Downlink Shared Channel Evaluation of LTE System

Master of Science Thesis in Communication Engineering

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Abstract

Long term evolution (LTE) of universal mobile telecommunications system (UMTS) is one of the most developed wireless broadband systems worldwide. Based on orthogonal frequency-division multiple access (OFDMA), it provides high-speed data packets access for various deployment scenarios.

Link adaptation is a technique used in the LTE system in order to exploit the benefits of the frequency selectivity of the wireless channels. With link adaptation, the spectral efficiency can be further improved. But to perform link adaptation, certain quality information of the channel is required at the transmitter side.

In the frequency-division duplex (FDD) LTE system, the channel quality information is fed back from the user equipment (UE) to the base station (eNB). For the purpose of minimizing the overhead, the channel quality information is quantized and the UE only feeds back the corresponding channel quality index (CQI) to the eNB. Various ways of calculating the CQI at the UE side has been proposed and one of the most accepted ways is the exponential effective SINR mapping (EESM) that is utilized in this thesis.

In order to minimize the control signal overhead, in the LTE standard, only one modulation and coding scheme (MCS) can be used for each UE in the downlink, though UE may feed back different CQI values for its preferred sub-band. 15 different CQIs and their corresponding MCSs have been defined as the uplink feedback values.

In this thesis work, we implement multiuser schedulers that allocate the available recourse blocks (RBs) and assign a proper MCS to different users within single input single output (SISO) transmission scheme in physical layer and investigate their performance.

Keywords: LTE; OFDMA; link adaptation; FDD; CQI; EESM; MCS; RB; SISO

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Contents

Abbreviation

AWGN	Additive White Gaussian Noise
BCH	Broadcast Channel
BLER	Block Error Rate
BPSK	Binary Phase-Shift Keying
CQI	Channel Quality Index
CRC	Cyclic Redundancy Check
DL-SCH	Downlink Shared Channel
EDGE	Enhanced Data Rates for GSM Evolution
EESM	Exponential Effective SINR Mapping
eNB	Base Station
ESM	Effective SINR Mapping
GSM	Global System of Mobile Communication
HSPA	High Speed Packet Access
ILP	Integer Linear Programming
KMT	Kwan. Maximum Throughput
L1/L2	Layer 1/Layer 2
LTE	Long Term Evolution
MAC	Medium Access Control
MCH	Multicast Channel
MCS	Modulation and Code Scheme
MIESM	Mutual Information Effective SINR Mapping
MIMO	Multiple Input Multiple Output
OMR	Optimal Max Rate
OPF	Optimal Proportional Fair
PCH	Paging Channel
QAM	Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RB	Resource Block
RE	Resource Element
RM	Rate Matching
SB	Scheduling Block
SINR	Signal to Interference plus Noise Ratio

SISO	Single Input Single Output
SMR	Suboptimal Max Rate
SNR	Signal to Noise Ratio
SPF	Suboptimal Proportional Fair
TTI	Transmission Time Interval
UE	User Equipment
UMTS	Universal Mobile Telecommunication System
ZF	Zero Forcing

1

INTRODUCTION

Long term evolution (LTE) is a standard for wireless communication of high-speed data for mobile phones and data terminals. It is based on global system of mobile communication (GSM)/enhanced data rates for GSM evolution (EDGE) and universal mobile telecommunication system (UMTS)/high speed packet access (HSPA) network technologies, increasing the capacity and transmission speed using a different radio interface together with core network improvements.

In this thesis work, we focus on the downlink physical-layer processing. In this chapter, a brief overview of the downlink physical-layer processing is presented, and the channel quality index (CQI) that plays an important role in this thesis is introduced, and a scope of this thesis and the organization of this report are also summarized.

1.1 Overview of Downlink Physical Layer Processing

In the LTE downlink physical-layer processing introduced in [1, pp. 143-149], the transport channels provide the interface between the medium access control (MAC) layer and the physical layer, and there are four different types of transport channels, the downlink shared channel (DL-SCH), the multicast channel (MCH), the paging channel (PCH) and the broadcast channel (BCH).

DL-SCH is the main type of downlink transport-channel in LTE and is used for transmission of user-specific higher-layer information, which contains user data information, dedicated control information and part of the downlink system information. The DL-SCH physical-layer processing is to a large extent applicable also to MCH and PCH transport channels with some additional constraints. But for BCH, the physical-layer processing and transmission structure is quite different. And in this section, we provide the description of physical-layer processing with DL-SCH transport channels.

1.1.1 Processing Steps

One or two transport blocks of dynamic size are delivered to the physical layer and transmitted over the radio interface for each carrier within every transmission time interval (TTI), each TTI lasts 1 millisecond corresponding to one subframe. The number of transport blocks transmitted within a TTI depends on the configuration of the multi-antenna transmission scheme[1].

There are eight main steps in the DL-SCH physical-layer processing, and the different steps outlined in Figure 1.1.

A. Cyclic Redundancy Check (CRC) Insertion Per Transport Block

In the first step of the physical-layer processing, a 24-bit CRC is calculated for and appended to each transport block. The CRC allows for error detection in the decoded transport block lasts at the receiver side.

B. Code-Block Segmentation and Per-Code-Block CRC Insertion

The LTE Turbo-coder internal inter-leaver is only defined for a limited number of code-block sizes (maximal block size of 6144 bits). If the transport block, including the transport-block CRC, exceeds this limited code-block size, code-block segmentation is applied before the channel coding (Turbo coder). It means that the transport block is segmented into smaller code blocks, whose sizes should match the set of code-block sizes supported by the Turbo coder.

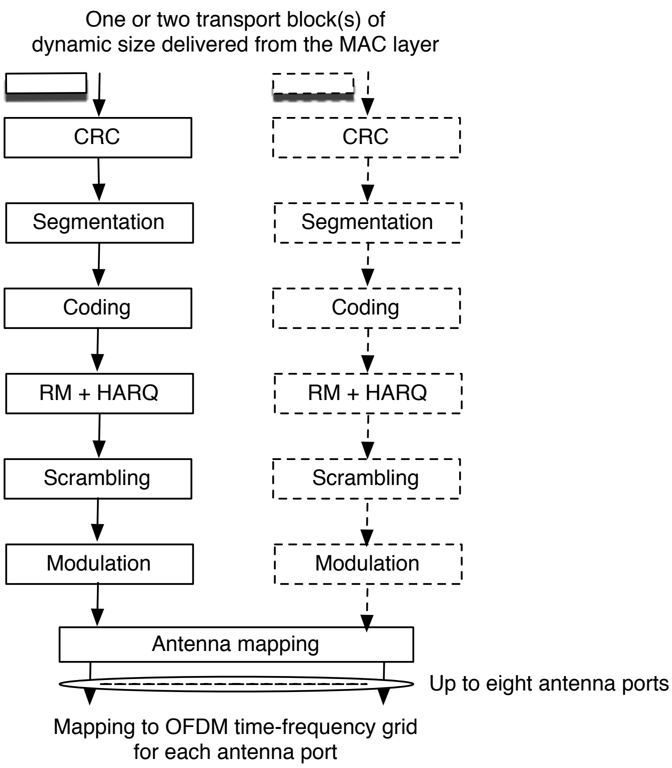

Figure 1.1. Physical-layer processing for DL-SCH [1, pp. 144].

C. Channel Coding

Channel coding for DL-SCH is based on Turbo coding, and during every transmission interval, the base station (eNB) selects different code rate for different users depending on the channel quality information sent back by the user equipments (UEs).

D. Rate Matching (RM) and Physical-Layer Hybrid-ARQ Functionality

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[1] In the case of no spatial multiplexing there is at most a single transport block in a TTI, and in the case of spatial multiplexing, there are two transport blocks in a TTI.

The objective of this step is to extract the exact set of code bits to be transmitted within a given scheduling period from the blocks of code bits delivered by the channel coder.

The outputs of Turbo coding contain three parts: systematic bits, first parity bits and second parity bits. First the outputs are separately interleaved, and then the interleaved bits are inserted into what can be described as a circular buffer with systematic bits inserted first, followed by alternating insertion of the first and second parity bits.

Then the bit selection extracts consecutive bits from the circular buffer to an extent that matches the number of available resource elements (REs) in the resource block (RB) assigned for the transmission. The number of bits that matches the available REs is one of the aspects in this thesis.

E. Bit-Level Scrambling

LTE downlink scrambling implies that the block of code bits delivered by the hybrid-ARQ functionality is multiplied by a bit-level scrambling sequence. Without downlink scrambling, the channel decoder at the terminal could be equally matched to an interfering signal as to the target signals, thus being unable to properly suppress the interference. By applying different scrambling sequences for neighboring cells, the interfering signals after descrambling is randomized, ensuring full utilization of the processing gain provided by the channel code.

F. Data Modulation

The aim of modulation is to transfer a digital bit stream over an analog pass-band channel. The set of modulation schemes supported by the LTE downlink transmission includes quadrature phase-shift keying (QPSK), 16-quadrature amplitude modulation (QAM) and 64QAM. During the scheduling period, different modulation schemes are utilized according to different channel quality information fed back by different UEs.

G. Antenna Mapping

The antenna mapping jointly processes the modulation symbols corresponding to one or two transport blocks and maps the result to different antenna ports. In LTE release 10, it supports transmission using up to eight ports based on the exact multi-antenna transmission scheme. In this thesis, we utilize the single antenna transmission scheme.

H. Resource-Block Mapping

In the downlink in LTE, subcarriers are grouped into RBs of 12 adjacent subcarriers with an inter-subcarrier spacing of 15 kHz. Each RB has a time slot duration of 0.5 milliseconds, which corresponds to 6 or 7 OFDM symbols[2]. So there are 72 or 84 REs in every RB.

However, some of the REs within a RB are not available for the transport-channel transmission as they are occupied by different type of downlink reference signals and downlink layer 1/layer 2 (L1/L2) control signaling (one, two or three OFDM symbols at head of each subframe). The specific structure of RBs is illustrated in Figure 1.2.

The RB mapping takes the symbols to be transmitted on each antenna port and maps them to the REs of the set of RBs assigned to each user by the scheduler for the transmission during each scheduling period.

[2] There are 7 OFDM symbols in the case of normal cyclic prefix and 6 OFDM symbols for extended cyclic prefix. In this thesis, we utilize normal cyclic prefix.

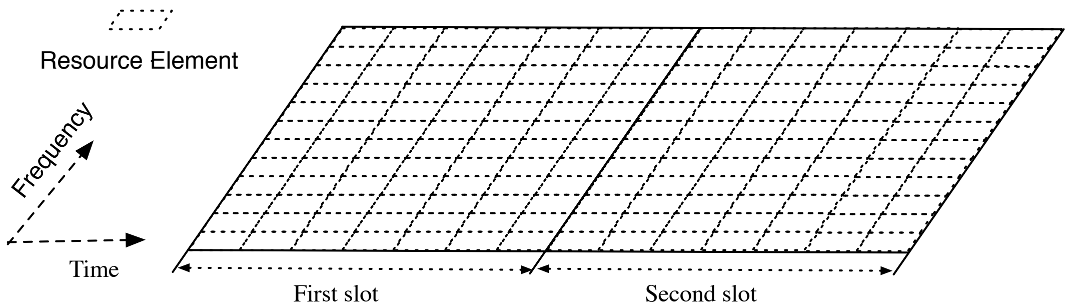

Figure 1.2. The structure of resource blocks.

1.1.2 Channel Quality Index

Table 1.1: 4-bit CQI Table

CQI index	Modulation	Code Rate x 1024	Efficiency
0	Out of range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

In the LTE downlink transmission, the eNB will, based on the channel quality, allocate the available RBs to different users and choose proper modulation and code scheme (MCS) for the multiple users. The channel quality is estimated by the UEs at the receiver side, and the receiver feeds back the channel quality information to the eNB. In order to minimize the overhead, the user does not feed back the channel quality information directly, instead it sends back the CQIs according to Table 1.1 [2, pp. 50]. In this table, each CQI value corresponds to one MCS, and the better the channel quality is, the better MCS the channel can support, and thus the CQI can reflect the channel quality.

In this thesis work, we use the 4-bit CQI indexes illustrated in Table 1.1, so the values of CQI range from 1 to 15, and as the value increases, the efficiency increases as well.

1.2 Scope of this Thesis

In this thesis, we concentrate on two parts: one is the method to calculate the CQI values at the UE side and the most important part, the multiuser scheduler at the eNB side.

In the first part, we investigate the exponential effective SINR mapping (EESM) method introduced in [3]. This technique maps the instantaneous channel state into a single scalar value, an effective signal to interference and noise ratio (SINR), which is then used to find an estimation of the block error rate (BLER) for this specific channel state. With this method, the UE can determine the specific CQI values that are going to fed back to the eNB and for the eNB, it can utilize the EESM to calculate proper CQI values used in the downlink transmission for different users. We discuss the details of this part in Chapter 2.

In the LTE downlink transmission, two constraints exist with single-input and single-output (SISO) scenario, one is that all RBs allocated to a given user in any scheduling period have to use the same MCS, the other one is that one RB can only be allocated to one user in a subframe. With these two constraints, the scheduler allocates available RBs to different users and assigns proper MCS to them. Different types of schedulers exist for different scheduling purposes, and in this thesis we investigate multiuser scheduling algorithms formulated in [4] and [5] based on the binary integer linear programming (ILP) algorithm discussed in [6] to allocate the resource blocks for different users and choose the proper MCS for the users. In the report, it is introduced in Chapter 3.

For this thesis work, we utilize the LTE link level simulator that has been proposed by [7] to investigate the relevant schemes.

In the thesis, we pay our effort to implement the scheduler in the simulator and investigate the performance with advanced simulation configuration, and the numerical results are presented in Chapter 4.

1.3 Organization of this Thesis

The rest of the report is organized as follows:

Chapter 2 introduces the EESM method, and discusses how it is formulated and how it is applied in the thesis.

Chapter 3 investigates the multiuser schedulers, who consist of max-rate and proportional fair scheduler, and introduces their basic algorithm, and shows how to use it to allocate RBs and choose proper MCS for different users.

Chapter 4 shows the numerical results we have simulated as well as proper comparison and discussion.

Chapter 5 draws brief conclusions of the whole project and also talks about the possible future work.

Appendix A shows two figures that are compared with figures in a reference to verify the correctness of our implemented code.

Appendix B presents additional figures to show a more comprehensive performance of the system.

2

EXPONENTIAL EFFECTIVE SINR MAPPING

The effective SINR mapping (ESM) technique maps the instantaneous channel state into a single scalar value, an effective SINR, which then is used to find an estimate of the BLER for this specific channel state. Now there are mainly two ESM techniques: mutual information ESM (MIESM) and EESM. In terms of the BLER prediction accuracy, the MIESM outperforms the EESM, but since there is not a closed form expression for mutual information between transmitted and received modulation symbols, or between transmitted and received coded bits, the MIESM method is more complex than EESM on the computational complexity and thus it is more inefficient. In this thesis work, we focus on the efficient EESM method presented in [3].

2.1 Derivation of EESM

In this part, we derive the EESM from a simple situation step by step to a more general condition.

For transmission over an additive white Gaussian noise (AWGN) channel with the modulation scheme of Binary Phase-Shift Keying (BPSK), let γ be the signal to noise ratio (SNR) and 1 be the symbol distance, the error rate P_e is

$$P_e(\gamma,1) = Q(\sqrt{2\gamma}) . \quad (2.1)$$

If there is a high enough SNR, Eq. (2.1) can be upper bounded by the Chernoff union bound, thus the possibility of error should be

$$P_e(\gamma) \le e^{-\gamma} . \quad (2.2)$$

For transmissions over N AWGN channels with SNR γ_i, if at least one error occurs, the possibility of error becomes

$$P_e = 1 - \prod_{i=1}^{N}(1 - P_e(\gamma_i)) \approx \sum_{i=1}^{N} e^{-\gamma_i} . \quad (2.3)$$

This is the BLER for an N symbols block. The purpose of EESM is to find an equivalent SNR value γ_{eff} that makes the possibility of error is the same as (2.3). Let $\gamma_{eff} = \gamma_i$ in (2.3), it becomes

$$Ne^{-\gamma_{eff}} = \sum_{i=1}^{N} e^{-\gamma_i} . \tag{2.4}$$

Solving this equation for γ_{eff}, thus the result is formulated as

$$\gamma_{eff} = -\ln \frac{1}{N} \sum_{i=1}^{N} e^{-\gamma_i} . \tag{2.5}$$

For QPSK, the solution for γ_{eff} can be shown as

$$\gamma_{eff,QPSK} = -2\ln \frac{1}{N} \sum_{i=1}^{N} e^{\frac{-\gamma_i}{2}} . \tag{2.6}$$

For other modulation with higher order, like 64QAM, it is not easy to get the actual expression as above. Instead, a general EESM equation is proposed with a parameter β to match the ESM to a concrete MCS. So the general EESM is defined in [3, pp. 34] as

$$\gamma_{eff} = EESM(\gamma, \beta) = -\beta \ln \frac{1}{N} \sum_{i=1}^{N} e^{\frac{-\gamma_i}{\beta}} , \tag{2.7}$$

where $\gamma = [\gamma_1, \gamma_2, \ldots, \gamma_n]$ is the tone SINR for each subcarrier and β is determined for every specific MCS.

2.2 Parameters of EESM

Eq. (2.7) defines a generalized EESM expression, and it contains two key parameters: the tone SINR γ and the parameter β adjusted to each MCS. The next two sections show how to determine these two parameters.

2.2.1 Effective Symbol SINR with SISO

In this thesis, we concentrate on the SISO transmission scheme. Within SISO transmission scheme, the SINR is simply the tone SINR:

$$SINR = \frac{\|h\|^2}{\sum_i \|v_i\|^2 + \sigma^2} , \tag{2.8}$$

where h is the channel coefficient, v_i is the received interference and σ is the noise covariance.

2.2.2 Calibration of β

To calibrate β for a specific MCS, several channel realizations are created from different channel models. For every channel realization, the BLER is determined by different simulation, which leads to a mapping from effective SINR to BLER. An AWGN reference curve is utilized for the same MCS, this BLER is mapped to an AWGN equivalent SNR to determine β. Therefore the specific β value can be calculated by

$$\beta = \arg\min_{\beta} \left\| \mathbf{SNR}_{AWGN} - \Gamma_{eff}(\beta) \right\|, \tag{2.9}$$

where $\mathbf{SNR}_{AWGN} = [SNR_{AWGN,1}, SNR_{AWGN,2}, ..., SNR_{AWGN,n}]$ and the vector with channel realization elements is $\Gamma_{eff}(\beta) = [\gamma_{eff,1}(\beta), \gamma_{eff,2}(\beta), \ldots, \gamma_{eff,n}(\beta)]$.

The β values corresponding to the CQI values in Table 1.1, which we use in the simulation, are shown in Table 2.1, and these data are originally presented in [8].

Table 2.1: β values vs. 4-bits CQI

CQI	0	1	2	3	4	5	6	7
β	5.00	5.01	5.01	0.84	1.67	1.61	1.64	3.87
CQI	8	9	10	11	12	13	14	15
β	5.06	6.40	12.59	17.59	23.33	29.45	29.45	33.05

2.3 Application

We can use the EESM method to calculate the effective SINR on both the UE side and the eNB side:

- On the UE side, each UE feeds back CQI values to the eNB who utilizes these CQI values to allocate RBs and choose MCS for different UEs.

  With the EESM method, the UE can calculate the effective SINRs for all the RBs, and then depending on these effective SINRs, find the proper CQI values that will be fed back to the eNB.

  In the simulator we use, based on the channel coefficients estimated on every RE, the tone SINR of each subcarrier can be computed by (2.8). Then with these tone SINRs, by the EESM equation (2.7), for a group of RBs the UE calculates one vector of effective SINRs with the different β values for different MSC levels.

  After the UE gets the effective SINRs for each group of RBs, it compares these effective SINR vectors with the SNR values that are calibrated within a single MCS at the level of BLER equals 0.1[1, pp. 283]. The SNR values corresponding to different CQI values with BLER equals to 0.1, also originally presented in [8], are shown in Table 2.2.

  Table 2.2: The SNR vs. CQI with BLER = 0.1

CQI	0	1	2	3	4	5	6	7
SNR(dB)	-500	-6.934	-5.147	-3.18	-1.254	0.761	2.70	4.697
CQI	8	9	10	11	12	13	14	15
SNR(dB)	6.528	8.576	10.37	12.3	14.18	15.89	17.82	19.83

  With the comparison, the UE can find the largest SNR value that is smaller than its corresponding effective SINR, and then the UE sends back this SNR's corresponding index (Table 2.2) as the CQI value of the group of RBs.

- On the eNB side, since a significant constraint in LTE downlink (non-multiple-input and multiple-output (MIMO) configuration) scheduling is that all RBs allocated to a given user in any given scheduling period have to use the same MCS, after the eNB allocates the RBs to different UEs by the scheduler (Chapter 3), we can use the EESM method to choose the MCS for the UEs as well.

  When the multiuser scheduler allocates several groups of RBs to one UE, with the corresponding CQI values fed back by this UE, the eNB can choose the proper MCS in the downlink transmission for the UE.

First of all, the eNB utilizes the corresponding CQI values of the allocated groups of RBs to get the SNR values with Table 2.2, and these SNR values are the approximate effective SINRs that are calculated by the UE in the previous subframe.

Then the eNB regards these SNR values as γ_i, the tone SINRs of these allocated groups of RBs in the EESM method equation (2.7). With EESM, the eNB will get a vector of effective SINR, and find a proper CQI the same way as the UE does above.

Each CQI value has a corresponding MCS, as shown in Table 1.1, and therefore the eNB knows which modulation order and code rate to choose in the downlink processing for the allocated group of RBs allocated to this UE.

3

MULTIUSER SCHEDULING

In the LTE downlink scheduling, since we apply non-MIMO configuration, there are two constraints: one is that all RBs belonging to a single UE can only use the same MCS during every scheduling period, and the other one is that one group of RBs can only be allocated to one UE. Due to these two constraints, different multiuser scheduling algorithms have been proposed for various purposes.

In this chapter, several different multiuser schedulers are introduced in the first section, and then two schedulers formulated in [4] and [5] are investigated in the latter part.

3.1 Introduction of Multiuser Scheduling

Due to the two constraints introduced at the beginning of this chapter, the objectives of a multiuser scheduler are RBs allocation and MCS selection for multiple users. But different schedulers have different purposes, such as maximizing the throughput of the whole bandwidth, guaranteeing the fairness for different users that have different average SNRs, etc. Now we introduce several different multiuser schedulers that are presented in [9].

A. Resource Fair Scheduler

The resource fair scheduler tries to maximize the total rate of all UEs, and at the same time guarantee fairness with respect to the number of RBs that one UE gets.

B. MaxMin. Scheduler

The purpose of maxmin. scheduler is to maximize the minimum of the user throughputs. But we should note that the rate of one UE cannot be increased without decreasing the rate of another UE that has a higher rate than the one considered.

C. Max Rate Scheduler

The task of max rate scheduler is to maximize the sum throughputs of all users without considering any fairness among different UEs.

D. Proportional Fair Scheduler

The proportional fair scheduler trends to improve the fairness among different users, especially when they have various average SNRs. Under the premise of proportional fairness, the scheduler considers the sum rate of all users as well.

In this thesis, we investigate the max rate scheduler and proportional fair scheduler, and these two schedulers have a similar algorithm to implement. The next section introduces our investigation on this algorithm.

3.2 Multiuser Scheduling based on Binary Integer Linear Programming

Now we investigate the multiuser scheduling algorithm formulated in [4] and [5] to achieve the maximal rate or proportional fairness. For convenience to illustrate the algorithm, before that we first introduce the basic system model of the LTE downlink transmission on physical layer.

3.2.1 Basic System Model

In the LTE downlink transmission, the smallest resource unit that a scheduler can assign to a user is a scheduling block (SB), which consists of two consecutive RBs, spanning a subframe time duration of 1 millisecond. The main problem of multiuser scheduling is how SBs are to be allocated to multiple users under two constraints in LTE downlink transmission, given that the channel qualities of each SB fed back by every UE are different.

An SB consists of N_{sb} (12 or 14) OFDM symbols, and let L (normally 12) be the total number of subcarriers and $L_d(v) \le L$ be the number of subcarriers that carry useful data for OFDM symbol v, where $v = 1,2,\ldots,N_{sb}$. Let $R_j^{(c)}$ be the code rate related to MCS j, where $j \in \{1,2,\ldots,J\}$, M_j be the constellation size of MCS j and T_s be the OFDM symbol duration, then the bit rate of a single SB is

$$r_j = \frac{R_j^{(c)} \log_2(M_j)}{T_s N_{sb}} \sum_{v=1}^{N_{sb}} L_d(v). \tag{3.1}$$

Let U be the number of simultaneous users, and N_{tot} be the number of the entire available SBs during each subframe. Let $\mathbb{N}_i$ be a subset of the N_{tot} SBs with the CQI values fed back by user i; the size of $\mathbb{N}_i$ is N_i, and assuming that the N_i highest SB CQI values are reported back by user i.

Furthermore, let $\mathbf{x}_{i,n}$, $n = 1,2,...,N_i$ be a real scalar or vector sent back by user i to indicate the collective channel qualities of all the subcarriers within the nth reported SB, and $q_{i,\max}(\mathbf{x}_{i,n}) \in \{1,2,...,J\}$ be the index of the highest-rate MCS that can be supported by user i for the nth SB at CQI value $\mathbf{x}_{i,n}$. Here for convenience, we assume that the MCS rate increases monotonically with CQI j.

In this multiuser scheduling algorithm, we utilize the theory that when an MCS is assigned to one user, in any allocated SB, the highest-rate MCS reported back by this user should not be lower than the assigned MCS rate. For example, as Figure 3.1 shows, there are six SBs with the corresponding CQI values fed back by user i, if we assign the MCS with corresponding CQI value of 5 to user i for its downlink transmission, then all the six SBs can be allocated to user i, but if the MCS with CQI value of 8 is assigned, only SB 4 and 5 can be allocated to this user. With different MCS assigned to this user, we can achieve different bit rate, and how to choose a proper MCS for one or multiple users to achieve a good performance is one of the issues to be dealt within the algorithm that is introduced later.

CQI value	5	7	6	9	11	7
SB index	1	2	3	4	5	6

Figure 3.1. Resource block with its corresponding CQI values.

As we have mentioned at the beginning of this chapter, there are two constraints in the LTE downlink scheduling. Now we illustrate the two constraints in mathematical form in order to introduce the algorithm conveniently.

Let $Q_{\max}(i)=\max_{n\in\mathbb{N}_i}\{q_{i,\max}(\mathbf{x}_{i,n})\}$, and $\mathbf{b_i}=[b_{i,1},b_{i,2},...,b_{i,Q_{\max}(i)}]$ be the MCS vector for user *i*, if MCS *j* is assigned to user *i* in the downlink transmission, then $b_{i,j}=1$, otherwise $b_{i,j}=0$. Thus we can formulate the first constraint as

$$\sum_{j=1}^{Q_{\max}(i)} b_{i,j}=1,\forall i\,. \tag{3.2}$$

Eq. 3.2 makes sure that any user *i* can only be assigned one MCS between 1 and $Q_{\max}(i)$.

For the other constraint that one SB that can only be occupied by a single user, let $\mathbf{a_n}=[a_{1,n},a_{2,n},...,a_{U,n}]$ be the vector shows which user occupies the *n*th SB, $a_{i,n}=1$ means that the *n*th SB is allocated to user *i* and $a_{i,n}=0$ implies that user *i* does not occupy the *n*th SB. Then we can express this constraint as

$$\sum_{i=1}^{U} a_{i,n}=1, n\in\bigcup_{i=1}^{U}\mathbb{N}_i\,. \tag{3.3}$$

Eq. (3.3) ensures one SB can only be allocated to one user.

3.2.2 Joint Optimization with Binary Integer Linear Programming

Based on the system model introduced in the previous section and subject to the constraints (3.2) and (3.3), in order to achieve the maximal throughput or proportional fairness, scheduling problem is formulated as

$$(P1)\text{:}\ \max_{\mathbf{A},\mathbf{B}}\sum_{i=1}^{U}\sum_{n\in\mathbb{N}_i} a_{i,n}\sum_{j=1}^{q_{i,\max}(\mathbf{x}_{i,n}(t))} b_{i,j}\left(\frac{r_i}{\varphi_i(t)}\right), \tag{3.4}$$

where $\mathbf{A}=\{a_{i,n}, i=1,2,...,U, n\in\bigcup_{i=1}^{U}\mathbb{N}_i\}$ and $\mathbf{B}=\{b_{i,j}, i=1,2,...,U, j=1,2,...,Q_{\max}(i)\}$.

With the solution **A** and **B** of problem *P1*, we can know the way to choose MCS and allocate SBs for different users.

In problem *P1*, if the objective is to achieve the maximal throughput, then let $\varphi_i(t)=1$, and problem *P1* becomes the form to maximize the throughput.

If the purpose is to consider the proportional fairness among multiple users, then let $\varphi_i(t)=\overline{R}_i(t)$, where

$$\overline{R}_i(t)=(1-\alpha)\overline{R}_i(t-1)+\alpha R_i(t-1)\ . \tag{3.5}$$

In (3.5), α is a coefficient that is selected between 0 and 1, and in our simulation, we choose it as 0.1. $\bar{R}_i(t)$ is the average bit rate up to time *t*-1 for user *i* and $R_i(t)$ represents the bit rate assigned to user *i* at time *t*. This makes the scheduler trends to allocate more resources to the users who have lower bit rate in the previous scheduling period to achieve the fairness.

Since *P1* is a non-linear problem with the product $a_{i,n}b_{i,j}$, it could be very difficult to solve. To overcome this difficulty, *P1* can be transformed to an equivalent linear problem. Let $t_{n,i,j} = a_{i,n}b_{i,j}$, then problem *P1* becomes

$$(P2): \max_{\mathbf{A},\mathbf{B},\mathbf{T}} \sum_{i=1}^{U} \sum_{n\in\mathbb{N}_i} \sum_{j=1}^{q_{i,\max}(\mathbf{x}_{i,n}(t))} t_{n,i,j}\left(\frac{r_i}{\varphi_i(t)}\right). \tag{3.6}$$

The new problem *P2* subjects to constraints (3.2) and (3.3) as well. But in [10] cross products of form *xz*, with *z* a non-negative variable bounded by a constant *M*, can be handled by replacing *xz* with a new variable *y*, which is required to satisfy

$$Mx \geq y \geq z + Mx - M \text{ , with} \tag{3.7}$$

$$z \geq y . \tag{3.8}$$

With (3.7) and (3.8), the new constraints that (3.6) should also subject to are

$$t_{n,i,j} \leq b_{i,j}, \tag{3.9}$$

$$t_{n,i,j} \leq a_{i,n}M \text{ , and} \tag{3.10}$$

$$t_{n,i,j} \geq b_{i,j} - (1 - a_{i,n})M . \tag{3.11}$$

Subject to constrains (3.2), (3.3), (3.9), (3.10) and (3.11), the linear problem *P2* can be solved by using standard binary ILP techniques [6]. We should note that with ILP, the solution of the problem may not be the actual solution but an approach of the optimal solution.

On our simulation platform, we can utilize the binary ILP provided by Matlab to find the optimal solution. But with this algorithm, as the number of users and bandwidth increase, the simulation time increase very quickly. So even if the number of users and bandwidth are not very large, the time for our simulation could be unacceptable. The simulation results of this optimal algorithm are shown in Chapter 4.

In the real system, since one subframe only lasts 1 millisecond, the system cannot handle too complex algorithm during such a short time, and it can be seen later that this computational complexity is worthless. To compromise the complexity of the joint optimization method, a more practical method was introduced in both [4] and [5].

3.2.3 Multiuser Sequential Suboptimal Scheduling

In this way to achieve the maximal throughput or proportional fair multiuser scheduler, instead of assigning the MCSs and SBs to different users jointly, the scheduler does it sequentially.

This suboptimal scheduler handles the scheduling algorithm in two steps. First all available SBs are assigned to every user to determine the ranking order of the highest rate that each user can support. Then based on the ranking order, the scheduler allocates SBs and chooses MCS for each user sequentially. The details are shown below.

In the first step, within the whole available SBs, the scheduler determines the MCS to make each user get the highest rate with the formula

$$(P3)\text{: } \max_{\mathbf{b_i}} \sum_{n \in \mathbb{N}_i} \sum_{j=1}^{q_{i,\max}(\mathbf{x}_{i,n})} b_{i,j} r_j \text{ .} \tag{3.12}$$

Problem *P3* subjects to constraint (3.2).

Problem *P3* can be easily resolved. By solving *P3,* an MCS is assigned to user *i*, and the SBs with larger CQI values than the corresponding CQI values of this assigned MCS is allocated to this user. This procedure is repeated for every user within all the available SBs, then each user gets its highest rate, let denote the bit rate as ϕ_i.

If we want to achieve the max rate scheduler, let $\varphi_i = \phi_i$; if we want it to be the proportional fair scheduler, let $\varphi_i = \phi_i / \overline{R}_i(t)$, where $\overline{R}_i(t)$ is the same as (3.5).

Then φ_i is ranked in descending order, for convenience, let us assume $\varphi_1 \geq \varphi_2 \geq \ldots \geq \varphi_U$.

In the second step, the allocation of SBs is done in a sequential way, one user at a time, according the φ_i ranking order. Thus with our assumption, the procedure starts with user 1, and the initial set of SBs for user 1 is the complete available SBs, so $\mathbb{N}_1 = \mathbb{N}$. The assigned MCS and the set of allocated SBs, K_1, for user 1, is determined with *P3*. Then after handling user 1, the remaining SBs for the next user are $\mathbb{N}_2 = \mathbb{N}_1 - \mathrm{K}_1$, and these remaining SBs is made available to user 2. This process continues until all the SBs have been assigned or all the users have been handled.

The performance of this suboptimal method is of course not as good as the one with joint optimization (the performance comparison is shown in the next chapter), but the performance is acceptable, and we discuss this in the next chapter. Moreover, the suboptimal method is more efficient and practical than the joint optimal method and can be utilized in a real system.

4

NUMERICAL RESULTS AND DISCUSSION

In this chapter, we compare several simulation results to see the performance of the algorithms introduced in Chapter 3. In the first part of this chapter, we introduce the measurement methods of the performance: the throughput and BLER. In the second part, we compare the throughput and BLER results within different simulation scenarios, and discuss the algorithms' performance. The LTE link level simulator proposed by [7] is utilized to get the simulation results.

4.1 Performance Measures

Two aspects of the performance are investigated in the thesis: bit rate and accuracy. The rate of bit is shown by the throughput value and the accuracy is measured by the BLER. Now we give a brief introduction to the concepts of throughput and BLER.

4.1.1 Throughput

To achieve a high throughput capability is one of the key goals of LTE, so to calculate and analyze the throughput of the system is very important and it is also a significant part in this report.

To compute the throughput, Eq. (3.1) in Chapter 3 is utilized. With this equation, the throughput of every SB in the whole bandwidth can be calculated. There are two types of throughput: cell-specific throughput and UE-specific throughput. For the cell-specific throughput, it is the total throughput of the whole bandwidth configured in the system, and the UE-specific throughput is the sum throughput of SBs allocated to a specific UE.

4.1.2 BLER

Except the high throughput, the accuracy of the received data is very important as well. BLER is one way to show this accuracy, and it is the ratio between the number of erroneous blocks and the total number of received blocks.

The lower the BLER value is, the better the system performance will be, but the performance is acceptable if the BLER value is under a specific threshold[3] [1, pp. 283]. If the BLER is too high, there will be too many errors in the transmitted data we received, and the data will be useless. For the BLER, there are cell-specific BLER and UE-specific BLER too.

4.2 Numerical Results and Discussion

We have tested the schedulers with the configuration in Table 1 in [9], and compared the results with some curves in Figure 2 and Figure 3 of [9] to verify the correctness of our code. The Kwan. Maximum throughput (KMT) scheduler in [9] is based on the same algorithm with our suboptimal max rate scheduler. From the comparison, we can see the performance of our suboptimal max rate scheduler is very close to the performance of KWT scheduler, and the tiny performance difference is from the different implemented code, thus the correctness of our implemented code is verified. The comparison results are presented in Figure A.1 and Figure A.2 in Appendix A.

In this part several system parameters is settled and numerical results are presented, compared and analyzed.

4.2.1 Comparison between Optimal and Suboptimal Algorithm

Table 4.1: Simulation Parameters

Parameter	Value
System bandwidth	1.4 MHz
Number of users	2
Channel model	ITU-VehA[11]
Antenna configuration	1 transmit, 1 receiver (1x1)
Receiver	Zero Forcing (ZF)
Uplink delay	0 TTI
User speed	0 km/h
Multiuser Scheduler	Optimal max rate (OMR) Optimal proportional fair (OPF) Suboptimal max rate (SMR) Suboptimal proportional fair (SPF)

The principal simulation parameters are shown in Table 4.1, and in this part we just want to see the difference between the performance of optimal and suboptimal algorithm, so the system is set without uplink delay. As it has already been mentioned in Section 3.2.2, the simulation time of this optimal algorithm increases very quickly as the number of users and bandwidth increase, so here we just simulate these scheduling algorithms in an narrow bandwidth with only two users, but this is enough for us to know the two different algorithms' performance.

As the shown in Figure 4.1 and Figure 4.2, with the same average SNR, the performance of optimal algorithm is always better than the suboptimal one no matter it is max rate scheduler or proportional fair scheduler, and the throughput of the optimal algorithm is approximately 1% ~7% higher than the suboptimal algorithm. It is reasonable that the optimal algorithm has the better performance, but its throughput is just a little higher than the suboptimal one, and the performance of the suboptimal algorithm is still acceptable for the communication system.

[3] The system defines the acceptable threshold of BLER is 0.1.

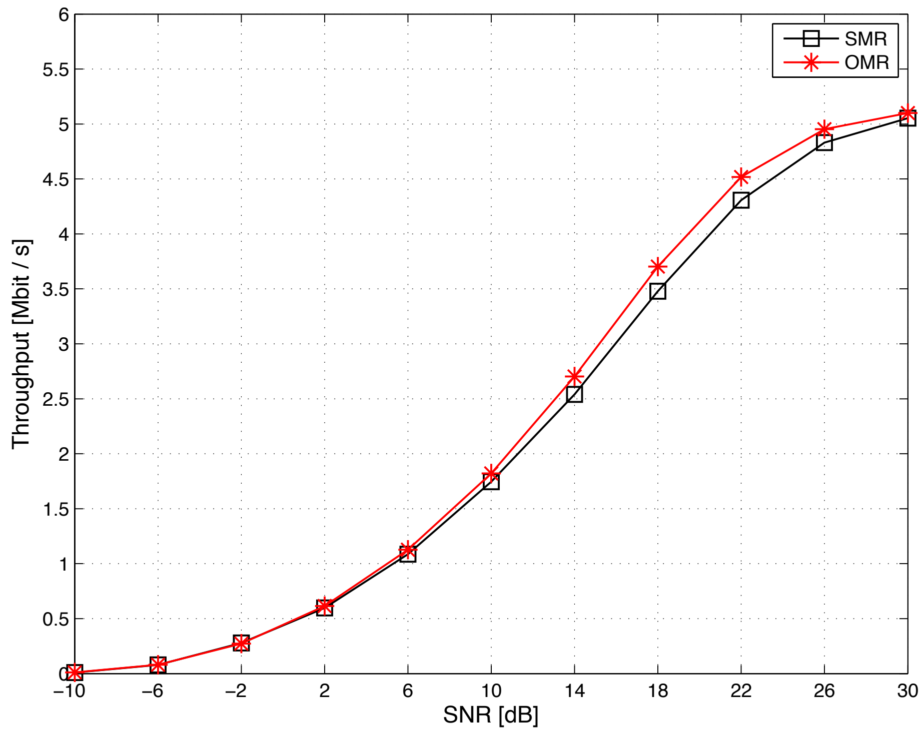

Figure 4.1. Cell-specific throughput of optimal and suboptimal max rate scheduler on the same average SNR level with 2 users and no delay.

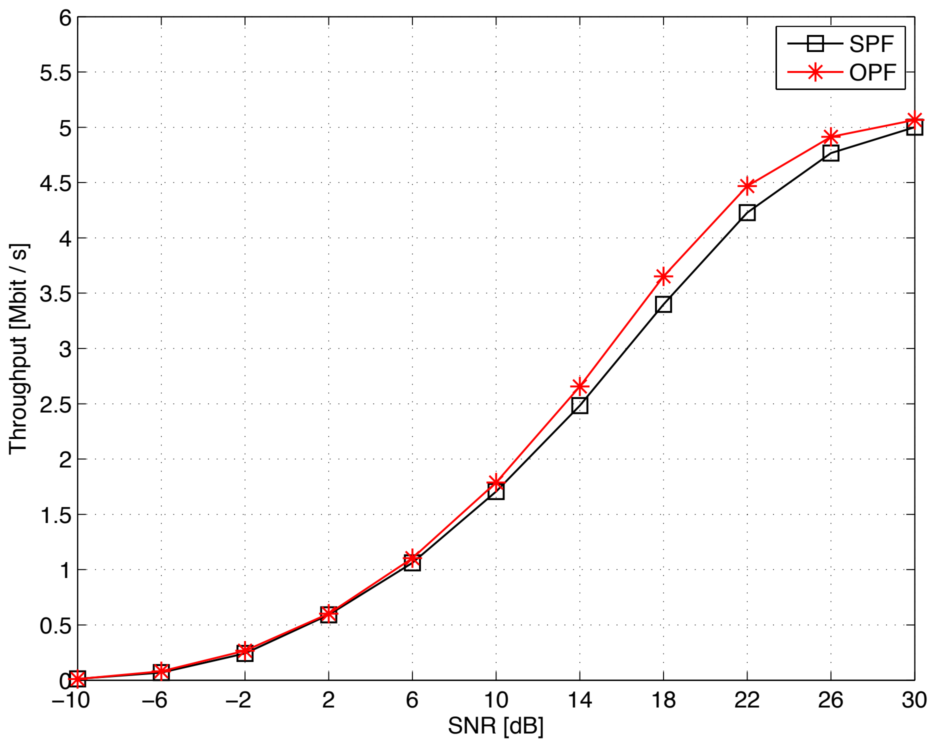

Figure 4.2. Cell-specific throughput of optimal and suboptimal proportional fair scheduler on the same average SNR level with 2 users and no delay.

According to the discussion above, due to the inefficiency of the optimal algorithm and the acceptable performance of the suboptimal algorithm, it is enough to just use the suboptimal algorithm to see the scheduler's performance. So we investigate the aspects of the scheduler's performance based on the suboptimal algorithm in the next section.

4.2.2 Investigation of Multiuser Scheduler Performance

In this part, we investigate the performance of the suboptimal multiuser scheduler introduced in Section 3.2.3. Here the schedulers are tested under different conditions, as shown in Table 4.2. This time 5 MHz bandwidth is utilized, and the scheduler is simulated with 3, 5 and 10 users. Moreover, the scenario with the users' moving speed at 50 km/h and 2 or 5 TTIs uplink delay is also tested.

Table 4.2: Simulation parameters

Parameter	Value
System bandwidth	5 MHz
Number of users	3, 5 or 10
Channel model	ITU-T VehA[11]
Antenna configuration	1 transmit, 1 receive (1x1)
Receiver	ZF
Uplink delay	0 TTI (user speed = 0) 1, 2 or 5 TTI (user speed = 50 km/h)
User speed	0 or 50 km/h
Multiuser Scheduler	SMR SPF

A. Comparison of Cell-Specific Throughput with Different Number of users and Schedulers

In this part we compare the difference of throughput simulated with both suboptimal max rate and proportional fair scheduler. Figure 4.3 shows the results with 3, 5 and 10 users without delay.

First let us consider the curves in Figure 4.3 with the same scheduler. No matter what type of scheduler it is, the throughput is getting larger and larger as the number of users increases. One reason is that in our simulation configuration the scheduler with more users has higher average SNR. But even if all the users in the simulation have the same average SNR, the one with more users will have a higher throughput. This is because after allocating the bandwidth to multiple users, some RBs may not be occupied. The scheduler with more users has a higher possibility to allocate more RBs than the one with fewer users, and so the system with more users has a better cell-specific throughput performance. When the number of users is large enough, all the RBs will be occupied and the throughput will not increase any more as the number of users goes up. Even if the user has a high moving speed that arises feedback delay in the uplink transmission, the trend keeps the same. The throughput comparison with uplink delay is presented in Figure B.1 – Figure B.4 in Appendix B.

Comparing the curves with the same number of users, the throughput of max rate scheduler is always larger than the rate of proportional fair scheduler, and this is due to the different scheduling targets of these two schedulers. The max rate algorithm just wants to achieve the highest rate regardless of the fairness among different users and apparently the proportional fair scheduler sacrifices the rate to achieve the fairness. For example, in a system with two users, if the scheduler allocates an RB A to user 1, there will be M bits data passing through A during one subframe, and if it allocates A to user 2, there will be N bits data transmitted through A during one TTI. Assuming that M is greater than N, then with max rate scheduler, A will be allocated to user 1, but with proportional fair scheduler, to achieve fairness between the two users, it probably allocates A to user 2. This is the main reason why, with the same number of users, the throughput of max rate scheduler is always larger than the other one in Figure 4.3. These kinds of differences between the two schedulers also appear in BLER, and we will see that in the later section.

In Figure 4.3, we have noticed that although with the same number of users, the throughput of the max rate scheduler is always higher than the other one, but the difference between the two schedulers' rate is getting larger and larger as the number of users increases. It is caused by the same reason that the throughput is higher with more users. With fewer users, there will be more available RBs remained for proportional fair scheduler to utilize to achieve fairness without sacrificing too much throughout, but as the number of users increases, the remaining available RBs will become fewer and fewer, and as discussed above, to achieve the fairness, the scheduler has to allocate some RBs to a low throughput user rather than a high throughput one and this will slow the rate down. So with the number of users increasing, the gap of throughput between the two schedulers will widen.

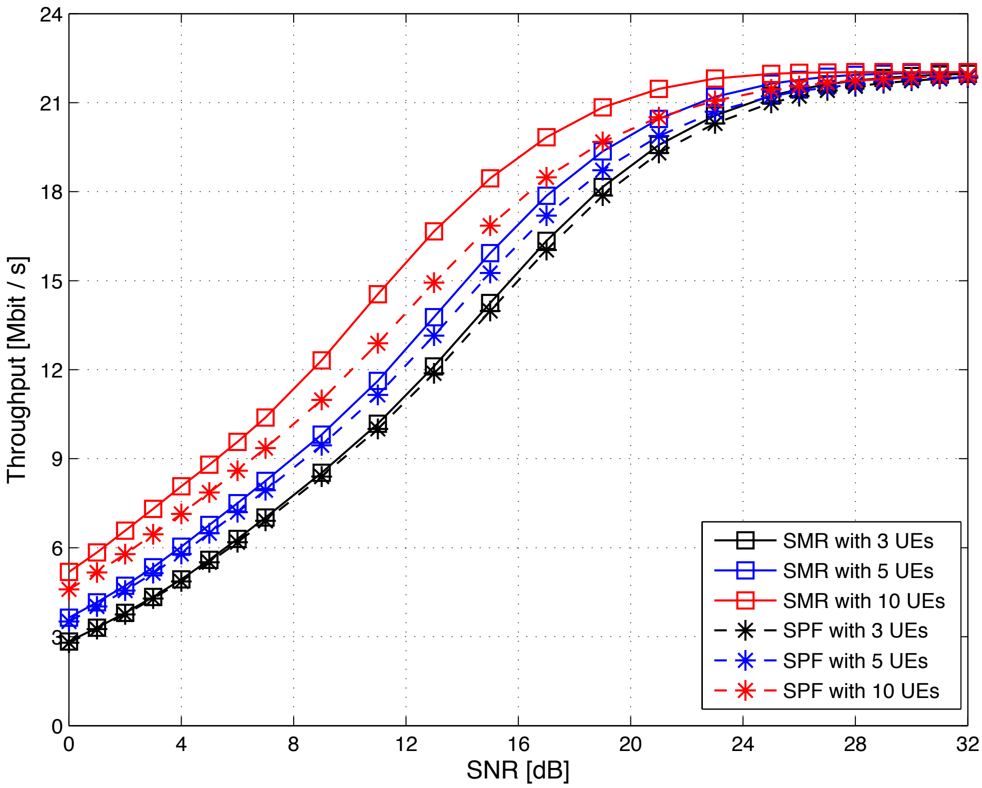

Figure 4.3. Cell-specific throughput of suboptimal max rate and proportional fair scheduler with 3, 5 and 10 users without delay.

B. Comparison of Cell-Specific Throughput with Different Delay

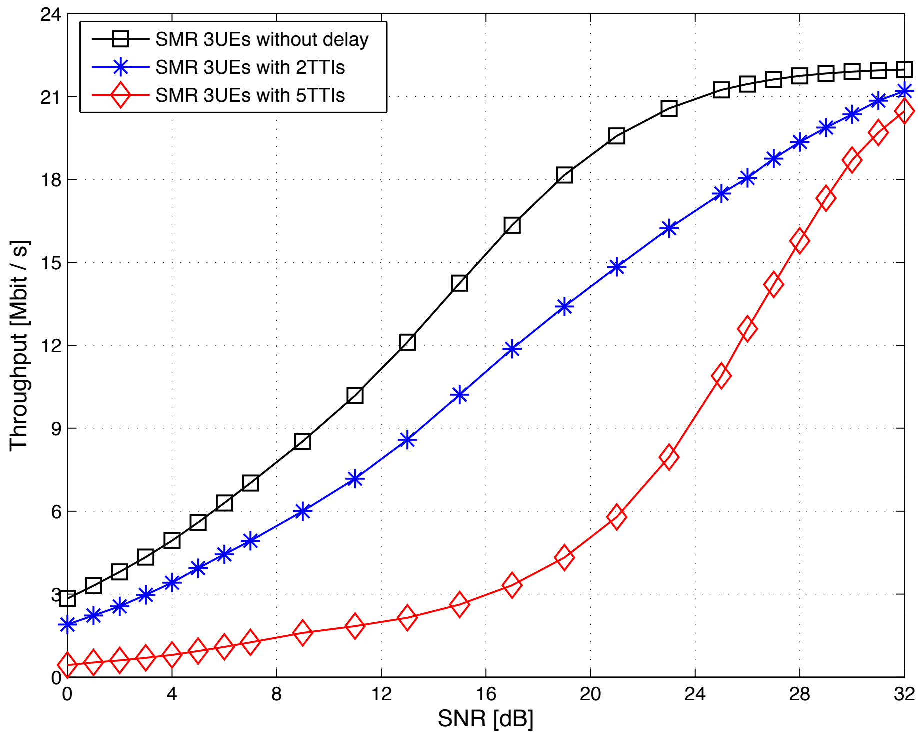

Figure 4.4. Cell-specific throughput of suboptimal max rate scheduler with 3 users and 0, 2 and 5 TTIs delay.

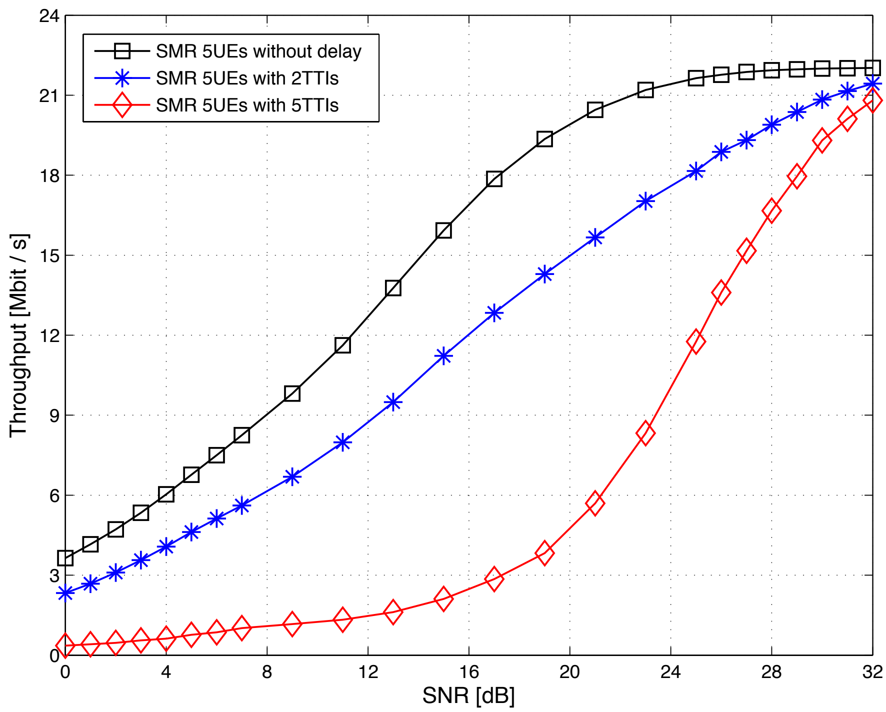

Figure 4.5. Cell-specific throughput of suboptimal max rate scheduler with 5 users and 0, 2 and 5 TTIs delay.

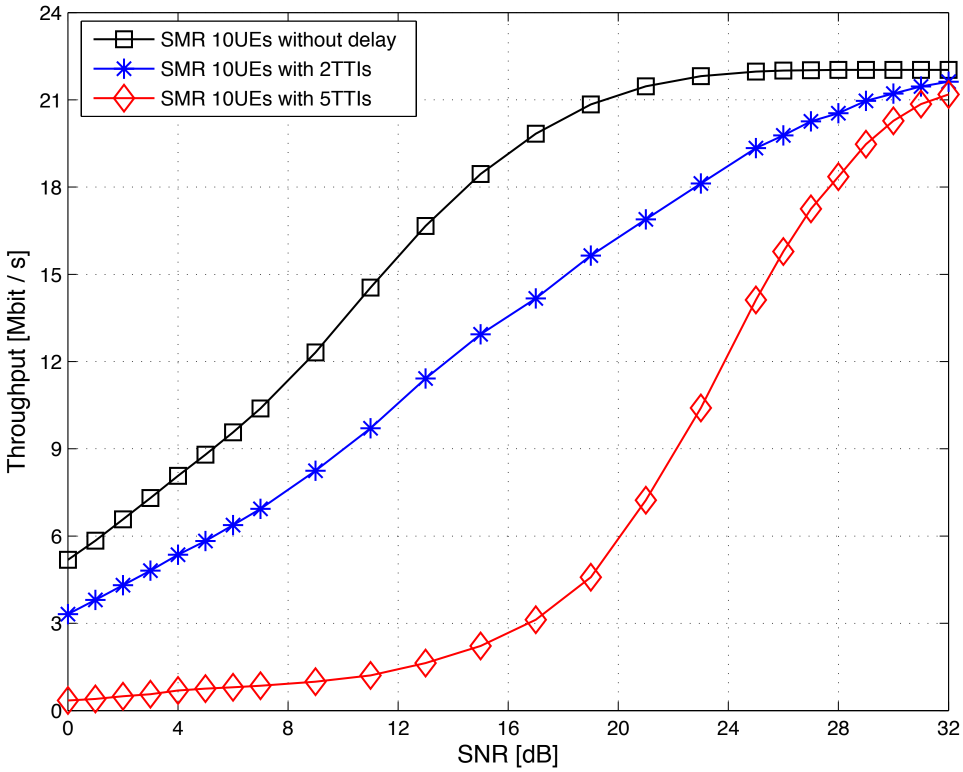

Figure 4.6. Cell-specific throughput of suboptimal max rate scheduler with 10 users and 0, 2 and 5 TTIs delay.

As discussed in the last section, different number of users can affect the throughput of the system, so in this part, we keep the number of users the same but give the users a moving speed. The moving speed will delay the uplink transmission and thus it will have a big impact on the downlink transmission performance.

When the users do not move or move very slowly, there would be no uplink delay. In the simulation, a speed of 50 km/h is given to the users and it is tested with 2 and 5 TTIs uplink delay. The results are shown in Figure 4.4 – Figure 4.6.

As shown in these figures, no matter how many users there are, the trend of performance keeps the same: the performance becomes worse as the delay value goes up, and that means the uplink delay has a big impact on the multiuser scheduling algorithm. Here the influence on the throughput is shown, and the affect on BLER is introduced in later part.

The Figure 4.4 – Figure 4.6 show the throughput performance with delay for the suboptimal max rate scheduler, and for the suboptimal proportional fair scheduler. The tendency is similar and the results of the latter scheduler are presented in Figure B.5- B.7 in Appendix B.

C. Comparison of UE-Specific BLER with the Same Scheduler and Delay

In this part, we compare the UE-specific BLER with the same scheduler without delay. Since it is too complicated to plot the curves of BLER with 5 or 10 users, here we only compare the results with 3 users, but the trend of the performance is similar.

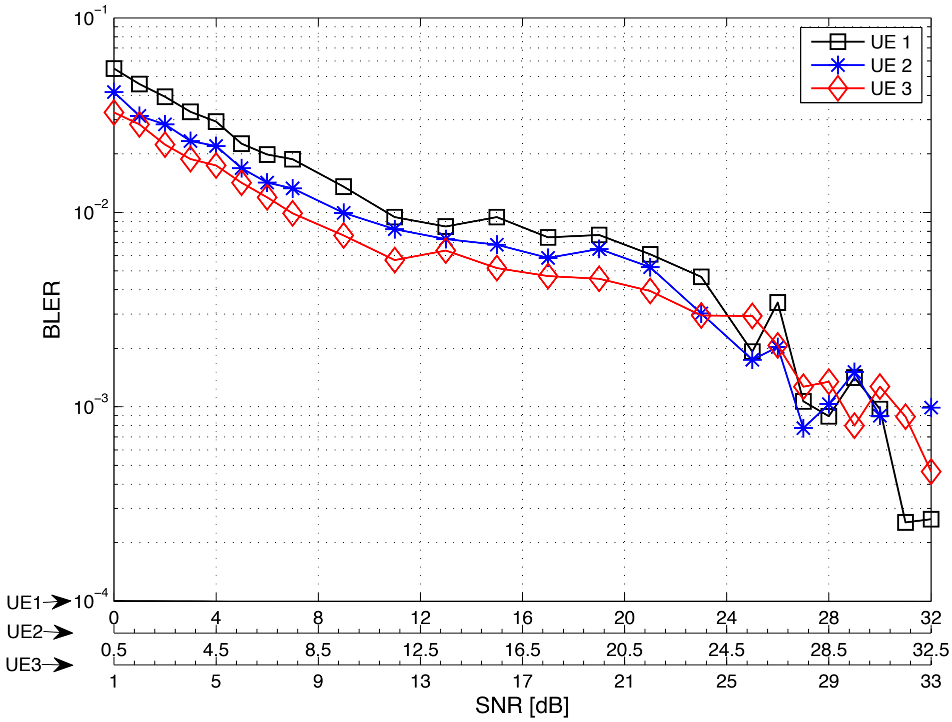

Figure 4.7. UE-specific BLER of suboptimal max rate scheduler with 3 users and 0 TTI delay, and UE1 has the lowest average SNR while UE 3 has the highest.

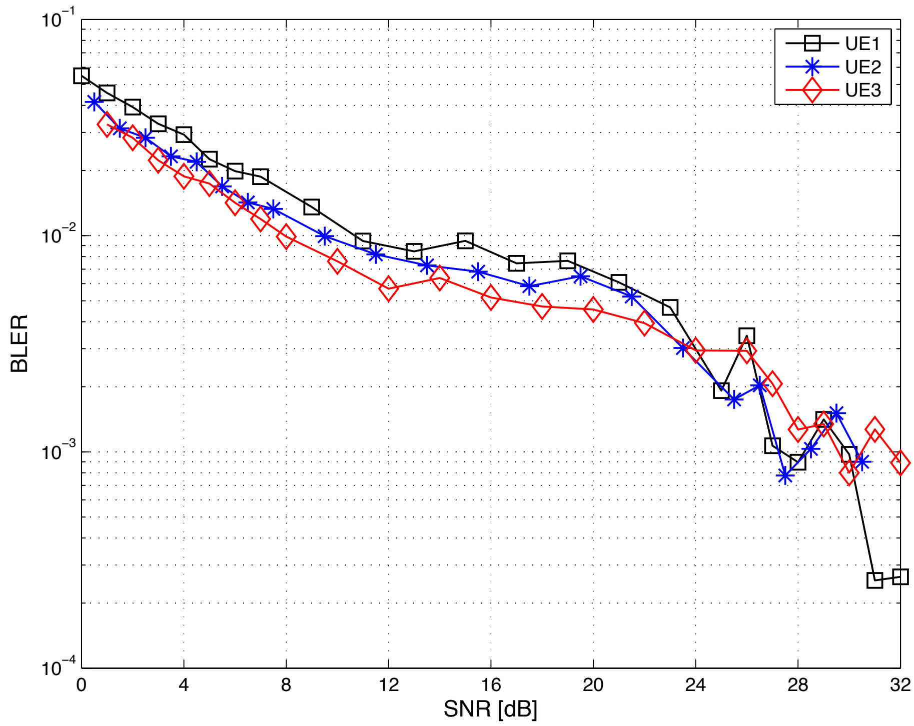

Figure 4.8. Shifted UE-specific BLER of suboptimal max rate scheduler with 3 users and 0 TTI delay, and the curves of UE 2 and UE 3 are shifted left to have the same average SNR with UE1. In the simulation, each user has a different average SNR value that UE 1 has the lowest value and UE 3 has the highest, and the difference of average SNR among them is 0.5 dB.

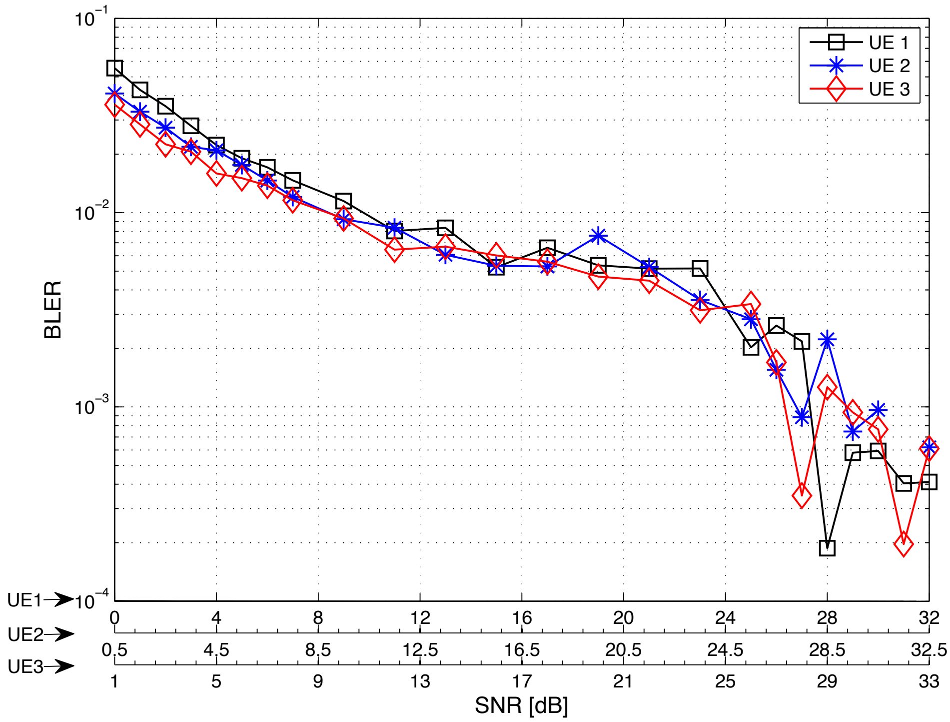

Figure 4.9. UE-specific BLER of suboptimal proportional fair scheduler with 3 users and 0 TTI delay, and UE 1 has the lowest average SNR while UE 3 has the highest.

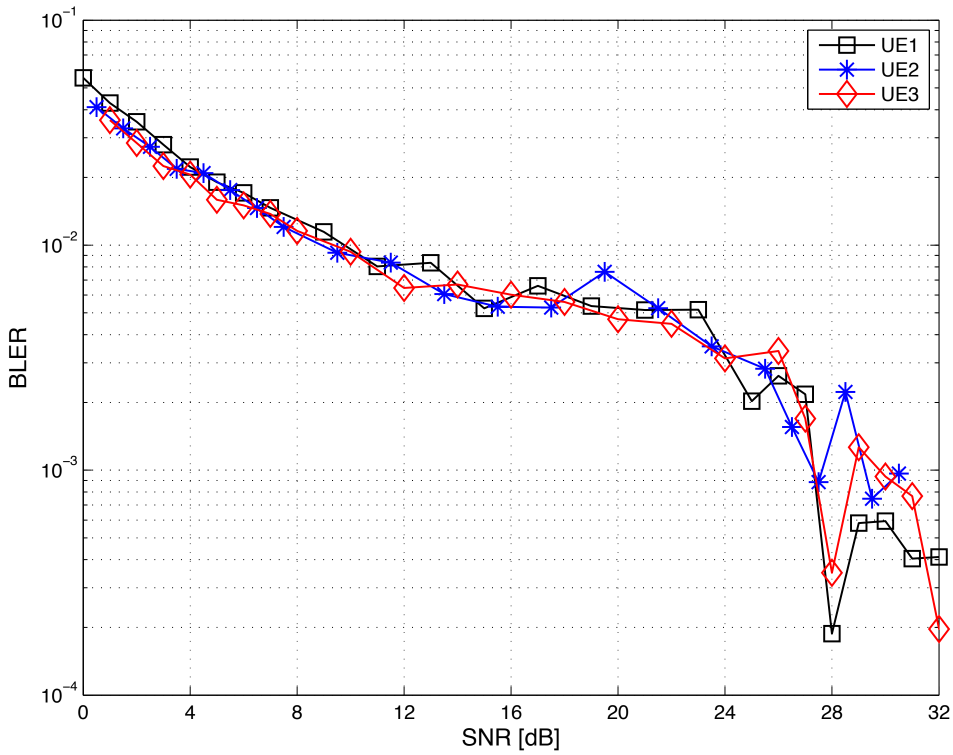

Figure 4.10. Shifted UE-specific BLER of suboptimal proportional fair scheduler with 3 users and 0 TTI delay, and the curves of UE 2 and UE 3 are shifted left to have the same average SNR with UE1. In the simulation each user has a different average SNR value that UE 1 has the lowest value and UE 3 has the highest, and the difference of average SNR among them is 0.5 dB.

From Figure 4.7 and Figure 4.9, we can see that without delay, both of the two schedulers satisfy the BLER requirement: the performance is acceptable with BLER under 0.1. When the average SNR is less than 19.83 dB (Table 2.2), the user with higher average SNR has a better channel condition and support better MCS and thus it can transmit more data with higher CQI efficiency, and the schedulers tend to allocate better resources to this user, thus the users with higher average SNR has a better performance, no matter it is the BLER or the throughput. When the average SNR is larger than 19.83 dB, the channel quality is good enough to support the best MCS, in this case every user has the same performance, and as the average SNR increases their performance will not get better any more.

In Figure 4.8 and Figure 4.10, we have shifted the BLER curves to the same average SNR. In Figure 4.8, for the suboptimal max rate scheduler, after shifting the curves, the gaps among the curves still exist. But in Figure 4.10, the shifted curves are almost at the same position. This meets the expectation of the proportional fair scheduler, who tries to make the users have the same performance at the same average SNR level.

D. Comparison of Cell-Specific BLER with the Same Scheduler and Different Delay

In this part, we compare the cell-specific BLER with the same number of users and with different uplink delay.

The tendency of the curves in Figure 4.11 and Figure 4.12 is the same, and that means in this comparison, the performance of two schedulers is similar. The figures show that the BLER goes up as the delay increases. With uplink delay, if the average SNR of the users is not large enough, the BLER even cannot meet the required BLER level [1, pp. 283]. It also shows that the feedback delay has a big impact on the performance of the schedulers. The corresponding curves of the cell-specific BLER with 5 and 10 users has similarity with the ones above, and they are presented in Figure B.8 – Figure B.11 in Appendix B.

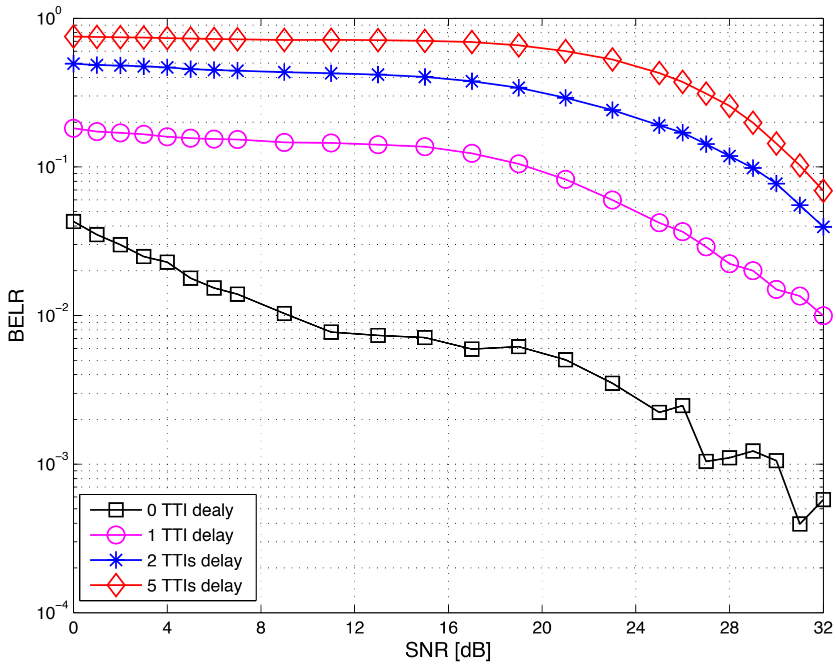

Figure 4.11. Cell-specific BLER of suboptimal max rate scheduler with 3 users and 0, 1, 2 and 5 TTIs delay.

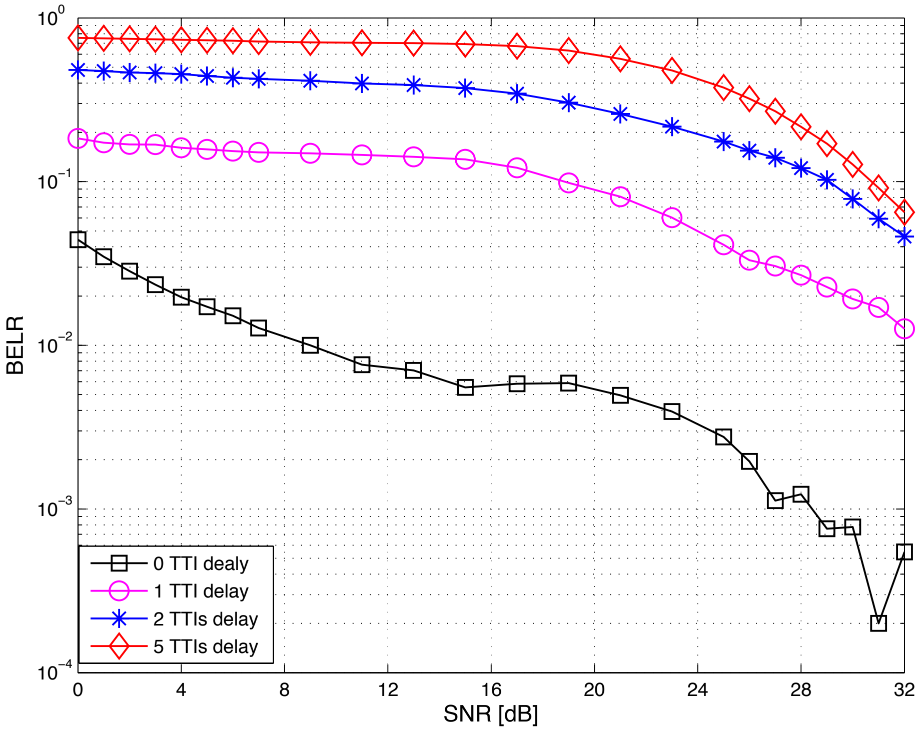

Figure 4.12. Cell-specific BLER of suboptimal proportional fair scheduler with 3 users and 0, 1, 2 and 5 TTIs delay.

5

CONCLUSION AND FUTURE WORK

In this chapter, we draw some brief conclusions based on the discussion in Chapter 4, and then discuss the possible future work to improve the schedulers' performance.

5.1 Conclusions

According to the numerical results showed in Chapter 4, we can know that all of the algorithms meet the requirement of performance. The max rate scheduler tends to achieve the maximal throughput for the communication system and the proportional fair algorithm tries to balance the resources for different users to maintain the fairness, so the throughput of max rate scheduler is always larger than the one of proportional fair scheduler with the same system configuration.

Although the performance of optimal algorithms is a little better than the one of suboptimal algorithms, the latter algorithms as the compromise provide an acceptable performance, and more importantly, the suboptimal methods are much more effective and practical than the optimal ones and therefore they can be implemented in the real system.

As discussed in Chapter 4, the performance of the algorithms could be affected by the number of users and uplink delay. Because the algorithm of the schedulers allows available RBs with bad channel condition remained after allocating the bandwidth to multiple users, with the number of the users increasing, the cell-specific throughput becomes larger and larger until no remaining available RBs. The uplink delay has a big impact on the system performance, and it leads to a much higher BLER and of course a worse throughput performance. With uplink delay, the users should have a higher average SNR to meet the system BLER performance requirements.

5.2 Future Work

From the figures related to BLER, when no feedback delay exists, we can see that the BLER curves are much lower than the system's acceptable BLER threshold. This provides the room for us to improve the performance, because the transmission bit rate can be increased with the relaxation of BLER.

The aspects described below may contribute the performance improvement.

In this thesis the effective SINR mapping utilized is EESM, but it is a little conservative, since it tends to calculate a lower effective SINR than the actual one, and this makes the scheduler try to pick up a smaller MCS for the download transmission, and thus it slows the bit rate. We have mentioned at the beginning of Chapter 2 that there is another ESM named MIESM, and it has a better performance than the EESM but it is much more complex to be implemented. This part can allow more work to be done to find a better ESM.

Most of the results in this report are simulated based on the suboptimal algorithms, because the optimal methods are too inefficient and unpractical to be simulated and implemented. But the performance of the optimal algorithms are indeed better than the suboptimal ones. For future work, a better solution of implementation could be investigated to improve the schedulers' performance.

In the scheduler, when it assigned an MCS to a user, the MCS's corresponding CQI value could not be larger than the lowest value of the CQIs fed back by this user within the allocated RBs. For instance, if the scheduler allocates three RBs to user 1, and the corresponding CQI values of the three RBs fed back by this user are 9, 10 and 10, and in the algorithms, it tends to assign the corresponding MCS of CQI 9 to user 1 in the downlink transmission. But in this case, if it assigns the corresponding MCS of CQI 10 to this user, the downlink transmission can achieve a higher bit rate and the BLER may not surpass the BLER threshold. The specific mechanism of this is unclear, and this may be an interesting research area.

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Appendix

A: Verification Results

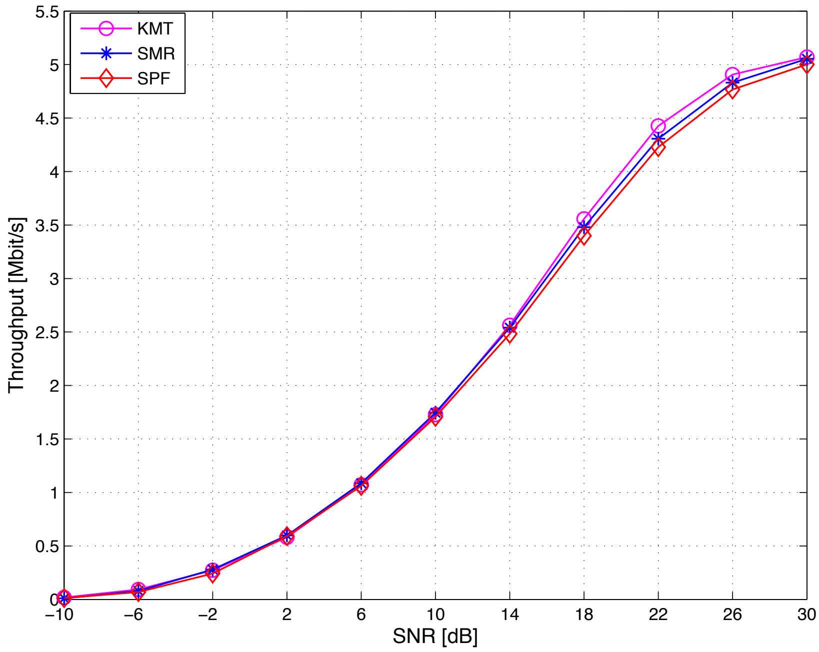

Figure A.1. Sum throughput obtained with three different schedulers plotted over average SNR for UE 1 and UE 2.

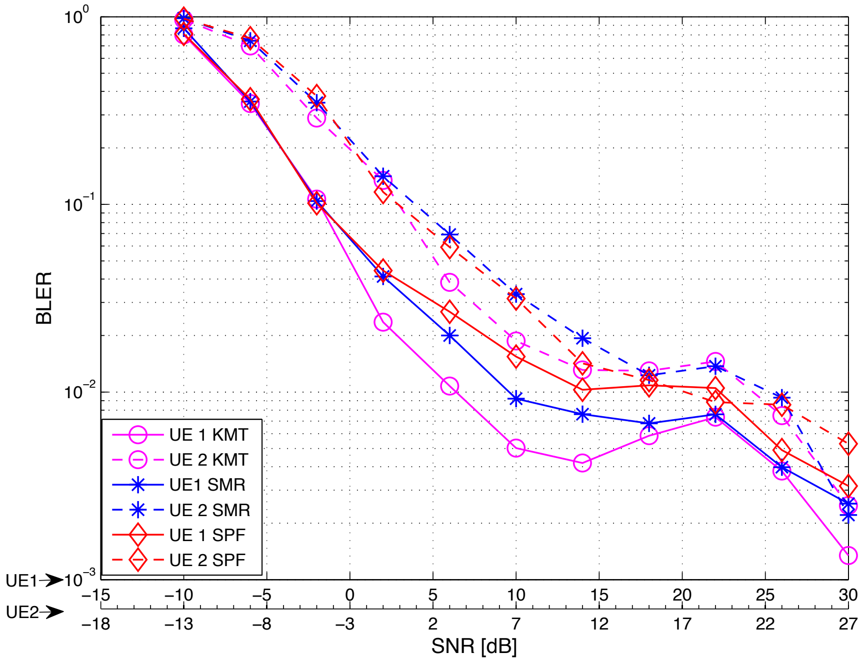

Figure A.2. BLER obtained with three different schedulers plotted over average SNR for UE 1 and UE 2.

B: Additional Results

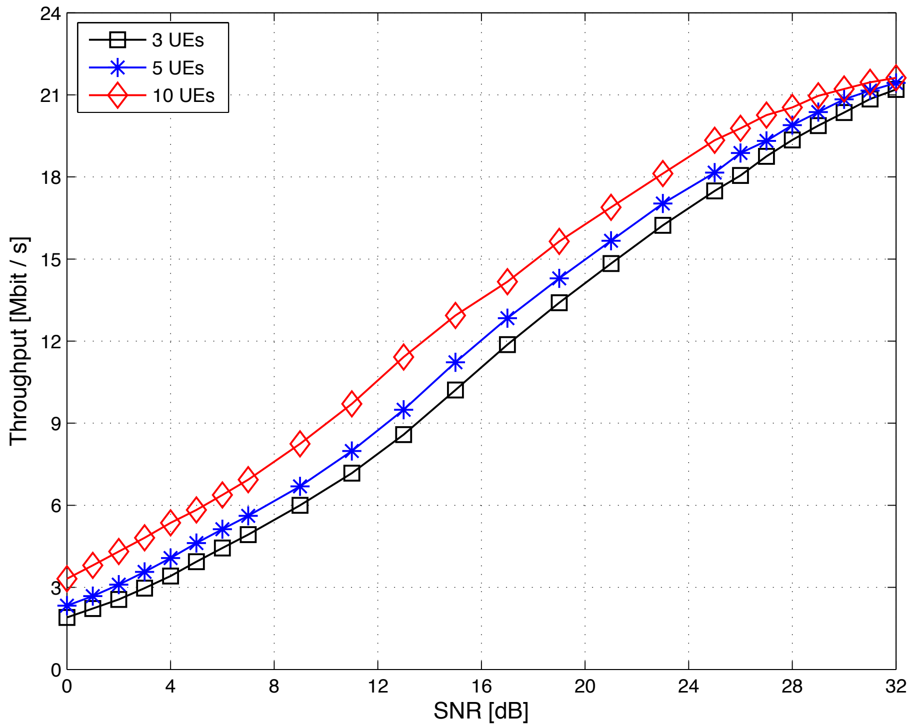

Figure B.1. Cell-specific throughput of suboptimal max rate scheduler with 3, 5 and 10 users and 2 TTIs delay.

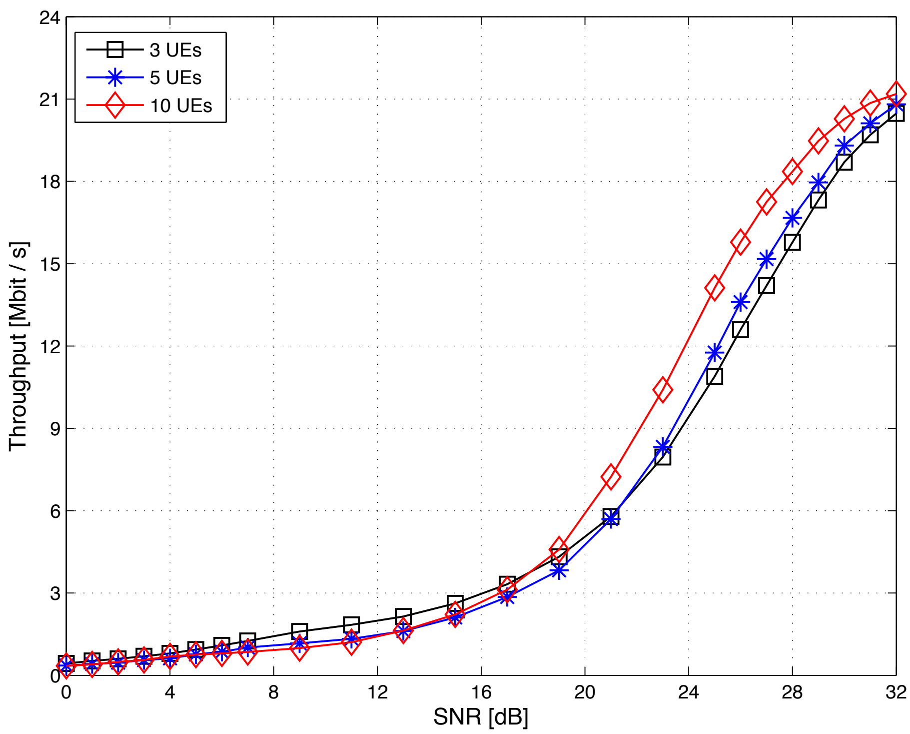

Figure B.2. Cell-specific throughput of suboptimal max rate scheduler with 3, 5 and 10 users and 5 TTIs delay.

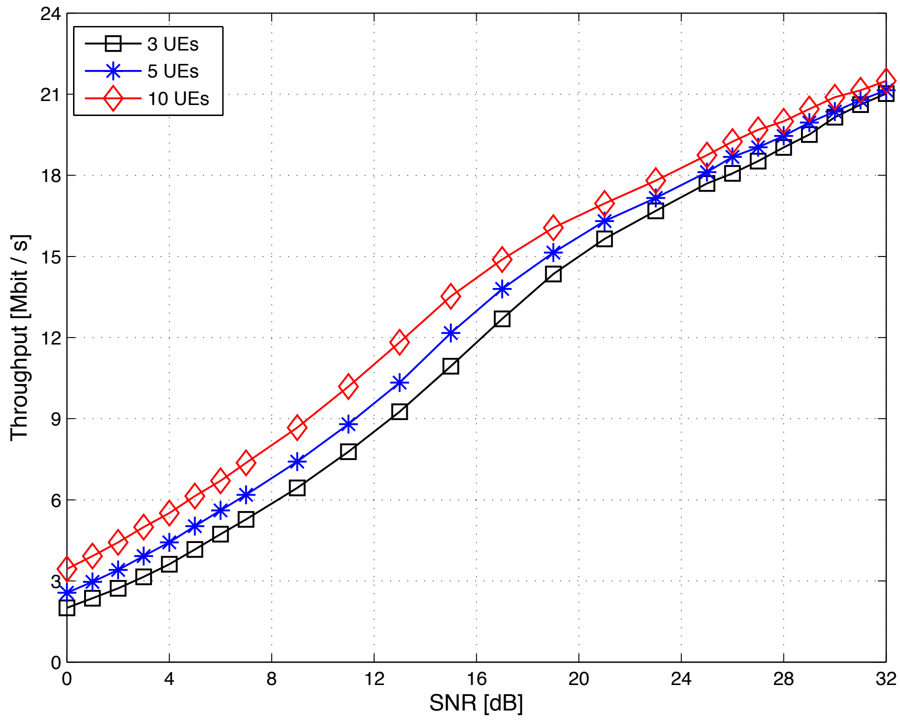

Figure B.3. Cell-specific throughput of suboptimal proportional fair scheduler with 3, 5 and 10 users and 2 TTIs delay.

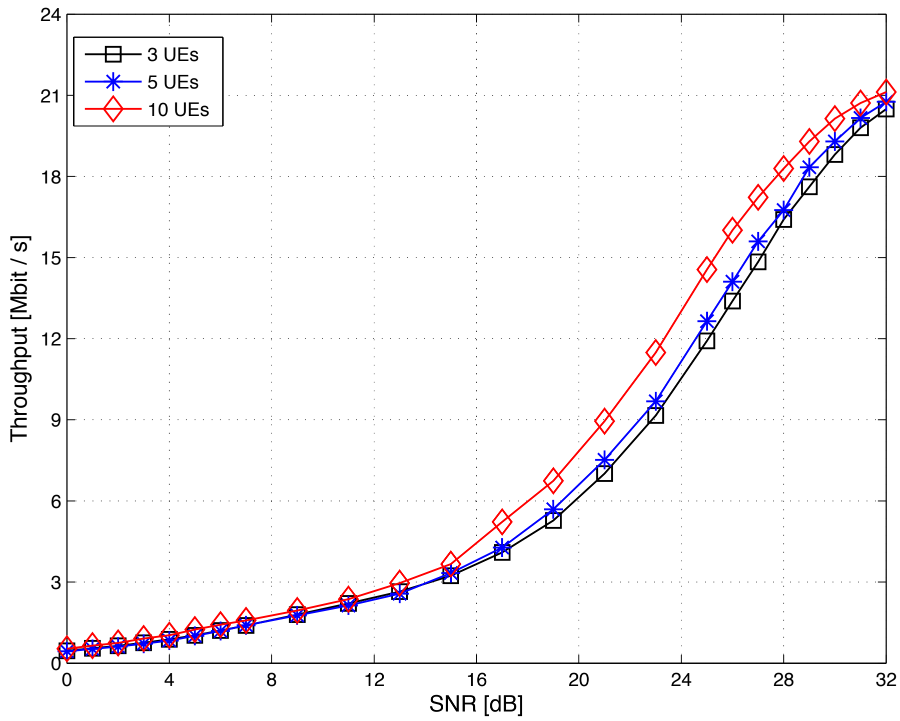

Figure B.4. Cell-specific throughput of suboptimal proportional fair scheduler with 3, 5 and 10 users and 5 TTIs delay.

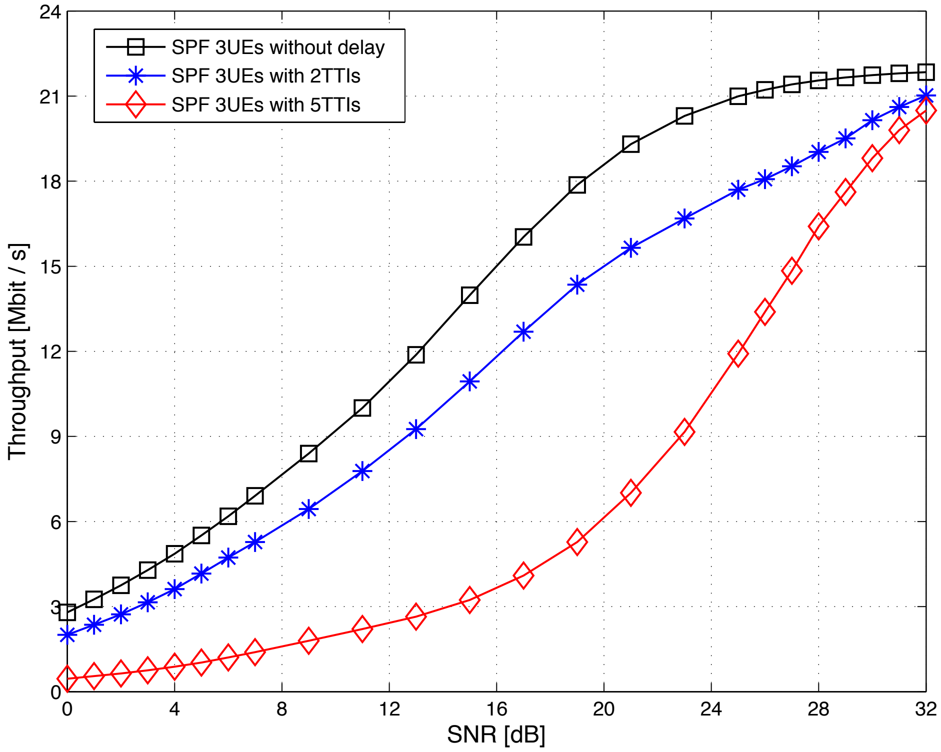

Figure B.5. Cell-specific throughput of suboptimal proportional fair scheduler with 3 users and 0, 2 and 5 TTIs delay.

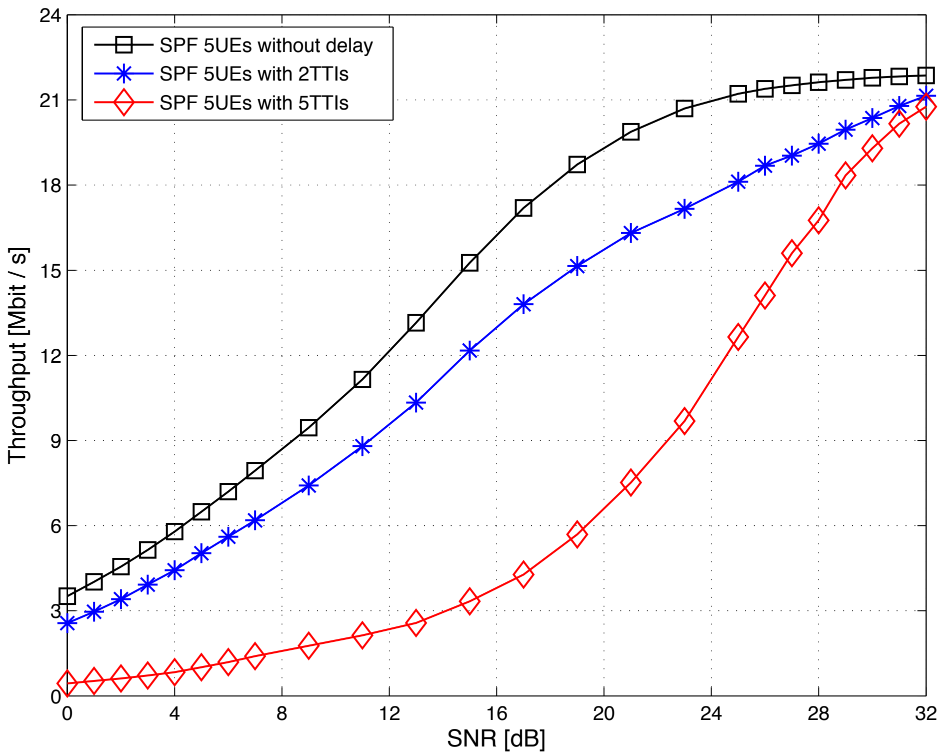

Figure B.6. Cell-specific throughput of suboptimal proportional fair scheduler with 5 users and 0, 2 and 5 TTIs delay.

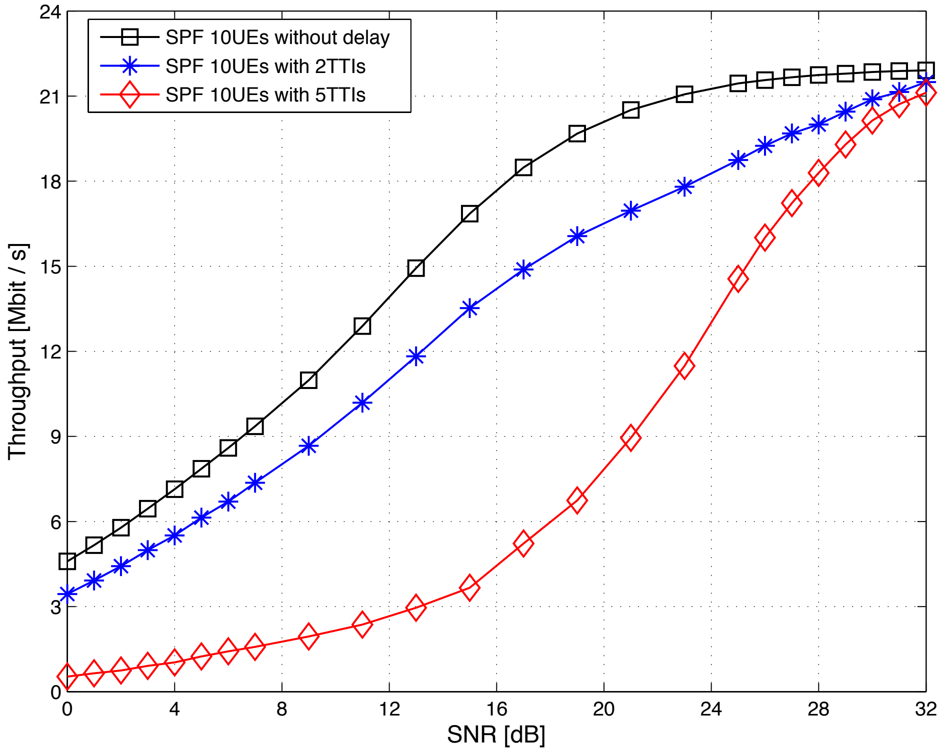

Figure B.7. Cell-specific throughput of suboptimal proportional fair scheduler with 10 users and 0, 2 and 5 TTIs delay.

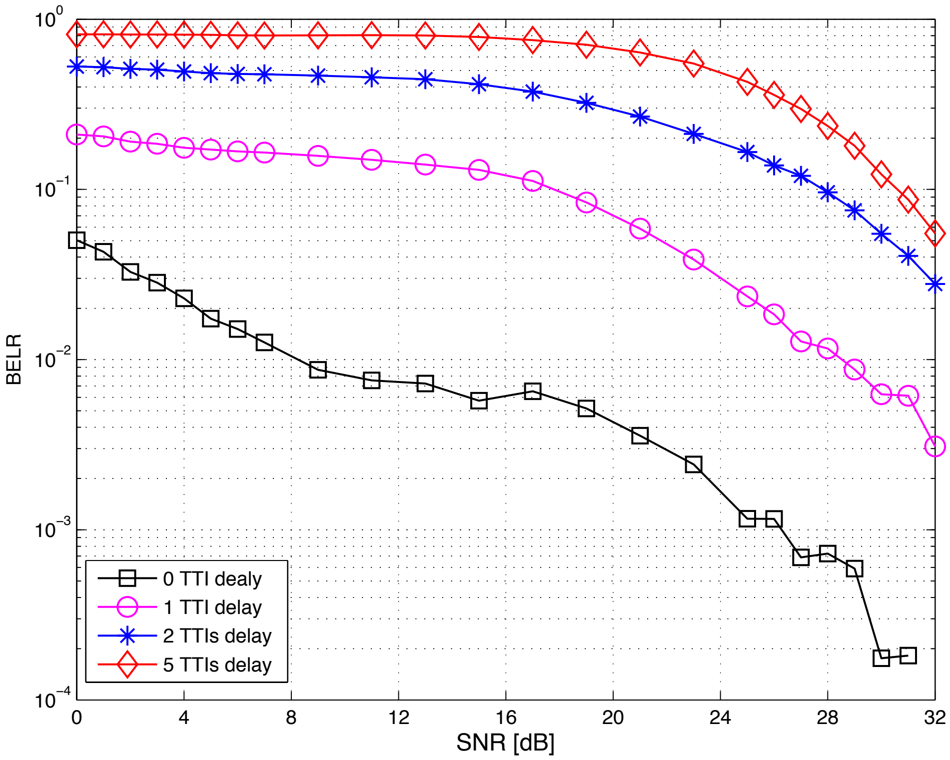

Figure B.8. Cell-specific BLER of suboptimal max rate scheduler with 5 users and 0, 1, 2 and 5 TTIs delay.

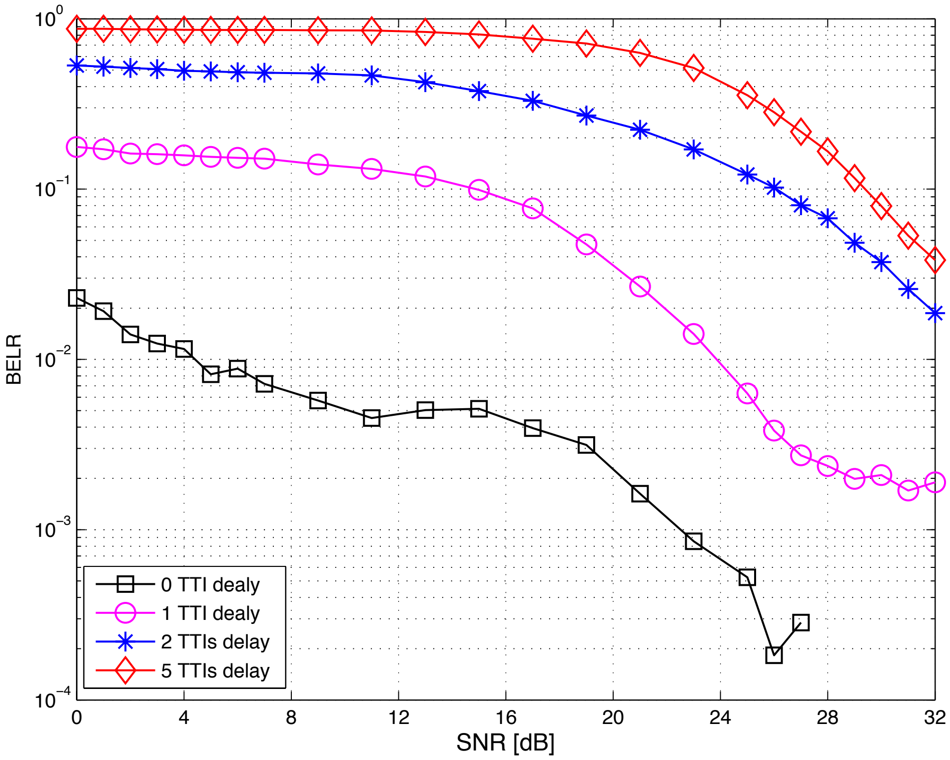

Figure B.9. Cell-specific BLER of suboptimal max rate scheduler with 10 users and 0, 1, 2 and 5 TTIs delay.

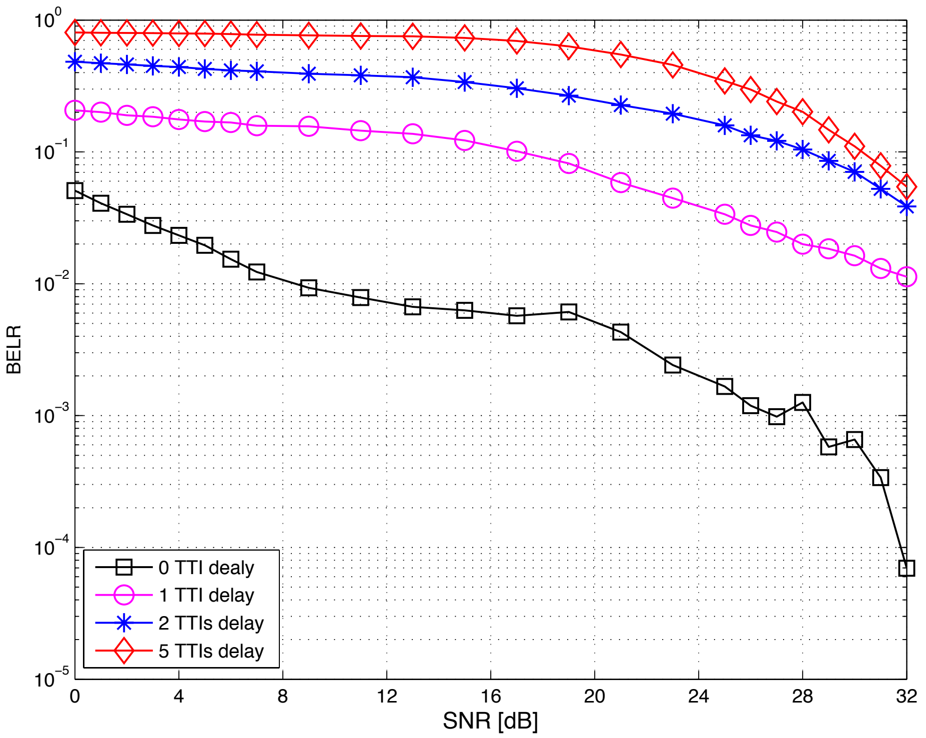

Figure B.10. Cell-specific BLER of suboptimal proportional scheduler with 5 users and 0, 1, 2 and 5 TTIs delay.

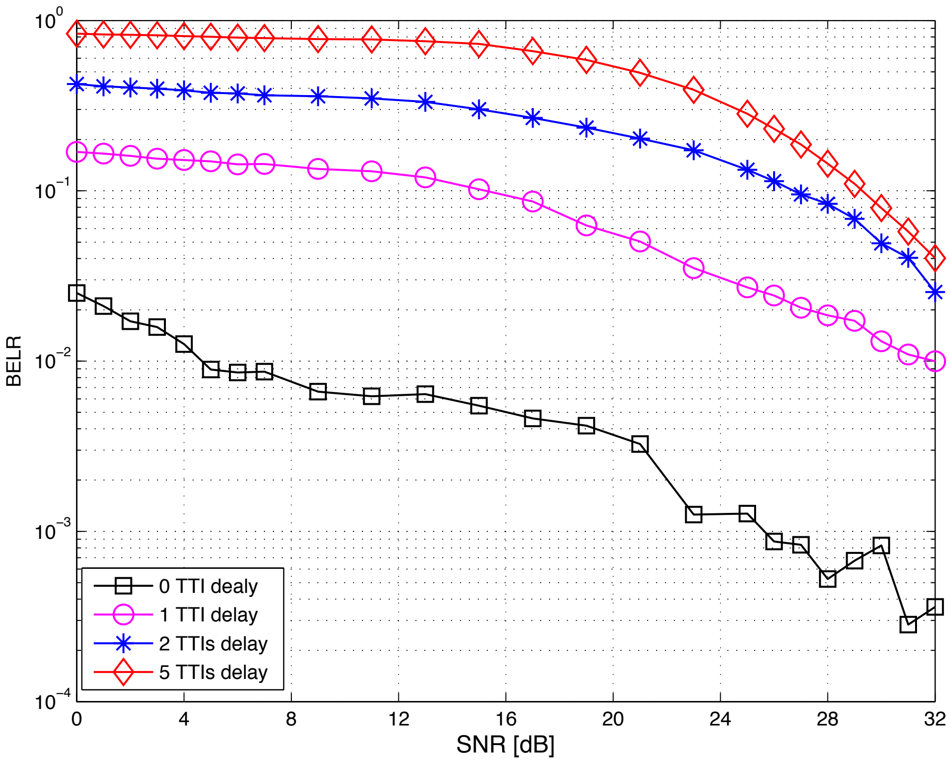

Figure B.11. Cell-specific BLER of suboptimal proportional fair scheduler with 10 users and 0, 1, 2 and 5 TTIs delay.