Master Thesis

Resource Allocation for Layered Transmission in Multicast OFDM Systems

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December 1, 2014

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Theme

Multicast radio resource allocation for multimedia applications is a challenging problem in wireless networks since different users experience different channel conditions. The simplest solution is to allocate the system resources with respect to the user with the weakest channel condition, e.g. the cell edge user. Although such method is able to guarantee the quality of service (QoS) of the weakest user, it does not fully utilize the radio resources and impairs the QoS of other users. In the literature, there are many approaches in striking a balance between spectral efficiency and guaranteeing QoS in multicast systems. One appealing approach to the problem is to use multiple layered coding. Basically, using layered multimedia transmission enable for more degrees of freedom for resource allocation, and hence allows all users to receive multimedia streams most of the time with different rates/qualities, depending on their own channel states. Indeed, the concept of layered coding has been applied to video standards such as H.264. Nevertheless, the introduction of layered coding requires an unequal error protection over different layers which are not considered in most resource allocation algorithms.

In this Master thesis, we aim to design a practical resource allocation algorithm which takes into account unequal error protection for multicast wireless communication networks.

Declaration

To the best of my knowledge and belief this work was prepared without aid from any other sources except where indicated. Any reference to material previously published by any other person has been duly acknowledged. This work contains no material which has been submitted or accepted for the award of any other degree in any institution.

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Contents

Abstract

In traditional multicast scheme, the system throughput is restricted by the user which has the worst channel status. This makes the system spectrum efficiency kept in a low level. To avoid this disadvantage, we design a multicast resource allocation based on layered coding scheme, which can effectively allocate radio resource of OFDM multicast to maximize the system throughput while providing a minimum quality of service (QoS). In this paper, the subcarrier assignment and power allocation for video or multimedia multicast services in wireless OFDM system is analyzed. We utilize an radio resource allocation algorithm in the downlink of OFDM wireless multicast system. In the meanwhile, an optimized power allocation is deployed into this model system. A three-level optimization hierarchy is proposed to provide a clear view on the performance comparison between different resource allocation schemes. In level 1, we provides a very basic scheme which has no any optimization scheme deployed. In level 2, we deploy power allocation scheme but without radio resource allocation. In level 3, we deploy both power allocation and radio resource allocation. An effective convex method is adopted to optimize the system. A simplified process on optimization is suggested to reduce the computational complexity. Simulation results show that the proposed scheme can have an obvious performance improvement comparing to the traditional scheme.

Glossary

Abbreviations

OFDM	Orthogonal Frequency Division Multicast
BL	Base layer
EL	Enhancement Layer
BS	Base Station
CSI	Channel Status Information
QoS	Quality of Service
SC	Subcarrier
SDP	Semidefinite Programming

Operators

$1(A)$	Indicator function, becomes 1 when the condition A is met and 0 otherwise

Symbols

B	Total available system bandwidth in Hz
$\overrightarrow{w_l}$	Beamforming vector of subcarrier l
$\overrightarrow{h}_k$	Channel gain of user k in subcarrier l
N_0	Noise power density
r_k^l	Achievable transmission data rate of user k in subcarrier l
L	Number of subcarriers
T_x	Transmitter
R_x	Receiver
$B_{k,l}$	Base layer transmission rate of user k in subcarrier l
BL_{req}	Minimum required base layer transmission rate per user
EL_{req}	Minimum required enhancement layer transmission rate per user
δ_l	Indicator that shows which layer data the subcarrier transmits
P_{max}	Maximum allowed power consumption

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Chapter 1.

Introduction

1.1. Motivation and Overview

In recent years, we are moving to a world where everyone intends to have immediate and convenient communication services that could be offered anywhere anytime by making use of mobile terminals, such as mobile phone, tablet computer and so on. The multimedia applications involve various types of data including video, voice, data and image. Among all the service types, the video transmission applications for video call, internet TV, video conference and distance education and so on, have occupied a large percentage which is already over 53 percent. This no wonder creates a huge requirement to the bandwidth of wireless communication system. The lack of bandwidth would create a lot of problems, like long-time buffer, low-definition image/video, voice morphing. Figure 1.1 shows an overview on current wireless communication applications.

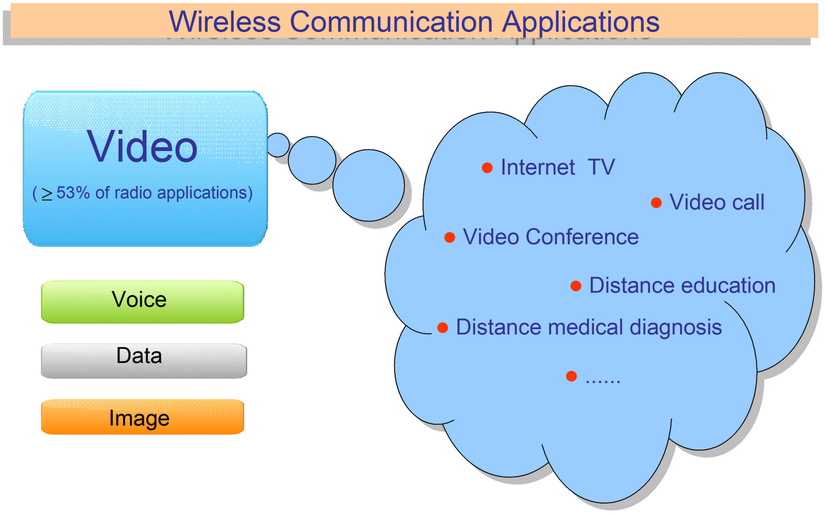

Figure 1.1.: Overview of Wireless Communication Applications.

In wireless system, the spectrum resource is limited and expensive, and the channel varies according to users due to fading. Thus we need to make efficient utilization of the limited spectrum resource, to improve the bandwidth/spectral efficiency of existing wireless communication systems. In this paper, we adopt Layered Coding Scheme in the downlink OFDM multicast system to improve the network throughput/spectral efficiency.

1.2. Introduction to OFDM Multicast

Orthogonal frequency-division multiplexing (OFDM) is a method of encoding digital data on multiple carrier frequencies [1]–[13]. It has developed into a popular scheme for wideband digital communication that has been used in applications such as digital television, 3G LTE (Long Term Evolution), 4G mobile communications and so on[1].

The principle of the OFDM technology is to divide the total system bandwidth into a large number of orthogonal narrowband subcarriers. The data is transmitted through one or more subcarriers to the users. Every user can get data transmission through multi-subcarrier (subchannel), see [2] Figure 1.2 and [3] Figure 1.3 . OFDM is a frequency-division multiplexing scheme used as a digital multi-carrier modulation method. A large number of closely spaced orthogonal subcarrier signals are used to carry data on several parallel data streams or channels. Each subcarrier is modulated with a conventional modulation scheme (such as quadrature amplitude modulation or phase-shift keying) at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes with the same bandwidth.

The primary advantage of OFDM over single-carrier schemes is its ability to cope with for example frequency-selective fading without utilizing complex equalization filters. The low symbol rate makes the use of a guard interval between symbols affordable, making it possible to eliminate inter symbol interference and utilize echoes and time to achieve a diversity gain, i.e. a signal-to-noise ratio improvement.

OFDM has been regarded as one of the most promising technologies which enable reliable and highly cost-effective data transmission in wireless communication systems [14, 15]. With the help of OFDM scheme, the wireless communication networks can efficiently utilize the radio resource and guarantee required QoS services for all the users. It has become one of the most important technologies for the wireless communication networks. In this paper, we will study the layered transmission scheme in the downlink

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[1] From http://en.wikipedia.org/wiki/Orthogonal-frequency-division-multiple-access

[2] From http://thefutureofthings.com/3898-the-future-of-wimax/

[3] http://kambing.ui.ac.id/onnopurbo/library/library-ref-eng/ref-eng-3/physical/wimax/wikipedia/OFDMA-files/OFDMA-subcarriers.png

OFDM system. With the function of OFDM multiacst scheme, we can have much benefit for our current wireless communication networks and services.

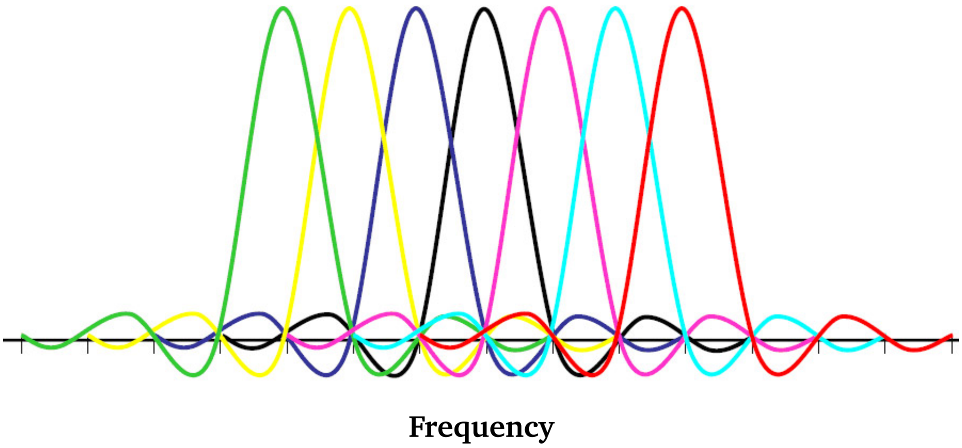

Figure 1.2.: OFDM Subcarrier Division.

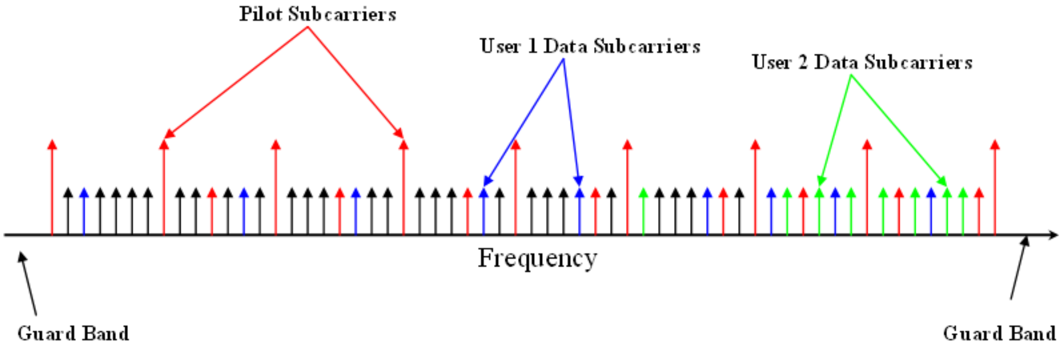

Figure 1.3.: OFDM Subcarrier Allocation and Utilization.

The basic LTE downlink physical resource can be seen as a time-frequency grid, as illustrated in Figure 1.4 . To overcome the effect of multipath fading problem available in UMTS (Universal Mobile Telecommunications System), LTE uses OFDM for the downlink - that is, from the base station to the terminal to transmit the data over many narrow band carriers of 180kHz each instead of spreading one signal over the complete 5MHz carrier bandwidth. OFDM meets the LTE requirement for spectrum flexibility and enables cost-efficient solutions for very wide carriers with high peak rates.

The OFDM symbols are grouped into resource blocks. The resource blocks have a total size of 180kHz in the frequency domain and 0.5ms in the time domain. Each

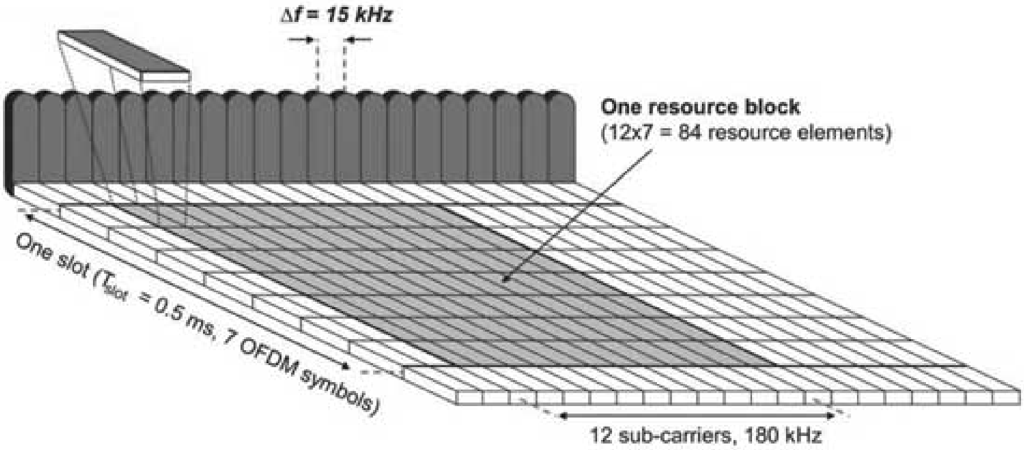

Figure 1.4.: LTE Resource Block.

1ms Transmission Time Interval consists of two slots. Each user is allocated a number of so-called resource blocks in the time frequency grid. The more resource blocks a user gets, and the higher the modulation used in the resource elements, the higher the bit-rate. Which resource blocks and how many the user gets at a given point in time depend on advanced scheduling mechanisms in the frequency and time dimensions[4].

1.3. Introduction of Layered Coding

1.3.1. Introduction to Layered Coding Scheme

In multicast OFDM systems, the difference in link conditions of users complicates adaptive modulation because modulation should be adjusted to serve the user who experiences the worst channel condition. If we assume that the multicast data are separated into layers and any combination of the layers can be decoded at the receiver, the network throughput can be increased by performing subcarrier allocation. In this paper, in order to increase network throughput, we develop a subcarrier allocation method that maximizes the throughput of the system. This scheme is Layered Coding Scheme as Figure 1.5 shows.

In the layered coding transmission mechanism, the original multicast data stream is firstly encoded into multilayers, including a base layer and several enhancement layers [16, 17, 18]. The base layer is used to transmit the most essential information that can help to guarantee the minimum Quality of Service (QoS) of all the users. It transmits data with the highest priority. Base layer data should be correctly decoded by

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[4] http://www.tutorialspoint.com/lte/lte-ofdm-technology.htm

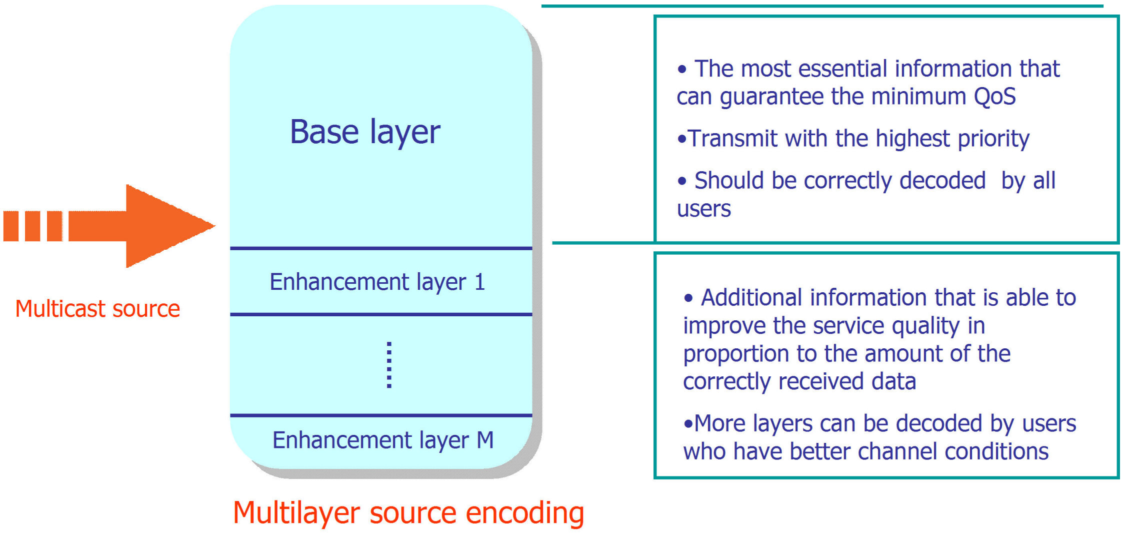

Figure 1.5.: Work Principle of Layered Coding Scheme.

all the users in the system. The enhancement layer is used to transmit the additional information that is able to improve the service quality in proportional to the amount of the correctly received and decoded data on the user side. Those users who have better channel conditions can decode more enhancement layers. The more enhancement layers the user can decode, the better the transmission data rate/quality of service would be.

In the system side, OFDM system divides the total system bandwidth into a large number of orthogonal narrowband subcarriers. While Layered Coding Scheme encodes the transmission data into one base layer and several enhancement layers. So the data in base layer and enhancement layer is transmitted through one or more subcarriers to the users. Every user can get data transmission through multi-subcarrier (subchannel). For the data transmission, we can deploy optimization schemes that dynamically allocate the subcarriers to transmit base layer data and enhancement layer data, then to optimize this transmission to approach the target we require. By utilizing of layered coding in OFDM system, we could divide the transmitted data into different layers with different priorities of transmission and achieve benefits from advantages from both OFDM system and Layered Coding Scheme, which could improve significantly the system throughput, as well as the spectrum efficiency.

1.3.2. Applications of Layered Coding

The main application of layered coding is H.264/MPEG-4 AVC video. H.264 or MPEG-4 Part 10, Advanced Video Coding (MPEG-4 AVC) is a video compression format that is currently one of the most commonly used formats for recording, compression, and distribution of video content. H.264 is a new video codec standard which can achieve high quality video in relatively low bit rates. It is treated as the "successor" of the existing formats (MPEG2, MPEG-4, DivX, XviD, etc.) as it aims in offering similar video quality in half size of the formats mentioned before. H.264/MPEG-4 AVC is a block-oriented motion-compensation-based video compression standard developed by the ITU-T Video Coding Experts Group (VCEG) together with the ISO/IEC JTC1 Moving Picture Experts Group (MPEG)[5].

The H.264 video format has a very broad application range that covers all forms of digital compressed video from low bit-rate Internet streaming applications to HDTV broadcast and Digital Cinema applications with nearly lossless coding. The best known utilization of H.264/MPEG-4 AVC is one of the video encoding standards for Blu-ray Discs. All Blu-ray Disc players can decode H.264. It is also widely used by streaming internet sources, such as videos from YouTube, the iTunes Store, web softwares such as the Adobe Flash Player, Microsoft Silverlight, various HDTV broadcasts over terrestrial and satellite. Apple has adopted H.264 as the format for QuickTime. H.264/MPEG-4 AVC is also one of the formats that can be supported by high-definition DVD standards.

1.4. Overview on Multicast

With development of communications and networking, Multicast and Broadcast Services have become main trends of wireless networks. MBMS (Multimedia Broadcast and Multicast Service) [19, 20] introduced by 3GPP in Release 6 is the representative mechanism supporting multicast and broadcast services.

In traditional multicast service, in order to guarantee all users can have data rates, the transmission rate is dictated by the rate of the user with the worst channel in the multicast group [17]. Since traditional multicast scheme only exploits the multicast gain, without considering the multiuser diversity gain, so it easily creates throughput limitation. The layered coding scheme explores not only the multicast gain, but also the user diversity gain, with which we can achieve great benefit.

Currently, many researches have focused on dynamic resource allocation for multicast in OFDM system. In [21, 22] a resource allocation scheme has been introduced to obtain the maximum throughput of all multicast groups. However the minimum required transmission data rate of enhancement layer has not been considered. In [17] a dynamic subcarrier and bit allocation method has been considered to realize maximum throughput by assuming that the multicast data transmitted through layer combinations can be decoded at the receiver side. However user's QoS requirement has not been taken account into. In [23] an optimal subcarrier allocation algorithm has been proposed

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[5] From Wikipedia, the free encyclopedia, H.264/MPEG-4 AVC

to maximize the overall system throughput considering QoS requirement, but the computational complexity is prohibitively high. This limits the total throughput as it does not fully utilize multi-user diversity on each subcarrier. In [24] the Weighted Sum Rate (WSR) Maximization methods under various system constraints are discussed. In [25] a heuristic resource allocation scheme has been used, but it can only achieve some suboptimal results.

1.5. Overview of Thesis

In this paper, we study the optimal subcarrier allocation and power allocation of multicast services in downlink OFDM multicast systems. We utilize the video coding technique in a way that its layered transmission can help to solve the capacity limitation problem of the downlink multicast channels. We utilize a frequency selective Rayleigh Fading channel. Specifically, we develop a subcarrier allocation scheme that can help to improve the total enhancement layer throughput and correspondingly the system spectral efficiency, as well as guaranteeing the minimum QoS of every user in the multicast group. We also involve the optimization of power allocation into our target to realize cost-effective power consumption.

This thesis is organized as follows. In chapter 2, we introduce the modelling system and system design goal. Then we formulate the radio resource allocation algorithm for Maximum Throughput (MT) of a whole multicast group while at the same time guaranteeing QoS requirements of every user in the multicast group. In chapter 3, we formulate the resource allocation problem as an optimization problem. To facilitate an efficient algorithm design, we propose a three-level optimization which includes a baseline scheme, a suboptimum scheme 1 and a suboptimum scheme 2. With these three optimization levels, we can clearly discover how the optimization algorithms work on the OFDM multicast system. In chapter 4, we take a deep look into how to execute the simulation over the three schemes, we assume required simulation parameters according to the real LTE OFDM multicast system and our requirement of the system. Thereafter we get simulation numerical results. In chapter 5, we make an overall conclusion on the whole paper.

Chapter 2.

System Model and Problem Formulation

2.1. System Model

Figure 2.1 shows the downlink multicast OFDM system with layered coding scheme that we consider in this paper.

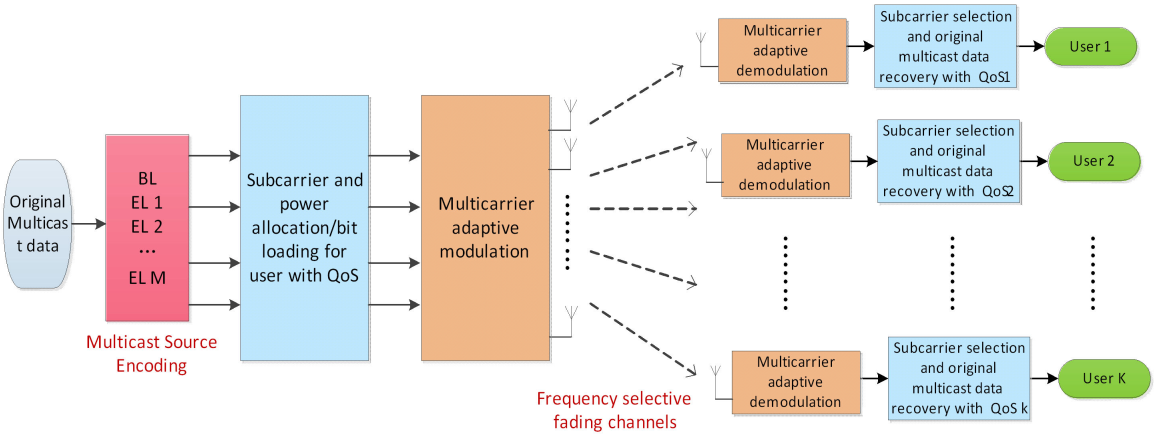

Figure 2.1.: Block Diagram of MISO OFDM Multicast System.

In practice, multiple antennas technology has been implemented to improve the performance of wireless communication systems [14]–[38]. In particular, multiuser multiple input multiple-output (MIMO) has been proposed where a transmitter equipped with multiple antennas services multiple single-antenna users. This special form on MIMO shifts the signal processing burden from the receivers to the transmitter side which makes this technology more suitable for mobile devices [39]–[42]. We consider a MISO OFDM multicast system, which has one multicast group equipped with $N_t (N_t > 1)$

transmit antennas. The overall system bandwidth is divided into L subcarriers. The base station (BS) serves K mobile users, and each user is a single-antenna receiver.

Initially, the multicast data is encoded into one base layer and several enhancement layers by layered coding at the multicast server. The base layer is used to transmit the most essential information that can guarantee the minimum level required video quality if the minimum required base layer transmission rate/Quality of Service(QoS) for every user could be satisfied. The enhancement layer is used to transmit the additional information that can help to improve the video quality of users. The more the correct data can be decoded by the user, the better the quality of service for the user would be.

Secondly, the subcarrier assignment and power allocation will be activated with guaranteeing the QoS for all the users. Both the base layer data and enhancement layer data would be transmitted through the wireless communication system of the cell to every single user. On the user side, the multicarrier adaptive demodulation would be firstly executed, and then the subcarrier selection and original multicast data recovery. The recovery would be executed with guaranteeing of QoS for every user. Each user keeps tracking of the channel state information (CSI) of all subcarriers and feeds back the CSI to the base station(BS) over a feedback channel. The BS utilizes the CSI to decide how many bits need to be loaded to each subcarrier and then assign each subcarrier to base layer or enhancement layer.

2.2. System Design Goal

In this paper, our system design goal is to maximize the spectral efficiency/system throughput with layered transmission scheme (layered coding with base layer and enhancement layer transmission) in the downlink OFDM multicast system utilizing frequency selective fading channel. We deploy the optimized power allocation algorithm into our modelling system to improve the system performance. To have a clear view on the effects of our layered coding scheme and power allocation scheme, we design our work targeting on three optimization levels. In different optimization levels, we will have different scheme combinations with subcarrier allocation and power allocation.

Besides, there are several main constraints need to be considered. The first one is to guarantee the required QoS of every single user in the multicast group. Second one is to control the power consumption not over some specific limitation that we require. Finally we still need to have a specific constraint about the rank of input matrix when we work with SDP relaxation(will be deeply introduced in later chapter) to convexify our problem formulation. Note that the constraint on the rank of input matrix is only an intermediate parameter.

2.3. Problem Formulation

2.3.1. System Performance Metric

We denote B as the total available system bandwidth in Hz, $\overrightarrow{w_l} \in C^{N_t \times 1}$ as the beamforming vector of subcarrier l , and $\overrightarrow{h_k} \in C^{N_t \times 1}$ as the channel gain of the subcarrier l seen by user k . We also denote N_0 as the noise power density in subcarrier l. The achievable transmission data rate of user k in subcarrier l is:

$$r_k^l = \frac{B}{L} \log_2(1 + \frac{|\overrightarrow{h_k}^H \cdot \overrightarrow{w_l}|^2}{N_0 \cdot B/L}). \tag{2.1}$$

2.3.2. System Base Layer

To formulate the optimization problem, we need to decide the transmission rate of base layer and the enhancement layer for each subcarrier.

We set the user set as $U = \{1, ..., K\}$, and the subcarrier set allocated to transmit base layer is $S = \{1, ..., L\}$. As the base layer transmission rate is limited by the weakest user with the worst CSI, so this base layer transmission data rate of subcarrier l should be set to be the minimum achievable transmission data rate of user k in subcarrier l , which is $B_{k,l} = \min_{k,l} r_k^l$. The total base layer transmission data rate of user k is $\sum_{l=1, l \in S}^{L} B_{k,l}$.

For every single user, the aggregate base layer rate from all the subcarriers should be larger than the base layer transmission rate requirement (QoS), so as to provide the minimum level video quality to all the users. For this purpose, we set a base layer transmission rate constraint BL_{req} to every single user in the cell. We have:

$$\sum_{l=1, l \in S}^{L} B_{k,l} \geq BL_{req}, \forall k. \tag{2.2}$$

Note that the total transmission rate higher than the requirement can′t be used to improve the video quality, only the enhancement layer transmission data can.

2.3.3. System Enhancement Layer

First of all, we can manually set some specific enhancement layer threshold transmission rate on the control side of base station, which is also the enhancement layer transmission rate. Only those users who can have larger achievable rate than the threshold can have enhancement layer transmission, and the enhancement layer transmission rate of those users is just this threshold transmission rate.

According to above principle, we set an enhancement layer transmission threshold/criterion transmission rate EL_{req} per user. When the user′s achievable transmission rate is higher than EL_{req} , it means that this user can have enhancement layer transmission, and the enhancement layer transmission rate of this user is EL_{req} . We set the subcarrier set that is composed of all the subcarriers allocated to enhancement layer as $\overline{S} = \{1, ..., L\}$. Note that the subcarriers allocated to transmit base layer are different with the subcarriers allocated to transmit enhancement layer.

For every user, when the following requirement is satisfied, the user can have enhancement layer transmission:

$$EL_k = \sum_{l=1, l \in \overline{S}}^{L} r_{k,l} \geq EL_{req}. \tag{2.3}$$

Those users who have better channel conditions as well as larger enhancement layer transmission compose the enhancement layer throughput, and the enhancement layer transmission rate for every such user is just the enhancement layer threshold/criterion rate EL_{req}. To calculate the system total enhancement layer throughput, we just need to add up all the enhancement layer transmission rate together, which is the enhancement layer threshold times the number of users who have enhancement layer transmission. Then the total system enhancement layer throughput is[43] [44]:

$$EL_{total} = \sum_{k=1}^{K} EL_{req} \cdot 1(\sum_{l=1, l \in \overline{S}}^{L} r_k^l \geq EL_{req}). \tag{2.4}$$

Here we use an indicator function $1(A)$ to help distinguishing if the enhancement layer transmission rate is larger than the threshold transmission rate. $1(A)$ becomes 1 when the condition A is met and 0 otherwise.

2.3.4. Maximization of System Throughput

Considering the required minimum base layer throughput of the system is fixed, we maximize the total system throughput through maximizing the enhancement layer throughput, as shown in Figure 2.2.

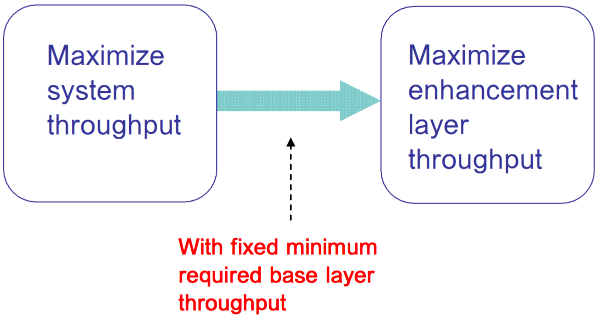

Figure 2.2.: Concept of System Throughput Maximization.

2.3.5. Problem Formulation

Now we formulate the subcarrier allocation problem by maximizing the total throughput of enhancement layer transmission. To indicate how the subcarrier is assigned to base layer or enhancement layer, we utilize a parameter δ_l and a subcarrier allocation indication vector $\overrightarrow{\delta_l}$ to show which layer the subcarrier would be assigned to transmit. δ_l becomes 1 when the subcarrier is assigned to transmit base layer, and 0 when the subcarrier is assigned to transmit enhancement layer.

To calculate the enhancement layer transmission of every user, we calculate the receivable enhancement layer transmission rate for every user in the subcarrier set $\overline{S}$ which is the subcarrier set of all the subcarriers that are assigned to transmit enhancement layer. We get the set with the help of the indicator δ_l. When the total enhancement layer transmission rate of the user is greater than the required enhancement layer threshold/criterion EL_{req}, the user would have enhancement layer transmission. And the enhancement layer transmission rate of the user is just the enhancement layer threshold/criterion EL_{req}. Then the system total enhancement layer throughput is the enhancement layer threshold/criterion EL_{req} times the number of users who have enhancement layer transmission. Then we can get the following formula to maximizeing the system total enhancement layer throughput/spectral efficiency.

$$\max_{\overrightarrow{w_l},\delta_l} EL_{total} = \max_{\overrightarrow{w_l},\delta_l} \sum_{k=1}^{K} EL_{req} \cdot 1\Big(\sum_{l=1, l\in\overline{S}}^{L} (1-\delta_l) r_k^l \geq EL_{req} \Big). \tag{2.5}$$

By substituting the receivable transmission data rate r_k^l (equation 2.1) into the above formula, we obtain our objective function - the maximization of total enhancement layer throughput:

$$\max_{\overrightarrow{w_l},\delta_l} EL_{total} = \max_{\overrightarrow{w_l},\delta_l} \sum_{k=1}^{K} EL_{req} \cdot 1\Big(\sum_{l=1,l\in\overline{S}}^{L} (1-\delta_l)\frac{B}{L}\log_2(1+\frac{|\overrightarrow{h_k}^H \cdot \overrightarrow{w_l}|^2}{N_0 \cdot B/L}) \geq EL_{req}\Big). \tag{2.6}$$

Meanwhile, we have several other requirements for the above objective function as constraints. The first one is the minimum required base layer transmission rate (QoS) BL_{req} for every user in the cell, as above equation 2.2. The second one is that we need to control the total power consumption of the system and to optimize the power allocation to make full use of the power input. To get the total system power consumption, we just directly add up all the power consumption of beamforming vector $\overrightarrow{w_l}$ for all users. We can set some specific maximum allowed power consumption P_{max} on the control side of BS. We have:

$$\sum_{l=1}^{L} ||\overrightarrow{w_l}||^2 \leq P_{max}. \tag{2.7}$$

Then, we need to consider the subcarrier allocation. We denote an indicator δ_l to show which layer the subcarrier would be assigned to. When $\delta_l = 1$, it means that the subcarrier is assigned to transmit base layer data. When $\delta_l = 0$, it means that the subcarrier is assigned to transmit enhancement layer. In this paper, we will use different strategies with this important parameter in the subcarrier allocation matrix or vector for different optimization levels. We have:

$$\delta_l \in \{0, 1\}. \tag{2.8}$$

In this way, we can easily express the subcarrier allocation. Every single subcarrier can transmit either base layer data or enhancement layer data in this multicast group in the same time slot.

From above calculation, we can get the problem basic formulation group as the basement for our later optimization work. We have:

- (Equation 2.1) $r_k^l = \frac{B}{L}\log_2(1+\frac{|\overrightarrow{h_k}^H \cdot \overrightarrow{w_l}|^2}{N_0 \cdot B/L})$.

- (Equation 2.2) $\sum_{l=1, l \in S}^{L} B_{k,l} \geq BL_{req}, \forall k.$
- (Equation 2.4) $EL_k = \sum_{l=1, l \in \bar{S}}^{L} r_{k,l} \geq EL_{req}.$
- (Equation 2.4) $EL_{total} = \sum_{k=1}^{K} EL_{req} \cdot 1(\sum_{l=1, l \in \bar{S}}^{L} r_k^l \geq EL_{req}).$
- (Equation 2.6)
  $\max\limits_{\overrightarrow{w_l}, \delta_l} EL_{total} = \max\limits_{\overrightarrow{w_l}, \delta_l} \sum_{k=1}^{K} EL_{req} \cdot 1(\sum_{l=1, l \in \bar{S}}^{L} (1 - \delta_l) \frac{B}{L} \log_2(1 + \frac{|\overrightarrow{h_k}^H \cdot \overrightarrow{w_l}|^2}{N_0 \cdot B/L}) \geq EL_{req}).$
- (Equation 2.7) $\sum_{l=1}^{L} \|\overrightarrow{w_l}\|^2 \leq P_{max}.$
- (Equation 2.8) $\delta_l \in \{0, 1\}.$

Chapter 3.

System Optimization Strategy

3.1. Overview of System Optimization

Our target of system optimization is to maximize the system throughput/spectral efficiency. We have two variables to optimize which are subcarrier/radio resource allocation and power allocation. There are two main obstacles in solving the problem. Firstly we have a binary optimization problem in our system including the subcarrier allocation optimization and power allocation optimization. Secondly we have non-convex parts in our problem formulation as Figure 3.1 highlighted :

$$r_k^l = \frac{B}{L}\log_2\left(1+\frac{\boxed{\left|\overrightarrow{h_k}^H \cdot \overrightarrow{w_l}\right|^2}}{N_0 \cdot B/L}\right)$$

$$\boxed{\sum_{\substack{l=1\\ l\in S}}^{L} B_{k,l}} \geq BL_{req}, \forall k.$$

Figure 3.1.: Non-convex Parts of Problem Formulation.

To show clearly the performance of system optimization with different algorithms, we divide our work into three optimization levels according to the strategy of system design, as table 3.1 shows. In the later chapters of this paper, we will make detailed explanation on every optimization level. With the three optimization levels, we could have a clear comparison view on the performance of our layered coding scheme and power allocation algorithm. Table 3.1 shows the work principles of three optimization levels.

Table 3.1.: Three Levels of Optimization.

Scheme	**Power Allocation**	**Subcarrier Allocation**
`L1-Baseline Scheme`	Equal power allocation	Given $\delta_l \in \{0,1\}$
`L2-Suboptimum Scheme-1`	Optimized power allocation	Given $\delta_l \in \{0,1\}$
`L3-Suboptimum Scheme-2`	Optimized power allocation	$\delta_l \in \{0,1\}$

3.2. System Optimization Levels

3.2.1. Optimization Level 1 - Baseline Scheme

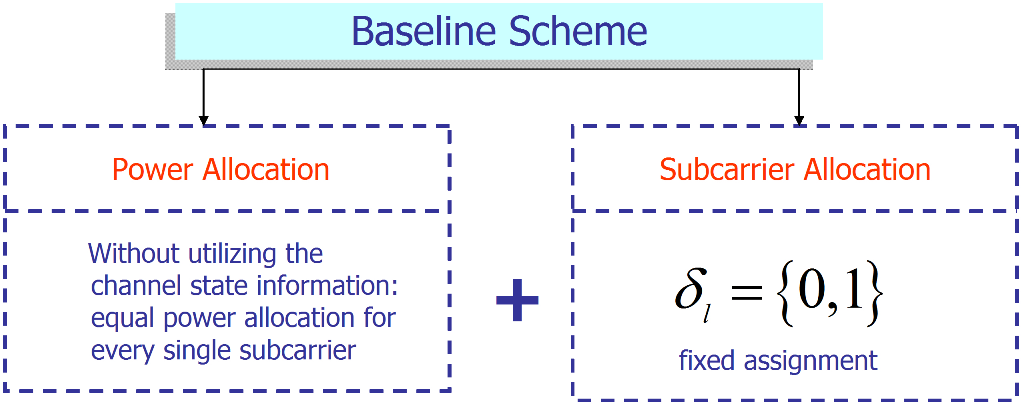

Figure 3.2.: Block Diagram of Optimization Level 1- Baseline Scheme.

Figure 3.2 shows the concept of baseline scheme(optimization level 1). In this optimization level, we make only very basic assumption, that is, we don't make any optimization to either subcarrier allocation or to power allocation. This baseline scheme is regarded as the traditional multicast scheme, which is used as starting point for comparing with our advanced multicast schemes including layered coding scheme. We set the work principle for optimization level 1 in the following way. The power is equally allocated to every subcarrier, which means, every subcarrier has the same power input. For subcarrier/radio resource allocation, we make use of the subcarrier allocation indicator function δ_l, we set $\delta_l = \{0,1\}$, every subcarrier can only transmit base Layer data or enhancement Layer data in every time slot. When $\delta_l = 0$, it means this subcarrier transmits only enhancement layer data, when $\delta_l = 1$, it means this subcarrier transmits only base layer data.

Firstly, to solve the power allocation problem. We have beamforming matrix $w_{N_t,l} = \begin{pmatrix} w_{11} & \cdots & w_{1L} \\ \vdots & \ddots & \vdots \\ w_{N_t1} & \cdots & w_{N_tL} \end{pmatrix}$.

The corresponding beamforming vector is $\overrightarrow{w_l} = w_{N_t,l}(:,l) = \begin{pmatrix} w_1 \\ w_1 \\ \vdots \\ w_{N_t} \end{pmatrix}$

As we assumed, we deploy equal power allocation for every single subcarrier and transmit antenna. The power allocated to every subcarrier is $\frac{P_{max}}{N_t \cdot L}$, which is also the element value for all the elements in the beamforming matrix $w_{N_t,l}$ and beamforming vector $\overrightarrow{w_l}$. So the beamforming matrix and corresponding beamforming vector are:

$$w_{N_t,l} = \begin{pmatrix} w_{11} & \cdots & w_{1L} \\ \vdots & \ddots & \vdots \\ w_{N_t1} & \cdots & w_{N_tL} \end{pmatrix} = \begin{pmatrix} \frac{P_{max}}{N_t \cdot L} & \cdots & \frac{P_{max}}{N_t \cdot L} \\ \vdots & \ddots & \vdots \\ \frac{P_{max}}{N_t \cdot L} & \cdots & \frac{P_{max}}{N_t \cdot L} \end{pmatrix}.$$

$$\overrightarrow{w_l} = \begin{pmatrix} w_1 \\ w_1 \\ \vdots \\ w_{N_t} \end{pmatrix} = \begin{pmatrix} \frac{P_{max}}{N_t \cdot L} \\ \frac{P_{max}}{N_t \cdot L} \\ \vdots \\ \frac{P_{max}}{N_t \cdot L} \end{pmatrix}.$$

For subcarrier assignment in this baseline scheme, we use a simple and direct strategy. Firstly, we get base layer transmission rate of user k in subcarrier l with equation 2.1. As the base layer transmission rate is limited by the weakest user with the worst CSI, so this base layer transmission data rate of subcarrier l should be set to be the minimum achievable transmission data rate of user k in subcarrier l, that is, $B_{k,l} = \min_{k,l} r_k^l$ (equation 2.2). Secondly, we manually assign the subcarriers into two subset. We assign the subcarriers with the first index numbers to transmit base layer with the subcarrier subset $l \in S = \{1, ..., LL\}$, and all the rest subcarriers with larger index numbers are assigned to transmit enhancement layer with the subcarrier subset $l \in \overline{S} = \{LL + 1, ..., L\}$. We need to find the last subcarrier indexed LL that transmits base layer data. For this purpose, we add up sequentially one by one from the first subcarrier that transmit base layer transmission data until the QoS of base layer transmission requirement can be satisfied for every user in the cell(equation 2.2). Then we can find the last subcarrier LL that transmits base layer. The next subcarrier $LL+1$ is the first subcarrier that is assigned to transmit enhancement layer. All the rest subcarriers from $LL+1$ to the last subcarrier L of the whole subcarrier set are assigned to transmit enhancement layer.

Thirdly, we need to get the total enhancement layer transmission throughput. To realize this, we need to do two small steps. First, we need to compare the transmission rate of $r_k^l, l \in \overline{S} = \{LL+1, ..., L\}$ with the enhancement transmission rate criterion EL_{req} , if the receivable transmission rate of the user is larger than this criterion(equation 2.3), it means this user can have enhancement layer transmission, then not. Second, we add up all the enhancement layer transmission rate of all the users to get the total system enhancement layer throughput(equation 2.4).

Therefore , we have the following problem formulation for optimization level 1 (Baseline Scheme). The problem formulation includes one objective function, which is the maximization of total enhancement layer throughput, and three constraints. The constraint 1 is the minimum required transmission rate of base layer for every user in the multicast group. Constraint 2 is the maximum allowed system power consumption of the whole system. Constraint 3 is the requirement of subcarrier/radio resource allocation δ_l, which is manually assigned as above principle in optimization level 1 (Baseline Scheme). Note that there is no any optimization scheme utilized in this baseline scheme.

$$\max_{\overrightarrow{w_l}} EL_{total} = \max_{\overrightarrow{w_l}} \sum_{k=1}^{K} EL_{req} \cdot 1\Big(\sum_{l=1, l\in\overline{S}}^{L} (1-\delta_l)\frac{B}{L}\log_2\big(1+\frac{|\overrightarrow{h_k}^H \cdot \overrightarrow{w_l}|^2}{N_0 \cdot B/L}\big) \geq EL_{req}\Big). \tag{3.1}$$

subject to:

- C1: $\sum_{l=1,l\in S}^{L} B_{k,l} \geq BL_{req}, \forall k.$
- C2: $\sum_{l=1}^{L} ||\overrightarrow{w_l}||^2 \leq P_{max}$. with
  $$\overrightarrow{w_l} = \begin{pmatrix} w_1 \\ w_1 \\ \vdots \\ w_{N_t} \end{pmatrix} = \begin{pmatrix} \frac{P_{max}}{N_t \cdot L} \\ \frac{P_{max}}{N_t \cdot L} \\ \vdots \\ \frac{P_{max}}{N_t \cdot L} \end{pmatrix}.\ \text{(without optimization)}$$
- C3: $\delta_l \in \{0,1\}$. (without subcarrier allocation)

3.2.2. Optimization Level 2 - Suboptimum Scheme 1

In this optimization level, for the subcarrier/radio resource allocation, we use the same strategy as level 1 $\delta_l = \{0, 1\}$, which means, for every subcarrier it can only transmits either base layer data or enhancement layer data in every time slot. When $\delta_l = 1$, this subcarrier transmits only base layer. When $\delta_l = 0$, this subcarrier transmits only enhancement layer data. Figure 3.3 shows the concept of optimization level 2 (Suboptimum Scheme 1).

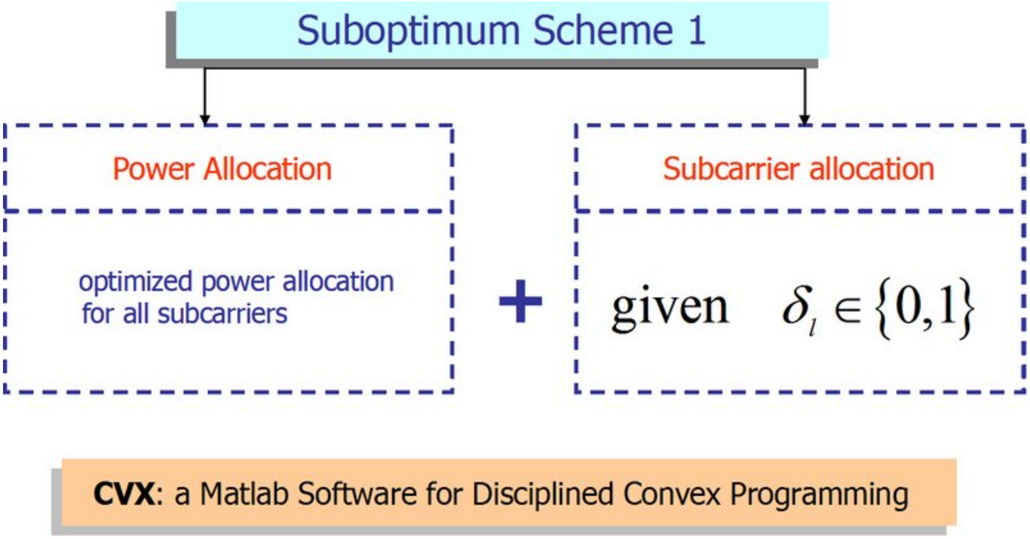

Figure 3.3.: Block Diagram of Optimization Level 2 - Suboptimum Scheme 1.

Therefore we have the following problem formulation for optimization level 2 (Suboptimum Scheme 1). The problem formulation includes one objective function, which is the maximization of total enhancement layer throughput, and three constraints. Constraint 1 is the minimum required transmission rate of base layer for every user in the multicast group, and this formula in level 2 has no different with level 1. Constraint 2 is the maximum allowed system power consumption of the whole system. Different from level 1, we deploy optimized power allocation in level 2, and the method and work principle will be explained in detail in later chapter. Constraint 3 is the requirement of subcarrier/radio resource allocation δ_l, which allocate the subcarrier sequentially as in optimization level 1 (Baseline Scheme). Note that difference between optimization level 1 (Baseline Scheme) and optimization level 2 (Suboptimum Scheme 1) is we deploy optimized power allocation scheme in optimization level 2(Suboptimum Scheme 1).

$$\max_{\overrightarrow{w_l}} EL_{total} = \max_{\overrightarrow{w_l}} \sum_{k=1}^{K} EL_{req} \cdot 1\Big(\sum_{l=1,l\in\overline{S}}^{L} (1-\delta_l)\frac{B}{L}\log_2\Big(1+\frac{|\overrightarrow{h_k}^H \cdot \overrightarrow{w_l}|^2}{N_0 \cdot B/L}\Big) \geq EL_{req}\Big). \tag{3.2}$$

subject to:

- C1: $\sum_{l=1,l\in S}^{L} B_{k,l} \geq BL_{req}, \forall k$.
- C2: $\sum_{l=1}^{L} ||\overrightarrow{w_l}||^2 \leq P_{max}$. (with optimization)
- C3: $\delta_l \in \{0,1\}$. (without subcarrier allocation)

In optimization level 2, we deploy power allocation. We use convex optimization to realize our target, that is, to have optimized power allocation for every subcarrier as well as to reduce the power consumption at the same time. To utilize convex optimization, we firstly need to deal with the non-convex parts in the problem formulation. In particular, we convexify the non-convex parts in the problem formulation. For this purpose, we utilize Semi-definite Programming (SDP relaxation) scheme.

3.2.2.1. Convexifying Problem Formulation with SDP Relaxation

1. Introduction of SDP

Semidefinite programming (SDP) is a subfield of convex optimization concerned with the optimization of a linear objective function (a function to be maximized or minimized) over the intersection of the cone of positive semidefinite matrices with an affine space, i.e., a spectrahedron. Semidefinite programming is a relatively new field of optimization which is of growing interest for several reasons. Many practical problems in operations research andcombinatorial optimization can be modeled or approximated as semidefinite programming problems. In automatic control theory, SDP's are used in the context of linear matrix inequalities. SDPs are in fact a special case of cone programming and can be efficiently solved by interior point methods. All linear programs can be expressed as SDPs, and via hierarchies of SDPs the solutions of polynomial optimization problems can be approximated. Semidefinite programming has been used in the optimization of complex systems. In recent years, some quantum query complexity problems have been formulated in term of semidefinite programs[1].

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[1] Refer from http://en.wikipedia.org/wiki/Semidefinite-programming

Semidefinite programming (SDP) is an optimization model where the objective is linear, and the constraints involve affine combinations of symmetric matrices that are required to be positive semi-definite. SDPs include as special cases LPs, when all the symmetric matrices involved are diagonal; and SOCPs, when the symmetric matrices have a special $arrow$ form. General SDPs are perhaps one of the most powerful forms of convex optimization[2].

SDP has been used in the optimization of complex systems. Semidefinite programs constitute one of the largest classes of optimization problems that can be solved with reasonable efficiency - both in theory and practice. They play a key role in a variety of research areas, such as combinatorial optimization, approximation algorithms, computational complexity, graph theory, geometry, real algebraic geometry and quantum computing.

In SDP, we use real-valued vectors to take the dot product of vectors with semidefinite constraints on matrix variables. A general semidefinite programming problem can be defined as any mathematical programming problem in the form:

$$\max_{x^1,\ldots,x^1 \in R^n} \textstyle\sum_{i,j\in[n]} c_{i,j}(x^i \cdot x^j).$$

$$\text{s.j.t. } \textstyle\sum_{i,j\in[n]} a_{i,j,k}(x^i \cdot x^j) \leq b_k, \forall k.$$

$\max\limits_{x^1,\ldots,x^1 \in R^n} \sum_{i,j\in[n]} c_{i,j}(x^i \cdot x^j).$ is the objective funtion.
$\sum_{i,j\in[n]} a_{i,j,k}(x^i \cdot x^j) \leq b_k, \forall k.$ is constraint to the objective function.

SDPs arise in a wide range of applications. For example, they can be used as sophisticatedrelaxations (approximations) of non-convex problems, such as boolean problems with quadratic objective. They are also useful in the context of analyzing the stability, or more generally, the time-behavior, of linear dynamical systems subject to perturbations. They can also allow to solve data visualization problems, in particular those where sparsity constraints are imposed on the vectors on which the data is projected.

2. Work Principle of SDP Relaxation for Layered Coding

In this paper, to facilitate the SDP relaxation [45] [46], we define $\overline{W_l} = \overrightarrow{w_l}\overrightarrow{w_l}^H$ and $\overline{H_k} = \overrightarrow{h_k}\overrightarrow{h_k}^H$.

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[2] https://inst.eecs.berkeley.edu/ ee127a/book/login/l-sdp-main.html

We define a three-dimensional matrix W:

$$W = W(l, N_t, N_t) = \begin{pmatrix} w_{11} & \cdots & w_{1N_t} \\ \vdots & \ddots & \vdots \\ w_{N_t1} & \cdots & w_{N_tN_t} \end{pmatrix}_1 \begin{pmatrix} w_{11} & \cdots & w_{1N_t} \\ \vdots & \ddots & \vdots \\ w_{N_t1} & \cdots & w_{N_tN_t} \end{pmatrix}_2 \cdots \begin{pmatrix} w_{11} & \cdots & w_{1N_t} \\ \vdots & \ddots & \vdots \\ w_{N_t1} & \cdots & w_{N_tN_t} \end{pmatrix}_L .$$

Then we have $\overline{W_l} = W(l, :, :) = \begin{pmatrix} w_{11} & \cdots & w_{1N_t} \\ \vdots & \ddots & \vdots \\ w_{N_t1} & \cdots & w_{N_tN_t} \end{pmatrix}$.

As we know, the beamforming matrix is a $(Nt - by - L)$ matrix, which is

$w_{N_t,l} = \begin{pmatrix} w_{11} & \cdots & w_{1L} \\ \vdots & \ddots & \vdots \\ w_{N_t1} & \cdots & w_{N_tL} \end{pmatrix}$.

The corresponding beamforming vector is $\overrightarrow{w_l} = w_{N_t,l}(:, l) = \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_{N_t} \end{pmatrix}$ and

$\overline{w_l}^H = (w_1 w_2 \cdots w_{N_t})$.

So we have $\overrightarrow{w_l}\overrightarrow{w_l}^H = \begin{pmatrix} w_1 \\ w_1 \\ \vdots \\ w_{N_t} \end{pmatrix} (w_1 w_2 \cdots w_{N_t}) = \begin{pmatrix} w_{11} & \cdots & w_{1N_t} \\ \vdots & \ddots & \vdots \\ w_{N_t1} & \cdots & w_{N_tN_t} \end{pmatrix}$.

From above definition, we can see $\overline{W_l} = \overrightarrow{w_l}\overrightarrow{w_l}^H = \begin{pmatrix} w_{11} & \cdots & w_{1N_t} \\ \vdots & \ddots & \vdots \\ w_{N_t1} & \cdots & w_{N_tN_t} \end{pmatrix}$

So, we can define $\overline{W_l} = \overrightarrow{w_l}\overrightarrow{w_l}^H$.. Same principle to the definition $\overline{H_k} = \overrightarrow{h_k}\overrightarrow{h_k}^H$.

3. Convexifying Problem Formulation on the Non-convex Parts

In the problem formulation of optimization level 2 (Suboptimum Scheme 1)(equation 3.2) , we have two formulas that have non-convex part (see Figure 3.1), one is the basic formula of the achievable transmission data rate of user k in subcarrier l (equation 2.1), another one is constraint of minimum required base layer transmission rate BL_{req} for every single user in the cell(equation 2.2).

1) Rewrite problem formulation(equation 3.2)

As we define $\overline{W_l} = \overrightarrow{w_l}\overrightarrow{w_l}^H$ and $\overline{H_k} = \overrightarrow{h_k}\overrightarrow{h_k}^H$, we have

$$\overline{H_k W_l} = (\overrightarrow{h_k}\overrightarrow{h_k}^H)(\overrightarrow{w_l}\overrightarrow{w_l}^H) = \begin{pmatrix} h_1^2 w_1^2 & \cdots & h_1^2 w_{N_t}^2 \\ \vdots & \ddots & \vdots \\ h_{N_t}^2 w_1^2 & \cdots & h_{N_t}^2 w_{N_t}^2 \end{pmatrix}.$$

Devoting trace function, we have $Tr(\overline{H_k W_l}) = h_1^2 w_1^2 + h_2^2 w_2^2 + \cdots + h_{N_t}^2 w_{N_t}^2$.

While $|\overrightarrow{h_k}^H \cdot \overrightarrow{w_l}|^2 = h_1^2 w_1^2 + h_2^2 w_2^2 + \cdots + h_{N_t}^2 w_{N_t}^2$, so we have $Tr(\overline{H_k W_l}) = |\overrightarrow{h_k}^H \cdot \overrightarrow{w_l}|^2$. Now, we can rewrite the basic formula of the achievable transmission data rate of user k in subcarrier l (equation 2.1) to be:

$$r_k^l = \frac{B}{L}\log_2\left(1 + \frac{Tr(\overline{H_k W_l})}{N_0 \cdot B/L}\right). \tag{3.3}$$

Then rewrite the constraint of minimum required base layer transmission rate BL_{req} for every single user in the cell(equation 2.2) to be

$$\sum_{i=1,i\in S}^{L} B_{k,l} = \sum_{l=1,l\in s}^{L} \frac{B}{L}\log_2\left(1 + \frac{Tr(\overline{H_k W_l})}{N_0 \cdot B/L}\right) \geq BL_{req}, \forall k. \tag{3.4}$$

Then we can rewrite the formula of power consumption(equation 2.7) to be:

$$\sum_{l=1}^{L} P_l = \sum_{l=1}^{L} ||\overrightarrow{w_l}||^2 = \sum_{l=1}^{L} Tr(\overrightarrow{w_l}\overrightarrow{w_l}^H) = \sum_{l=1}^{L} Tr(\overline{W_l}) \leq P_{max}. \tag{3.5}$$

Therefore we can rewrite the problem formulation(equation 3.2) of optimization level 2 (Suboptimum Scheme 1) as following formulation. As equation 3.2, the objective function is maximization of system total enhancement layer throughput with three constraints. Constraint 1 is the minimum required transmission rate of base layer for every user in the cell. Constraint 2 is the maximum allowed system power consumption of the whole system. Constraint 3 is the requirement of subcarrier/radio resource allocation δ_l, which allocate the subcarrier sequentially without optimization scheme deployed. We have an additional constraint 4 which is requirement on rank of the input matrix $\overline{W_l}$, we will make detailed introduction to this requirement in later chapter3.2.2.2.

$$\max_{\overrightarrow{w_l}} EL_{total} = \max_{\overrightarrow{w_l}} \sum_{k=1}^{K} EL_{req} \cdot 1(\sum_{l=1, l\in \overline{S}}^{L} (1-\delta_l)\frac{B}{L}\log_2(1+\frac{Tr(\overline{H_k W_l})}{N_0 \cdot B/L}) \geq EL_{req}). \tag{3.6}$$

Subject to:

- C1: (equation 3.4) $= \sum_{l=1, l\in s}^{L} \frac{B}{L}\log_2(1+\frac{Tr(\overline{H_k W_l})}{N_0 \cdot B/L}) \geq BL_{req}, \forall k.$
- C2: (equation 3.5)$\sum_{l=1}^{L} Tr(\overline{W_l}) \leq P_{max}$. (with optimization)
- C3: $\delta_l = \{0,1\}, \forall l.$ (without subcarrier allocation)

2) Convexifying the problem formulation

As we can see, in the problem formulation(equation 3.6) of optimization level 2 (Suboptimum Scheme 1), the objective function and the first constraint C1 are still not convex, so we need to transform them to be convex first of all. For this purpose, we define a variable $\tau_{k,l}$ to substitute the $\frac{Tr(\overline{H_k W_l})}{N_0 \cdot B/L}$ part, we define $\tau_{k,l} = \frac{Tr(\overline{H_k W_l})}{N_0 \cdot B/L}, \forall k,l$. With this variable $\tau_{k,l}$, we can transform the problem formulation(equation 3.6) to be convex as following.

As equation 3.6, we still have one objective function that is to maximize the total system enhancement layer throughput. As we define another variable $\tau_{k,l}$ and we need to include this requirement into our formula as one constraint 1, so we we have five constraints in total. Constraint 2 is still the basic requirement of Qos which is the minimum required base layer transmission rate for every user in the multicast group. Constraint 3 is maximum allowed power consumption limitation. Constraint 4 is the subcarrier/radio resource allocation which is without any optimization in this suboptimum scheme. Constraint 5 is the requirement to guarantee the effect of SDP convex optimization which will be discussed in the next chapter.

$$\max_{\tau_{k,l},\delta_l} EL_{total} = \max_{\tau_{k,l},\delta_l} \sum_{k=1}^{K} EL_{req} \cdot 1(\sum_{l=1, l\in\overline{S}}^{L} (1-\delta_l)\frac{B}{L}\log_2(1+\tau_{k,l}) \geq EL_{req}). \tag{3.7}$$

Subject to:

- C1: $\tau_{k,l} = \frac{Tr(\overline{H_k W_l})}{N_0 \cdot B/L}, \forall k, l.$
- C2: $\sum_{l=1, l\in s}^{L} \frac{B}{L}\log_2(1+\tau_{k,l}) \geq BL_{req}, \forall k.$
- C3: $\sum_{l=1}^{L} Tr(\overline{W_l}) \leq P_{max}$. (with optimization)
- C4: $\delta_l = \{0,1\}, \forall l.$(without subcarrier allocation)
- C5: $Rank(\overline{W_l}) = 1, \forall l.$

3.2.2.2. Process of $Rank(\overline{W_l}) = 1$ Requirement

In the above problem equation(equation 3.7), we denote $Rank(\overline{W_l}) = 1, \forall l$ in C5 as the rank of an input matrix, in the scenarios we consider in this paper, $Rank(\overline{W_l}) = 1$ are imposed to guarantee that $\overline{W_l} = \overrightarrow{w_l}\overrightarrow{w_l}^H$ holds after optimizing $\overline{W_l}$. The transformed problem above is still non-convex due to the rank constraint in C5. To overcome this problem, we remove this constraint C5 from the problem formulation in the initial calculation, and then the reformulated problem becomes a convex SDP. Thus, the SDP relaxation can be solved efficiently. In particular, if the obtained solution admits rank-one matrices $\overline{W_l}, \forall l$, then it is the optimal solution of the original problem in the above problem formulation. Therefore, we need to analyze if $\overline{W_l}, \forall l$ is rank-one matrix. Then we make study on the rank of $\overline{W_l}$, and then discover that $Rank(\overline{W_l}) = 1, \forall l$, this means we can obtain the optimal power allocation for a given subcarrier/radio resource allocation[45].

If $\exists l : Rank(\overline{W_l}) \neq 1$, then we have to consider to construct a suboptimal power allocation with rank-one matrix through some specific methods. We have two approaches.

1) Suboptimal Power Allocation Scheme 1:

The first proposed suboptimal power allocation scheme is a hybrid scheme based on the solution of the SDP relaxation. In particular, we firstly solve our objective function by SDP relaxation. If the solution admits rank-one $\overline{W_l}, \forall l$, then the global optimal solution is obtained. Otherwise, we need to construct a suboptimal solution set $\overline{W_l} = \overrightarrow{w_l}\overrightarrow{w_l}^H$, where $\overrightarrow{w_l}$ is the eigenvector corresponding to the maximum eigenvalue of beamforming matrix $\overline{W_l}$, where $\overline{W_l}$ is the solution of the SDP relaxation with $Rank(\overline{W_l}) > 1, \forall l$. Then we define L scaling constant $\alpha_l, \forall l \in \{1, ..., L\}$. The problem formulation is convex with respect to the optimization variable, in particular, it serves as a suboptimal solution for our problem.

2) Suboptimal Power Allocation Scheme 2:

The second proposed suboptimal power allocation scheme is also a hybrid scheme. In particular, it is based on the solution of the SDP relaxation and the rank-one Gaussian randomization scheme [47] . Besides, a similar approach to solve the problem is adopted as in suboptimal power allocation scheme 1, except for the choice of beamforming matrix $\overrightarrow{W_l}$ when $Rank(\overline{W_l}) > 1, \forall l$. Specifically, we calculate the eigenvalue decomposition of $\overrightarrow{W_l} = \overrightarrow{U_l}\overrightarrow{\Sigma_l}\overrightarrow{U_l}^H$, where $\overrightarrow{U_l}$ and $\overrightarrow{\Sigma_l}$ are an $N_t \times N_t$unitary matrix and a diagonal matrix, respectively. Then we adopt the suboptimal beamforming vector as $\overrightarrow{w_l} = \overrightarrow{U_l}\overrightarrow{\Sigma_l}^{1/2} r_l$, $\overrightarrow{W_l} = \alpha_l \overrightarrow{w_l}\overrightarrow{w_l}^H$, where $r_l \in \mathbb{C}^{N_t}$ and $r_l \sim \mathcal{CN}(0, \mathbf{I}_{N_t})$. Subsequently, we follow the same approach as in suboptimal scheme 1 for optimizing $\{\alpha_l, W_e\}$ and obtain suboptimal rank-one solution $\alpha_l \overline{W_l}$. Figure 3.4 shows the work principle of processing $Rank(\overline{W_l}) = 1$ Requirement.

3.2.2.3. The Base Layer Process

For the base layer process, we do the same work as in optimization level 1. There is only one base layer constraint requirement needs to be met, which is the minimum required base layer transmission rate (QoS) should be satisfied for every user in the multicast group(equation 2.2).

Eventually, we can conclude the final problem formulation of optimization level 2 (Suboptimum Scheme 1) in the following formulation which is a fully convex one that can be used through convex optimization for the system optimization. We have one objective function that is to maximize the total system enhancement layer throughput with five constraints. Constraint 1 is to define the substitution variable $\tau_{k,l}$. Constraint 2 is the basic requirement of Qos which is the minimum required base layer transmission

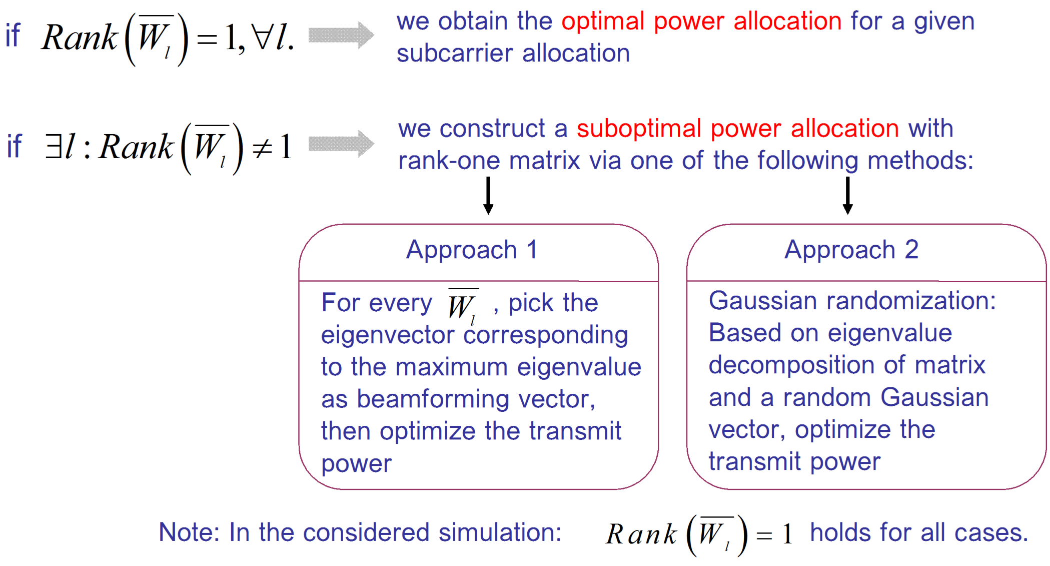

Figure 3.4.: Work Principle of $Rank(\overline{W_l}) = 1$ Requirement.

rate for every user in the multicast group. Constraint 3 is maximum allowed power consumption limitation. Constraint 4 is the subcarrier/radio resource allocation which is without any optimization in this suboptimum scheme. Constraint 5 is the requirement to guarantee the effect of SDP convex optimization, this constraint will be removed in the initial calculation, then to study if it can be satisfied after initial calculation, if yes, means the system has been optimized, if not, we need to construct a suboptimal power allocation with rank-one matrix through some specific methods.

$$\max_{\tau_{k,l}} EL_{total} = \max_{\tau_{k,l}} \sum_{k=1}^{K} EL_{req} \cdot 1(\sum_{l=1,l\in\overline{S}}^{L} (1-\delta_l)\frac{B}{L}\log_2(1+\tau_{k,l}) \geq EL_{req}). \tag{3.8}$$

Subject to:

- C1: $\tau_{k,l} = \frac{Tr(\overline{H_k W_l})}{N_0 \cdot B/L}, \forall k, l.$
- C2: $\sum_{l=1,l\in s}^{L} \frac{B}{L}\log_2(1+\tau_{k,l}) \geq BL_{req}, \forall k.$
- C3: $\sum_{l=1}^{L} Tr(\overline{W_l}) \leq P_{max}$.(with optimization)
- C4: $\delta_l = \{0,1\}, \forall l.$ (without subcarrier allocation)
- C5: $Rank(\overline{W_l}) = 1, \forall l.$

3.2.3. Optimization Level 3 - Suboptimum Scheme 2

In optimization level 3, we use fully optimization scheme that is to optimize both subcarrier/radio resource allocation and optimized power allocation as Figure 3.5 shows.

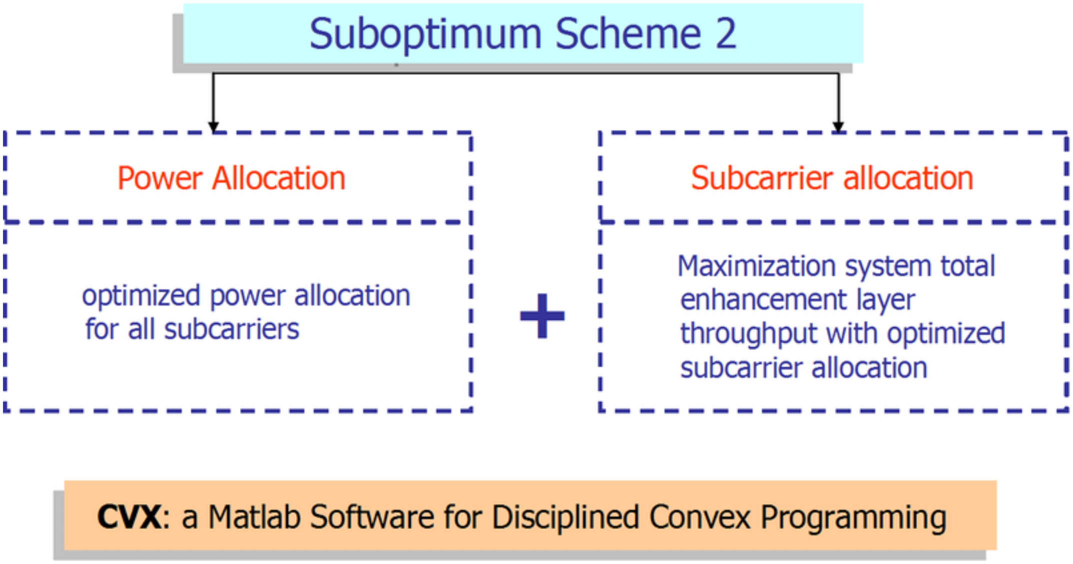

Figure 3.5.: Block Diagram of Optimization Level 3 - Suboptimum Scheme 2.

To optimize the power allocation, we utilize the same principle as in optimization level 2, that is, to use convex optimization to get this power allocation. For this purpose, we firstly need to process the non-convex part, that is, to convexify the problem formulation with the two equations shows in figure 3.1. This process is totally same with optimization level 2 in Chapter 3.2.2.1.

To optimize the subcarrier/radio resource allocation, different with optimization level 1 (Baseline Scheme) and level 2 (Suboptimum Scheme 1) that sequentially add up the transmission rate from the first subcarrier one by one, we use a scheme that can intelligently select the optimized algorithm to find which subcarriers transmit base layer and which subcarriers transmit enhancement layer according to our requirement. We have two options to optimize the subcarrier/radio resource allocation. First one is to use the subcarriers with best channel status transmit base layer. The second one is to allocate the subcarriers with the worst channel status transmit the base layer. Table 3.2 shows the two study directions.

Table 3.2.: Simulation Directions of Optimization Level 3 - Suboptimum Scheme 2.

Principle	**Power Consumption**	**Total Throughput**
`Best Channel for BL`	lower for BL	Comparatively lower
`Worst Channel for BL`	higher for BL	Comparatively higher

1) Utilize the best channel to transmit base layer data

The first direction is to utilize the best channel to transmit base layer data. The channel with best CSI i.e.with largest receivable transmission rates r_k^l is easy to satisfy the basic QoS requirement of base layer. Correspondingly, as every user utilizes the best channel to transmit the base layer data, the required power consumption will be in comparatively lower level. But at the same time, as the best channel is occupied by base layers, only those channels with comparatively worse CSIs would be used to transmit enhancement layer data, the transmission rate in those worse channels would have comparatively lower transmission rate, correspondingly the number of users who can have larger enhancement layer transmission rate would become less. In this way, the total enhancement layer throughput would be comparatively low. In this way we would have a smaller system enhancement layer total throughput.

2) Utilize the worst channel transmit base layer data

The second direction is to utilize the worst channel transmit base layer data. The channel with worst CSI i.e. with smallest receivable transmission rates r_k^l is not easy to satisfy the basic QoS requirement of base layer. Correspondingly, as every user utilizes the worst channel to transmit the base layer data, the required power consumption will be in comparatively higher level. But at the same time, as the worst channel is occupied by base layer, those channels with comparatively better channel status would be used to transmit enhancement layer data. The transmission rate in those better channels would have comparatively higher transmission rate. Correspondingly the number of users who can have larger enhancement layer transmission rate would become large. In this way, the total enhancement layer throughput would be comparatively higher. Therefore we can have a larger system enhancement layer total throughput in this research direction.

To realize the above two purposes, we make use of subcarrier allocation vector. The subcarrier allocation matrix would be:

$$\delta_{l,k} = \begin{pmatrix} \delta_{11} & \cdots & \delta_{1K} \\ \vdots & \ddots & \vdots \\ \delta_{L1} & \cdots & \delta_{LK} \end{pmatrix}. \tag{3.9}$$

Then the subcarrier allocation vector is $\overrightarrow{\delta_l} = \delta(:,l) = \begin{pmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_L \end{pmatrix}$, here $\delta_l = \{0,1\}, \forall l.$

When the subcarrier transmits base layer, $\delta_l = 1, \forall l.$. When the subcarrier transmits enhancement layer, $\delta_l = 0, \forall l.$. In this way, the subcarrier allocation vector finally would become a vector whose elements are either 0 or 1, depending on our optimization results. We get optimized subcarrier allocation vector through optimization algorithm with following problem formulation. Different with previous two optimization levels, we have optimized subcarrier/radio resource allocation in this optimization level.

We can conclude the final problem formulation of optimization level 3 (Suboptimum Scheme 2) in the following formulation which is a fully convex one that can optimize both subcarrier/radio resource allocation and power allocation. We have one objective function that is to maximize the total system enhancement layer throughput with five constraints. Constraint 1 is to define the substitution variable $\tau_{k,l}$. Constraint 2 is the basic requirement of Qos which is the minimum required base layer transmission rate for every user in the multicast group. Constraint 3 is maximum allowed power consumption limitation that would be optimized in this optimization level. Constraint 4 is the subcarrier allocation which is optimized in this scheme. Constraint 5 is the requirement to guarantee the effect of SDP convex optimization, this constraint will be removed in the initial calculation, then to study if it can be satisfied after initial calculation, if yes, means the system has been optimized, if not, we need to construct a suboptimal power allocation with rank-one matrix through some specific methods.

$$\max_{\tau_{k,l},\delta_l} EL_{total} = \max_{\tau_{k,l},\delta_l} \sum_{k=1}^{K} EL_{req} \cdot 1(\sum_{l=1,l\in\overline{S}}^{L} (1-\delta_l)\frac{B}{L}\log_2(1+\tau_{k,l}) \geq EL_{req}). \tag{3.10}$$

Subject to:

- C1: $\tau_{k,l} = \frac{Tr(\overline{H_k W_l})}{N_0 \cdot B/L}, \forall k,l.$

- C2: $\sum_{l=1,l\in s}^{L} \frac{B}{L} \log_2(1+\tau_{k,l}) \geq BL_{req}, \forall k.$
- C3: $\sum_{l=1}^{L} Tr(\overline{W_l}) \leq P_{max}$.(with optimization)
- C4: $\delta_l = \{0,1\}, \forall l.$ (with subcarrier allocation)
- C5: $Rank(\overline{W_l}) = 1, \forall l.$

Chapter 4.

Simulation Results

4.1. Simulation Parameters

To realize our simulation, we make the following simulation parameters.

1) Channel

We utilize the frequency selective fading channel with Rayleigh Fading channel gain.

2) System bandwidth

As it is a LTE(Long Term Evolution) system, we assume we have a $10MHz$ bandwidth for our model system.

3) Cell size

We assume a cell with 200 meters radius.

4) Tx-antenna

4 transmit antennas in the base station side.

5) User
Wee assume that there are 4 users in the cell i.e. the user set is $k \in U = \{1, 2, 3, 4\}$.

6) Subcarriers

We assume there are 600 subcarriers.

7) Maximum allowed system total power consumption

We set 46dBm as the maximum allowed system total power consumption, and this is also a constraint for our problem formulation.

8) Minimum Base layer data rate requirement

$1 bps/Hz$ per user.

9) Minimum enhancement layer data rate requirement

$4 bps/Hz$ per user.

10) Other parameters

- Antenna gain: 10 dBi
- Reference distance: 30 meters

  Considering the cell size is 200 meters, we allocate the users uniformly in the referred area, that is, in the area with distance of 30-200 meters to the BS.
- Receiver noise source of users

  We utilize the thermal noise formula $N_0 = KTB$, where:
  - Noise is thermal noise in dBm/Hz.
  - $N_0 = KTB$ is the noise power density in dBm/Hz.
  - $K = 1.38 \times 10^{-23}$ Boltzmann′s constant
  - T is the temperature, in degrees $Kelvin[K]$, here we use 300.
  - B is the bandwidth in Hz
- Path loss

  As above mentioned, we have assumed 1000 multipath realization in our system model, and then we would have 1000 path loss to simulate. We generate the user positions from the uniform distribution on the interval [30,200] area of the cell around base station. According to 3GPP path loss model for a carrier frequency of 2GHz, we get the path loss for every user.

4.2. Simulation Procedure

4.2.1. Optimization Level 1 - Baseline Scheme

The work concept of the optimization level 1 - Baseline Scheme includes two parts.

The first part is to consider the power allocation. The power allocation in baseline scheme is equally allocated, that is, for every single subcarrier, we allocate the same power:

$$\overrightarrow{w_l} = \begin{pmatrix} w_1 \\ w_1 \\ \vdots \\ w_{N_t} \end{pmatrix} = \begin{pmatrix} \frac{P_{max}}{N_t \cdot L} \\ \frac{P_{max}}{N_t \cdot L} \\ \vdots \\ \frac{P_{max}}{N_t \cdot L} \end{pmatrix}$$

For the subcarrier allocation, we process it in the following steps:

Step 1 Get base layer transmission rate of user k in subcarrier l

As the Base Layer transmission rate is limited by the weakest user with the worst CSI, this base layer transmission data rate of subcarrier l should be set to be the minimum achievable transmission data rate of user k in subcarrier l , as $B_{k,l} = \min_{k,l} r_k^l$.

Step 2 Find the final subcarrier index that transmits base layer data

We manually assign the subcarriers into two subset. We assign the subcarriers with the first index numbers to transmit base layer with the subcarrier subset $l \in S = \{1, ..., LL\}$, and all the rest subcarriers with larger index numbers are assigned to transmit enhancement layer with the subcarrier subset $l \in \overline{S} = \{LL + 1, ..., L\}$. We need to find the last subcarrier indexed LL that transmits base layer data. For this purpose, we add up sequentially one by one from the first subcarrier that transmit base layer transmission data until the QoS of base layer transmission requirement can be satisfied for every user in the cell(equation 2.2). Then we can find the last subcarrier LL that transmits base layer. The next subcarrier $LL + 1$ is the first subcarrier that is assigned to transmit enhancement layer. All the rest subcarriers from $LL + 1$ to the last subcarrier L of the whole subcarrier set are assigned to transmit enhancement layer.

Step3 Get the total enhancement layer transmission throughput

To realize this, we need to do two small steps. First, we need to compare the transmission rate of $r_k^l, l \in \overline{S} = \{LL+1, ..., L\}$ with the enhancement transmission rate criterion EL_{req} , if the receivable transmission rate of the user is larger than this criterion(equation 2.3), it means this user can have enhancement layer transmission, then not. Second, we add up all the enhancement layer transmission rate of all the users, then we can get the total system enhancement layer throughput(equation 2.4).

Figure 4.1 shows the work principle of baseline scheme (the optimization level 1). Based on the above work principle, we can establish the baseline scheme (the optimization level 1) solution.

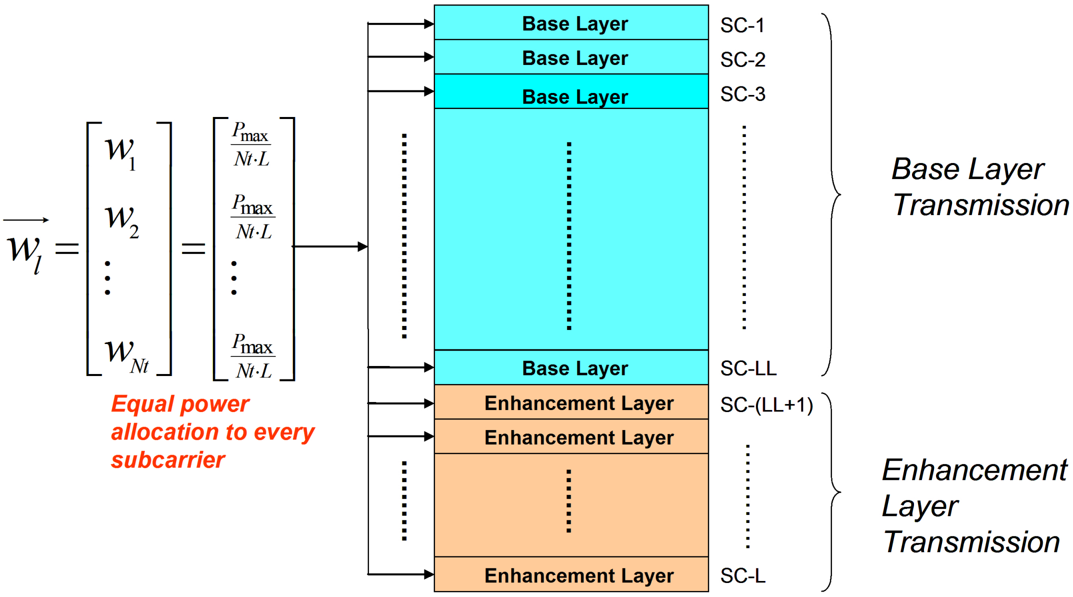

Figure 4.1.: Block Diagram of Work Principle of Optimization Level-1.

The simulation steps of baseline scheme (the optimization level 1) process is as following:

1. Initialization
   a) Set subcarrier set $l \in L = \{1, ..., L\}$ and beamforming vector $\overline{w_l}$, user set $k \in K = \{1, ..., K\}$, base layer QoS BL_{req} , enhancement layer QoS EL_{req}. Create the channel gain h_k^l for every user with consideration of path loss.
   b) Finalize the beamforming vector $\overline{w_l}$.
2. Iteration

a) Find the base layer transmission rate for user k in subcarrier l through $B_{k,l} = \min_{k,l} r_k^l$.

b) For $k = 1 : K$ and $l = 1 : L$, find the last subcarrier of subcarrier from index 1 to L that can meet the QoS requirement(equation 2.2).

c) Find those users who have enhancement layer transmission with the help of equation 2.3, then finalize the subcarrier allocation vector $\overrightarrow{\delta_l}$, then maximize the enhancement layer throughput(equation2.3).

4.2.2. Optimization Level 2 - Suboptimum Scheme 1

4.2.2.1. Work Principle

In this optimization level, we will simulate the system based on the baseline scheme (optimization level 1).

Firstly, for the subcarrier allocation, we do the same work with baseline scheme (optimization level 1), that is, to decide the base layer transmission rate as the minimum receivable transmission data rate $B_{k,l} = \min_{k\in U, l\in L} r_k^l$, then sequentially add up the base layer transmission data rate one by one from the first subcarrier on, until the minimum QoS of base layer requirement for every user in the cell can be met. We still follow the subcarrier allocation as baseline scheme $\delta_l = \{0, 1\}$, that is, the subcarrier transmits base layer data or enhancement layer data in every time slot. When$\delta_l = 0$, it means the subcarrier transmits enhancement layer. When $\delta_l = 1$, it means this subcarrier transmits base Layer.

In the case of enhancement layer, only those users who can have larger transmission rate than the threshold transmission rate can have enhancement layer transmission, and the enhancement layer transmission rate of this user is equal to threshold transmission rate. We set the subcarrier set that is composed of all the subcarriers allocated to enhancement layer as $\overline{S} = \{1, ..., L\}$. To calculate the system total enhancement layer throughput, we add up all the enhancement layer transmission rate together, which is the enhancement layer threshold times the number of users who have enhancement layer transmission.

From the prospective of power allocation, it has totally different algorithm with baseline scheme. We need to optimize the power allocation. For this purpose, we use SDP relaxation. From the above discussion(3.2.2.1), we have known that we need to facilitate the SDP relaxation with defining $\overline{W_l} = \overrightarrow{w_l}\overrightarrow{w_l}^H$ and $\overline{H_k} = \overrightarrow{h_k}\overrightarrow{h_k}^H$, and we have the final problem formulation as equation 3.7.

Figure 4.2 shows the work principle of optimization level 2. We allocate optimized power to every subcarrier. For the subcarrier allocation, we just sequentially add up the base layer transmission data one by one from the first subcarrier until all the user can have the minimum base layer transmission data rate.

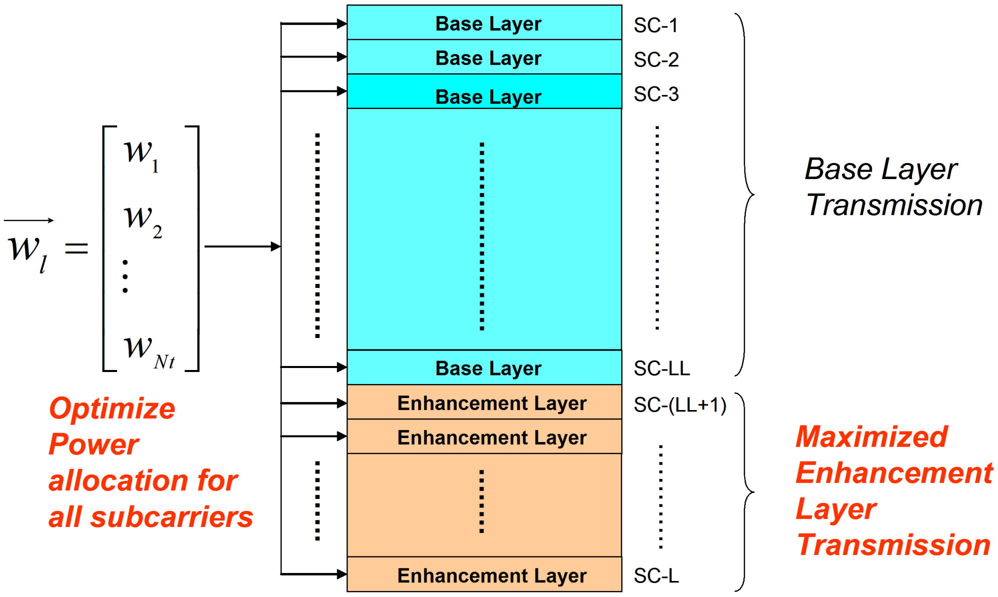

Figure 4.2.: Block Diagram of Work Principle of Optimization Level-2.

4.2.2.2. Simulation Process

1. Initialization

   Set subcarrier set as $l \in L = \{1, ..., L\}$, beamforming vector $\overline{w_l}$, user set $k \in K = \{1, ..., K\}$, base layer QoS BL_{req} and enhancement layer QoS EL_{req}. Define the maximum power consumption as P_{max} and create the channel gain h_k^l for every user with consideration of path loss.

2. Iteration

   a) Utilize SDP relaxation with CVX to maximize objective function as equation 3.7. Then set the subcarrier allocation vector δ_l.

   b) For $k = 1 : K$ and $l = 1 : L$, set the three constraints.

      i. the substitution of non-convex problem $\tau_{k,l} = \frac{Tr(\overline{H_k W_l})}{N_0 \cdot B/L}, \forall k, l$..

      ii. set the maximum power consumption constraint as equation 3.5.

iii. find the last subcarrier of subcarrier from index 1 to L that can meet the QoS requirement as equation 2.2.

4.2.3. Optimization Level 3 - Suboptimum Scheme 2

4.2.3.1. Work Principle

For this optimization level, we have two directions as follows.(see 3.2.2)

1) Utilize the best channel transmits base layer data

To utilize the best channel(channel with best CSI and with largest receivable transmission rates) transmits base layer data. In this way, the required power consumption will be in comparatively lower levels. Correspondingly, we have a smaller system enhancement layer total throughput.

2) Utilize the worst channel transmits base layer data

To utilize the worst channel(channel with weakest CSI and with smallest receivable transmission rates) transmits base layer data. In this way, the power consumption would be kept in a higher level. But at the same time, we can have a comparatively higher system enhancement layer total throughput.

The work principle is as Figure 4.3. The subcarrier allocation is not sequentially arranged as optimization level 1 and level 2, it is arranged randomly according to the results of optimization on system resource to realize the maximum system throughput/spectral efficiency.

4.2.3.2. Simulation Process

The power allocation algorithm is in the same work principle as optimization level 2, our work emphasis lies in the subcarrier allocation. For every user, there is a the subcarrier

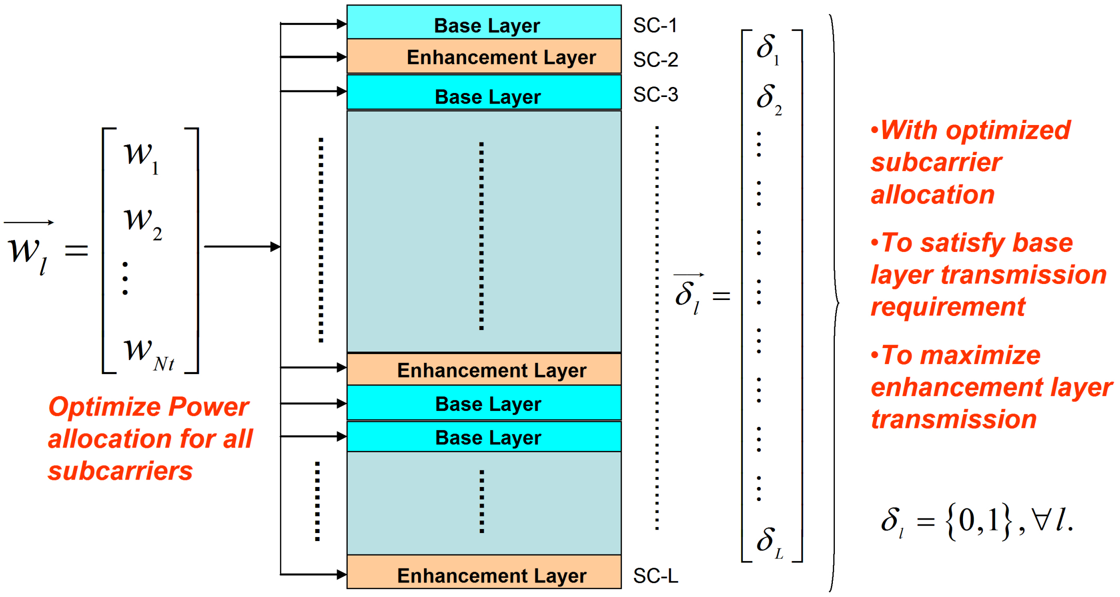

Figure 4.3.: Block Diagram of Optimization Level-3.

allocation vector $\overrightarrow{\delta_l} = \begin{pmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_L \end{pmatrix}$, here $\delta_l = \{0,1\}, \forall l$. When the subcarrier transmits base layer, $\delta_l = 1, \forall l$, when enhancement layer,$\delta_l = 0, \forall l$.

The work direction 1 that is of utilizing the best channel to transmit base layer data

1) To decide the subcarrier allocation vector

For user , to find out the best channel, we need to rank all the subcarriers according to the channel conditions which are also the receivable transmission rates in descending order. Then we add up the receivable transmission rate of the subcarriers from the subcarrier with the best channel until the base layer QoS requirement can be met for every user k in the cell. Then we assign the subcarrier that transmits base layer with $\delta_l = 1, \forall l$, all the other subcarriers are assigned with $\delta_l = 0, \forall l$. In this way, we can get the subcarrier allocation vector for every user k. With the same principle, we can get our final subcarrier allocation vector:

$$\overrightarrow{\delta_l} = \begin{pmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_L \end{pmatrix} \text{,here } \delta_l = \{0,1\}, \forall l$$

2) Maximization of system total enhancement layer throughput

From above work part 1), we can therefore to maximize our system total enhancement layer throughput. The problem formulation is as equation 3.7. We need to sort out subcarriers that transmit the enhancement layer data ($\delta_l = 0$) for all the users. Then we use indicator function $1(A)$ to find out the users with enhancement layer transmission. After that, we can add up all the enhancement layer transmission, which is our final target.

1. Initialization

   Set subcarrier set $l \in L = \{1, ..., L\}$, beamforming vector $\overline{w_l}$, user set $k \in K = \{1, ..., K\}$, base layer QoS BL_{req} and enhancement layer QoS EL_{req}. Define the maximum power consumption P_{max} and create the channel gain h_k^l for every user with consideration of path loss.

2. Iteration

   a) Utilize SDP relaxation with CVX to maximize objective function(equation 3.7), set the subcarrier allocation vector δ_l and set the subcarrier allocation vector δ_l.

   b) For $k = 1 : K$ and $l = 1 : L$, set the three constraints.

      i. the substitution of non-convex problem $\tau_{k,l} = \frac{Tr(\overline{H_k W_l})}{N_0 \cdot B/L}, \forall k, l..$

      ii. set the maximum power consumption constraint(equation 3.5).

      iii. utilize the subcarrier with the best channel transmits base layer or utilize the subcarrier with the worst channel transmits base layer, then to find the last subcarrier of subcarrier from index 1 to L that can meet the QoS requirement(equation 2.2).

For the second optimization direction that utilizes the worst channel to transmit base layer, the only difference is, after ranking the receivable transmission rate in descending order we add up the receivable transmission rate of the subcarriers starting from the subcarrier with the worst channel status until when the base layer QoS requirement can be met for every user k in the cell.

4.3. Numerical Results

In this section, we verify performance for the proposed three optimization level schemes via simulation. In the three optimization levels, we denote three different combinations of subcarrier and power allocation. Optimization level 1 is a baseline scheme which no optimization is performed with. In optimization level 2, we deploy optimization only on power allocation. In optimization level 3, we deploy suboptimum resource algorithm on both power allocation and subcarrier allocation.

We employ the system model proposed in Figure 2.1. Simulations are performed with the following assumptions. $B = 10MHz$ and the number of subcarriers is $L = 600$. The number of users is 4. All users are uniformly distributed in a cell with a 200 meters cell radius. The number of path realization is 1000. The channel between the base station and the users are modelled as frequency selective Rayleigh fading channel. Please refer to Chapter 4.1 for more details.

A. Average Enhancement Layer Throughput per User vs. Minimum Required Base Layer Throughput per User

Figure 4.4 shows the comparison between four different scenarios of subcarrier allocation and power allocation in three optimization levels, we have the following observations.

1. the upper two scenarios which are $L3D1$ (Direction 1 of optimization level 3, with utilizing the best channel for transmitting base layer and with power allocation) and $L3D2$ (Direction 2 of optimization level 3, with utilizing the worst channel transmitting base layer and with power allocation) achieve much more larger average enhancement layer throughput than the other two scenarios which are $L2$ (optimization level 2, without subcarrier allocation but with power allocation) and $L1$ (optimization level 1, with neither subcarrier allocation nor power allocation). We can observe that there is large difference on system throughput between upper two scenarios and lower two scenarios. This is because the upper two scenarios deploy Layered Coding Scheme, while the lower two not. This clearly illustrates that the Layered Coding Scheme can significantly improve the system total throughput/spectral efficiency.

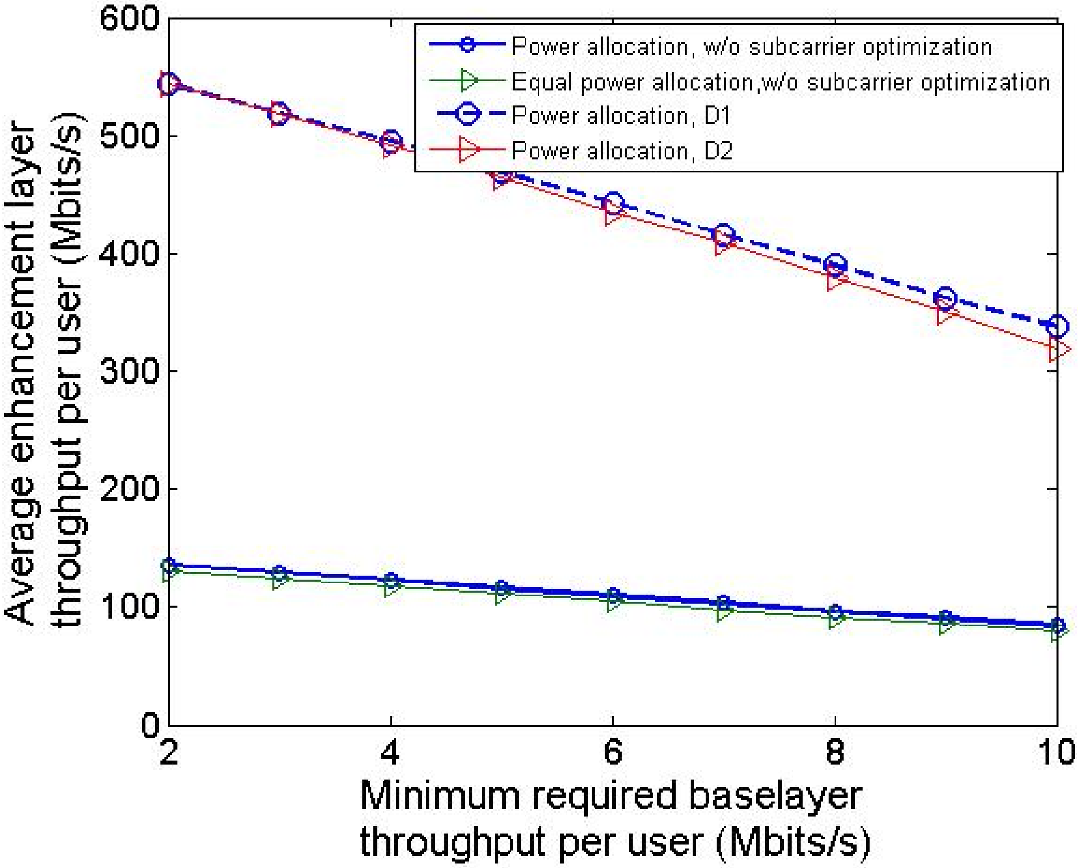

Figure 4.4.: Average Enhancement Layer Throughput per User vs. Minimum Required Base Layer Throughput per User.

2. Compare the upper two scenarios $L3D1$ which use the best channel transmitting BL and $L3D2$ which use the worst channel transmitting BL, we can discover that $L3D1$ has slightly better performance than $L3D2$. This explains that utilizing best channel transmitting BL can help the system to have a larger system throughput/spectral efficiency. And among the four scenarios that we study, $L3D1$ is the best scheme.

3. It can be observed that even the upper two scenarios have very similar curve in the diagram and so does the lower two scenarios, they still have slightly different performance. This slight difference comes from the power allocation algorithm. So we can see that the power allocation scheme can also help to improve the system throughput/spectral efficiency.

When we increase the minimum required BL, we can see that the average enhancement layer throughput per user deceases. This is because the number of subcarriers that transmit base layer data increases with the increase of minimum required BL rate. Then the number of subcarriers that transmit enhancement layer decreases respectively.

B. Average Enhancement Layer Throughput per User vs. Maximum Power Consumption

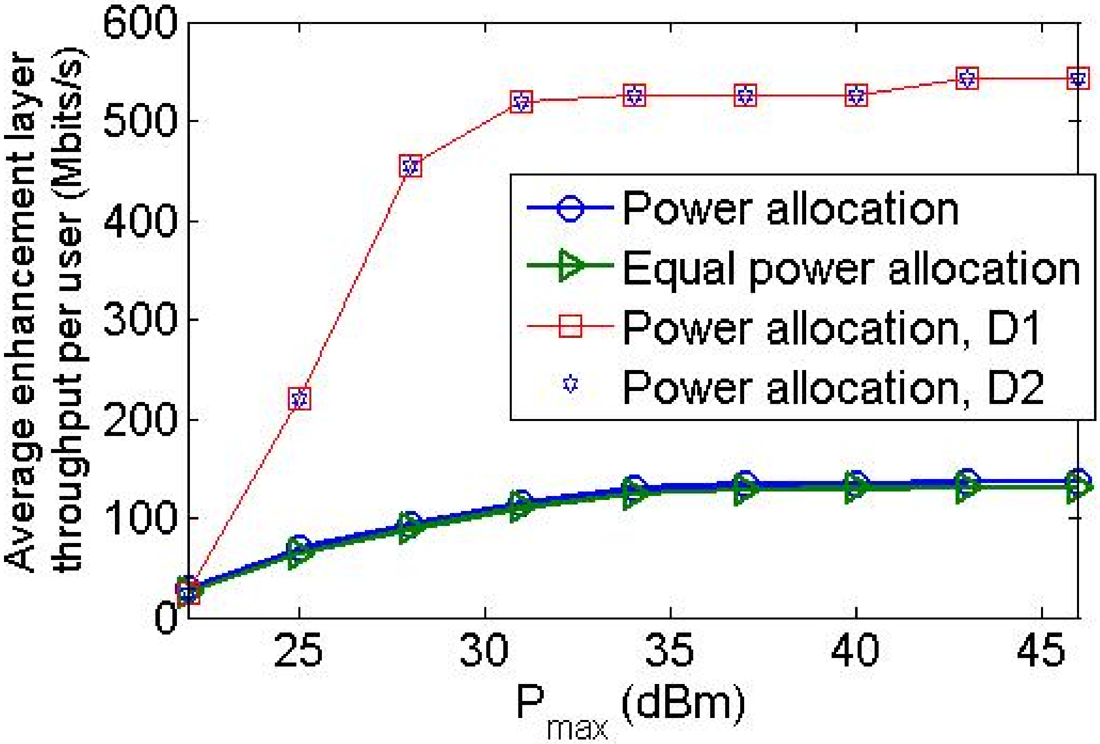

Figure 4.5.: Average Enhancement Layer Throughput per User vs. Maximum Power Consumption.

Figure 4.5 shows the comparison between four different scenarios of subcarrier allocation and power allocation in three optimization levels on relation of maximum power consumption and average enhancement layer throughput per user. In Figure 4.5 when given the same power input, we can observe the upper two scenario of $L3D1$ and $L3D2$ have much larger average enhancement layer throughput than the lower two scenarios $L2$ and $L1$. This is because the upper two scenarios are deployed with Layered Coding Scheme. The subcarrier allocation in the system is optimized and can achieve a much larger enhancement layer throughput respectively.

When we need the system to achieve same enhancement layer throughput, we can see that the scenario of $L3D1$ and $L3D2$ demand the smallest required power consumption. So we can know, even with the same power allocation, the optimization with Layered

Coding Scheme is much more cost-effective on power consumption than those without Layered Coding Scheme.

Besides, we observe that in Figure 4.5 the performance of scenario $L3D1$ and $L3D2$ are very similar when given same power input. This illustrate that under same power input the two directions have very similar performance, which means, transmitting BL with the best channel or worst channel are not so distinguished.

From above two simulations we try on the four different scenarios in three different optimization levels , we see that, the wireless communication system can achieve much better performance on the system throughput/spectral efficiency with the help of Layered Coding Scheme in radio resource allocation and power allocation in the downlink OFDM multicast system. In this way, we can finally conclude that the Layered Coding algorithm can help to improve the system throughput/spectral efficiency, and reduce the power consumption simultaneously.

Chapter 5.

Conclusions

In this paper, we introduced the radio resource for layered coding transmission scheme in OFDM multicast systems. We consider a MISO system that consists of Nt Tx-antennas, K users and L subcarriers, where every user just has one Rx antenna. We deploy Layer Coding Scheme into this system. With different algorithms on power allocation and subcarrier allocation (radio resource optimization), we design three different optimization levels with three different algorithms. Our target is to maximize the whole system throughput/spectral efficiency based on our assumption and simulation parameters.

In Chapter 2, we introduce in details our proposed system model and problem formulation. Except the main work target i.e. to maximize the system throughput/spectral efficiency, we have to optimize the power allocation to make it cost-effective. We utilize convex optimization to realize our optimization. Besides, we have to consider other several constraints. One is the total power consumption constraint, which is very important parameter for us as it is expensive resource. Another one is, in the layered coding scheme, as it has two types of layers (one base layer and several enhancement layers), of which the base layer transmits the most essential information, so we have to guarantee the minimum QoS of the service, that is, we need to guarantee the minimum required base layer transmission rate for every user. To realize our work target, we have two main difficulties. One is that we are working on a binary optimization which includes not only the subcarrier allocation optimization, but also the power allocation optimization. Another difficulty is that we have non-convex parts in our problem formulation that we have to convexify them then we can go on with the next convex optimization work.

In Chapter 3, we introduce three optimization levels and two directions for optimization level 3 according to three different strategies of optimization based on power allocation and subcarrier/radio resource requirements. In optimization level 1 (Baseline Scheme), we don′t use any optimization on the system, but just make it work with the basic settings. That is, the transmit power is equally allocated to every single subcarrier. And the subcarrier allocation strategy is to sequentially add up the subcarrier transmission data rate one by one from the first subcarrier until the base layer QoS requirement can be satisfied, then the subcarrier from index 1 until the last one that meets the requirement would be assigned to base layer, and all the other subcarriers would be assigned to enhancement layers. In optimization level 2 (Suboptimum Scheme 1), we deploy the same strategy with optimization level 1 on the subcarrier allocation. But we deploy optimization strategy on the power allocation. In optimization level 3 (Suboptimum Scheme 2), we deploy optimization strategies on both power allocation and subcarrier allocation.

In Chapter 4, we introduce the process of problem formulation and simulation. As there are non-convex parts of the problem formulation, we introduce SDP relaxation to convexify the problem formulation. To optimize the subcarrier allocation, we use two strategies, one is to utilize the best channel to transmit base layer. In this way, we can save much power but with comparatively lower enhancement layer throughput. Another way is to utilize the worst channel to transmit base layer. In this way, we need more power allocation, but we have comparatively higher enhancement layer throughput. At the same time, we introduce how to simulate our systems. To simplify the simulation, we denote CVX.

Finally, we get numerical results with two compare diagrams. One is minimum average enhancement layer throughput per user versus required base layer per user, and another one is the average enhancement layer throughput versus the maximum power consumption versus. From the two diagram with simulation results of four simulation scenarios, we can easily conclude that the layered coding scheme cooperated with power allocation can significantly improve the wireless communication system throughput/spectral efficiency.

In our future work, we are interested to find solution that can optimize the LTE OFDM multicast system to achieve an optimum system throughput/spectral efficiency.

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Appendix A.

Appendix

Problem Formulation

Followed are formulas that have been used in this thesis. For any detail, please refer to corresponding chapters.

1) Basic Formulas

The achievable transmission data rate of user k in subcarrier l:
(equation 2.1) $r_k^l = \frac{B}{L}\log_2(1 + \frac{|\overrightarrow{h_k}^H \cdot \overrightarrow{w_l}|^2}{N_0 \cdot B/L})$.

Base layer transmission rate constraint BL_{req} to every single user in the cell:
(equation 2.2) $\sum_{l=1, l\in S}^{L} B_{k,l} \geq BL_{req}, \forall k$.

Enhancement layer requirement for every user:
(equation 2.3) $EL_k = \sum_{l=1, l\in \overline{S}}^{L} r_{k,l} \geq EL_{req}$.

Total enhancement layer throughput:
(equation 2.4) $EL_{total} = \sum_{k=1}^{K} EL_{req} \cdot 1(\sum_{l=1, l\in \overline{S}}^{L} r_k^l \geq EL_{req})$.

Maximization of total enhancement layer throughput:
(equation 2.6)
$\max\limits_{\overrightarrow{w_l}, \delta_l} EL_{total} = \max\limits_{\overrightarrow{w_l}, \delta_l} \sum_{k=1}^{K} EL_{req} \cdot 1(\sum_{l=1, l\in \overline{S}}^{L} (1-\delta_l)\frac{B}{L}\log_2(1 + \frac{|\overrightarrow{h_k}^H \cdot \overrightarrow{w_l}|^2}{N_0 \cdot B/L}) \geq EL_{req})$.

Maximum allowed power consumption P_{max}.
(equation 2.7) $\sum_{l=1}^{L} ||\overrightarrow{w_l}||^2 \leq P_{max}$.

Subcarrier allocation:

(equation 2.8) $\delta_l \in \{0, 1\}$.

2) Optimization Level 1 - Baseline Scheme

(equation 3.1)
$\max\limits_{\overrightarrow{w_l}} EL_{total} = \max\limits_{\overrightarrow{w_l}} \sum_{k=1}^{K} EL_{req} \cdot 1(\sum_{l=1, l \in \overline{S}}^{L} (1 - \delta_l) \frac{B}{L} \log_2(1 + \frac{|\overrightarrow{h_k}^H \cdot \overrightarrow{w_l}|^2}{N_0 \cdot B/L}) \geq EL_{req})$.
subject to:

- C1: $\sum_{l=1, l \in S}^{L} B_{k,l} \geq BL_{req}, \forall k$.
- C2: $\sum_{l=1}^{L} ||\overrightarrow{w_l}||^2 \leq P_{max}$. with
$$\overrightarrow{w_l} = \begin{pmatrix} w_1 \\ w_1 \\ \vdots \\ w_{N_t} \end{pmatrix} = \begin{pmatrix} \frac{P_{max}}{N_t \cdot L} \\ \frac{P_{max}}{N_t \cdot L} \\ \vdots \\ \frac{P_{max}}{N_t \cdot L} \end{pmatrix} \text{(without optimization)}$$
- C3: $\delta_l \in \{0, 1\}$. (without subcarrier allocation)

3) Optimization Level 2 - Suboptimum Scheme 1

(equation 3.8)
$\max\limits_{\tau_{k,l}} EL_{total} = \max\limits_{\tau_{k,l}} \sum_{k=1}^{K} EL_{req} \cdot 1(\sum_{l=1, l \in \overline{S}}^{L} (1 - \delta_l) \frac{B}{L} \log_2(1 + \tau_{k,l}) \geq EL_{req})$.
Subject to:

- C1: $\tau_{k,l} = \frac{Tr(\overline{H_k W_l})}{N_0 \cdot B/L}, \forall k, l$.
- C2: $\sum_{l=1, l \in s}^{L} \frac{B}{L} \log_2(1 + \tau_{k,l}) \geq BL_{req}, \forall k$.
- C3: $\sum_{l=1}^{L} Tr(\overline{W_l}) \leq P_{max}$.(with optimization)
- C4: $\delta_l = \{0, 1\}, \forall l$. (without subcarrier allocation)
- C5: $Rank(\overline{W_l}) = 1, \forall l$.

4) Optimization Level 3 - Suboptimum Scheme 2

(equation 3.10)

$\max\limits_{\tau_{k,l},\delta_l} EL_{total} = \max\limits_{\tau_{k,l},\delta_l} \sum_{k=1}^{K} EL_{req} \cdot 1(\sum_{l=1,l\in\overline{S}}^{L} (1-\delta_l)\frac{B}{L}\log_2(1+\tau_{k,l}) \geq EL_{req})$.
Subject to:

- C1: $\tau_{k,l} = \frac{Tr(\overline{H_k W_l})}{N_0 \cdot B/L}, \forall k, l.$
- C2: $\sum_{l=1,l\in s}^{L} \frac{B}{L}\log_2(1+\tau_{k,l}) \geq BL_{req}, \forall k.$
- C3: $\sum_{l=1}^{L} Tr(\overline{W_l}) \leq P_{max}$.(with optimization)
- C4: $\delta_l = \{0,1\}, \forall l.$ (with subcarrier allocation)
- C5: $Rank(\overline{W_l}) = 1, \forall l.$