摘要

LTE 為 3GPP 制訂的標準，是目前 4G 網路最具前景的科技之一，其目標為提供高速資料傳輸、彈性頻寬使用、減少傳輸延遲時間、以及支援高速移動傳輸等技術性服務。為了達成此目的，LTE 在下行系統和上行系統分別使用 OFDMA 與 SC-FDMA 的編碼技術，使它能突破傳統無線網路技術上的限制，晉升為 4G 網路的一員

為了達到提升系統效能與使用者多樣性增益的目的，在 LTE 下行系統中是採行傳統的通道相依排程演算法(CDS)，此方法會收集所有使用者的通道狀況資訊，之後讓通道較佳的使用者能優先分配到資源區塊(RB)來傳輸封包。然而因為 SC-FDMA 有兩大先天的限制：第一個為資源區塊配置連續性的規定，第二個為所有配置區塊需使用相同的編碼技術，因為這兩個限制使得通道相依排程演算法並不適用於 LTE 上行系統。在此論文中，我們首先考量此兩大先天限制，提出在 LTE 上行系統中資源分配問題的表示式，並找出其最佳可行解。由於此問題已經被證實是一個 NP-hard 的問題，為了降低計算複雜度，我們進而提出兩個啟發式的演算法，嘗試去逼近問題的最佳解。模擬結果顯示我們的方法不僅增加了系統的資料總吞吐量，減少了傳輸延遲的時間，同時也降低了拿不到傳輸資源的使用者比例。

Abstract

Long Term Evolution (LTE), one of most promising technology for 4G mobile networks, is the latest standard of 3rd Generation Partnership Project (3GPP). The goal of LTE is to provide high data rate transmission, flexible frequency usage, smaller latency, and supportable transmission in high mobility. To achieve this, LTE employs the modulation technique by OFDMA in downlink and SC-FDMA in uplink, breaking the technical limitations of traditional wireless, and makes itself be the one of members of 4G mobile networks.

To increase the cell throughput and multi-user diversity gain, channel dependent scheduling (CDS) is implemented for the OFDMA-based multi-user scenario to allocate resource blocks (RBs) to users experiencing better channel conditions. Nevertheless, CDS may not perform well in SC-FDMA due to its two inherent constraints－one is contiguous RB assignment and the other is robust modulation and coding mode. In this paper, the formulation of resource allocation for a SC-FDMA system upon considering two inherent constraints is proposed. Since the optimization problem of resource allocation in SC-FDMA is NP-hard, we further propose two heuristic algorithms to find feasible solutions. We evaluate the proposed formulation and heuristic algorithms by conducting simulation. The simulation results show that our methods achieve significant performance improvement in not only system sum throughput, but also transmission delay and outage ratio.

致謝

時間過得很快，轉眼間已到了寫論文和口試的日子。回首碩士班兩年來的點點滴滴，我很高興我把握了生活中的每分每秒，努力至最後一刻，只求為我大學四年的渾渾噩噩做一個遲來的彌補。

我很感謝我的老師，趙禧綠教授，從我們碩零暑假起，碩一修課、找尋題目，碩二潛心研究、會議投稿，一直到現在畢業前夕完成論文、通過口試，老師在各方面不斷地給予我們刺激、嘗試、挑戰以及鼓勵。或許在其他人的眼中我們是辛苦的，但我知道這一切終會是值得的，而我也願意相信。如今兩年過去了，我從懞懞懂懂的新生轉變為能獨當一面的老鳥，在我們即將走出學校進入社會之際，我想向老師說一聲：「謝謝您，老師，您辛苦了。」

另外，我也要謝謝實驗室裡所有的學姐、同學以及學弟，雖然我與大家相處的時間很少，但是在我碰到麻煩的時候你們總是給我很多的幫助，讓我可以沒有後顧之憂地努力做研究，順利完成碩士學位。沒有你們的付出，我想我是很難一個人獨力完成這麼多事情的，所以我在此由衷地感謝你們，也希望你們未來會有好的開花結果。

最後我要感謝交通大學，謝謝學校給我一切學習所需要的資源。謝謝工程三館，給我一間上課、寫程式、開會的會議室和實驗室；謝謝體育館，讓我能發揮我的排球專長，大專聯賽、梅竹賽，盡情揮灑汗水在每一刻每一個角落；謝謝綜合一館，無論是學期中或是寒暑假，兩年來幾乎有一大半時間都是在綜一度過，不管是打工還是做研究。出國前的最後一次下午打工，看著夕陽下寧靜的奶油廚房和空蕩蕩的棒球場，我喜歡學校這樣平靜的環境，我想畢業後我會想念這一切的。

天下沒有不散的宴席，終於還是走到了離別的這一步。就像那部電影裡頭講的，到了離別的那一刻，一草一木，一花一樹，都顯得特別的捨不得。人聚人散，花開花落，你我都只是這個地方的過客，在時間的洪流裡，我們因命運安排而相遇，也因命運安排而各奔東西，交集的時間或長或短，回憶的捲軸上卻也是增添一筆。

七年，兩千多個日子的旅程，我想我總算是沒有虛度。雖然這條路我走得辛苦，走得並不得意，但是我很滿足，因為我不是一個人，有好多好多的人陪我一起走，所以我並不孤獨。只是看似沒有盡頭的路，似乎也走到了分岔路口。是時候該說再見了，對於我來說，短暫的交集或許不能造就永恆，但是謝謝你們大家曾經豐富了我的生命，讓我這七年還算不曾白活。謝謝我所有的好朋友，再見了各位，再見交大。

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Chapter 1 Introduction

The Long Term Evolution (LTE) is the one of most important communication technique researches of 3rd Generation Partnership Project (3GPP) and has been finalized in 3GPP standardization in recent years. The specifications related to LTE are formally known as Evolved Universal Terrestrial Radio Access (E-UTRA) in early drafts, but are more commonly referred to LTE by now. Providing higher data rate (peak data rate 100.8 Mbps for downlink while 86.4 Mbps for uplink using single antenna), more flexible spectrum (1.4, 3, 5, 10, 15 and 20 MHz with FDD and TDD mode), smaller latency (5ms for small packet and 100ms for device wake-up) and better performance with supported mobility (0~350 km/h), LTE is well-prepared to meet user expectation in a 10-year perspective and beyond [1][2].

To achieve these objectives, Orthogonal Frequency Division Multiple Access (OFDMA) has been selected as the downlink (DL) access scheme for LTE cellular systems. Rather than transmitting a high-rate stream of data with a single carrier, OFDMA makes use of a large number of closely spaced orthogonal subcarriers that are transmitted in parallel which providing higher flexibility and lower complexity [3]. However, OFDMA is not suitable to be the uplink (UL) access scheme due to its high Pick to Average Power Ratio (PAPR) which consumes much more energy and shorten battery lifetime at user equipment (UE). Therefore, another modulation scheme — Single Carrier Frequency Division Multiple Access (SC-FDMA), is adopted for LTE UL transmission. Comparing to OFDMA, SC-FDMA performs a Discrete Fourier Transform (DFT) prior to the conventional Inverse Fast Fourier Transform (IFFT) operations, which spreads the data symbols over all the subcarriers and produces a virtual single-carrier structure [4]. This modification not only reduces power consumption significantly, but also keeps the advantages of OFDMA such as high spectral efficiency and robustness to multipath fading.

1.1 Resource Block and Scheduling

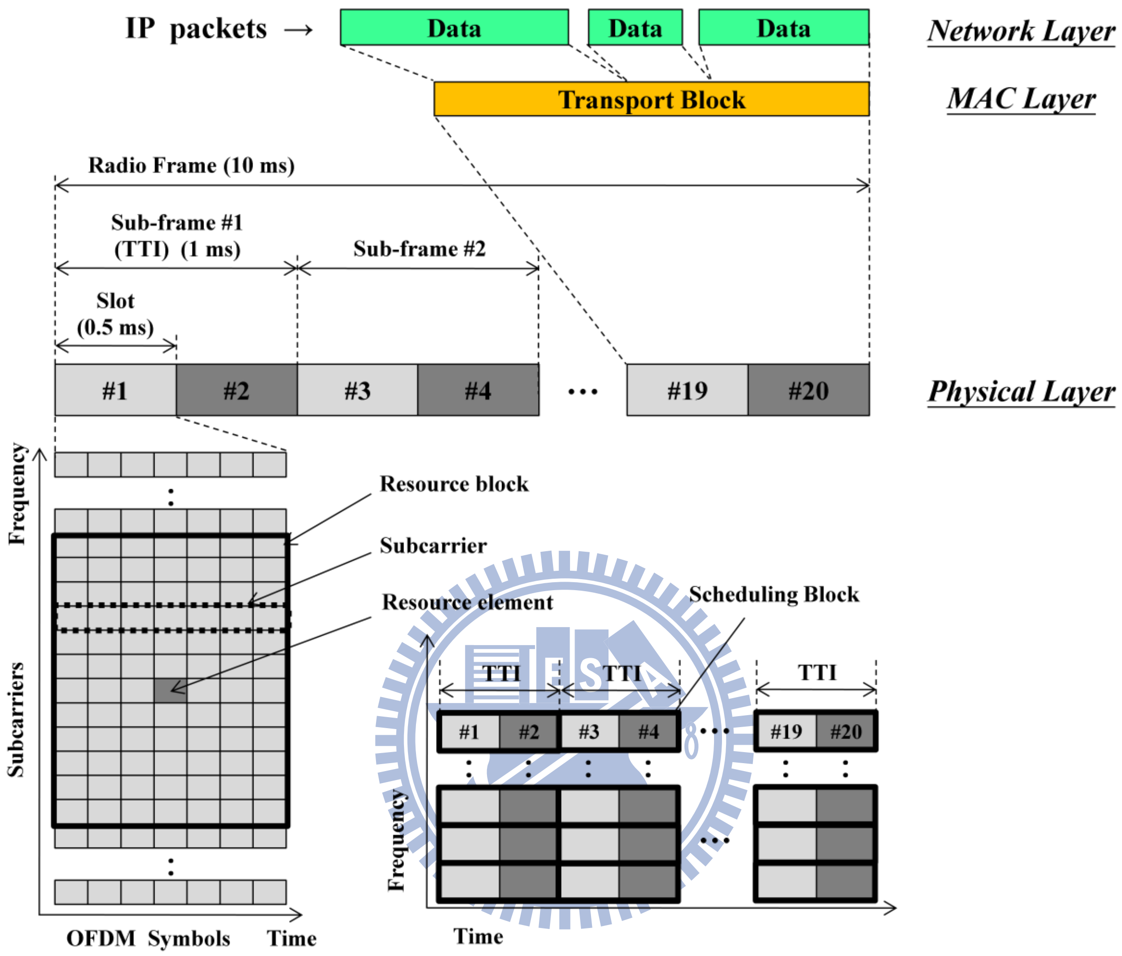

Figure 1. Resource Block and Radio Frame structure

3GPP claimed that the serving area in LTE will cover up to 100 km [5]. With increasing number of UEs and limited bandwidth, the resource allocation problem is becoming a hit. 3GPP defines some components related to resource allocation in an LTE cellular system and shown in Fig. 1. A full frame is 10 ms but we normally think in terms of the 1 ms sub-frame, which is the entity that contains the Transport Block (TB) [6]. A TB is used to carry multiple IP packets from network layer and passed to physical layer. The available spectrum in physical layer is divided into Resource Blocks (RBs), and a TB will be mapped to several

RBs by scheduler. Each RB consists of 12 adjacent subcarriers in frequency domain and either 6 or 7 OFDM symbols in time domain according to the normal or extended CP is employed. Two consecutive RBs form a single Scheduling Block (SB), which is the basic unit of bandwidth resource to be allocated. The duration of SB equals the length of a sub-frame and represents a scheduling period, named Transmission Time Interval (TTI) [7]. In the later part of thesis, we just use RB instead of SB. An OFDM symbol is called Resource Element (RE), which can carry from one to several data bits depending on which Modulation and Coding Scheme (MCS) mode the corresponding RB employs. Since a RB is the smallest allocated unit, we define the sum data bits of all REs within a RB as “RB capacity”.

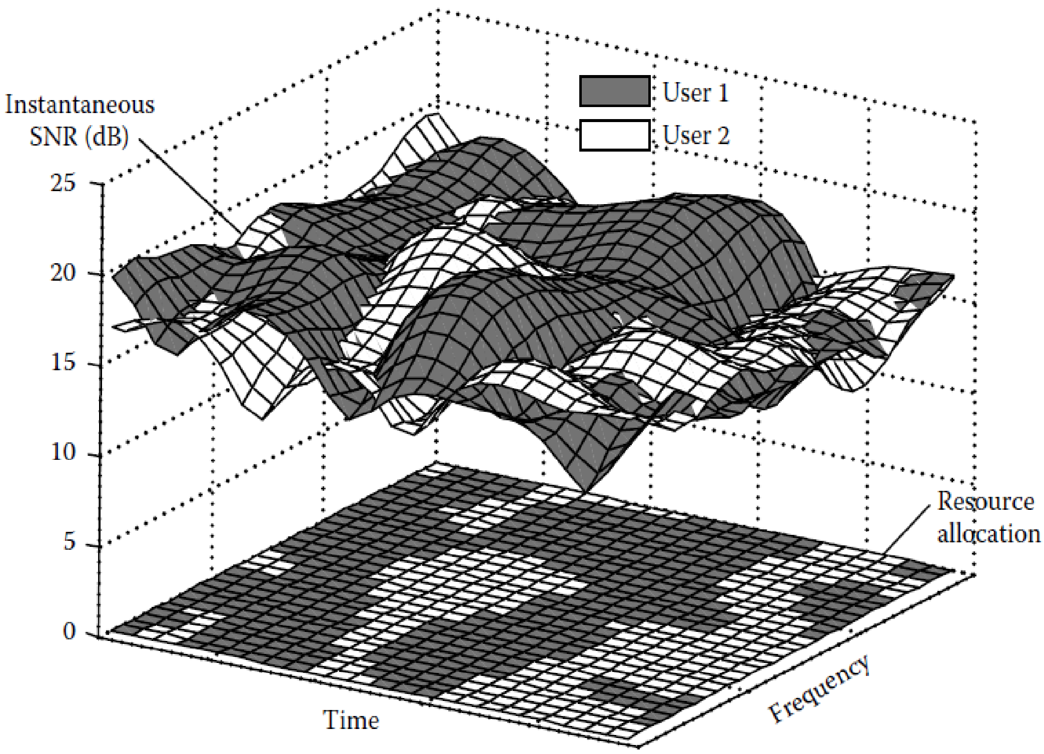

Figure 2. Resource allocation by Channe-Dependent Scheduling

In each TTI, the Packet Scheduler (PS) at base station, as known as eNodeB in LTE, makes a scheduling decision on how to allocate RBs according to Sounding Reference Signals (SRSs) from all serving UEs. The SRS is used at the eNodeB to extract the instantaneous channel state information (CSI) of the eligible RBs of UE, which the function is similar to the Channel Quality Indicator (CQI) in DL [8]. The better channel condition of a RB refers to the higher RB capacity can achieve. Since the channel conditions are distinct among different RBs and uncorrelated for different UEs, PS will assign UE a portion of bandwidth that is in its favorite conditions. This mechanism, as known as Channel Dependent Scheduling (CDS), is illustrated in Fig, 2. CDS assists the system to achieve the ambitious goal of multiuser diversity in a frequency selective fading environment.

1.2 Problem Statement

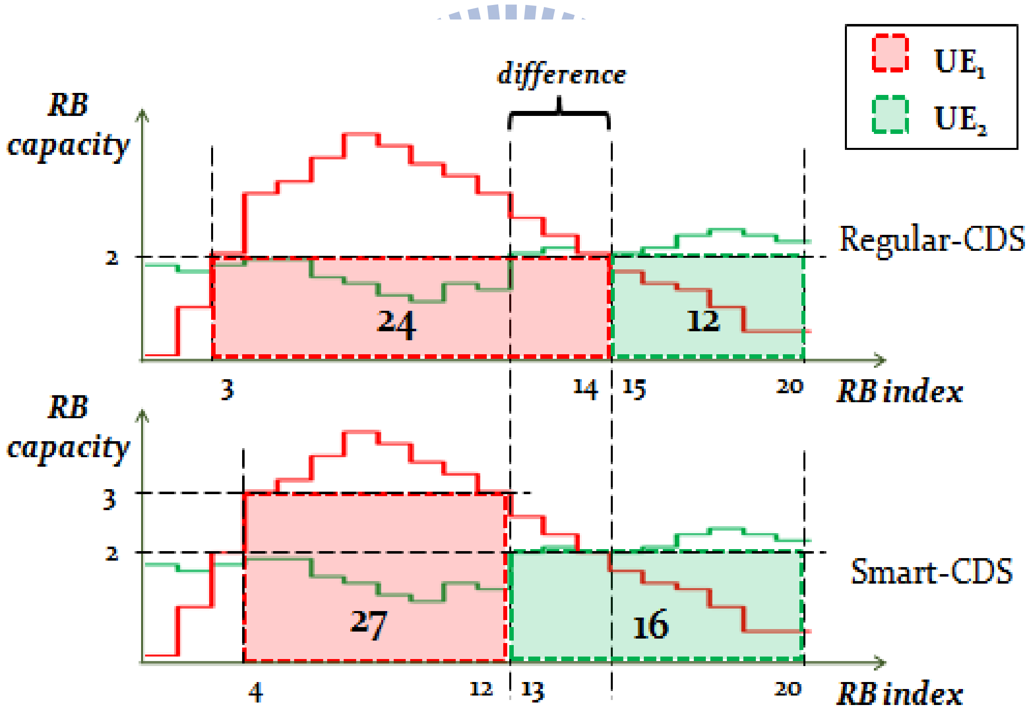

Figure 3. Regular-CDS vs. Smart-CDS

In an OFDMA-based multi-user system, RBs are allocated to the UEs that experience better channel conditions to maximize the multi-user diversity gain and increase the cell throughput. Therefore, CDS is well suitable for the LTE DL subsystem. However, for the LTE

UL subsystem, RBs are limited to be allocated to a single UE in a contiguous manner due to the requirement of SC-FDMA [2]. This constrait significantly reduces the freedom in resource allocation. In this thesis, we name this constraint as "contiguous RB assignment". Also, another constraint which also affects the throughput performance of UL by resource allocation is that a UE must utilize the same MCS mode on the allocated RBs [9]. Therefore, a UE can only utilize the lowest feasible RB capacity in all allocated RBs. We name this constraint as "robust MCS mode". How the constraint of contiguous RB assignment and robust MCS mode affects the throughput performance is shown in Fig. 3. In Fig. 3, the x axis is RB index and y axis is RB capacity. The two curves are the envelopes of the best RB capacity for UE_1 and UE_2 for all observed RBs, respectively. Since, UE_1 experiences better channel conditions among $RB_3 \sim RB_{14}$ than UE_2, these 12 RBs are allocated to UE_1 by performing Regular-CDS. On the other side, by considering both the constraints and sum throughput maximization, $RB_{15} \sim RB_{20}$ are allocated to UE_2. RB_1 and RB_2 are unused. The sum throughput performance of the Regular-CDS is 2*(20-3+1) = 36. Let's consider another feasible allocation as indicated Smart-CDS in Fig. 3. $RB_4 \sim RB_{12}$ and $RB_{13} \sim RB_{20}$ are allocated to UE_1 and UE_2, respectively. This allocation scheme benefits both UEs higher sum RB capacity. The sum throughput performance of Smart-CDS will be enhanced to 3*(12-4+1) + 2*(20-13+1) = 43. The major advantage of Smart-CDS algorithm is that UEs consume fewer RBs to deliver data, thus the channel utilization as well as the sum throughput are improved. Throuhgh above observation, we are inspired to look for a feasible way to maximize sum throughput performance in a cellular system with both two inherent constraints considered.

1.3 Organization

The remainder of thesis is organized as follows. The related works are presented in chapter 2. The system model of the LTE UL subsystem and the problem formulation are described in chapter 3. Two heuristic scheduling algorithms are proposed and detailed in chapter 4. The performance evaluation results are presented and discussed in chapter 5. Finally, the conclusions and future work are described in chapter 6.

Chapter 2 Related Work

The "contiguous RB assignment" constraint is a critical issue in LTE UL subsystem. Nevertheless, OFDMA has no such requirement which means the resource allocation problems are less challenge, most of the existing works concerning CDS usually focused on LTE DL subsystem [10][11][12][13][14]. Although these proposed algorithms indeed have great improvement on sum throughput performances, they may not be well suitable to UL. We first investigate how other scheduling methods associated with Regular-CDS to maximize the sum throughput for a cellular network in LTE UL subsystem, and then we give a brief summary to point out the drawbacks of those works.

Calabrese et al. in [15] propose a tree algorithm for the case that all resources are equally shared among UEs. The author derived each Resource Chuck (RC) contains equal amount of RBs and each UE can only be assigned one specific RC. This paper pointed out that the matrix algorithm, by which it cares about the highest metric of RC only, is not good to overall system throughput, so the second highest metric of RC is also considered and construct a binary tree instead of a matrix. Then the resource allocation is performed by searching and choosing the path, within the tree, with the highest sum value of global metrics. Fig. 4 illustrates the idea of the algorithm. The left diagram shows the matrix algorithms while the right diagram shows the tree algorithm. With more exhaustive search by proposed tree algorithm, the performances will globally improve.

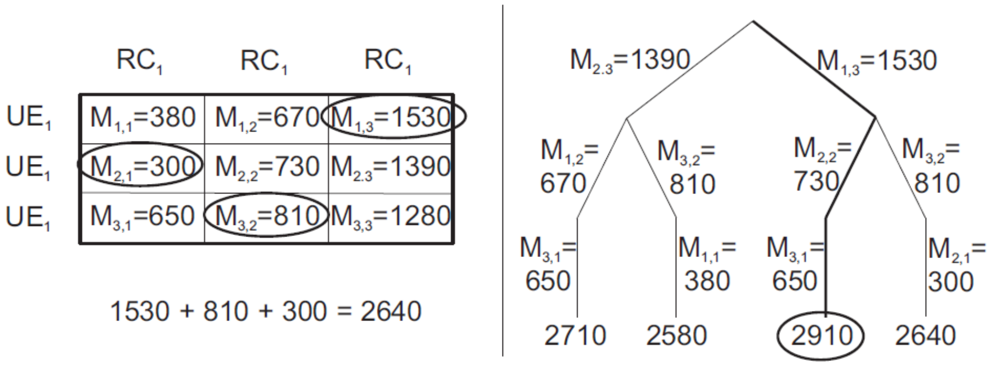

Figure 4. Matrix algorithm vs. Tree algorithm

Three channel aware scheduling algorithms, First Maximum Expansion (FME), Recursive Maximum Expansion (RME), and Minimum Area-Difference to the Envelope (MAD^E), are proposed in [16]. The resource allocation examples of the three algorithms are shown in Fig. 5. Each slice in frequency domain represents a RB while the metric indicates how much capacity a RB can achieve. The color blocks at the bottom of each diagram indicate who gets the portion of RBs to use. Despite of the different final results, general speaking, the scheduler scans all UE-RB pairs first and then constructs an "envelope" on those suitable pairs to reach the highest system throughput.

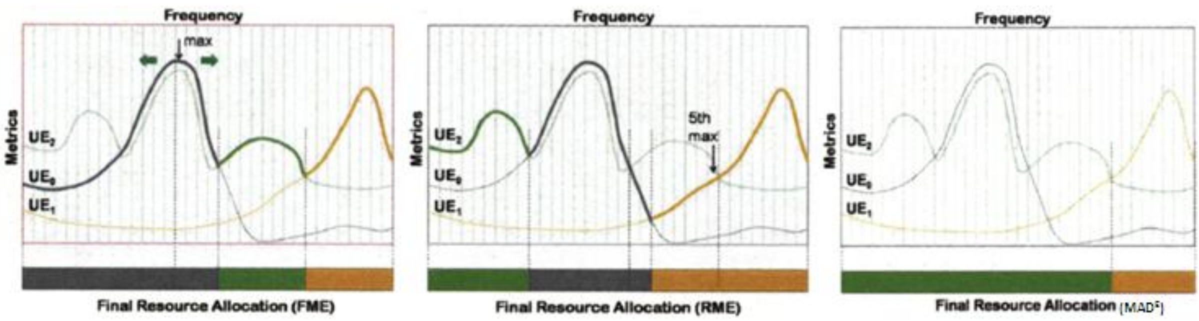

Figure 5. The resource allocation examples of RME, FME and MAD^E

The authors in [17] optimized the system throughput by employing a utility function. They first constructed the utility function by considering UE's throughput which is calculated through Shannon capacity formula with SNR estimations. Then the authors use the gradient of the utility function as input and applied the Heuristic Localized Gradient Algorithm (HLGA) to do resource allocation. This algorithm is mainly structured from the gradient algorithm for the scheduling but adopts a heuristic approach in the allocation of the scheduled resources. In addition, HLGA will check the buffer status of each UE. If a certain UE gets too much useless RBs, the "pruning" scheme will get started. By means of removing the extra resources and allocating them to other UEs in need, the overall utility of system will be further improved. Fig. 6 shows the pruning example. In this case, UE_1 got an extra RB space comparing to its buffer status, so HLGA will prune the extra RB from UE_1 and allocate it to UE_2 if UE_2 needs. Note that the pruned RB can only assign to neighbor UE for not violating the contiguous RB assignment constraint.

Figure 6. Pruning example

In [18], the authors model the resource allocation problem in LTE UL subsystem as a bargaining game, and use game theory to find the solution to the problem. An optimal solution to the bargaining game in game theory is called "Nash Bargain Solution (NBS)". Consider that each UE is a player who wants to maximize its payoffs, or say throughput. Cooperation is assumed between players. Players should share the resources in an optimal way, and the corresponding resources should be the RBs within each TTI. The solution to the cooperative allocation problem can be solved by maximizing the Nash Product:

$$NashProduct = \prod_{k=1}^{K} (W_k(X_k) - T_k) \quad (1)$$

where X_k represents the fraction of resources allocated to player *k*, $W_k(X_k)$ corresponds to the payoff of player *k* when X_k is allocated to it, and T_k is the payoff of player *k* in the case where no agreement is reached in the bargaining problem. In the LTE scheduling problem, the player payoff is the throughput achieved, i.e. $W_k(X_k)$ = throughput, and $T_k = 0$ since no transmission occurs if no agreement on RB allocation is reached.

In [19], the weighted sum rate maximization problem was reformulated as a pure binary-integer program called set partitioning problem. This problem has the following generic form:

$$max\ C^T x \quad (2)$$

$$s.t.\quad Ax = 1_r \quad (3)$$

$$x_j \in \{0, 1\} \quad \forall j \quad (4)$$

where **A** is a constraint matrix, and should be replaced by the contiguous RB assignment constraint here. ***C*** is a reward weight vector, and the RB capacity will be suitable. ***x*** is the vector of optimization variables. There should be a number of possible ***x*** satisfying the above constraints, and the optimized ***x*** will maximize the capacity ***C***, namely maximize the system throughput. They also proposed a heuristic method to solve the maximization problem for reducing the time complexity.

All these existing works described above did a great job, and all of them have dealt with the resource allocation properly without violating the contiguous RB assignment constraint. Nevertheless, a common issue of those scheduling algorithms for LTE UL is that UEs are assumed to operate at different MCS modes in their allocated RBs. In other words, a UE can change its RB capacity per-RB basis. This is impractical since that the modulation function in physical layer can only select one MCS mode to apply on allocated RBs, and this is used to determine the size of TB coming from MAC layer [20]. For this reason, a UE should only use the supportable MCS mode, which means, the robust MCS mode, for all its allocated RBs. However, researchers usually ignore this constraint. This observation inspires us to design a new scheduling algorithm, Smart-CDS, upon taking both the constraints of contiguous RB assignment and robust MCS mode into consideration. Our objective is to maximize the sum throughput performance. In this thesis, we first formulate this scheduling problem, and we name the problem formulation as "Two-Bar Assignment (TBA)". We further propose two heuristic scheduling algorithms for the sake of reducing the computation complexity.

Chapter 3 Proposed Algorithm

In this chapter, we first describe the adopted LTE UL system. Then followed, we formulate the scheduling problem and propose two heuristic algorithms to solve the problem. We consider a cellular network which consists of a fixed serving eNodeB and *n* active UEs. The UL bandwidth of this cellular network is divided into *m* RBs. At each TTI, multiple contiguous RBs can be assigned to a single UE, while each RB can be assigned to at most one UE. A UE operates at the same MCS mode in all assigned RBs. Since channel conditions typically depend on channel frequencies, user locations, and time slots, each RB has user-dependent and time-varying channel conditions. We assume that the eNodeB has this information about all RBs of each UE so that it can derive the most appropriate resource allocation for the cellular network.

3.1 System Model

The objective of our resource allocation algorithm is to assign each UE contiguous non-overlapped RBs for maximizing the sum throughput performance. Due to the constraint of robust MCS mode, the total RBs assigned to a specific UE will form a rectangle, and we name this rectangle as "RB rectangle". To simplify this problem, we introduce a novel idea, ***Bar***, which is used to not only for the formulation clarity but also assist the resource allocation. This idea is illustrated in Fig. 7 and some parameters are shown in Table I. The RB rectangle for UE_i at TTI *t* is enclosed by two bars, one is Bar-start, and the other is Bar-finish. We define $x_i^s(t)$ and $x_i^f(t)$ as the IDs of RBs which are positioned by Bar-start and Bar-finish, respectively. Take an example in Fig. 7. We assume that all RBs from RB_α to RB_β are allocated to UE_i. Therefore, $x_i^s(t)$ and $x_i^f(t)$ are set to be **α** and **β**, respectively.

Since different UEs will have different RBs with their RB rectangles at TTI *t*, we define $S_i(t)$ as the set of assigned RBs of UE_i and $|S_i(t)|$ represents the number of RBs in $S_i(t)$. Also, let $\delta_{i,j}(t)$ and $r(S_i(t))$ be the channel signal-to-noise ratio (SNR) measured by UE_i in RB_j and the robust RB capacity in UE_i's RB rectangle that UE_i operate, respectively. It's not difficult to find that the width and height related to a RB rectangle of UE_i equal to $|S_i(t)|$ and $r(S_i(t))$, respectively. Therefore, the area of a RB rectangle can be determined accurately. Now the sum throughput maximization problem can be transformed to the sum areas of RB rectangles maximization problem. The problem formulation is then derived in following paragraph.

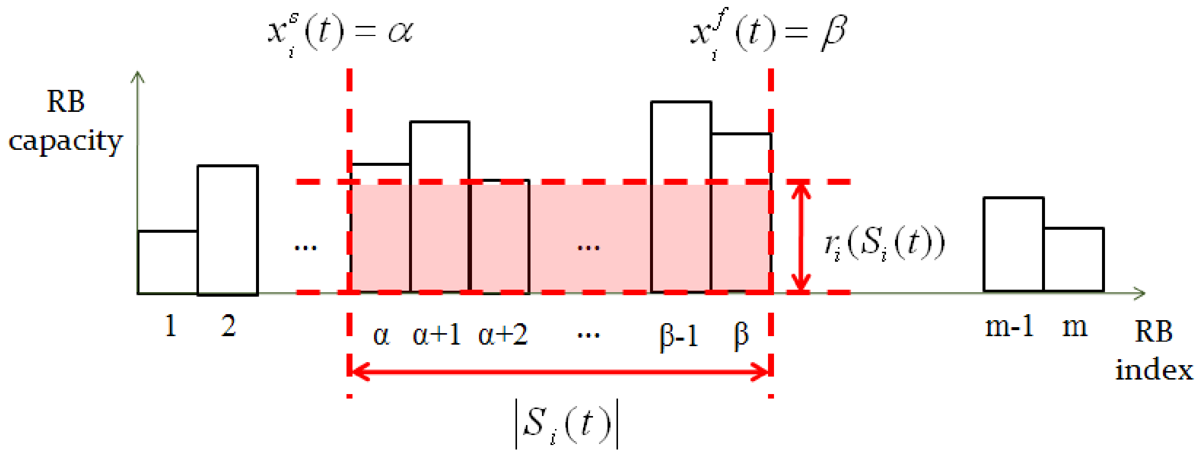

Figure 7. An illustration of RB rectangle, Bar-start, and Bar-finish

Table I. The definition of parameters in system model

Parameter	**Definition**
$x_i^s(t)$	Bar-start of UE_i, equaling the leftmost RB ID of UE_i
$x_i^f(t)$	Bar-finish of UE_i, equaling the rightmost RB ID of UE_i
$S_i(t)$	The set of assigned RBs within RB rectangle of UE_i
$\|S_i(t)\|$	The number of RBs in set $S_i(t)$
$r(S_i(t))$	The robust RB capacity of RB rectangle of UE_i

$\delta_{i,j}(t)$	The SNR value in RB_j of UE_i

3.2 Problem Formulation

Basically, a RB rectangle is a group of transmission bandwidth enclosed by Bar-start $x_i^s(t)$ and Bar-finish $x_i^f(t)$, so we can intuitively conclude that the value of $x_i^s(t)$ will be less than or equal to $x_i^f(t)$ if UE_i obtains at least one RB, otherwise $x_i^s(t)$ and $x_i^f(t)$ are set to 0. In addition, the number of allocated RBs $|S_i(t)|$ is also can be retrieved. Therefore, the relation between $x_i^s(t)$ and $x_i^f(t)$ as well as $|S_i(t)|$ of the RB rectangle can be expressed as follows:

$$\begin{cases} 1 \leq x_i^s(t) \leq x_i^f(t) \leq m, & if\ S_i(t) \neq \phi \\ x_i^s(t) = x_i^f(t) = 0, & otherwise \end{cases} \tag{5}$$

$$|S_i(t)| = x_i^f(t) - x_i^s(t) + 1 \qquad \forall S_i(t) \neq \phi \tag{6}$$

$$\sum_{i=1}^{n} |S_i(t)| \leq m \tag{7}$$

the equation (6) here implicitly implies the of contiguous RB assignment constraint for UE_i, and promise that all UEs in the scheduling procedure will not violate the requirement of SC-FDMA. Note that UE_i will not follow the equation (6) if $S_i(t)$ is empty. In this case, the width $|S_i(t)|$ should be equal to 0. Also, as shown in the equation (7), we need to guarantee that the total allocated RBs at TTI *t* would not exceed the supportable UL bandwidth.

In spite of the contiguous RB assignment constraint, the other inherent constraint, robust MCS mode, should also be followed. Since different RBs may support different MCS mod depending on channel conditions. For this reason, the height $r(S_i(t))$ of a RB rectangle would be the least RB capacity among all allocated RBs since this is the most supportable

MCS mode. At each TTI *t*, UEs report the instantaneous UL channel quality, as known as SNR value $\delta_{i,j}(t)$, on each RB_j to the serving eNodeB through SRS. The eNodeB maps the SNR value to achievable MCS mode on all RE within each RB, and then RB capacity of each RB is determined. The relative approach is proposed in [21]. So far, the height $r(S_i(t))$ of a RB rectangle can be expressed as follows:

$$r(S_i(t)) = f(min_{j \in S_i(t)} \delta_{i,j}) \quad (8)$$

where *f* function in equation (8) is to derive the corresponding RB capacity from a channel SNR value. In general, *f* function can be implemented by a look-up table in eNodeB as shown in Table II. The RB capacity can be calculated by equation (9) [22].

$$f(\cdot) = RB\ capacity = \frac{nbits}{symbol} \times \frac{nsymbols}{slot} \times \frac{nslots}{TTI} \times \frac{nsc}{RB} \quad (9)$$

where *nbits/symbol* computes how many bits carried per symbol, as the same as per RE, and it can be retrieved directly by which MCS mode is employed. *nsymbols/slot* is the number of symbols per slot, *nslot/TTI* is the number of slots per TTI and *nsc/RB* is the number of sub-carriers per RB. Table II shows the mapping results in which the MCS mode begins from QPSK(1/2) to 64QAM(3/4).

Table II. Look-up table

SNR range (dB)	MCS mode	nbits/RE	RB capacity (Kbps)
(1.7,3.7)	QPSK(1/2)	1	168
(3.7,4.5)	QPSK(2/3)	1.33	224

(4.5,7.2)	QPSK(3/4)	1.5	252
(7.2,9.5)	16QAM(1/2)	2	336
(9.5,10.7)	16QAM(2/3)	2.66	448
(10.7,14.8)	16QAM(3/4)	3	504
(14.8,16.1)	64QAM(2/3)	4	672
(16.1,+∞)	64QAM(3/4)	4.5	756

Since each RB can only be utilized by single UE, we need to ensure that any two RB rectangles from different UEs are non-overlapped, which means that $S_i(t) \cap S_{i'}(t) \neq \phi$ for any given UE_i and $UE_{i'}$. The derivation concept is illustrated in Fig. 8. In this example, we found that the overlapping situation would happen only if both conditions $x_i^s(t) < x_j^f(t)$ and $x_j^s(t) < x_i^f(t)$ are true. Therefore we provide a very simple inequality to check if any two RB rectangles are overlapped and stated in equation (10). By following equation (10), we can guarantee that overlapping situation will never occur in this system.

$$[x_i^s(t) - x_{i'}^f(t)] \cdot [x_i^f(t) - x_{i'}^s(t)] > 0 \tag{10}$$

Finally, we assume the scheduler performs resource allocation per TTI *t*. Therefore, the sum throughput maximization problem, equaling to the sum areas of RB rectangles maximization problem, can be well-formulated by equation (11) as listed in following:

$$max \sum_t \sum_i |S_i(t)| \, r(S_i(t)) \tag{11}$$

subject to the constraints (5)(6)(7)(8)(9)(10).

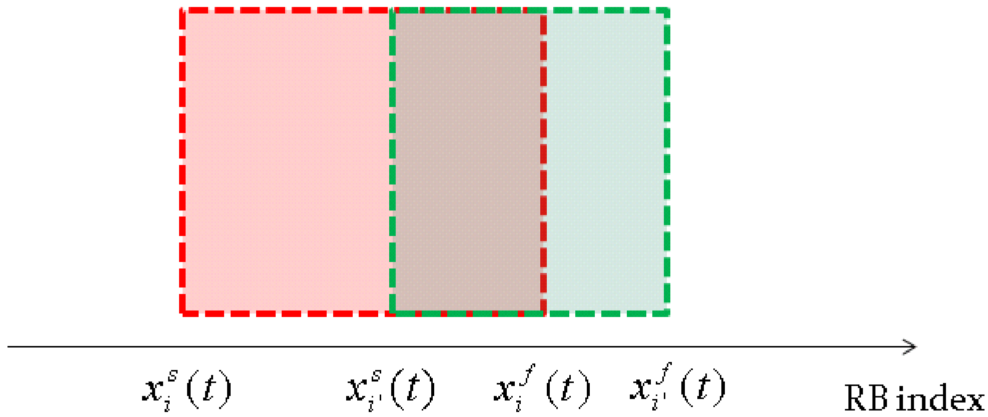

Figure 8. Derivation concept of two overlapped RB rectangles

3.3 Heuristic Methods

Though, upon taking both constraints of contiguous RB assignment and robust MCS mode into consideration, the proposed formulation can always find the feasible solution of UL resource allocation and achieve the maximal sum throughput performance, this optimization problem has been proven to be NP-hard [23]. To compromise with the computation complexity, we present two heuristic algorithms: Two-Tier Resource Allocation (TTRA) and Single-Tier Resource Allocation (STRA). Details of both algorithms are described in the remaining paragraph.

Before we start, extra symbols are introduced to help operate our algorithms. Again, we assume there are *m* RBs and *n* UEs at TTI *t*. Let $\mathcal{M}$ and $\mathcal{M}'$ be the sets of available and non-available RBs, respectively. Also, let $\mathcal{N}$ and $\mathcal{N}'$ be the sets of un-scheduled and scheduled UEs, respectively. Initially $\mathcal{M} = \{RB_1, RB_2, \ldots, RB_m\}$ and $\mathcal{N} = \{UE_1, UE_2, \ldots, UE_n\}$; $\mathcal{M}'$ and $\mathcal{N}'$ are both ϕ. For simplicity, we use $|\bullet|$ to indicate the number of elements in a set. For example, initially $|\mathcal{M}| = m$ and $|\mathcal{N}| = n$. Besides, $\delta_{i,j}(t)$, where $i \in \mathcal{N}$, $j \in \mathcal{M}$, represents the measured channel SNR value in RB_j of UE_i.

3.3.1. Two-Tier Resource Allocation (TTRA)

Two-Tier Resource Allocation (TTRA), literally, takes two tiers to finish the resource allocation at each TTI. The first tier is indeed a Regular-CDS; afterwards, the second tier fine-tunes the tier-one scheduling result for improving the sum throughput performance. The procedures of both tiers are described in the following:

(1) Tier-one resource allocation

Among all *m***n* channel SNR values, the UL scheduler first selects the highest $\delta_{i,j}(t)$, and allocates RB_j to UE_i. Due to the constraint of contiguous RB assignment, the scheduler further allocates adjacent RBs (e.g., {…, RB_{j-2}, RB_{j-1}, RB_{j+1}, RB_{j+2}, …}) to UE_i if that UE has higher channel SNR values than other UEs. The scheduler then removes all the allocated RBs and UE_i from $\mathcal{M}$ to $\mathcal{M}'$ and from $\mathcal{N}$ to $\mathcal{N}'$, respectively.

Next, from $|\mathcal{M}|*|\mathcal{N}|$ channel SNR values, the scheduler sequentially performs highest SNR value selection, RB assignment, adjacent RB assignment, and set updating. The scheduler keeps executing this process till $\mathcal{M} = \phi$.

The scheduler may incur one situation that all UEs are scheduled while some RBs are still available (i.e., $\mathcal{M} \neq \phi$ and $\mathcal{N} = \phi$). In such a case, these available RBs will be allocated to their left-side or right-side UEs, depending on which UEs have higher channel SNR value. For example, RB_k is available; RB_{k-1} and RB_{k+1} have been allocated to UE_a and UE_b, respectively. If $\delta_{a,k} > \delta_{b,k}$, then the scheduler will allocate RB_k to UE_a. When tier-one resource allocation is finished, all RBs are occupied and thus $\mathcal{M} = \phi$. It's not difficult to figure out that all existing RB rectangles are adjacent to its neighbor RB rectangles after tier-one resource allocation is performed. Here, we call a specific bar of a RB rectangle "*Adjacent-bar*" if this RB rectangle is adjacent to the neighbor one; otherwise, we call it "*Separate-bar*".

(2) Tier-two resource allocation

After performing tier-one resource allocation, each UE in $\mathcal{N}'$ has an RB rectangle, and the corresponding Bar-start and Bar-finish. For a specific bar, upon other bars being static, the scheduler calculates the updated sum throughput values of the system, as named as **system benefit**, by left shifting and right shifting that bar by one RB unit. Among all fine tuning possibilities, the one with the most system benefit is performed. The scheduler repeatively and sequentially shifts all bars till no further system benefits. The released RBs are removed to $\mathcal{M}$. If $\mathcal{M} \neq \phi$ and $\mathcal{N} \neq \phi$, the scheduler performs TTRA again; otherwise, the resource allocation at this TTI *t* is completed.

An illustrative example is shown in Figs. 9, in which there are six RBs (denoted as RB_1, RB_2, …, RB_6), and three UEs (denoted as UE_1, UE_2, and UE_3). Table III lists the measured channel SNR values of each RB of each UE. The mapping relation between SNR values and MCS modes can be retrieved from Table II.

Table III. The mapping relation between SNR and MCS

	RB_1	RB_2	RB_3	RB_4	RB_5	RB_6
UE_1	3.945	7.753	10.66	8.231	4.22	12.549
UE_2	2.579	5.606	7.462	10.58	19.647	16.01
UE_3	1.77	2.641	6.64	3.701	3.198	7.318

Since the highest SNR value is $\delta_{2,5} = 19.647$, the scheduler allocates RB_5 to UE_2. The scheduler then discovers that UE_2 has the highest SNR values in RB_4 and RB_6, compared with UE_1 and UE_3, thus both RBs are also allocated to UE_2. Now we know that $\mathcal{M}$ = {RB_1, RB_2, RB_3}, and $\mathcal{N}$ = {UE_1, UE_3,}. Since the highest SNR value now is $\delta_{1,3} = 10.66$, thus the scheduler allocates RB_3 to UE_1. Similarly, UE_1 has higher SNR values in RB_1 and RB_2 than UE_3, thus RB_1 and RB_2 are also allocated to UE_1. Note that after performing tier-one resource allocation, UE_3 does not get any RB grant, and thus it is still in $\mathcal{N}$.

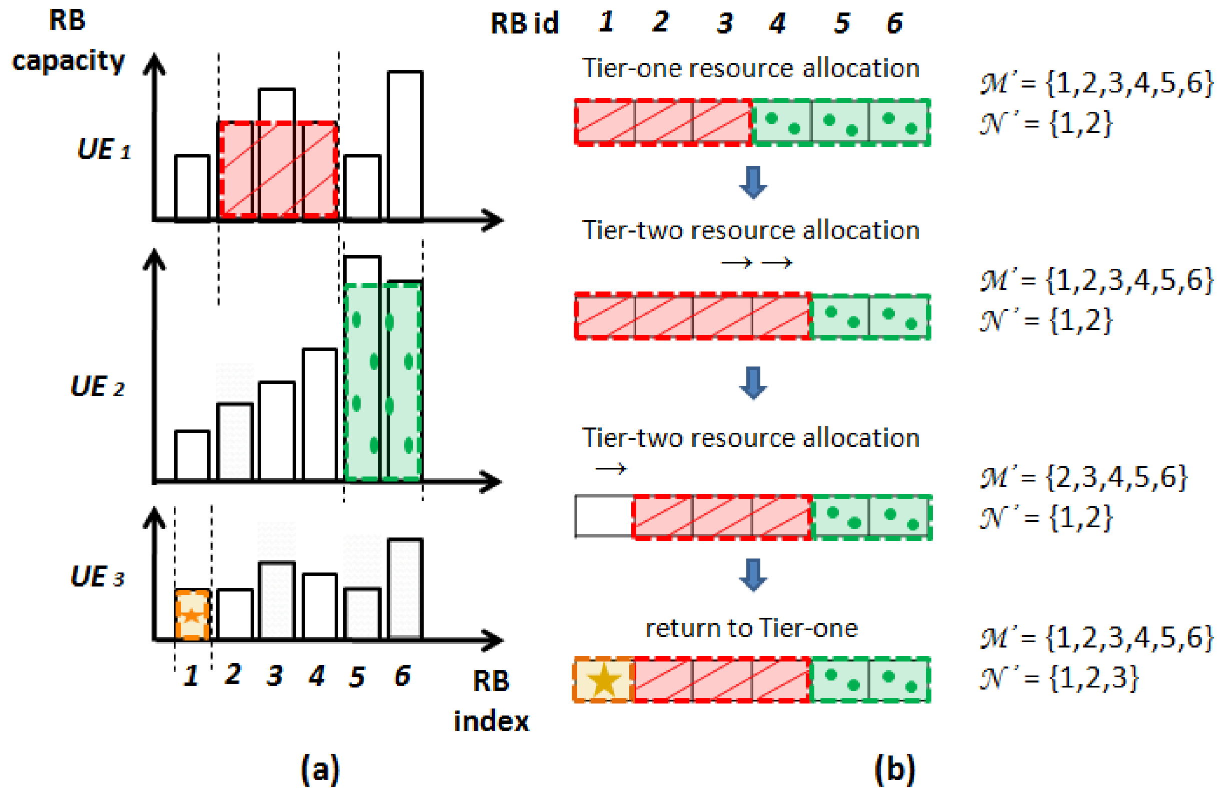

Figure 9. An example to illustrate the operations of TTRA: scheduling result

Then, in this example, we have two RB rectangles, and four bars. These bar indexes are $x_1^s(t)=1$, $x_1^f(t)=3$, $x_2^s(t)=4$, and $x_2^f(t)=6$. The scheduler then performs tier-two resource allocation. Each time the scheduler only shifts one bar and keeps other intact, unless this bar is an "*Adjacent-bar*". In such a case, the other RB rectangle also shifts the corresponding bar at the same direction. There are six possibilities of bar shifts, which are ($x_1^s(t)=2$, $x_1^f(t)=3$, $x_2^s(t)=4$, $x_2^f(t)=6$), ($x_1^s(t)=1$, $x_1^f(t)=2$, $x_2^s(t)=3$, $x_2^f(t)=6$), ($x_1^s(t)=1$, $x_1^f(t)=2$, $x_2^s(t)=4$, $x_2^f(t)=6$), ($x_1^s(t)=1$, $x_1^f(t)=3$, $x_2^s(t)=5$, $x_2^f(t)=6$), ($x_1^s(t)=1$, $x_1^f(t)=4$, $x_2^s(t)=5$, $x_2^f(t)=6$), and ($x_1^s(t)=1$, $x_1^f(t)=3$, $x_2^s(t)=4$, $x_2^f(t)=5$). Among all, the 5th bar-shift, ($x_1^s(t)=1$, $x_1^f(t)=4$, $x_2^s(t)=5$, $x_2^f(t)=6$), results the most system benefits and the new sum throughput is (1.33×4) + (4.0×2) = 13.32, thus

$S_1(t)$ ={RB$_1$, RB$_2$, RB$_3$, RB$_4$} and $S_2(t)$ ={RB$_5$, RB$_6$}. The scheduler keeps performing the same procedure till no further system benefits. The final result of resource allocation at this TTI *t* is $S_1(t)$ ={RB$_2$, RB$_3$, RB$_4$}, $S_2(t)$ ={RB$_5$, RB$_6$}, and $S_3(t)$ ={RB$_1$}. Note that we have one RB left unused, and the scheduler further allocates RB$_1$ to UE$_3$. The scheduling result is shown in Figs. 9(a) and 9(b).

3.3.2. Single-Tier Resource Allocation (STRA)

Obviously, TTRA always contributes better performance than Regular-CDS, however it may cost much time since it has two tiers to run. To more reduce complexity, STRA is proposed. The main characteristic of STRA is that it performs contiguous RB assignment and sum throughput maximization simultaneously by only single tier. Let ρ_i be the current sum throughput of UE$_i$.

(1) Step 1: for each UE$_i$ in $\mathcal{N}$, if it already has a RB rectangle (i.e., $S_i(t) \neq \phi$), it can only get the adjacent RBs of its RB rectangle. Among these two RB candidates, its maximum SNR value will be $max(\delta_{i,(x_i^s(t)-1)}, \delta_{i,(x_i^f(t)+1)})$; otherwise its maximum SNR value is set to be $max_{j \in M} \delta_{i,j}(t)$.

(2) Step 2: the scheduler temporarily allocates the RB with the highest SNR value to UE$_i$, $i \in \mathcal{N}$. Each UE$_i$ then calculates the updated sum throughput (denoted as $\overline{\rho_i}$) and the **user benefit** (denoted as $\Delta\rho_i$, which equals $\overline{\rho_i} - \rho_i$) will be determined.

(3) Step 3: among all $\Delta\rho_i > 0$ UE-RB assignment, the scheduler performs permanent allocation to UE$_k$, where UE$_k$ satisfies $k = \arg_i[\max_{i \in N}(\Delta\rho_i)]$. Also the scheduler updates UE$_k$'s $x_i^s(t)$ or $x_i^f(t)$. If no further user benefits, the algorithm will terminate at this step.

(4) Step 4: the scheduler removes the just allocated RB from $\mathcal{M}$ to $\mathcal{M}'$.

(5) Step 5: for all UE_i in $\mathcal{N}$, if $RB_{(x_i^s(t)-1)}$ and $RB_{(x_i^f(t)+1)}$ are both in $\mathcal{M}'$, the scheduler removes UE_i from $\mathcal{N}$ to $\mathcal{N}'$; otherwise, UE_i keeps staying in $\mathcal{N}$. The reason is that the scheduler cannot allocate non-contiguous RBs to UE_i. Finally, if $\mathcal{M} \neq \phi$ and $\mathcal{N} \neq \phi$, the scheduler goes back to step 1; otherwise, STRA algorithm at this TTI *t* is completed.

Again we take Table III as an example to explain the operations of STRA. The related procedure is demonstrated in Figs. 10. First of all, the best SNR values of UE_1, UE_2, and UE_3 are $\delta_{1,6} = 12.549$, $\delta_{2,5} = 19.647$, and $\delta_{3,6} = 7.318$, respectively. The scheduler allocates RB_5 to UE_2 to maximize the user benefit. Followed, UE_2 can only further get either RB_4 or RB_6, due to the constraint of contiguous RB assignment. Now the best SNR values of UE_1, UE_2, and UE_3 are $\delta_{1,3} = 10.66$, $\delta_{2,6} = 16.01$, and $\delta_{3,6} = 7.318$, respectively. The scheduler then calculates all user benefits of each UE, where $\Delta\rho_1 = 3.0$, $\Delta\rho_2 = 3.5$, and $\Delta\rho_3 = 2.0$, respectively. Since UE_2 contributes the most, thus RB_6 is allocated to UE_2. The scheduling result is shown in Fig. 10(a) and 10(b). Similar to TTRA, every UE gets at least one RB. Furthermore, RB_1 is unused.

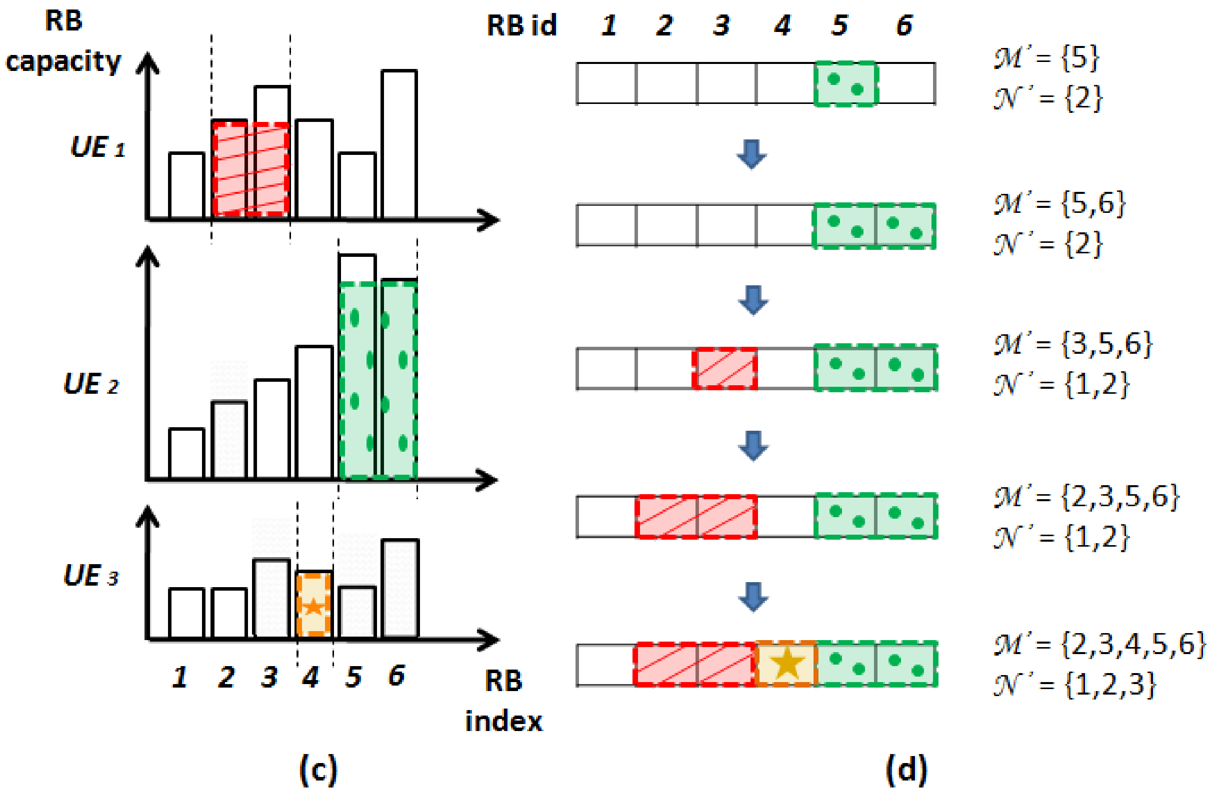

Figure 10. An example to illustrate the operations of STRA: scheduling result

3.3.3. Pseudo Code and Time Complexity

In this section we demonstrate the pseudo codes of TTRA and STRA. We are going to estimate the time complexity of both heuristic algorithms. In the beginning, we browse through the pseudo code, and then we cope with the corresponding calculations to come out the complexity. Note that the computation time of optimal formulation, TBA, is unacceptable, and its time complexity is $O(n^n)$ [23].

3.3.3.1. Complexity of TTRA

Table IV lists the pseudo code of TTRA. Line 1 defines the initial state of sets related to RBs and UEs. The main body starts from line 2 to line 15. Line 2 indicates that UEs in unscheduled set will join in the main body. Line 3 is tier-one resource allocation, in which we use [16] to implement. Tier-two resource allocation is listed from line 4 to line 14, where the system benefit of each bar is calculated and then the most one will be selected to do the RB assignment and set updating. Line 14 is used to make sure all the possible system benefits will be considered, in such case, it can be regarded as a for-loop scheme.

Table IV. Two-Tier Resource Allocation

1: Let $\mathcal{M}$ ($\mathcal{M}'$) be the set of available (non-available) RBs.
Let $\mathcal{N}$($\mathcal{N}'$) be the set of non-scheduled (scheduled) UEs
2: **while** $\mathcal{M} \neq \phi$ and $\mathcal{N} \neq \phi$ **do**
3: Execute Regular-CDS [16] *// Tier-one resource allocation*
4: **foreach** bar *k*, **switch case**: *// Tier-two resource allocation*
5: **case** *Separate-bar*:
6: Calculate system benefits $\Delta_k^{\leftarrow}$ and $\Delta_k^{\rightarrow}$ if the shift is valid *// left-shift & right-shift*
7: **case** *Adjacent-bar*:
8: Calculate system benefits $\Delta_k^{\leftarrow}$, $\Delta_k^{\rightarrow}$, $(\Delta_{k-1}^{\leftarrow} + \Delta_k^{\leftarrow})$, and $(\Delta_k^{\rightarrow} + \Delta_{k+1}^{\rightarrow})$ if the shift is valid
9: **end foreach**
10: **if** ∃(system benefit) > 0 **then**
11: The most system benefit with corresponding UE_{i*}, bar k^*, and (Bar-shift)* are selected
12: Update $S_{i^*}(t)$, $\mathcal{M}$ ($\mathcal{M}'$) and $\mathcal{N}$($\mathcal{N}'$)
13: **go to** line 4
14: **end if**
15: **end while**

The complexity of TTRA can be estimated from tier-one and tier-two resource allocation, respectively. We assume that there are *m* RBs and *n* UEs during this scheduling period. With tier-one resource allocation, we obtain the complexity is O(mn^2) from [16]. We provide a O(*n*) extra space to store the highest SNR value of a specific RB of each UE from m*n RB-UE pairs. This extra space reduces complexity of tier-one resource allocation to O(*mn*). Next, we divide tier-two resource allocation into three parts: system benefits calculation, set updating, and for-loop scheme. At the first part, each bar, in either *Separate-bar* case or *Adjacent-bar* case, calculates the system benefits. In the worst case, there are *n* RB rectangles, namely *2n* bars, to do system benefit calculations and it will cost O(n). The second part is set updating, and it will just cost O(1). Finally, the third part, for-loop scheme, is to recheck if there exist possible system benefits. A specific RB will belong to a specific UE permanently once the Bar-shifting has finished. In other words, a bar will not be shifted back and forth so that the most times of Bar-shiftings will equal m-1, less than m RBs. Therefore the for-loop scheme will cost O(m). Since the third part is to do a for-loop on the first part and the second part, the complexity of tier-two resource allocation is O(m)(O(n)+O(1)), equaling O(mn). TTRA repeats the resource allocation until either $\mathcal{M} = \phi$ or $\mathcal{N} = \phi$. In the worst case, tier-one and tier-two resource allocations will execute O(n) times. Therefore, the time complexity of TTRA is O(n)(O(mn)+O(mn)) and denoted as O(mn^2).

3.3.3.2. Complexity of STRA

Table V lists the pseudo code of STRA. Line 1 defines the initial state of sets related to RBs and UEs. Moreover, three more symbols are provided to record the current sum throughput, updated sum throughput and user benefit. The main body starts from line 2 to line 20. Line 2 indicates that the UEs in unscheduled set will join in the main body. User benefits are estimated from line 3 to line 10. If there exists any positive user benefit, line 12 will select the most one to do the RB assignment and set updating. The procedure from line 14 to line 18 is to guarantee a specific UE will not be take into considered anymore if its Bar-start and Bar-finish are adjacent to others. It is used to avoid any two RB rectangles overlapped.

Table V. Single-Tier Resource Allocation

1: Let $\mathcal{M}$ ($\mathcal{M}$ ') be the set of available (non-available) RBs.
Let $\mathcal{N}$($\mathcal{N}$ ') be the set of non-scheduled (scheduled) UEs
Let ρ_i ($\overline{\rho_i}$) be the current (updated) sum throughput of UE_i
Let $\Delta\rho_i$ be the user benefit of UE_i, which equals $(\rho_i - \overline{\rho_i})$

while $\mathcal{M} \neq \phi$ and $\mathcal{N} \neq \phi$ **do**
  foreach UE_i in $\mathcal{N}$
    if $S_i(t) \neq \phi$ **then**
      Select the RB respected to $max(\delta_{i,(x_i^s(t)-1)}, \delta_{i,(x_i^f(t)+1)})$ and obtain $\overline{\rho_i}$
    else
      Select the RB respected to $max_{j \in M} \delta_{i,j}(t)$ and obtain $\overline{\rho_i}$
    end if
    Calculate user benefits $\Delta\rho_{i^*}$
  end foreach
  if ∃(user benefit) > 0 **then**
    The most user benefit $\Delta\rho_{i^*}$ with corresponding UE_{i^*} and RB_{j^*} are selected
    Update $S_{i^*}(t)$, ρ_{i^*} and $\mathcal{M}$ ($\mathcal{M}'$)
    foreach UE_i in $\mathcal{N}$
      if both $x_i^s(t)$ and $x_i^f(t)$ are *Adjacent-bar* **then**
        Move UE_i from $\mathcal{N}$ to $\mathcal{N}'$
      end if
    end foreach
  end if
end while

The complexity of STRA is easier to figure out. Each time STRA selects the most user benefits from each UE in unscheduled set. If $S_i(t) = \phi$, then UE_i will search the highest channel SNR values in an *m*n* matrix space, and thus it costs O(*mn*). On the other hand, If $S_i(t) \neq \phi$, UE_i is allowed to consider the RBs being adjacent to its Bar-start and Bar-finish only. Therefore, it only costs O(1). In the worst case, STRA may assign least one RB to every UE so that the time complexity of STRA will be O(mn^2). Again, we provide a extra space O(*n*) as the same as TTRA. The complexity can be further reduced to O(*mn*).

Chapter 4 Simulation Results

In this chapter, we evaluate and compare the performances of proposed heuristic algorithms with Regular-CDS. The channel-aware scheduling [16], denoted as CAS, is selected as Regular-CDS. Due to the high complexity of TBA which may cost exponential time to finish scheduling, we first show the sum throughput performance of TBA upon setting 10 UEs and 10 RBs, and then we evaluate the system throughput, transmission delay, and outage ratio of TTRA, STRA and CAS with extended UEs and RBs. The parameter settings are listed in Table VI. Each simulation result is the average of 1,000 runs.

Table VI. Parameter settings of the LTE UL system

Parameter	Setting
System bandwidth	20 MHz
Subcarriers per RB	12
Symbols per subcarrier	7
Bandwidth of RB	180 kHz
Number of RBs	100
Number of active UEs	10 ~ 60
Location of UE	random
Transmission Time Interval (TTI)	1 ms
Simulation time	1000 TTIs
Modulation and Coding Scheme	QPSK (1/2、2/3、3/4) 16 QAM (1/2、2/3、3/4) 64 QAM (2/3、3/4)
Fading channel (μ)	Frequency-selective/Flat fading

4.1 System throughput

At first, we take an experiment in simple situation. The number of deployed UEs varies from 1 to 10. There are 10 RBs per TTI. The simulation result is shown in Fig. 11. We observe that TBA always performs the best performance among four approaches while CAS performs the worst. In addition, TTRA and STRA have similar sum throughputs. In CAS, though getting more RBs, the robust RB capacity of a UE will decrease due to the constraint of robust MCS mode. Therefore, the system sum throughput also decreases.

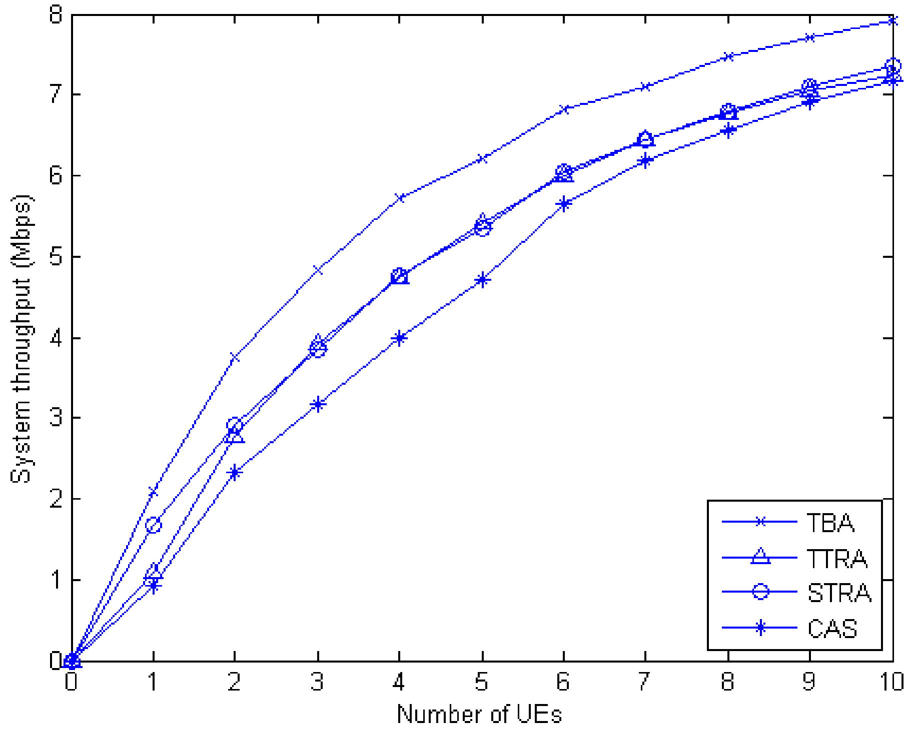

Figure 11. System throughputs of TBA, TTRA, STRA, and CAS

Then, we compare the sum throughput performance in more comprehensive situation. Both the number of RBs and UEs are extended and listed in Table VI. The results are shown in Fig. 12. There are two types of channel are employed: frequency-selective fading, which can be regarded as an independent fading channel, denoted as $\mu = 0$; flat fading, which can be seen as a highly correlated fading channel, denoted as $\mu = 1$.

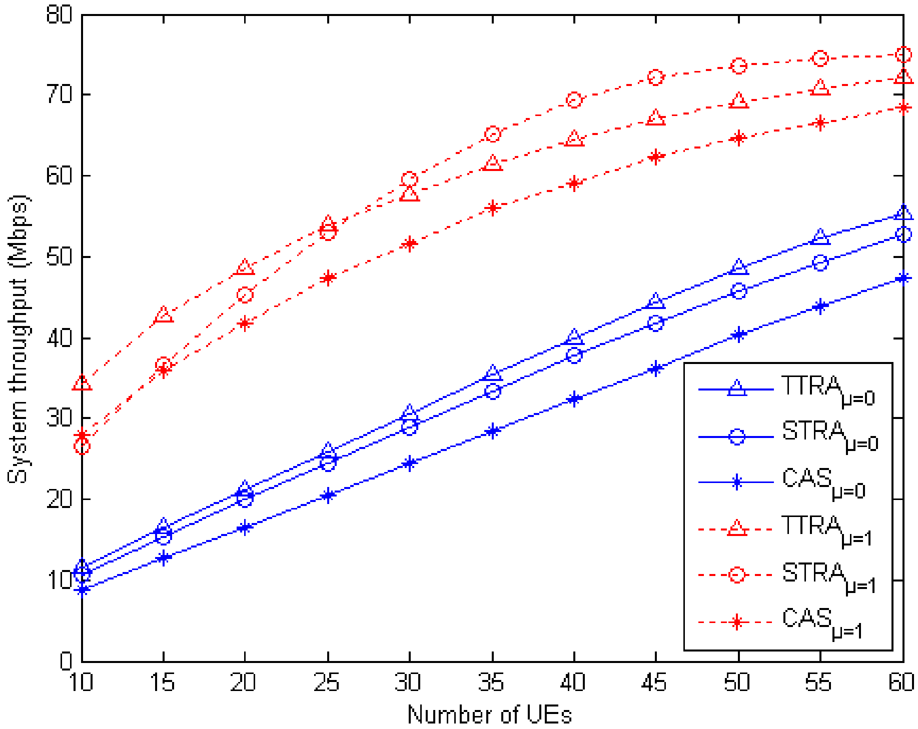

Figure 12. System throughput vs. Number of users

In Fig. 12, the sum throughput performances from TTRA are always better than from STRA when frequency-selective fading channel (μ = 0) is employed. The reason is that UEs by TTRA will grant more RBs than STRA, and thus system achieves better performance by means of "longer" RB rectangles of scheduled UEs. While in flat fading channel (μ = 1), TTRA results higher sum throughput than STRA does if UEs are not many. However, as UE increases, the performances of STRA begin to surpass the results of TTRA. Since there exists highly correlated property among RBs, All scheduled UEs in STRA have "taller" RB rectangles and therefore the sum throughput increases. It's worth to mention that the sum throughput of STRA is the worst if only few UEs are scheduled. Nevertheless, the service coverage of an eNodeB in LTE network is targeted to the scale of a city, such situation should rarely happen.

4.2 Transmission delay

The performance of transmission delay is also considered to further exhibit the merits of our proposed algorithms. We assume each UE has an M/D/1 queuing buffer with the data arrival rate of an average of 200 bits per frame. Note that our algorithms should be capable of implementing in more general queuing model. Since there usually existed correlated relations among closely RBs, we show the results with $\mu = 1$ for more reality. In Fig. 13, UEs in CAS suffer from more delays than our algorithms do. Moreover, the delay situation is more serious when the UEs increase. As we expect, since the bar-shifts of TTRA and STRA provide more scheduling opportunities to UEs, the delay reduction for our algorithms becomes significant.

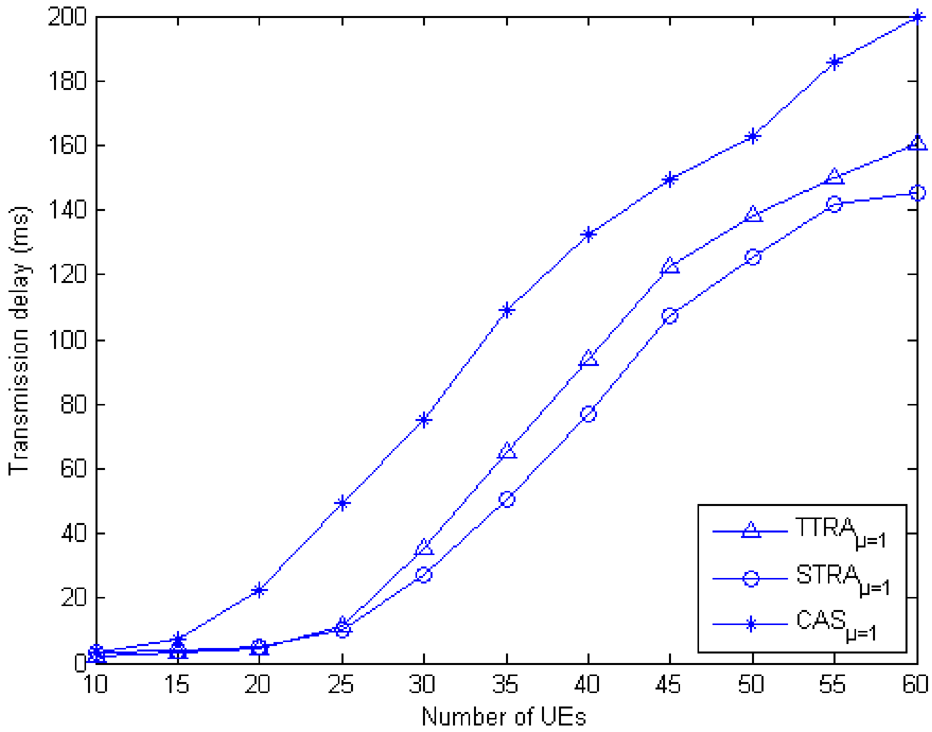

Figure 13. Transmission delay vs. Number of UEs

4.3 Outage ratio

Finally, due to the scarcity of wireless resources, UEs may grant no RBs. Moreover, if the channel quality of these non-scheduled UEs is poor often, they will suffer from no more

RBs to use. Therefore, we introduce the outage ratio to compare our proposed algorithms with CAS, as shown in Fig. 14. We consider the situation in which there are insufficient resources, ex: 30 RBs, to serve all active UEs in an LTE cellular system. Since TTRA saves some RBs from being occupied, unscheduled UEs will be possible to grant RBs at next round of resource allocation and thus the outage ratio will decrease. On the other hand, STRA tries to improve sum throughput by assign one specific RB at a time, this allocation scheme reduce the possibility that UEs have “long” RB rectangles. Therefore the outage ratio will be much lower than the one of TTRA.

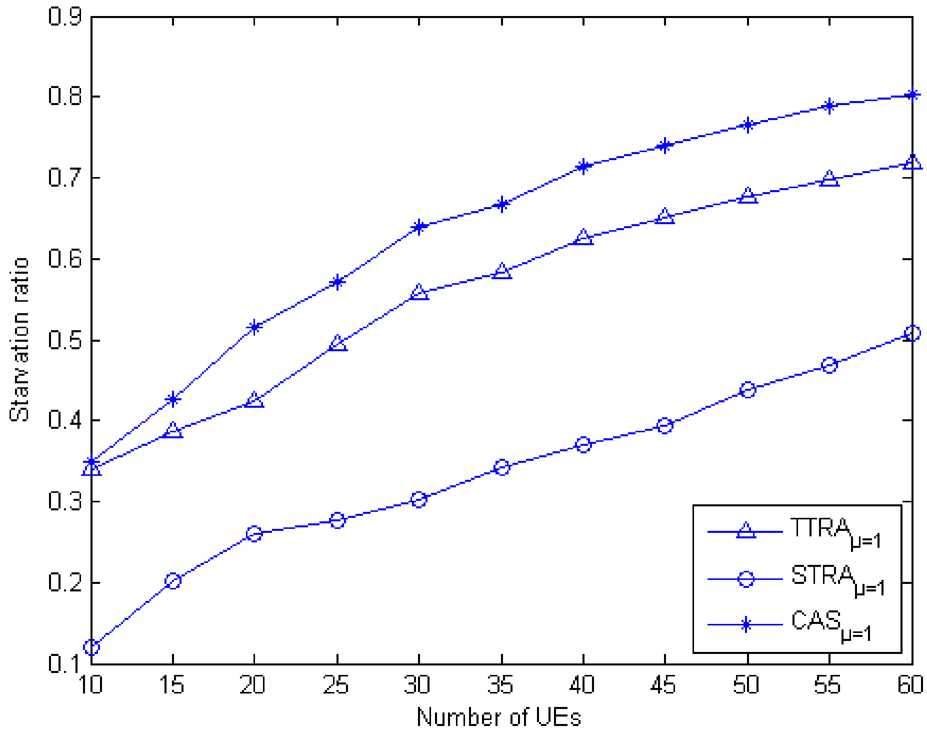

Figure 14. Outage ratio vs. Number of UE

Chapter 5 Conclusion and Future work

In this thesis, we first introduce two inherent constraints of SC-FDMA channel access scheme. Here we name these two constraints contiguous RB assignment and robust MCS mode. Taking the two constraints into consideration, we formulate the scheduling problem to maximize the sum throughput. The formulation is named Two-Bar Assignment (TBA). Due to the high complexity, we further design two heuristic algorithms－Two-Tier Resource Allocation (TTRA) and Single-Tier Resource Allocation (STRA). We evaluate TBA, TTRA, and STRA by simulation experiment. The simulation results show that TBA does provide an upper bound of the system sum throughput. Besides, TTRA and STRA perform not only better performances of sum throughput but also transmission delay and the outage ratio than Regular-CDS upon a UE operating at robust MCS mode in the allocated RBs.

As we expect, the sum throughput performance of TBA is always better than TTRA and STRA, therefore, how to shorten the gap between the optimal one with heuristic one will be our future work. Furthermore, "proportional fairness", as known as long-term fairness, is also a critical issue in the LTE scheduling problem. By considering the co-existence of optimal sum throughput and most proportional fairness, our proposed algorithms have to be modified. Therefore, we will continue to investigate into more sophisticated resource allocation situations and extend our work to achieve these goals.

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