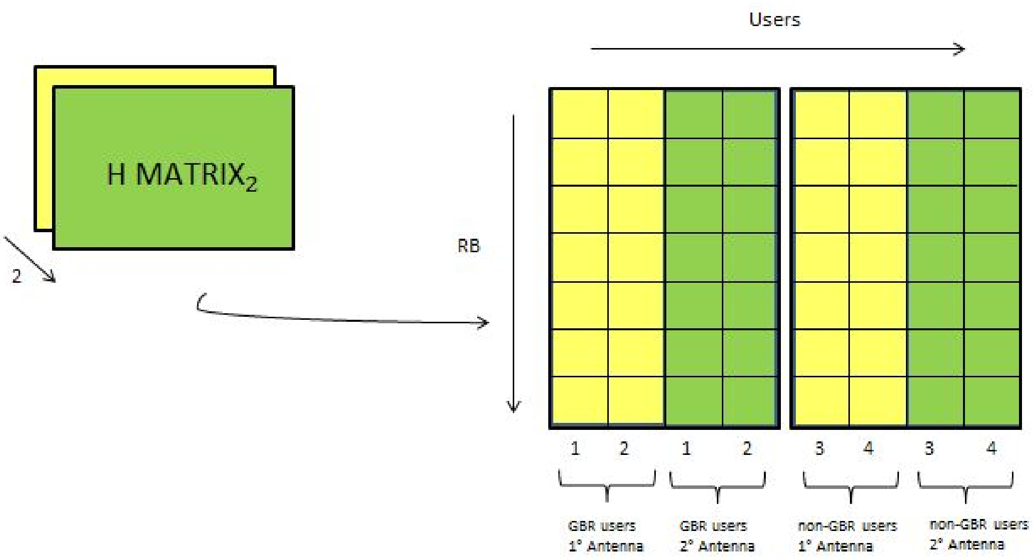

Figure 4.2: Antenna Selection adaptation scheme.

this is obtained by spacing the antennas BS side conveniently.

Spatial Multiplexing, in that case the adopted technique consists to place the matrices relating to the different antennas one above the other, as shown in figure 4.3 where it's chosen the example of two antennas at BS and 4 users. In this configuration, the GBR (Guaranteed Bit Rate) users are separated from the non-GBR users, because the GBR users have the allocation priority.

In the spatial multiplexing case, different information is transmitted on each antenna at the same frequency and at the same time by different users; an alternative solution could be to run the scheduling algorithm independently on each antenna but increasing simulation time as well as scheduler complexity. With the adopted solution the scheduling algorithm runs only once for the two antennas.

Moreover, multi-user and multi-antenna diversity are exploited massively. In fact, with the proposed solution a complete overview of the channel conditions is given to the scheduler, allowing a better allocation of resources.

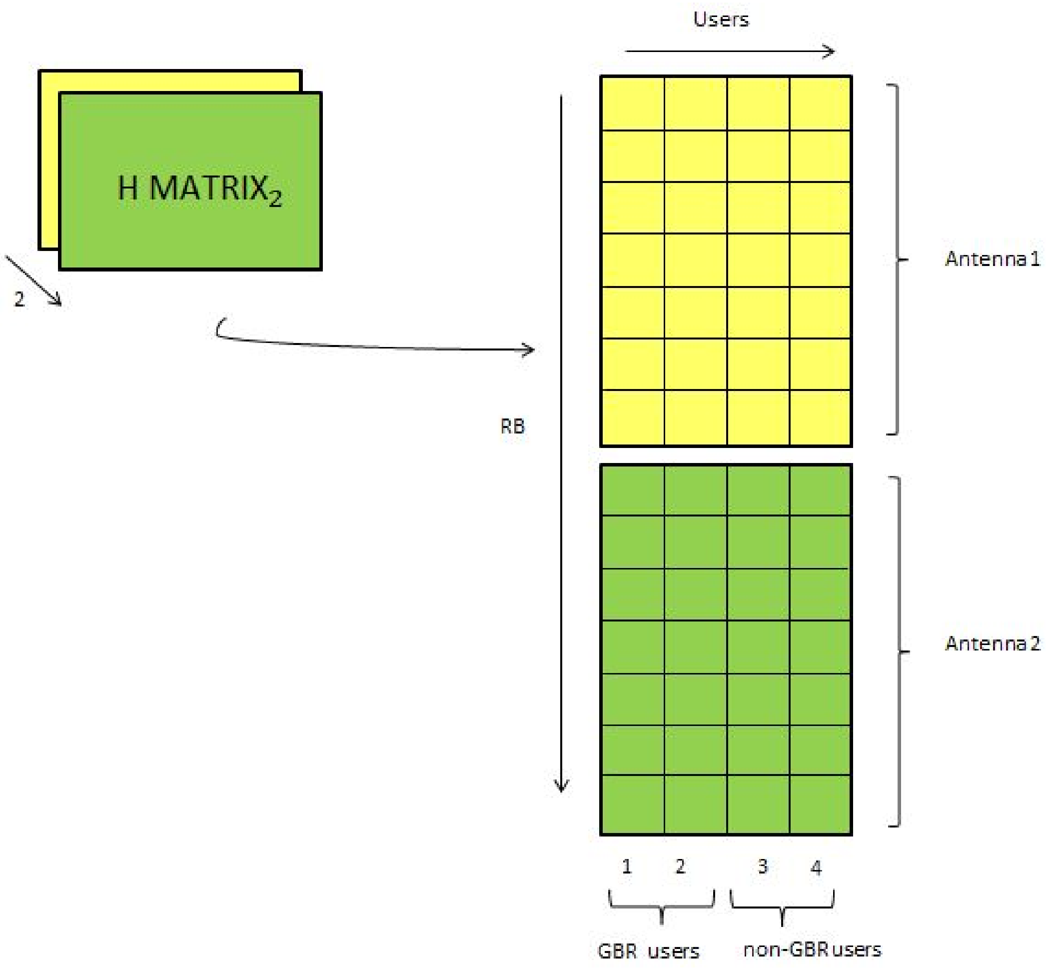

Figure 4.3: Spatial Multiplexing adaptation scheme.

Chapter 5

Simulation Scheme

This chapter describes the structure of the MAC scheduler LTE MIMO simulator.
The scenario under test is a single-cell with mobile terminals distributed uniformly with two different classes for the active users: GBR and non-GBR. The scenario is shown in Figure 5.1 and only downlink direction is considered. Figure 5.2 shows the main blocks of the simulation chain, where a MATLAB implementation of the 3GPP Spacial Channel Model Extended (SCME) [32], explained in the section 5.1, is used for the simulations.

5.1 3GPP Spacial Channel Model Extended (SCME)

The SCME model is an extension to the 3GPP Spacial Channel Model (SCM). SCM defines three environments: Sub-urban Macro, Urban Macro and Urban Micro. Urban Micro is differentiated in Line-Of-Sight (LOS) and non-LOS (NLOS) propagation. There is a fixed number of 6 paths in every scenario, each representing a Dirac function in the delay domain, but composed by 20 spatially separated sub-paths according to the sum-of-sinusoids method [33]. Paths powers, path delays and angular properties

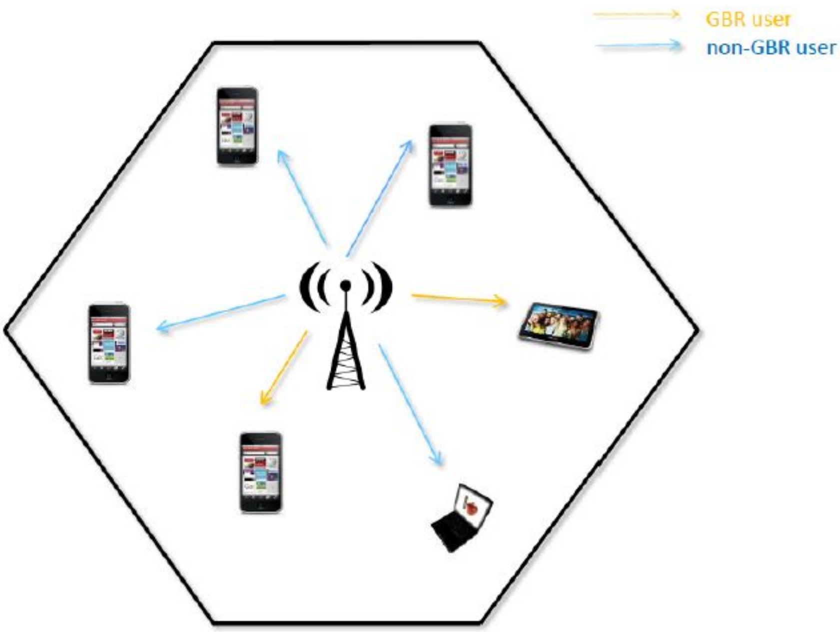

Figure 5.1: Example of Simulation Scenario.

for both sides of the link are modeled as random variables defined through probability density functions (PDFs) and cross-correlations. SCME is consistent and comparable to the SCM. In SCME is introduced an intra-path delay-spread (DS) to extend the model in a way such that its characteristics remain unchanged if compared at the original 5 MHz resolution bandwidth.

The SCM *path-loss* model is based on the COST-Hata Model for Sub-urban and Urban Macro and COST-Walfish-Ikegami-Model (COST-WI) for Urban Micro. Only few of them allow direct comparison between equivalent measurements at 2 and 5 GHz. These few however indicate that the most significant difference can be attributed to different gains in free-space-loss, which is 8 dB higher at 5 GHz compared to 2 GHz. In the SCM, the LOS model, consisting of path-loss and Ricean K-factor definition, is a switch selectable option for Urban Micro only. In the SCME the K-factor is extended to cover also Urban and Sub-urban Macro scenarios. It can be possible to see other

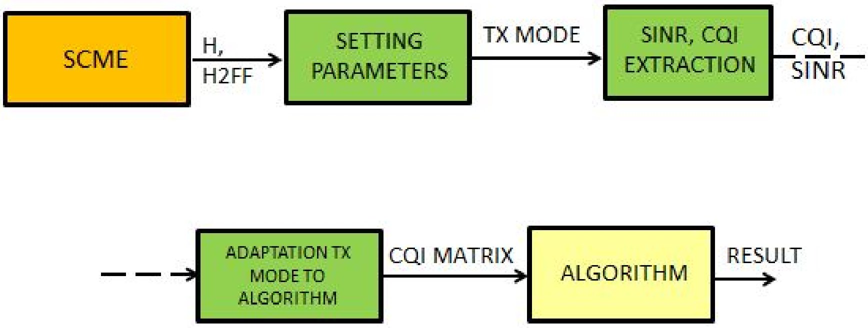

Figure 5.2: Simulation Chain.

extensions in [32].

Figure 5.3 shows the procedure for setting and generating the **H** matrices used in our simulations.

In each TTI we have H_n Matrix where n is the number of link from BS to

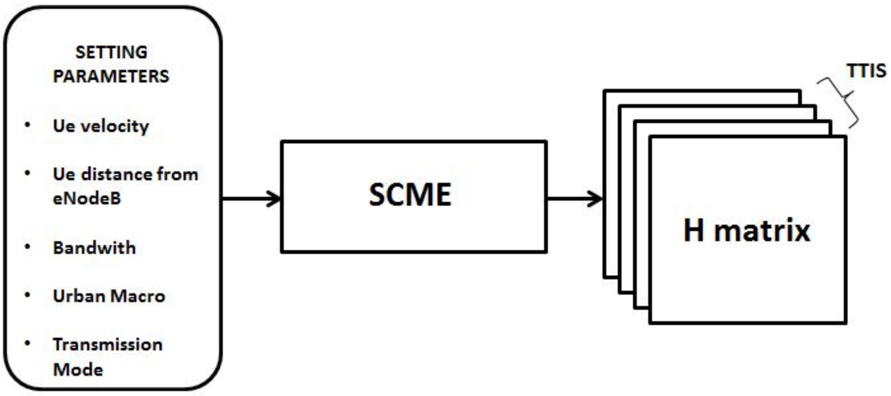

Figure 5.3: Generation of H matrices.

MS, the matrix's row represents the RBs while the columns represents the users like it's shown in figure 5.4.

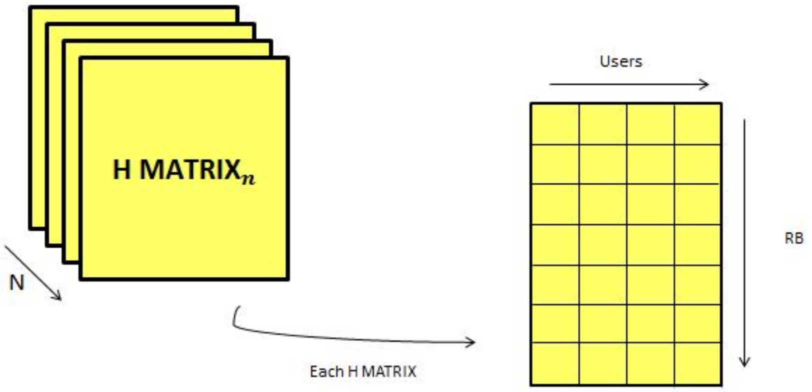

Figure 5.4: H matrix structure.

5.2 Architecture of LTE MAC-PS MIMO Simulator

Simulator structure implemented in MATLAB language is shown in Figure 5.5.

First of all, we set the parameters described to test a particular scenario: *Bandwidth*, *Number of users*, *Simulation period*, *Transmission Mode*, *QoS requirements*. After setting the parameters, the simulation can start. Depending on the type of transmission mode selected, it is necessary to calculate the hypothetical SNR value, for each RB seen in reception by each MS, as explained in the chapter 3. From SNR value the CQI is calculated and the result is the feedback that the MS sends to the BS. The channel matrix adopted is the one obtained by 3GPP SCME.

The SNR values are mapped onto CQI values. The SNR intervals versus CQI values, used of our simulations, are shown in Table 5.1

Figure 5.6 shows the process for generating the CQI matrices used in our simulations in single antenna case. The size of H matrices and of CQI matrices depends on the transmission mode selected.

For different number of active users in the cell, we run the scheduling algorithm for a set simulation period. For each TTI, the simulator adapt the CQI matrix as explained in Chapter 4, extracts the CQI matrix and trig-

SINR[dB]	**CQI values**
$<$-6.25	0 (No Transmission)
[-6.25, -4.35)	1
[-4.35, -2.45)	2
[-2.45, -0.55)	3
[-0.55, 1.35)	4
[1.35, 3.25)	5
[3.25, 5.15)	6
[5.15, 7.05)	7
[7.05, 8.95)	8
[8.95, 10.85)	9
[10.85, 12.75)	10
[12.75, 14.65)	11
[14.65, 16.55)	12
[16.55, 18.45)	13
[18.45, 20.35)	14
$\geqslant$ 20.35	15

Table 5.1: SINR interval vs CQI value.

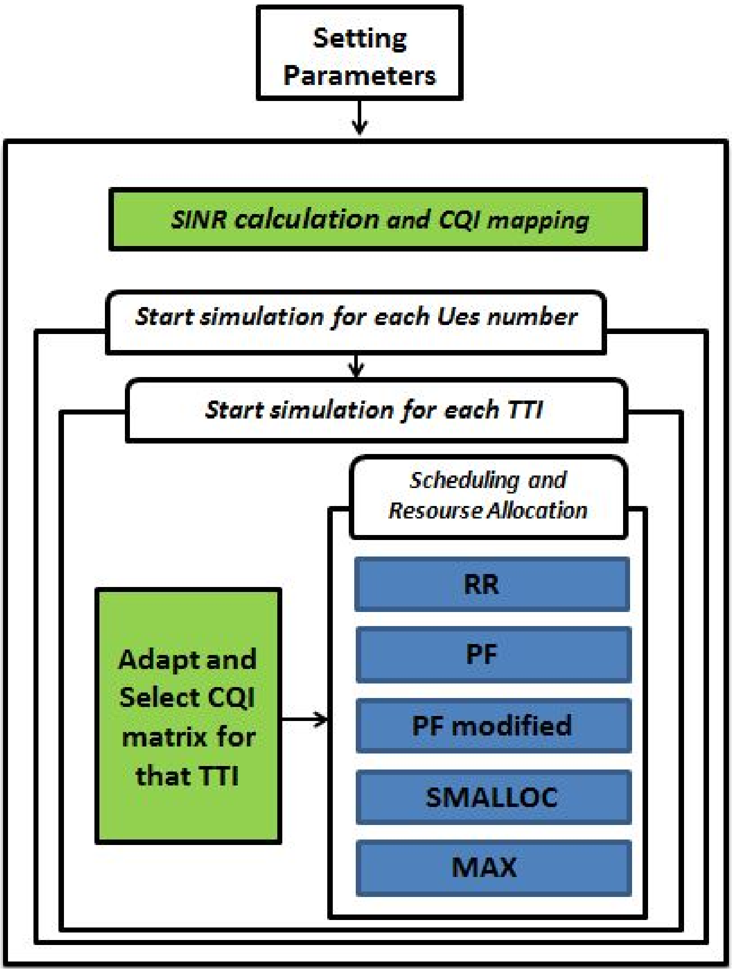

Figure 5.5: Example of new model simulator.

gers different scheduling and resource allocation algorithms: Round Robin (RR), Proportional Fair/Fairness (PF), Proportional Fair/Fairness modified (PF-mod), Max Rate (MAX-R) and the new smart allocation algorithm.

All the algorithms under test perform the scheduling/resource allocation using a simple cross-layer approach, as shown in Fig. 5.7, where users' priority and radio resources are evaluated jointly with significant improvement in the performance.

With simulator we can do two types of simulation: static and dynamic. Static when you want to do simulations with independent extractions of

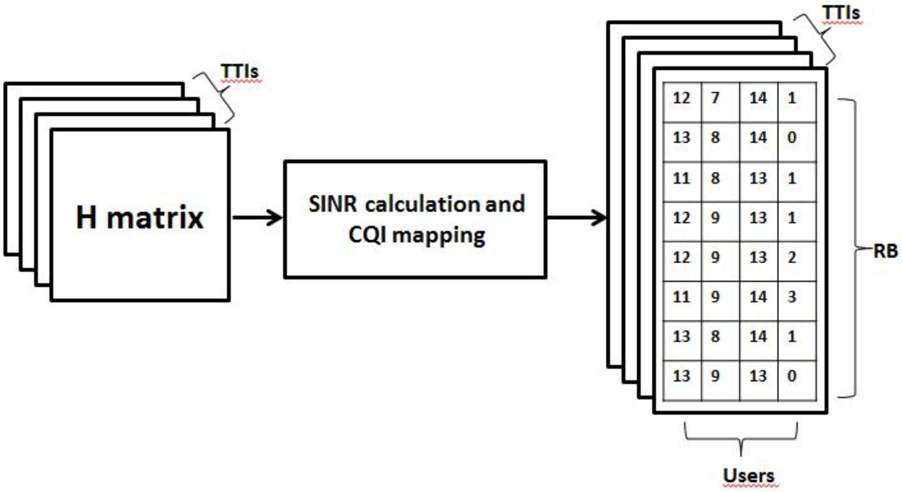

Figure 5.6: Generation of CQI matrices.

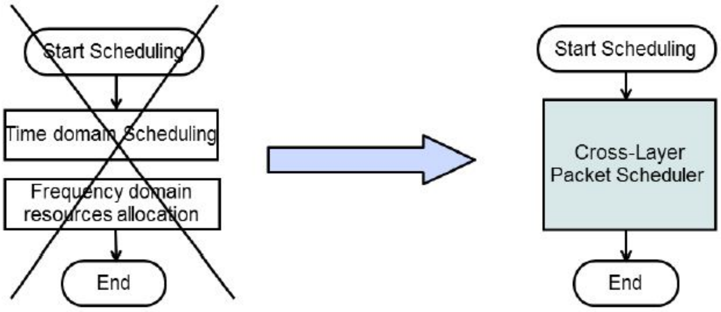

Figure 5.7: Example of Cross Layer Packet Scheduler

the channel (Snapshot), while dynamic when we want to consider a certain evolution in time of the simulation in this case the extractions have a certain degree of correlation which depends on the speed of the mobile station.

Chapter 6

Numerical Results

In this chapter performance analysis of Smalloc and the other techniques are presented; we are considered different transmission mode of standard LTE: Single Antenna, Transmitt Diversity, Closed-Loop Spatial Multiplexing and Open Loop Spatial Multiplexing.
We used a static scenario simulation. In other words, channel realizations are completely uncorrelated. Scheduler makes its decisions on channel's snapshots. In this way, we emphasized good performance reached by Smalloc.
The parameters used for the simulations are described in Table 6.1

6.1 Smalloc performance in different transmission mode

In this section, we want to underline the behavior of the algorithms with different transmission mode. Analyze the case where the required amount of necessary RBs for GBR users are fixed and non-GBR users do not have constraints about RBs. During the simulations, we set, every TTI, the limit of 4 RBs for each GBR users and we want to verify which algorithm is able to satisfy the users requirements with different transmission mode. Scheduler has a snapshot of the channel conditions each TTI. The scenario is com-

Parameters	Value
LTE rel. 9	B=20 MHz, 100 RBs, Nfft=2048, Ptx=46 dBm
scenario	3GPP-SCM2 urban-macro, urban-micro
Number of users	from 2 to 24 users, 50% GBR and 50% non-GBR
antenna eight	10m
user eight	1.5m
cell radius	500m
bandwidth	20MHz
presence of path-loss	yes
user velocity	$5Km/h$
period simulation	1000 Snapshot

Table 6.1: Parameters scenario.

posed of a single cell and interferences of the other cells are not considered. Packet scheduler has full knowledge of the channel. It means that scheduler knows CQI values on each resource block of each user.

Single Antenna case

Figure 6.1 shows the total bit rate achieved by the algorithms in Urban-macro scenario. Smalloc is able to obtain a significant gain over RR and PF, because multi-user diversity gain is higher. Total bit rate is increased by the non-GBR users, because they request high data (no RB constraints). Max-R has slight higher bit rate.

In Figure 6.2 shows bit rate per user, in urban-macro scenario, when 24 users are present in the cell, 12 GBRs and 12 non-GBRs. We notice that PF guarantees a great fairness among all the users. Smalloc provides a good QoS support to the GBR users.

Algorithm performance are also evaluated in Urban-micro scenario, as shown in Figure 6.3; also in that scenario we notice the good performance

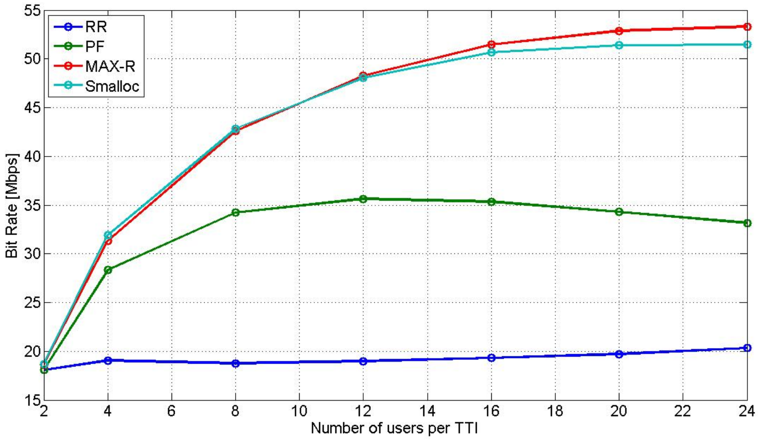

Figure 6.1: Urban-Macro: achieved bit rate versus different number of users RB constraints in Single Antenna case.

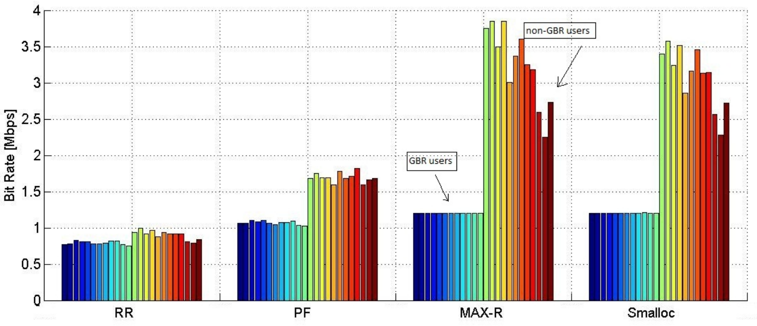

Figure 6.2: Urban-Macro, achieved bit rate for each user for different algorithms in Single Antenna case.

of smalloc algorithm.

Transmit Diversity

Figure 6.4 shows the total bit rate achieved by the algorithms, with transmit diversity case in urban-macro scenario. The difference with the sigle-antenna case is that the algorithms earn about 6 Mbps. This gain is given by the fact that the same information is transmitted from both antennas.

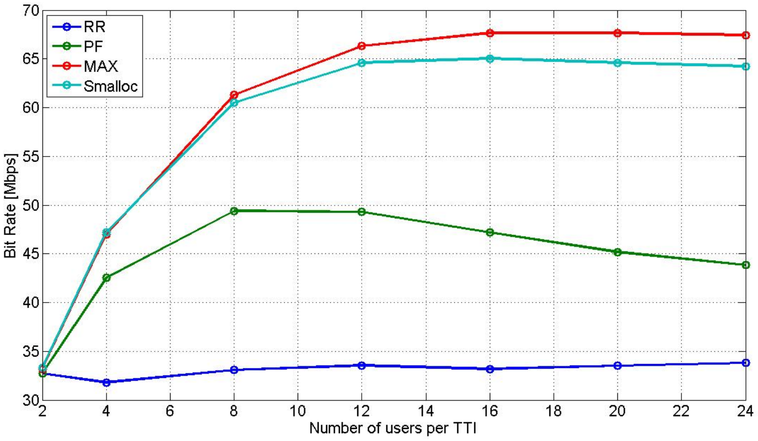

Figure 6.3: Urban-Micro, achieved bit rate for each user for different algorithms in Single Antenna case.

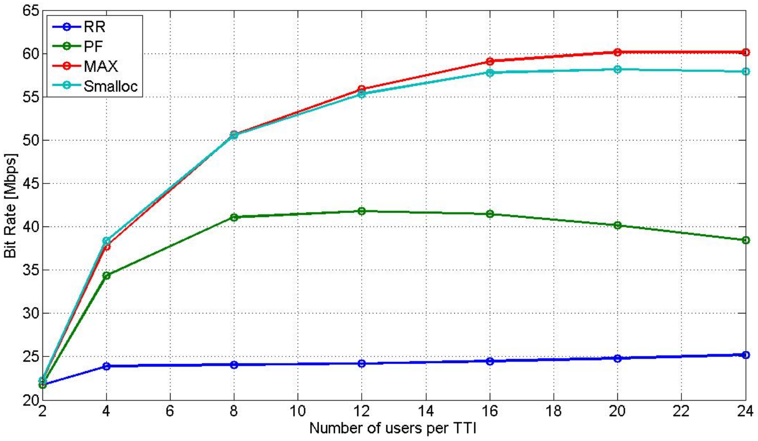

Figure 6.4: Urban-Macro, achieved bit rate versus different number of users RB constraints in Transmit Diversity case.

Closed-Loop Spatial Multiplexing (CL-SM)

In that case the channel is perfectly know at trasmitter, as explained in Chapter 3, the optimal spatial multiplexing scheme is Singular Value Decomposition (SVD) precoding, which spatially decomposes the MIMO channel into mutually orthogonal virtual channels onto which independently coded data streams are transmitted.

A good gain in throughput is given when the antennas are uncorrelated. Figure 6.5 shows the performance of the Smalloc, in urban-macro scenario, when the antennas, at BS, are at different distances. It is noted that the gain of CLSM is greater as much as the distance between the antennas is; by increasing the distance of the antennas, at BS, the correlation between them decreases.

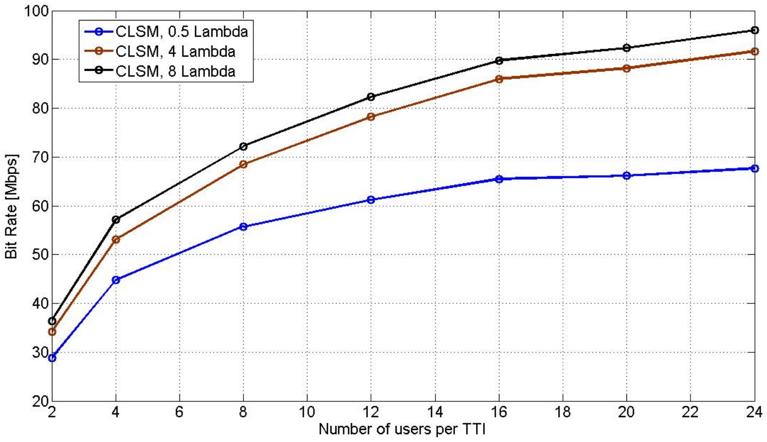

Figure 6.5: Urban-Marco: Smalloc performance in Closed-Loop Spatial Mult. with different distance between antenna element at BS.

In Figure 6.6 shows the total bit rate achieved by the algorithms when the distance between antennas at BS is 8 λ.

Open-Loop Spatial Multiplexing (OL-SM)

In open loop operations, the eNodeB receives minimal information from the UE, so the channel isn't perfectly kown. For this reason, the performance will be lower than CLSM.

Also in that case, as in CL-SM, good gain in throughput is given when the antennas are uncorrelated. We considered an urban-macro scenario and

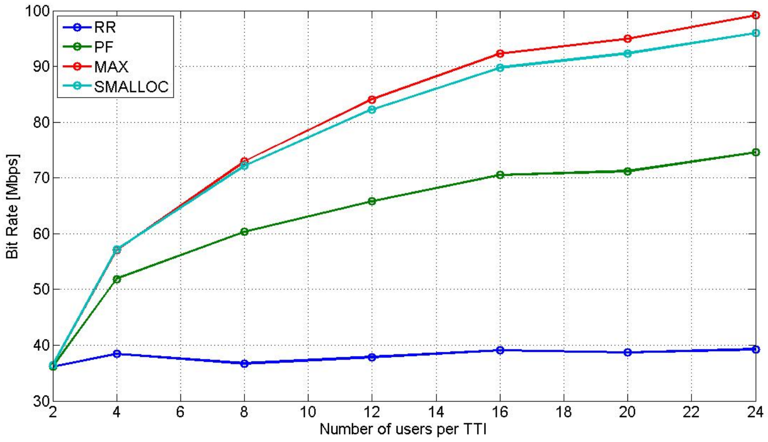

Figure 6.6: Urban-Macro: achieved bit rate versus different number of users RB constraints in Closed-Loop Spatial Mult. case.

Figure 6.7 shows the performance of the Smalloc when the antennas, at BS, are at different distances.

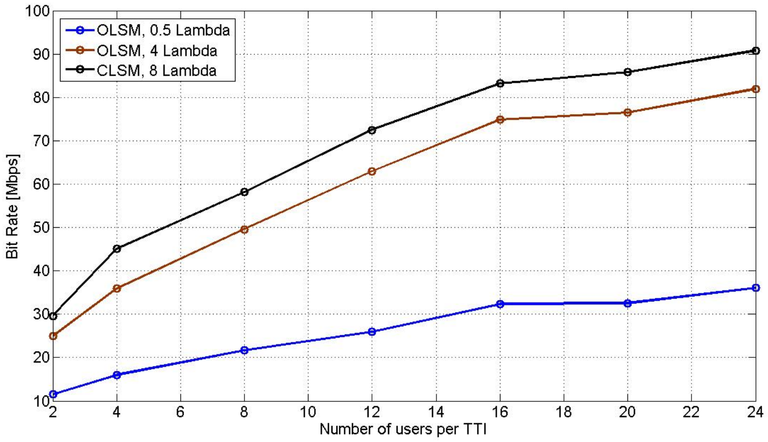

Figure 6.7: Urban-Macro:Smalloc performance in Open-Loop Spatial Mult. with different distance between antenna element at BS.

Figure 6.8 shows the total bit rate achieved by the algorithms when the distance between antennas at BS is 8 λ.

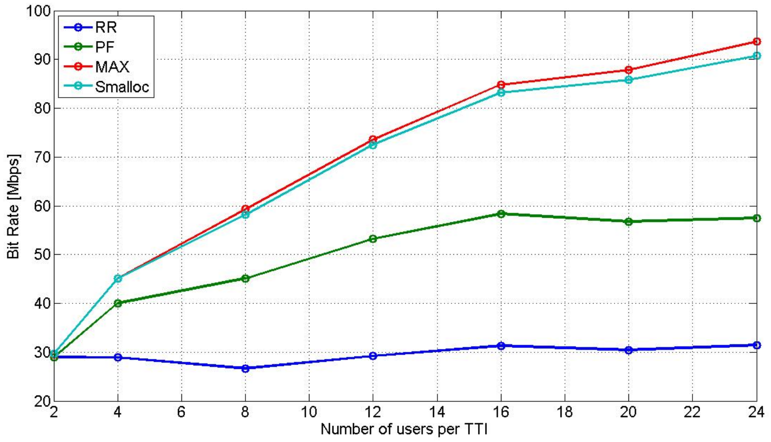

Figure 6.8: Urban-Macro: achieved bit rate versus different number of users RB constraints in Open-Loop Spatial Mult. case.

Figure 6.9 shows the performance of the Smalloc Algorithm with different transmission mode in Urban-Macro scenario. In this figure is more noticeable the difference in throughput between the various transmission mode.

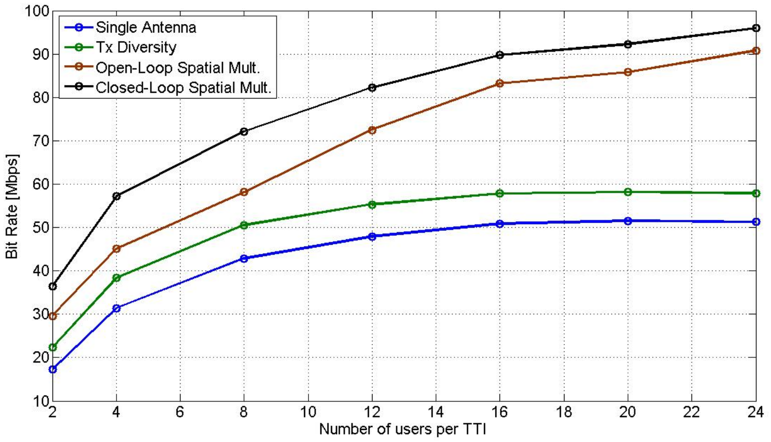

Figure 6.9: Smalloc performance in different transmission mode.

In Figure 6.10 the various transmission modes were compared at different distances from BS in Urban-Macro scenario. It is important to note that for distances greater than 210 meters Smalloc algorithm, in Tx diversity case, has better performance than Round Robin in Closed-Loop Spatial Multiplexing. Smalloc algorithm, in Tx diversity case, is better than Proportional Fair in Closed-Loop Spatial Multiplexing, for distance exceeding 430 meters. For distances of 230 meters Smalloc algorithm,in Single-antenna case, is better than Round Robin in Closed-Loop Spatial Multiplexing.

The BS, according to the considerations made, could change allocation algorithm or transmission mode, depending on the quality of the channel and depending on the distance of the users.

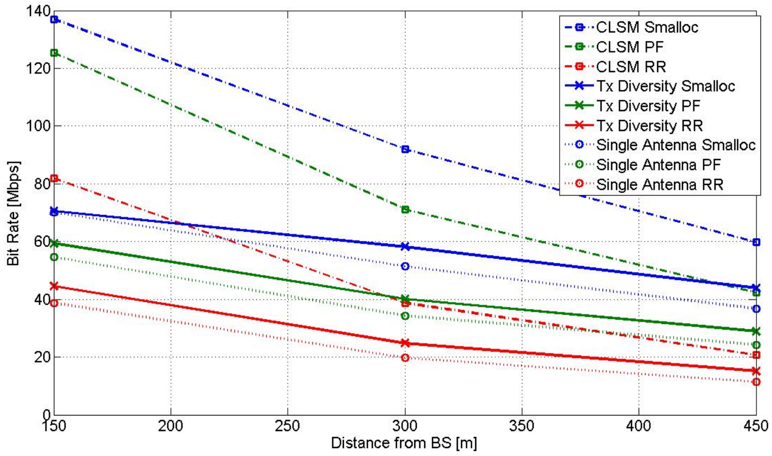

Figure 6.10: Transmission mode performance at difference distance from BS.

Conclusion

This thesis analyzes and develops an innovative scheduling algorithm for users to 4G LTE broadband systems, called Smalloc. We compared that algorithm with other algorithms as Round Robin, Proportional Fair (PF) and Max-Rate that are presented in the literature.

Moreover, an innovative technique has been developed; This gives the possibility to the MAC scheduler to work with different modes of transmission provided by the LTE standard: Single Antenna, Transmit Diversity, MIMO Closed Loop Spatial Multiplexing and MIMO Open Loop Spatial Multiplexing.

The implementation adopted has allowed the evolution of scheduling algorithms from the single-antenna case to multi-antenna case, without altering the structure of the algorithms and without adding additional computational complexity.

In order to test the performance of the proposed solution, a complete LTE system level simulator has been developed.

We analyzed the performance of the different transmission mode: in a single-antenna case, a single data stream is trasmitted on one antenna and received by the other one. The performance of Smalloc was evaluated by comparing different scheduling algorithms: we notice that the Smalloc is able to obtain a significant gain over RR and PF, because multi-user diversity gain is higher.

The trasmit diversity case involves the transmission of the same information stream on multiple antennas; the purpouse is to make transmission more robust. In this case the Smalloc has a gain of about 6 Mbps compared to the single antenna case. This gain is due to the fact that the SINR is improved. In Open-Loop Spatial Multiplexing (OL-SM), two information stream are trasmitted over two antennas; there is no explicit feedback from the user equipment. OL-SM provides much better peak throughput than trasmit diversity. Similar to OL-SM, two information stream are trasmitted; the difference is the precoding matrix indicator which is the feedback from UE to the BS. This feedback mechanism allows the transmitter to precode the data to optimize tranmission over the wireless channel so, the signal at the receiver can be easily separated into the original strams. This mode gives the highest performing mode of MIMO in LTE. It has been noted both in CL-SM and in OL-SM, that, the gain in throughput is greater as much as the distance between the antennas; by increasing the distance of the antennas, at BS, the correlation between them decreases.

that the gain of CLSM is greater as much as is the distance between the antennas, with increasing distance of the antennas, decreases the correlation between them.

Bibliography

[1] Evolved universal terrestrial radio access (E-UTRA); physical layer procedures, 3rd Generation Partnership Project (3GPP), Tech. Rep. TS 36.213, Mar. 2009.

[2] Christian Mehlfuhrer, Martin Wrulich, Josep Colom Ikuno, Dagmar Bosanska, Markus Rupp *"Simulating the Long Term Evolution Physical Layer".*

[3] J. Jang and K. B. Lee. *"Transmit power adaptation for multiuser OFDM systems"*, IEEE J. Select. Areas Commun., vol. 21, pp. 171-178, February 2003.

[4] W. Rhee; J. M. Cioffi. *"Increase in capacity of multiuser OFDM system using dynamic subchannel allocation"*, IEEE VTC, vol. 2, pp. 1085-1089, May 2000.

[5] Z. Shen; J. G. Andrews; B. L. Evans. *"Adaptive resource allocation in multiuser OFDM systems with proportional rate constraints"*, IEEE Trans. Wireless Commun., vol. 4, pp. 2726-2737, November 2005.

[6] Sadr S.; Anpalagan A; Raahemifar K. *"Radio Resource Allocation Algorithms for the Downlink of Multiuser OFDM Communication Systems"*, Communications Surveys and Tutorials, IEEE, 3rd Quarter 2009.

[7] Hans Jorgen Bang, Torbjorn Ekman and David Gesbert, *"A Channel Predictive Proportional Fair Scheduling Algorithm"*, IEEE 6th Workshop, Signal Processing Advances in Wireless Communications, pp. 620-624, Sep. 2005.

[8] Haipeng Lei; Lei Zhang; Xin Zhang; Dacheng Yang. *"A Packet Scheduling Algorithm Using Utility Function for Mixed Services in the Downlink of OFDMA Systems 2007 IEEE 66th."* Vehicular Technology Conference, 2007. VTC-2007 Fall.

[9] Ben-Shimol; Y. Kitroser; I. Dinitz, Y. *"Two-Dimensional Mapping for Wireless OFDMA Systems"*, Broadcasting, IEEE Transactions on, pages 388 - 396.

[10] Xin Wang; Giannakis G.B. *"Resource Allocation for Wireless Multiuser OFDM Networks"*, Information Theory, IEEE Transactions on; July 2011

[11] Wong I.C.; Evans B.L. *"Optimal Downlink OFDMA Resource Allocation with Linear Complexity to Maximize Ergodic Rates"*, Wireless Communications, IEEE Transactions on; March 2008

[12] Ying Jun Zhang; Letaief K.B. *"Multiuser adaptive subcarrier-and-bit allocation with adaptive cell selection for OFDM systems"*, Wireless Communications, IEEE Transactions on; Sept. 2004.

[13] Mohanram C.; Bhashyam S. *"Joint Subcarrier and Power Allocation in Channel-Aware Queue-Aware Scheduling for Multiuser OFDM"*, Wireless Communications, IEEE Transactions on; September 2007.

[14] G. Monghal; K. I. Pedersen; I. Z. KovÃ¡cs; P. E. Mogensen. *"QoS Oriented Time and Frequency Domain Packet Schedulers for The UTRAN Long Term Evolution"*, Vehicular Technology Conference, 2008. VTC Spring 2008, IEEE.

[15] Petteri Kela; Jani Puttonen; Niko Kolehmainen; Tapani Ristaniemi; Tero Henttonen; Martti Moisio. *"Dynamic Packet Scheduling Performance in UTRA Long Term Evolution Downlink"*, Wireless Pervasive Computing, 2008. ISWPC 2008. 3rd International Symposium on.

[16] Xiaowei Li; Bingbing Li; Bing Lan; Min Huang; Guanghui Yu. *"Adaptive pf scheduling algorithm in LTE cellular system"*, Information and Communication Technology Convergence (ICTC), 2010 International Conference on.

[17] Kian Chung Beh; Armour, S.; Doufexi, A. *"Joint Time-Frequency Domain Proportional Fair Scheduler with HARQ for 3GPP LTE Systems"*, Vehicular Technology Conference, 2008. VTC 2008-Fall. IEEE 68th

[18] Honghai Zhang, Narayan Prasad, Sampath Rangarajan, NEC Laboratories America, *"MIMO Downlink Scheduling in LTE systems "*. The 31st Annual IEEE International Conference on Computer Communications.

[19] Shubhodeep Adhikari, *" Downlink Transmission Mode Selection And Switching Algorithm For LTE "*,ISBN 978-1-4244-8953-4, 2011 IEEE.

[20] Zijian Bai, Spiegel, C. ; Bruck, G.H. ; Jung, P. ; Horvat, M. ; Berkmann, J. ; Drewes, C. ; Gunzelmann, B. *"Dynamic Transmission Mode Selection in LTE/LTE-Advanced System"*

[21] Jack H. Winters, *"The Diversity Gain of Transmit Diversity in Wireless system with Rayleigh Fading"*, ISBN 0018-9545/98, 1998 IEEE.

[22] Stefan Kaiser, *"Space Frequency Block Codes and Code Division Multiplexing in OFDM Systems"*

[23] Eckhard Ohlmer; Gerhard Fettweis *"Linear and Non-Linear Detection for MIMO-OFDM Systems with Linear Precoding and Spatial Correlation"*

[24] L. Galati Giordano; L. Reggiani; L. Dossi *"Discrete-Rate Allocation Schemes in Multi-Cel Scenarios with Power Adaptation"*, IEEE Personal Indoor Mobile Communications PIMRC 2010, pp.1799-1803, 26-30 Sept. 2010.

[25] L. Galati Giordano; D. Lopez Perez; L. Reggiani; L. Dossi; A. Juttner; J. Zhang, *"Two- Dimensional Radio Resource Allocation Algorithms with contiguity constraint for IEEE 802.16e Systems"*, IEEE Personal Indoor Mobile Communications PIMRC 2009, pp.2224-2229, 13-16 Sept. 2009.

[26] L. Galati Giordano; L. Reggiani; L. Dossi; *"Interference Evaluation in Multi-Cell Environment with Resource Allocation Algorithms"*, Vehicular Technology Conference, 2008. IEEE VTC2008-Spring, pp.1615-1619, May 2008.

[27] L. Reggiani; L. Galati Giordano; L. Dossi; *"Multi-user sub-channel, bit and power allocation in IEEE 802.16 systems"* Vehicular Technology Conference, 2007. VTC2007-Spring, volume 22-25, pp. 3120-3124, April 2007.

[28] L. Galati Giordano; L. Reggiani; L. Dossi; *"Radio Resource Management for New Generation Wireless Networks: Smart Allocation Techniques and Interference Evaluation"* VDM Verlag Dr. MÃ¼ller (17 Jun 2010), ISBN 978-3-639-26548-4, 112 pages.

[29] L. Reggiani; L. Galati Giordano; L. Dossi, *"Fast Power and Channel Adaptation for Mobile Users in OFDMA Multi-Cell Scenarios"* book chapter included in *"Vehicular Technologies: Increasing Connectivity"*, Miguel Almeida (ed.), ISBN: 978-953-307-223-4, InTech 2011.

[30] Zaki, Y.; Weerawardane, T.; Gorg, C.; Timm-Giel, A. *"Multi-QoS-Aware Fair Scheduling for LTE"*, Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd.

[31] Mohsen M. Tantawy ; Adly S. Tag Eldien ; Rokaia Mounir Zaki. *"A Novel Cross-Layer Scheduling Algorithm for Long Term-Evolution (LTE) Wireles System"*, Canadian Journal on Multimedia and Wireless Networks, Vol.2 No. 4, December 2011.

[32] D. S. Baum; J. Salo; G. Del Galdo; M. Milojevic, P. Kyosti; J. Hansen. *"An interim channel model for beyond-3G systems"*, in Proc. IEEE VTC'05, Stockholm, Sweden, May 2005.

[33] M. F. Pop; N. C. Beaulieu. *"Limitations of sum-of-sinusoids fading channel simulators"*, IEEE Trans. Commun., vol. 49, no. 4, Apr. 2001, pp. 699-708.