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# **4G++: Advanced Performance Boosting Techniques in 4<sup>th</sup> Generation Wireless Systems**

**A National Telecommunication Regulatory  
Authority Funded Project**

**Deliverable D3.1**

**Work Package 3**

## **Channel-Aware Radio Resource Management and Scheduling in LTE and LTE-Advanced Systems**

**List of Contributors (in alphabetical order):**

<b>Name</b>	<b>Title</b>	<b>Role</b>
Amira Affifi	External RA	Main author of sections 2 and 3 (provided as a paper sent for review).
Khaled Elsayed	PI	Co-author and reviewer of sections 2-5, editor of overall document.
Mahmoud Ismail	Lead Researcher	Co-author and reviewer of sections 4 and 5.
Rana Abd El-Aal	RA	Main author of sections 4 and 5.

## Abstract

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This document provides an overview of the radio resource management functions in LTE/LTE-A as tackled in the 4G++ project work package 3. The 4G++ project addresses two particular areas: LTE uplink scheduling under QoS constraints and Coordinate Radio Resource Management for Coordinated Multipoint Transmission systems.

## List of Abbreviations

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3GPP	The Third Generation Partnership Project
AC	Admission Control
AMC	Adaptive Modulation and Coding
BS	Base Station
CA	Carrier aggregation
CoMP	Coordinated Multi-Point
CS	Coordinated Scheduling
CSI	Channel State Information
DCS	Dynamic cell selection
DL	Downlink
eNB	Evolved node B (Similar to the base station)
FPC	Fractional Power Control
HARQ	Hybrid Automatic Repeat Request
ICSGC	Improved color-sensitive graph coloring
IRC	Interference rejection combining
JP	Joint Processing
LA	Link Adaptation
LTE	Long-Term Evolution
MRC	Maximal Ratio Combining
OFA	Orthogonal Frequency Allocation
OFDMA	Orthogonal Frequency-Division Multiple Access
PHR	Power Headroom Reports
PRB	Physical Resource Block
PS	Packet Scheduling
PUSCH	Physical uplink shared channel
QoS	quality-of-service
RA	Resource Allocation
RB	Resource Block
RFO	Reuse Factor of One
RRE	Remote Radio Equipment
RRM	Radio Resource Management
SC-FDMA	Single-Carrier Frequency Division Multiple Access
SDMA	Space Division Multiple Access
SINR	Signal to interference plus noise ratio
SLNR	Signal to leakage plus noise ratio
SoN	Self-Organizing Network



SR	Scheduling Request
UE	User Equipment
UL	Uplink

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# 1 Introduction

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As the services provided to mobile users become more demanding, the mobile telecommunications systems must evolve to meet these expectations. The Third Generation Partnership Project (3GPP) is specifying the Long Term Evolution (LTE) and LTE-Advanced as new radio access technology and network architecture for providing considerable performance improvement at a reduced cost. This work package proposes a radio resource management (RRM) scheme within the LTE/LTE-A framework. Specifically, we address two main interesting problems: uplink scheduling with quality-of-service (QoS) constraints, and resource allocation in coordinated scheduling for coordinated multipoint transmission (CoMP) systems.

To reach LTE's design goals set by 3GPP, LTE's new radio access technology and network architecture must be exploited when addressing the RRM design problem. The RRM functionalities include Admission Control (AC), Packet Scheduling (PS) including Hybrid Automatic Repeat Request (HARQ), and fast Link Adaptation (LA) including Adaptive Modulation and Coding (AMC) and Fractional Power Control (FPC). The RRM design problem can be summarized as providing these functionalities under the constraints introduced by the used technology such as contiguity constraint of SC-FDMA, and the constraints introduced by the design goals such as improving spectral efficiency and QoS provisioning. The goals of the **first task** in this work package is to investigate, proposes, and evaluate schemes for channel-aware scheduling in the uplink direction in LTE/LTE-Advanced. An important objective is to reduce interference in the uplink by using the minimum possible power at cell edges. Moreover, in CoMP systems the current state of the art is that the serving eNB selects resource blocks and power and provides this information to the cluster of eNB's that collaboratively transmitting to the UE. This is not optimum from the capacity point of view since other cells could have quite different links. Therefore, the objective of the **second task** is to make the allocation decision based on max sum rate seen collectively by the cluster not just the serving eNB.

This report is comprised of the following parts:

- An extended survey of LTE uplink scheduling schemes
- Initial model of LTE uplink scheduling scheme supplied as a paper currently under review
- A survey of resource allocation in CoMP
- Initial model of a coordinated resource allocation scheme in CoMP and results

## 2 LTE Uplink Scheduling: Problem Definition and Survey

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### 2.1 Problem Definition

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The 3GPP LTE standard was specified based on a set of requirements and design targets. To achieve these targets the LTE used new technologies such as multi-carrier, multiple antennae and packet switched radio interface. While these technologies help improve system performance, they impose new constraints and challenges for the design and implementation problem.

To exploit the new dimensions of frequency and space introduced by OFDM and MIMO respectively, cross layer techniques between the physical layer and the link layers should be implemented. Some of these techniques which exploit the frequency dimension include channel dependant scheduling, dynamic link adaptation and power control. It is noted that optimizing the RRM functionalities depend on the physical layer configurations and constraints.

In addition to the constraints and requirements introduced by the standard specifications and the technologies used, the RRM design must consider the requirements and constraints of the different types of applications or what is known as providing the appropriate QoS to the appropriate traffic type. Proportional to the importance of this issue is its complexity as more diverse applications with different requirements are introduced.

#### 2.1.1 RRM Functionalities

As radio resources are scarce and at the same time the number of users and their demands increase, managing the radio resources becomes a crucial point in the performance of any wireless network. The two main resources that need management are the transmission bandwidth and uplink power. The RRM functionalities are:

- Admission Control: This function ensures that a new user is not allowed to join the network unless there is enough resources to meet its QoS requirements. This function is performed only during EPS bearer establishment.
- Scheduling transmission bandwidth: The number of users is larger than the available bandwidth. The scheduler function is to determine each TTI which users to be served, the transmission bandwidth allocated to each user and the location of this bandwidth in the spectrum.
- Link Adaptation: The link adaptation determines the transport format of the packets for each user, i.e. it assigns a modulation and coding scheme. It also performs power control to have the users operate at a target SINR.

The overall RRM design is depicted in Figure 1.

#### 2.1.2 RRM Constraints and Challenges

The implementation of the above RRM functionalities must meet the requirements of the system and users while respecting the constraints of the technologies.

The constraints on the scheduler can be summarized as (1) the number of available PRBs, (2) for each PRB at most one user can be assigned. For the link adaptation functionality the constraints are (1) the available modulation schemes, (2) the available code rates, (3) the maximum transmission power.

SC-FDMA was chosen as the uplink transmission scheme for LTE. This adds a constraint on the scheduler functionality that the PRBs allocated to one user must be contiguous in frequency as shown in Figure 2.

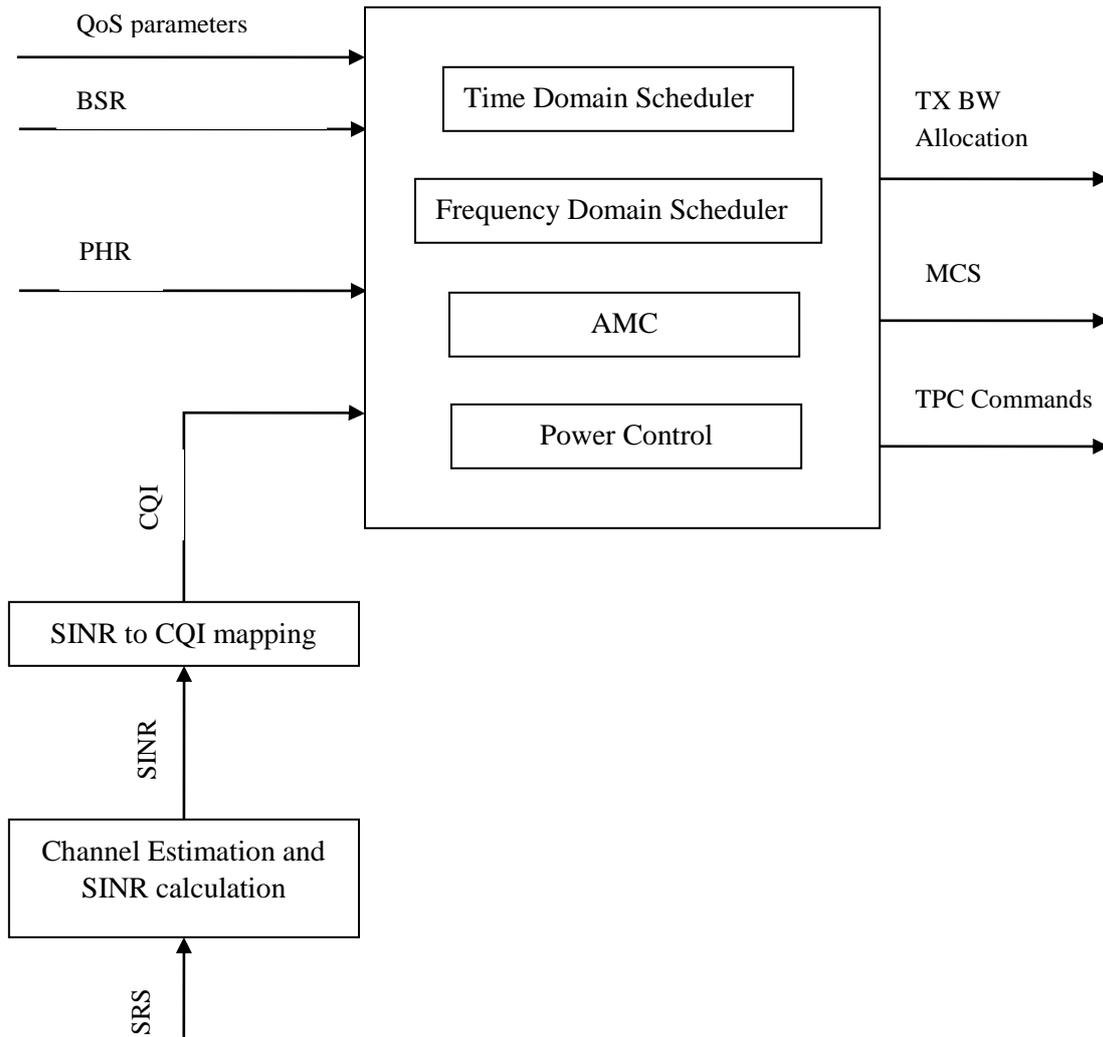


Figure 1: The RRM Design Problem Visualization

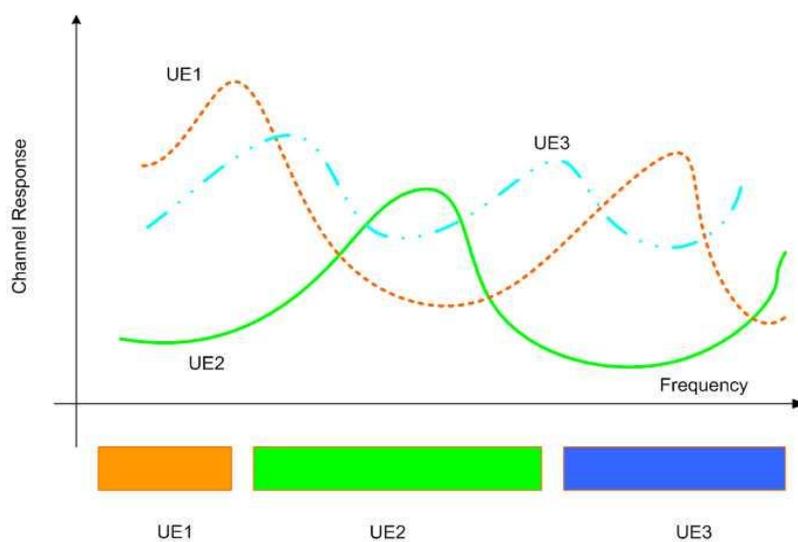


Figure 2: Contiguous Assignment of RBs in SC-FDMA

One of the main requirements the RRM functionalities must meet are those related to the QoS parameters. The RRM functionalities should provide each user with the QoS the connection was established based on. This includes meeting the guaranteed bit rate, maximum tolerated packet delay and maximum tolerated packet loss ratio.

Besides the constraints and requirements the RRM functionalities must address the issues of system performance. Design of RRM algorithms should consider issues such as maximizing spectral efficiency and overall system throughput, minimizing inter-cell interference and providing fairness among users.

### 2.1.3 Inputs to the RRM

To serve its purpose the RRM is provided with inputs to help it take informed decisions.

The channel conditions which are required for the link adaptation and scheduling can be estimated for the whole bandwidth for each user with the help of the channel sounding reference signals. The SINR is calculated for the SRS's and then mapped to a CQI. For the downlink the UE sends CSI reports to the eNB.

To distinguish active users with data in their buffers from idle users, each user with data pending in its buffers sends a one bit Scheduling Request (SR) to the eNB informing it with the need for UL grants.

The information about the amount of data available at each user's buffers is collected by means of buffer status reports.

The UE sends Power Headroom Reports (PHR) to the eNB to inform it about the amount of available power the UE have which is used in the power control and scheduling functionalities of the RRM. The PHR can also be used to estimate the downlink pathloss. The signalling between the UE-eNB is conceptually depicted in Figure 1.

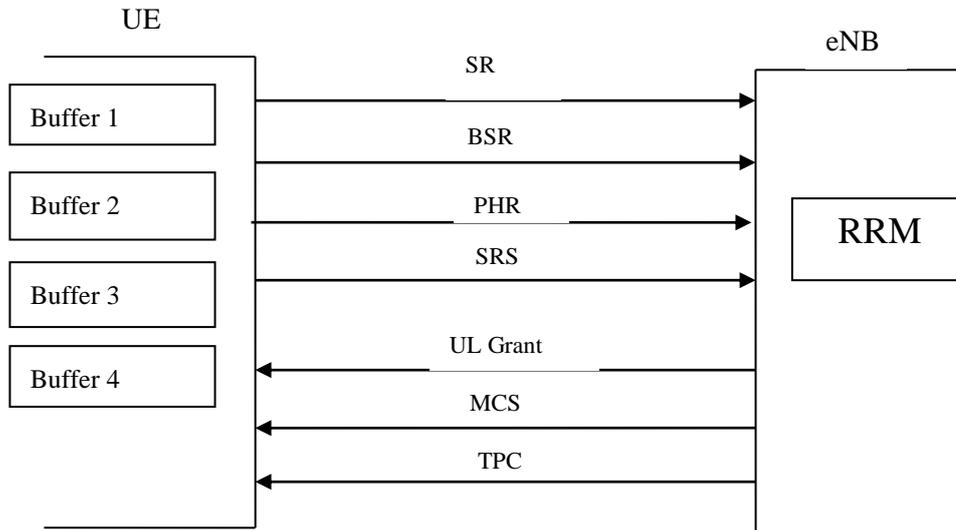


Figure 3: UE-eNB Signalling

### 2.1.4 Formulation of LTE Uplink Scheduling Problem

We provide the formulation for the uplink scheduling problem a mathematical optimization problem and discuss that in the general form, it is an NP-hard problem.

Let the number of users in the system be given by  $N$  and the number of resources blocks  $C$ . Let  $\mu_{i,n}$  be the achievable rate of RB  $n \in \{1, 2, \dots, C\}$  when allocated to user  $i \in \{1, 2, \dots, N\}$ . Similarly, let  $p_{i,n}$  be the uplink power transmitted by user  $i$  on RB  $n$  to achieve rate  $\mu_{i,n}$  and let  $\alpha_{i,n} \in \{0,1\}$  indicate whether RB  $n$

is allocated to user  $i$ . Define  $P_i^{Max}$  as the maximum allowed total power by user  $i$ . Let  $t$  refer to a specific frame. The uplink scheduler determines at each scheduling instant  $t$  the matrix  $\alpha(t) = [\alpha_{i,n}]$ . The uplink scheduling problem can be formulated as the following optimization problem:

$$\alpha(t) = \arg \max_{\alpha} \sum_{i=1}^N \sum_{n=1}^C \mu_{i,n} \alpha_{i,n} \quad (1)$$

Subject to

$$\alpha_{i,n} \in \{0,1\} \quad (2)$$

$$\sum_{i=1}^N \alpha_{i,n} \leq 1, n \in \{1, 2, \dots, C\} \quad (3)$$

$$\alpha_{i,n} - \alpha_{i,n+1} + \alpha_{i,m} \leq 1, m = n + 2, n + 3, \dots, C \quad (4)$$

$$\alpha_{i,n} - \alpha_{i,n-1} + \alpha_{i,m} \leq 1, m = n - 2, n - 3, \dots, 1 \quad (5)$$

$$\sum_{n=1}^C p_{i,n} \alpha_{i,n} \leq P_i^{Max}, i \in \{1, 2, \dots, N\} \quad (6)$$

The constraint (3) insures that a RB is allocated to only one user, while constraints (4) and (5) take into account the allocation contiguity for user  $i$  as mandated by SC-FDMA in the LTE uplink. On the other hand constraint (6) puts an upper bound on maximum transmission power for user  $i$ . Further constraints can be added, for example, if at any frame the rate seen by user  $i$  is required to be greater than a certain rate  $r_i$ , this can be captured by  $\sum_{n=1}^C \mu_{i,n} \alpha_{i,n} \geq r_i$ . Alternatively, the rates for the different users can be required to satisfy certain fairness constraints.

Another interesting constraint is handling HARQ retransmission, assuming synchronous non-adaptive HARQ and that user  $i$  has scheduled retransmissions, then the scheduler should reserve certain blocks for the user which can be captured by setting the constraint  $\alpha_{i,n} = 1$  for those RB's that has been allocated in the original transmission for the user.

As can be seen this formulation results in an ILP for the resource assignment problem and the solution is an NP-complete problem. Solutions using ILP solvers can be tractable for small values of  $N$  and  $C$ . In our work we design heuristics to obtain good solutions for the different types of problems. In addition, we handle the constraints on users' rates with fairness and delay constraints along with limiting uplink power.

## 2.2 Related Work

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### 2.2.1 Channel Dependant Scheduling

Frequency Domain Packet Scheduling also known as Channel Dependant Scheduling exploits the multiuser diversity to increase spectral efficiency and throughput. What is seen as a bad channel for one user is most likely to be a good channel for another user. The scheduling decision is the assignment of resource blocks to users in such a way as to maximize a utility function based on throughput. The channels for each user are

obtained by providing the SRS to a channel estimation algorithm. For simulation purposes perfect channel knowledge is assumed in the majority of the literature addressing this problem.

### 2.2.1.1 Heuristic Algorithms for Channel Dependant Scheduling

The following work tackled the channel dependant scheduling from a heuristic point of view to decrease computational complexity and provide a cost efficient implementation.

S. Lee et al. in [1] evolved the conventional Round Robin algorithm and introduced four algorithms to address the problem of uplink scheduling in the LTE.

- Algorithm 1: Carrier by Carrier in turn. Round robin on the RBs starting from RB number 1, the RB is assigned to the user with the highest metric on the RB without violating the contiguity constraint.
- Algorithm 2: Largest Metric Value RB First. Same as algorithm 1 but instead of starting with RB number 1 start with the RB with the highest metric value, the in-between RBs are assigned to the same user.
- Algorithm 3: Riding Peaks. The idea is based that there is correlation between adjacent RBs i.e. if for a user a certain RB has high metric it is with high probability that the neighboring RBs will also have high metrics. Same as algorithm 2 look at the highest metric value RB first, the RB is assigned to user  $i$  if the RB is adjacent to the previously assigned RBs of user  $i$  or user  $i$  has no RBs assigned yet. Otherwise it is not allocated and we move on to the next RB.
- Algorithm 4: RB Grouping. Algorithm 3 is expected to yield good results if the frequency domain exhibits high correlation between two adjacent RBs. However correlation in the frequency domain is not strong which implies that even though we have an overall frequency correlation the granularity of this correlation is not necessarily as small as one RB. To deal with this issue of small scale variations the unit of consideration will be RB group. A RB group is a number of contiguous RBs viewed as one block together.

In [2] a Search Tree Based packet scheduling algorithm is proposed. The idea is to draw a binary tree where each node has 2 branches the maximum utility and the second maximum utility. Allocation is decided at the end where the path with the highest overall global utility is chosen. In the simulations the bandwidth is assumed equal and fixed for all UEs therefore neglecting the adaptive transmission bandwidth problem, imperfect channel knowledge is considered through considering HARQ retransmissions, and open loop power control is implemented.

In [3] three heuristic algorithms were proposed. First Maximum Expansion algorithm assigns resources starting from the highest metric value and expanding the allocation on both sides, the allocation for a UE is stopped whenever another UE with a higher metric is found. The second algorithm Recursive Maximum Expansion is similar to the first one except that it performs a recursive search of the maximum. Minimum Area Difference to the Envelope is a more computationally expensive algorithm than the previous two however gives closer results to the optimal solution. This algorithm aims at minimizing the difference between its cumulative metric and the envelope metric. Improvements over Round Robin algorithm have been shown.

In [4] the authors combine the work of [2] and [3] and propose two improvements for the Recursive Maximum Expansion Algorithm. The first algorithm give higher flexibility in the RB expansion by not limiting the expansion only to the maximum but having it to be within a threshold, while the second algorithm Improved Tree Based Recursive Maximum Expansion gives even more flexibility in the expansion by considering the highest and second highest metric deriving a binary search tree. Results show that with a little higher complexity around 15% gain in spectral efficiency is obtained compared with conventional Recursive Maximum Expansion.

The authors in [5] looked at the problem from a different view by focusing on investigating different scheduling metrics, mainly a combination of two metrics throughput based in the time domain and SINR based in the frequency domain. Scheduling metrics affect the priority of the users. Evaluations are based on a RRM framework with open loop power control and AMC.

A Heuristic Localized Gradient Algorithm is discussed in [6]. The algorithm simplifies the optimal Localized Gradient Algorithm by following a simple heuristic in allocating the RBs to the users while maintaining the required allocation constraint and taking retransmission requests into consideration. The basic idea is to search for the RB-user pair with the highest metric value and assigning this RB to this user, if the user has previous allocations that is not contiguous to the new allocation, all in-between RBs are assigned to the user. The HLGA is compared to a reference algorithm LGA which defines and solves an optimization problem. In [7] the authors examined the performance of the HLGA when dynamic traffic models are assumed. To solve the problem of different buffer occupancies and therefore different users' requirements, a procedure called 'pruning' is introduced. The pruning procedure states that RBs are first assigned to users according to the HLGA regardless of their traffic requirement. Extra RBs allocated to users are then reallocated to either neighboring users in the spectrum or users with no assignments. Pruning is performed on edge RBs to preserve the contiguity constraint.

### 2.2.1.2 Optimization Problem of Channel Dependant Scheduling

The channel dependant scheduling problem was addressed as an optimization problem to obtain an optimal solution. As these solutions usually need high computation resources they are mostly used as a benchmark and reference for other suboptimal or heuristic solutions. In [6] and [8], the authors discussed the optimization problem and provided suboptimal algorithms to solve it.

In [6] the gradient metric was chosen as the scheduling metric for the scheme. The utility function is a strictly concave smooth utility function. An integer programming assignment problem is formulated with a contiguity constraint. The integer programming optimal solution assumes perfect channel knowledge, in case of measurement delays and estimation errors, the selection rule occasionally picks rates that do not match the channel capacity. Synchronous non adaptive HARQ is assumed to take care of these errors and therefore a constraint is added to allocate to the users having HARQ processes operating on certain RBs those same RBs until successful transmission is achieved. In this case the solution provided is not the optimal one.

In [8] a general LTE UL FDPS problem is formulated. The problem defines a profit function which is a general term used to represent various scheduling policies. The aim is to schedule the RBs in a time slot such that the profit is maximized. The LTE UL FDPS problem is shown to be NP-hard and therefore two approximation algorithms are introduced which computes solutions close to the optimum. The first heuristic algorithm is a greedy strategy based algorithm which divides the LTE UL FDPS problem into several sub problems according to the profit and then apply a greedy method to each problem. The second algorithm is based on a local ratio technique.

The aforementioned algorithms have all assumed full buffer traffic model, fixed traffic classes and only focusing on increasing overall throughput with no regards to interference on other cells.

### 2.2.2 QoS Oriented Scheduling

QoS oriented scheduling considers in addition to increasing throughput, per-flow metrics such as packet loss and packet delay. In today's wireless networks, more diverse applications, such as video and interactive gaming, are introduced leading to different QoS requirements. The scheduling scheme should consider these variations when assigning resources. QoS parameters including maximum allowed packet delay, maximum allowed packet drop ratio, priority and guaranteed bit rate GBR must be respected. In the channel dependant scheduling problem, the utility function is usually a function of the overall rate is to be maximized under the

contiguity constraint. When QoS classes are accounted for in the resource assignment, this will add further constraints on the scheduler.

### 2.2.2.1 Downlink QoS Oriented Scheduling

The following papers discussed QoS-oriented scheduling but from the downlink point of view. Downlink scheduling is a simpler problem than the uplink as the contiguity constraint is removed. Another issue that is different in the downlink from the uplink is that the HOL packet delay in the downlink is available at the eNB while in the uplink it is either estimated or the buffer status is used instead.

The authors in [9] expanded the channel dependant scheduling problem to include buffer status awareness. AMC is also implemented where, the MCS is chosen depending on the CQI reported by the UE. Proportional fairness is achieved by preferring users with good channel conditions to be scheduled but at the same time if the user is scheduled frequently the priority of the user is decreased. A priority function is proposed to achieve four objectives 1) maximize system throughput 2) decrease packet drop ratio 3) keep certain fairness among users 4) guarantee QoS of multimedia services. The priority is a function of the buffer status, the instantaneous data rate, the average data rate, priority of the service class and GBR for RT services. For each subband the priority function is calculated for all the users and the subband is allocated to the user with the highest priority on this subband.

In [10] a decoupled time and frequency domain scheduler is proposed. The time domain scheduler helps in reducing the complexity of the frequency domain scheduler by minimizing the set of schedulable users. Users are added to the set of schedulable users if they satisfy that they have data to be transmitted and that the data has passed either the buffer amount threshold or the head of line threshold. The schedulable users are then prioritized according to a set target bit rate. The frequency domain scheduler then selects for PRB  $k$  the user  $n$  that maximizes a chosen metric. Three metrics are investigated

1) Proportional Fair:

$$M_{PF} = \frac{\hat{d}[k,n]}{R[n]}$$

where  $R[n]$  is the past average throughput of user  $n$  and  $\hat{d}[k,n]$  is the estimated achievable throughput for user  $n$  on PRB  $k$

2) Proportional Fair Scheduled:

$$M_{PFsch} = \frac{\hat{d}[k,n]}{R_{sch}[n]}$$

where  $R_{sch}[n]$  is an estimate of the user throughput if user  $n$  was scheduled every sub-frame.

3) Carrier Over Interference to Average.

$$M_{ColtA} = \frac{\widehat{C}OI[k,n]}{\sum_{k=1}^{k=N_{PRB}} \widehat{C}OI[k,n]}$$

where  $\widehat{C}OI[k,n]$  is an estimation of the SINR on the  $k^{th}$  PRB of the  $n^{th}$  user. The denominator describes the average channel quality of the user.

In [11] the authors propose a delay prioritized scheduling algorithm consisting of three steps. Step 1 the algorithm computes for each user the remaining time of the HOL packet delay to approach the delay threshold. Step 2 the user with the lowest difference between the HOL delay and the threshold is chosen. Step 3 finds the RB with the highest gain for the selected user and assigns the RB to it.

In [12] a similar approach is adopted where the users are classified into three categories according to their HOL packet delay and then the packet scheduler allocates RBs to corresponding users according to their priorities.

### 2.2.2.2 Uplink QoS Oriented Scheduling

The QoS oriented scheduling was discussed in the uplink in the following papers.

In [13] two algorithms are proposed which consider the end to end packet delay constraint in addition to the contiguity constraint imposed in LTE uplink scheduling. The first algorithm goes through each RB and assigns it to a user taking into account the contiguity constraint if the maximum delay and minimum throughput requirements are satisfied for all the users. Otherwise it assigns first the users with critical delay or throughput as long as RBs are available and do not violate the contiguity constraint. The second algorithm differs from the first one in the use of a different metric value and that RBs are not assigned in order but with respect to users with critical delay requirement. Both algorithms tend to assign one block per user and therefore are not efficient in the case when the number of users is smaller than the number of RBs, also in both algorithms some users may never be assigned RBs.

In [14] the constraint of the queuing delay is studied under the goal to minimize power transmission. An optimization problem is formulated and a suboptimal algorithm is proposed and evaluated.

### 2.2.3 Uplink Power Control and Interference Coordination

The problem of power control is closely associated with inter-cell interference. An optimum transmission power is the power that can maximize system throughput. System throughput is a function of the cell throughput and the inter-cell interference. The higher the transmission power the higher the cell throughput but also the higher the inter-cell interference and subsequently the inter-cell interference decrease the throughput for the neighboring cells. So basically power control objective is to achieve a transmission power that maximizes user and cell throughput but at a reasonable inter-cell interference level. The argument for this concept is that if all eNB's control the level of interference they cause to neighboring cells, then each individual eNB will also receive limited interference from its neighbors resulting in an overall good performance. This behavior is desirable as it is in synchrony with the concept of self-organization (SoN) that is being promoted by 3GPP and other forums to enhance the configuration, optimization, and operations of future wireless networks [15] [16].

The LTE uplink power control mechanism constitutes of a closed loop component operating around an open loop point of operation. The open loop component is derived based on a parameterized power control scheme. Conventional power control schemes assume full compensation for the pathloss where all users are received with the same SINR, which means that the higher the pathloss the higher the transmission power. Since the pathloss to the serving eNB is inversely proportional to the pathloss to the neighbouring eNB's, the conventional power control scheme with full compensation could lead to high inter-cell interference levels. The uplink power equation as stated in the 3GPP LTE standard allows the use of Fractional Power Control (FPC) where users with higher pathloss operate at a lower SINR requirement. To further improve the performance in terms of interference a closed loop component is added to the open loop. The closed loop component is left to the implementation of the vendor where usually it is associated with a SINR or interference target.

While the open loop term determines the tradeoff between cell capacity and cell outage by compensating for slow variations, the closed loop term affect the long term performance tradeoff between inter-cell interference and system throughput by compensating for fast variations.

### 2.2.3.1 Performance Evaluation of the LTE Uplink Power Control mechanism

In [17] and [18] the authors have evaluated the performance of the uplink power control mechanism defined in the LTE standard.

The authors in [17] evaluate the FPC equation and study the effect of the different parameters on the interference levels and the SINR which gives an indication on the throughput. The paper's focus was only on the open loop power control therefore depending on the aim of the PC scheme whether it is to increase capacity or to improve outage performance, a choice for the different parameters of the open loop power control equation was made to achieve that.

While [17] focused on the open loop performance, [18] evaluated the performance of both the open loop and closed loop power control mechanisms. Investigations of the different parameter sets to give (a) high bit rate and (b) high capacity have been done.

### 2.2.3.2 Uplink Power Control and ICIC

The following work studied the uplink power control problem and proposed power control techniques but neglected the effect of some RRM functionalities.

In [19] the author designed and implemented a closed loop power control scheme in combination with the fractional pathloss compensation factor. An investigation for the different values of the pathloss compensation factor has been provided as well as a choice for the optimal value that gives best cell edge and mean user throughput. The SINR Target is set by the eNB as the target SINR that a UE should be using. The SINR Target affects two parameters, the throughput and the interference. A mathematical model for setting the SINR Target based on the pathloss is described. The proposed model assigns a higher SINR Target for users with low pathloss therefore allowing these users to transmit at a higher power. Implementing this model will decrease the inter-cell interference but at the expense of lower throughput for the cell edge users.

In [20] the author studied the open loop power control and introduced two closed loop power control algorithms to enhance the performance.

The **first algorithm** is designed to set the transmission power spectral density according to the tradeoff between the UE's generated signal and interference powers to achieve a higher SINR for this UE. The algorithm calculates the total interference generated by a UE and compares it to an interference limit. While the interference spectral density limit is equal to all users the interference limit is dependent on the allocated bandwidth to the users, but the author assumes equal bandwidth allocation to all users in the simulation. The transmitting power spectral density is set using the interference spectral density limit.

A further modification is introduced by adding a factor similar to the pathloss compensation, to tune the pathloss of the UE to the neighbouring eNBs. The two pathloss terms (pathloss between UE and serving eNB, and pathloss between UE and neighbouring eNBs) with their compensation factors are combined in a formula to obtain the transmitting power spectral density.

The **second algorithm** is designed to set the transmission power according to a throughput measure. While a user may represent a better tradeoff between signal and interference powers, it is not necessary to represent a better tradeoff between gain in throughput and interference. For each user two parameters are calculated, the gain to the system calculated as the increase in throughput due to the increase in power, and the cost to the system calculated as the increase in interference due to the increase in power. To calculate the increase in throughput an estimate of the interference this user is experiencing is estimated. An "interference budget" of the cell is managed by allowing iteratively one UE to increase its transmission power by one step until the target interference is met. The UE will be chosen based on the gain/cost criteria.

In [21] an uplink radio resource management scheme is proposed with an emphasis on admission control, packet scheduling and handover. The admission control algorithm is based on fractional power control. The admission decision for a new user is based on the availability of enough PRBs to satisfy his QoS requirements. To calculate the number of PRBs required for fulfilling the requested GBR, the open loop fractional power control equation is used. The number of required PRBs of existing users is obtained by using the average number of PRBs allocated to these users by the packet scheduler.

The admission control algorithm is then combined with a packet scheduler. The packet scheduling is done in two phases: Time Domain and Frequency Domain. The time domain scheduler prioritizes the users according to their GBR requirements giving higher priority to the user further below his GBR and then selects  $N$  users to input to the frequency domain scheduler. The frequency domain scheduler allocates flexible number of PRBs to the users by using an adaptive transmission bandwidth based scheduling which aims at maximizing the sum of a frequency domain metric. QoS is included in the frequency domain by weighting the frequency domain metric according to the QoS requirements. The combined admission control and packet scheduling is evaluated for different traffic profiles.



### **3 Proposed LTE Uplink Scheduling Scheme**

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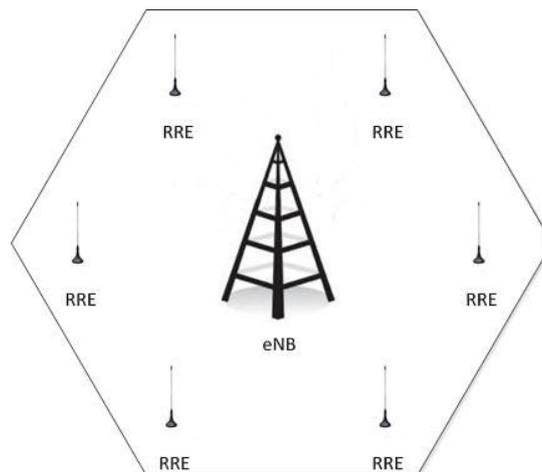
The 4G++ project team working on the uplink scheduling scheme devised a QoS based uplink scheduling scheme combining uplink power control and was documented in the paper titled “A Radio Resource Management Framework for the 3GPP LTE Uplink”. This paper is attached as a PDF and is currently under review.

## 4 Coordinated Radio Resource Allocation in CoMP

The capacity of wireless cellular networks is mainly restricted by interference. In cellular systems, a geographical region is divided into cells. These handle interference through the use of pre-defined frequency reuse patterns so that near cell-edge users belonging to adjacent cells do not share similar frequencies. Recently, as bandwidth progressively becomes a more scarce resource, and future cellular networks shift gradually closer to the maximal frequency reuse of unity. Consequently, the Radio Resource Management (RRM) as well as scheduling will play an essential role in upcoming future networks.

Coordinated multi-point (CoMP) transmission is one of the candidate techniques for Long Term Evolution-Advanced (LTE-A) systems to increase the average cell throughput and cell-edge user throughput in both the uplink and downlink. The basic idea of CoMP is to eliminate the interference through cooperation between neighbor cells and turns interference from neighbor cells into useful signal. Although CoMP naturally increases the system complexity, it provides significant capacity and coverage benefits, making it worth a more detailed consideration. In this survey, different CoMP systems are investigated. The aim of this survey is to study different RRM, power control, and scheduling methods for interference mitigation together with CoMP to achieve a considerable gain in terms of capacity and cell-edge user throughput [22].

In LTE-A, a cell consists of several Remote Radio Equipments (RREs), which can be connected to a central base station (BS/eNB) [23]. An example to such cell is shown in Figure 4. Hence, full coordinated transmission or reception is achieved among RREs through unified radio resource management at the central BS. Since the interface connecting the central BS and the RREs can be implemented through the use of optical fibers or radio interface, high-speed transfer of signals is possible. RREs are effectively used in the existing third generation networks by installing small BSs in limited space and reducing the cable loss. Thus, RRM employing RREs is deployed to achieve CoMP transmission and reception between different cell sites designed for LTE-A.



**Figure 4: Cell scenario with several RRE**

The bandwidth available for each cell is divided into a set of resource blocks (RBs) through frequency division. A RB is a collection of subcarriers that are handled together as an allocation unit available for data transmission. When an RB is allocated to certain user equipment (UE), this means a definite frequency channel is assigned to this UE. To reach fairness among UEs, each UE must be allocated multiple RBs in each frame. Different power allocations can be made to each of these RBs to take into account the performance objectives of the sector as well as the interference caused on neighboring sectors. RA techniques must be considered to optimize the throughput and decrease the interference. The rate achieved

by a UE depends on: the downlink channel environment of the UE, the number of RBs allocated to each UE, the power allocated to each RB, and the implemented interference approach [24].

In [25], RB optimization was explored considering a single RB. Two sectors and two UEs were considered such that each sector serves one UE. The purpose was to maximize the sum rate for both UEs. The conclusion was that the optimal power allocation is binary; either both sectors transmit with full power or just one of them transmits at full power and the other is turned off.

In the case of multiple RBs, an algorithm must determine which RB should be allocated to a specific UE and how much power should be allocated to each of the scheduled RBs given the overall power limitation. An optimization problem should be solved to maximize the sum rate subject to power and bandwidth constraints while taking into consideration the interference between sectors. In [25], a model with two sectors and multiple RBs was considered. It was shown that if one RB is used by both sectors, then all RBs need to be used by both sectors (i.e. a frequency reuse of 1). Similarly, if one RB is used by exactly one sector, then all RBs need to be used by exactly one sector. Moreover, it was stated that uniform power allocation is optimal, which is not clearly proved. It might be optimum in case of one user per sector (the very simplified case assumed in the paper); however, more study is required in order to prove that it is optimal in case of the existence of more than one user that needs to be served simultaneously. Hence, in the general case (multi-user case); optimal power allocation may or may not be uniform.

## 4.1 CoMP Schemes

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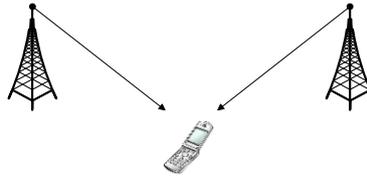
CoMP is a technology introduced for LTE-Advanced to meet the requirement of IMT-Advanced. CoMP systems are able to exchange data, control information and Channel State Information (CSI) between all RREs under the command of the eNB and, consequently, coordinate interference. In other words, the RREs will coordinate together to serve the UEs in order to reduce the interference. The main objectives of CoMP are to mitigate the interference, provide high spectral efficiency over the entire cell area, and increase the overall throughput especially the cell-edge throughput [24].

### 4.1.1 CoMP Transmission Schemes

In the downlink (DL) of CoMP systems, several approaches are often considered. The first approach is Joint Processing (JP) where the data is made available at each RRE and is transmitted from several RREs simultaneously to each UE. Other approaches include; Dynamic cell selection (DCS) and Coordinated Scheduling (CS) where, in both cases, the data is transmitted from one RRE at a time with scheduling decisions being made with coordination between RREs.

#### 4.1.1.1 Joint Processing (JP)

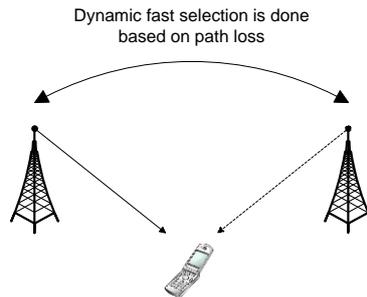
Multiple RREs work as a distributed antenna array under coordination of the eNB. Each UE may receive useful signals from multiple RREs. In other words, multiple RREs are allowed to transmit the data to a single UE simultaneously over the same RB (i.e. from the serving RRE and non serving RREs as well). The main target of JP is to improve the coverage and the cell edge user throughput by maximizing the Signal-to-interference-plus-noise ratio (SINR). The RREs' outputs are chosen in ways to minimize the interference, and hence to increase the downlink system capacity. When the interference is mitigated, the links can operate in the high SINR regime. This enables the cellular network to enjoy the great spectral efficiency improvement associated with using multiple RREs. Moreover, by using the multiple coherent transmissions, the cell-edge user throughput will be enhanced. Figure 5 shows JP in the DL. JP requires the exchange of UE data among RREs as well as UE channel information and consequently, requires significant backhaul resources; high requirements in terms of signaling and measurements, as well as high speed links or dedicated radio links are needed [24]. In [22] a JP scheme has been proposed and it has been shown that this scheme can bring significant gains to both the average cell throughput and the cell-edge user throughput.



**Figure 5: Joint Processing CoMP**

#### 4.1.1.2 Dynamic Cell Selection (DCS)

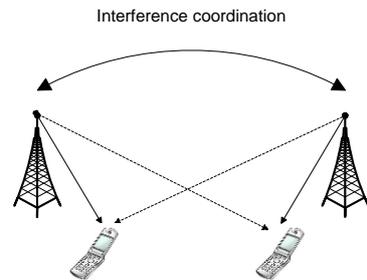
In this approach, the data is transmitted from a single RRE. However, the decision of which RRE should transmit is done jointly. For example, the RRE with the minimum path loss could be selected through fast scheduling. Figure 6 illustrates the DCS idea. The data must be available at all cooperative RREs, but only the selected one sends the data, and the others will be muted. Since; the best RRE is selected and also the UE does not receive interference from the other neighbouring RREs, the SINR will be improved and the throughput will be enhanced.



**Figure 6: Dynamic Cell Selection CoMP**

#### 4.1.1.3 Coordinated Scheduling (CS)

In this case, a transmission to a scheduled UE is performed by a unique RRE (each UE receives the data from a single RRE), see Figure 7 for reference. But; the RREs coordinate their transmissions using scheduling and transmission weights that are jointly adapted for all UEs in order to reduce the unnecessary interference. So, the cell-edge user throughput can be improved due to the increase in the received SINR. The basic difference between this approach and the DCS is that it is not based on path-loss. It has many different algorithms for scheduling so as to reduce the interference [24].



**Figure 7: Coordinated Scheduling CoMP**

### 4.1.2 CoMP Reception Schemes

In CoMP reception in the uplink (UL), the physical uplink shared channel (PUSCH) is received at multiple cells. In this case, maximal ratio combining (MRC) is used at multiple RREs. CoMP has reception schemes

such as interference rejection combining and coordinated scheduling reception. In [24], the cell throughput and cell edge user throughput performance were evaluated for CoMP reception schemes.

#### 4.1.2.1 Interference Rejection Combining (IRC)

In this approach, multiple UEs transmit the PUSCH simultaneously using the same RB; however, received weights are generated so that the received SINR or signal power after combining at the central BS is maximized. The minimum mean squared error (MMSE) or zero forcing (ZF) algorithms are typically used to combine the received PUSCHs at multiple cell sites. Cell-edge user throughput is improved due to the increase in the received signal power [24].

#### 4.1.2.2 Coordinated Scheduling Reception

In this case, only one UE transmits the PUSCH using an RB based on the coordinated scheduling among cells in CoMP reception. Using this approach, the cell-edge user throughput will be improved as shown in [24].

## 4.2 CoMP Resource Allocation Schemes

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Finding an optimal RA for CoMP schemes so as to maximize the sum rate is a very complicated problem. Hence, many suboptimal strategies have been proposed.

### 4.2.1 Downlink CoMP Schemes

CoMP appears as a promising technology to boost system throughput and to allow for an efficient RA. In [26], a model was proposed that addresses the downlink of a CS system. The model is as follows: each eNB has several geographically distant RREs. All signal processing is accomplished at the eNB. A group of adjacent RREs are called a group cell, and they serve UEs within their coverage area. An SINR matrix is formulated for all available RBs, the row vectors denote user flags and the column vectors denote carrier flags. Elements in the matrix denote the SINR value of a certain user over a certain subcarrier. The RB is assumed to be  $K$  subcarriers. The maximum consecutive  $K$  elements in the SINR matrix are chosen. Assume those elements are in the  $i$ th row and span the  $j$ th through the  $(j+k)$ th columns. This means that the  $i$ th UE will be allocated the  $j$ th through the  $(j+k)$ th subcarriers. After this allocation step, those elements will be cleared to zeros in the matrix until the UE releases those subcarriers (RB).

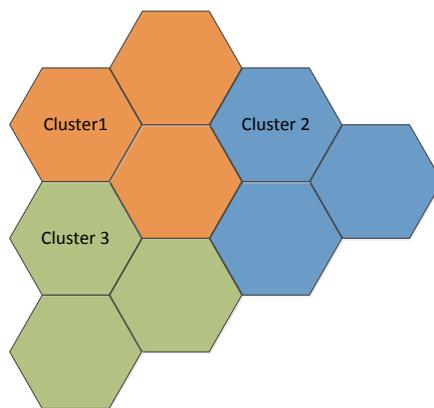
Although simulation results in [26] showed that this technique provides high gains in terms of throughput and reduces the blocking probability, this technique does not maintain fairness among users; For example, if a certain user has a very good channel, all subcarriers (RBs) might be allocated to him/her and the other users will not get a chance to be served. Moreover, since the throughput is calculated as a sum rate, then it will never show the exact distribution of RBs among users. Consequently, a necessary update to this technique is to limit the number of RBs allocated to each user to a certain threshold. By this, other users will get a chance to be served even if they face bad channels.

In [27], RA algorithms that exploit coordination in the DL of CoMP systems to improve system throughput have been proposed. Spatial multiplexing techniques have been applied for joint data transmission. In particular, Space Division Multiple Access (SDMA) and precoding techniques have been used to achieve throughput gains by exploiting the spatial degrees of freedom. The scheduling algorithm proposed was for JP CoMP systems in which users are multiplexed via SDMA schemes. In such systems, the transmission quality considerably degrades if users with spatially correlated channels are to be served over the same RB. Hence, the target of the work presented in [27] is to serve UEs that are highly correlated over different RBs so as to reduce interference. The approach presented uses zero forcing SDMA precoding schemes by deciding, for

each RB, which users are to be served to maximize the performance. It was shown that quite high throughput gains are achieved through the proposed RA algorithms.

In [28], carrier assignment in the DL JP CoMP has been investigated through the use of Carrier aggregation (CA). Carrier assignment problem has been abstracted into a graph coloring problem, and an improved color-sensitive graph coloring (ICSGC) algorithm has been proposed to find out a suboptimal solution. The ICSGC algorithm has shown high gains in terms of total throughput.

In [29], a JP CoMP in the DL is proposed where the BSs are grouped together in a static cluster. Several cluster strategies are investigated as well. Results have been provided for various system loads for different static cell clustering approaches. An example to a static cell clustering is shown in Figure 8. In this example each cluster consists of three hexagonal cells. It has been assumed that each UE belongs to only one cluster and it is served by all BSs within the same cluster. The model addressed assumes that there is no coordination between clusters.



**Figure 8: Static Cell Clustering Example**

The model proposed in [29] is a centralized model, where there is a central scheduler available in each cluster. The central scheduler in each cluster has the knowledge of the CSI of all UEs being served by the same cluster and it is responsible for managing all resources of the cluster. Therefore, one of the cells of the cluster is preconfigured in the proposed architecture as master cell. All other cells within the cluster act as slaves. Once the central scheduler has allocated the resources to the scheduled UEs, the information of the resource allocation is distributed to the rest of the BSs. The results show that the JP CoMP with static cell clustering can really enhance the system throughput significantly.

In [30], a DL JP CoMP transmission approach of an LTE-A operating in real time has been implemented and evaluated. Since the first requirement of JP CoMP is that the physical layer and radio front-ends are tightly synchronized, a precise clock reference has been obtained from the global positioning system (GPS). Many features besides clock synchronization have been addressed, such as; synchronous data exchange between the base stations; cell-specific pilots; feedback of multi-cell CSI; and precoder design. The proposed model consists of a group of BSs forming a cluster in which each BS in the cooperation cluster has the same CSI and data available, and it can compute independently from other BSs. In order to evaluate the proposed trial, Interference-limited transmission experiments have been conducted using optimum combining with interference-aware link adaptation and cross-wise interference cancellation between the cells. It has been proved that JP CoMP can improve the total throughput in real implementations.

#### 4.2.2 Uplink CoMP Schemes

In [31], a heuristic approach for a model of an UL transmission of a multi-cell system has been studied. Its objective is maximizing the sum rate subject to specific power constraints as well as minimizing the total power needed to meet a sum-rate target. Those two objectives are achieved by optimizing the SINR targets

in multiple cells so as to minimize the total power and also to maximize the sum rate. Setting SINR targets is an efficient mean to control fairness and multi-cell throughput performance. Also there is no delay due to setting the SINR targets since CoMP systems allow the adjustment of these SINR targets on a time scale that is similar to scheduling and power control. Significant gains of the joint SINR target and power optimization is achieved depending on the degree of fairness imposed.

In [32], a heuristic UL scheduling scheme in CoMP has been proposed, in which UEs are connected to RREs deployed throughout the cell and a central BS. Results show that systems with RREs achieve better throughput than systems with conventional BS while allowing edge users better chances of accessing the resources.

In [33], a real implementation of Uplink CoMP has been introduced. Many challenges have been addressed such as multi-cell synchronization and multi-cell channel estimation. The model addressed is an outdoor deployment of two cooperating BSs and two UEs. It has been proved that the Uplink concept do in fact yield significant spectral efficiency gains.

## 5 Proposed Coordinated Resource Allocation Scheme in CoMP

This section presents a sophisticated Resource Allocation (RA) technique based on Signal-to-Leakage-plus-Noise-Ratio (SLNR) for LTE-Advanced. In addition, it compares the proposed strategy to the RA based on Signal-to-Interference-plus-Noise-Ratio (SINR) strategy. This report provides a comprehensive comparison between two RA strategies; the first strategy is our proposed scheme based on SLNR, and the second one is the scheme addressed in [27] based on SINR. Both strategies are analyzed through simulations. Both algorithms take advantage of coordination in the downlink of CoMP system to control the interference and improve the overall performance. Furthermore, it discusses the complexity evaluation for both strategies. It is shown that the RA strategy based on SLNR achieves an improved performance compared to [27].

### 5.1 System Model

The CoMP cell model consists of one eNB,  $M$  RREs under its control, and serves  $K$  UEs. A CoMP cell paradigm is shown in Figure 9. There exist  $N$  Resource Blocks (RBs) in the system and each of them may be assigned to one or more UEs. Uniform Power Allocation among RBs is considered and the overall transmit power available on each RRE  $p$  is uniformly divided among the  $N$  RBs. So, the power allocated to each RB is simply:  $p_n = p/N$ .

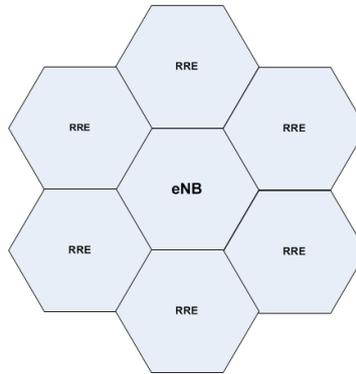


Figure 9: CoMP Cell Paradigm

In this system, the major link measurement considered is the Signal-to-Leakage-plus-Noise-Ratio (SLNR) of the UEs in the system. The SLNR  $\beta$  considered at UE  $k$  can be expressed as:

$$\beta_k = \frac{P_n |h_k w_k|^2}{\sum_{k' \neq k}^K P_n |h_{k'} w_k|^2 + |\eta_k|^2}, \quad (7)$$

where  $k \in \{1, 2, \dots, K\}$ ,  $h_k$  is the channel vector (i.e. Which models the connection between the  $k^{th}$  UE and all  $M$  RREs of the CoMP cell),  $w_k$  is the weighting vector for the link connecting all the RREs of the CoMP cell and the  $k^{th}$  UE, and  $\eta_k$  is the Additive White Gaussian Noise.

In [27], CS-CoMP model was also studied; the major metric considered was the SINR measured at each UE. In contrast, our proposed model considers SLNR as a major metric, which greatly reduces complexity and so it is considered more suitable for real cellular systems.

### 5.2 Efficient Suboptimal RA strategy

For each CoMP cell, the scheduler will select a group of UEs to be given data over the same RB. The group of UEs sharing the same RB will be called UE-set ( $S$ ). Scheduling decisions can be taken to determine dynamically which UEs can simultaneously use the same RB.

- The weighting vector  $w_k$  will be set in order to maximize (7).
- The UE-set will be formulated in the following manner:

- a. The UE with maximum SLNR will be added initially to the UE-set.

$$s = \arg_k \max \{ \beta_k \},$$

- b. Leakage value vector from UE-set in the direction of the rest of UEs will be calculated.

$$L_{s,s'} = |h_{s'} W_s|^2, \quad s' \notin S$$

- c. The UE with the smallest amount of leakage will be added to the UE-set.

$$S = S \cup \arg_{s'} \min \{ L_{s,s'} \}$$

- d. Repeat from step b till the minimum overall leakage value reaches a certain threshold or repeat from step b till the number of UEs in the set reaches certain value.

### 5.3 Complexity Evaluation

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When it comes to complexity, SLNR strategy is way enhanced than SINR strategy. Maximizing the SLNR metric for each user simply needs  $m$  iterations, where  $m$  is the number of RREs. This is for the reason that maximizing the SLNR for each user is an **independent** process (i.e. each user has only  $m$  possibilities, and its SLNR value is not function of other users). Consequently, the complexity of maximizing the SLNR metric for each user is of order  $m$ .

On the contrary, maximizing the SINR metric is very exhaustive process, as the SINR for each UE cannot be optimized independently. This is because the interference at each UE is **dependent** on the other UEs' links. Thus, to optimize the SINR metric for a certain UE, it should try linking with all possible links ( $m$  possibilities). Moreover, for each possibility it should try linking other users with all possible links. Accordingly, the complexity of maximizing the SINR metric for each user is of order:

$$\begin{aligned} \text{Complexity order} &= \frac{m!}{(m-k)!}, & m > k \\ &= m * \frac{(k-1)!}{(k-m)!}, & \text{otherwise} \end{aligned}$$

In [27], the SINR metric was not maximized (because as described above it is an extremely complicated process). However, the weights corresponding to the maximum channel gain have been selected, and then the SINR metric has been computed.

### 5.4 Stopping Criteria

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Choosing the stopping criteria is extremely important step as it directly reflects on the throughput. So to guarantee the throughput enhancement the following stopping criteria was investigated.

#### 5.4.1 The Optimal SLNR Threshold

The optimal SLNR threshold is the value that is responsible for terminating the RA strategy as described in the previous section. The relationship between the optimal SLNR threshold and the number of UEs per cell is assumed to be linear. The precise equation is provided in the Appendix.

The RA strategy based on SLNR assures stopping when achieving nearly the highest throughput per RB. On the other hand, the RA strategy based on SINR terminates when the throughput decreases which does not assure achieving the highest value. For example, consider the scenario where three users are grouped and if a

fourth UE is added, the total throughput will decrease (SINR strategy will come to an end here). However, adding the fourth UE may be useful if by adding a fifth one; the total throughput will increase more than it was when the group had only three UEs. Such scenario is expected to occur. As for adding a new UE to the group sharing the same RB, there is a throughput loss as well as a throughput gain and both values depend on the channel environment.

#### 5.4.2 Marginal Utility

In this method a utility function is defined as the log function. In this stopping approach, a condition is checked so as to allow sharing the RB (to allow grouping). This condition is:

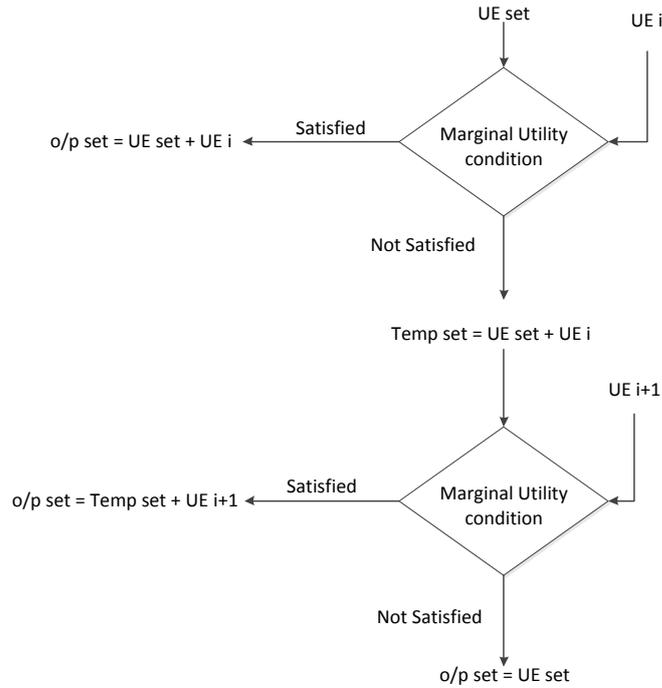
$$U_{UES_{new}} + U_{UE_{new}} \geq U_{UES_{old}} \text{ ,} \quad (8)$$

In which,  $U_{UE_{new}}$  is the utility function of the UE that is recently added to the set,  $U_{UES_{new}}$  is the Utility of UEs previously in the group computed after adding the new UE, and  $U_{UES_{old}}$  is the Utility of the set computed before adding the new UE. If equation (8) is satisfied then the UE will be added; otherwise the grouping will be terminated.

This approach is efficient and provides high overall throughput gains but it doesn't take into consideration the case when the throughput drops at once while it has not reached the maximum throughput (critical peak that is supposed to be reached) and so the algorithm might terminate before reaching the highest achievable throughput.

#### 5.4.3 Marginal Utility with look-ahead criteria

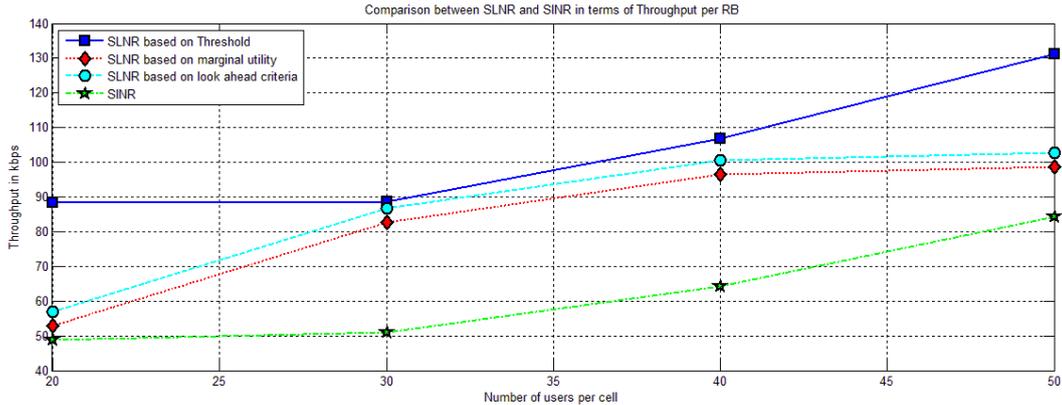
In this method, the same marginal utility condition is used. However, if the condition is not fulfilled, there is an extra possibility to add the UE to the set via constructing a temporary set that includes the original set plus  $UE_i$  (where  $UE_i$  is the user that may or may not be added to the set. Then another user ( $UE_{i+1}$ ) will be selected and the marginal condition will be checked for the temporary set with  $UE_{i+1}$ . If it is still not satisfied then the algorithm will terminate with the original set (not the temporary). However, if the condition is fulfilled then the algorithm will terminate with a new set which is the temporary set and  $UE_{i+1}$ . The algorithm is described in more details in Figure 10.



**Figure 10: Marginal Utility with Look-ahead Flow Chart**

## 5.5 Simulation Results

The proposed strategy achieves high throughput gains as shown in Figure 11.



**Figure 11: Throughput Comparison for Different Stopping Approaches**

As shown, The RA strategy based on SLNR with threshold presents performance about an average of 50% higher than that of the SINR strategy. It is basically due to the perfect choice of the stopping threshold and also for the reason that the weights are determined more accurately so as to maximize the SLNR metric for all UEs. SLNR strategy with marginal utility with look-ahead criteria presents a gain of an average of approximately 45% higher than that of the SINR strategy, and finally SLNR strategy based on marginal utility only presents a gain of an average of approximately 35% compared to that of the SINR strategy.

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