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Adaptive Modulation and Subcarrier Allocation for Multiuser OFDM/CDMA Systems

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in fulfillment of the requirements for the degree of

Doctor of Philosophy

2008

Statement of Originality

I hereby certify that the content of this thesis is the result of work done by me and has not been submitted for a higher degree to any other University or Institution.

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Date   Zhang Hua

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Summary

Orthogonal frequency-division multiplexing (OFDM) is a promising technology to resist Intersymbol Interference (ISI) for transmitting data at extremely high rates, splits up the data stream and sends the data symbols simultaneously at a drastically reduced symbol rate over a set of parallel subcarriers. The focus of this thesis is on the adaptive modulation and subcarrier allocation methods for single- and multi-service transmissions with limited transmitted power in the Multi-Carrier DS-CDMA (called OFDM/CDMA in this thesis) system.

Conventional FDMA and TDMA have hard capacity limitations, since they use a finite number of orthogonal resources. The comparisons of the OFDM/CDMA, OFDM Interleaved-FDMA and OFDM Group-FDMA have been analyzed for the data transmission. Because of the near-unity reuse factor, one of the important merits of CDMA, the combination of OFDM and CDMA, known as OFDM/CDMA, brings substantial increase in the transmission data rate per unit bandwidth when the frequency resources are limited. Even though the multiple access interference exists in OFDM/CDMA systems, better performance can still be achieved than that in other OFDM systems.

Based on the OFDM/CDMA system and perfect channel estimation, a novel adaptive modulation method is developed for users to perform the single-service transmission with the given bit-error-rate (BER), data rate and transmitted power. It is significant that the quality of service (QoS) of this service transmission should be guaranteed and system capacity should be improved under the condition of the limited channel resource and power. Comparably, Some related research works emphasize particularly on the maximization of data rates, minimization of BER or minimization of power consumption. From a novel aspect to enhance the transmission efficiency in this thesis, a suboptimal solution to minimize the interference from each user is put forward in the first step. Then the bit allocation adjustment scheme in the second step is presented to make the best use of the subchannels and reduce the interference further. By evaluating the performance of this algorithm and other related algorithms, we can know that the proposed algorithm for single-service provides better BER performance, higher data rates and higher system capacity, which is more vigorous to meet the demand of supporting more users in the future.

For multi-service (Voice and Data) transmissions, voice and data services have different priorities, BER requirements, transmission rates and power consumption. Based on some related research works, these respective features of voice and data transmissions, such as delay tolerances and power consumptions, are slightly considered. In order to meet requirements of voice and data respectively, the subcarrier allocation and bit loading are adopted for the voice transmission at first. Then an adaptive modulation scheme for the data transmission is developed to maximize the data rate of each user according to the remaining subchannels and transmission power. Consequently the realtime transmission and QoS of voice are guaranteed and the data throughput is maximized simultaneously. Additionally, limited resources, i.e., the bandwidth and transmission power, are utilized efficiently. By comparing the performance between the proposed algorithm for multi-service and the other two adaptive schemes, we can know that higher data rates, lower BERs and outage probabilities can be achieved.

The above two algorithms are performed based on the perfect channel estimation. However, the ideal estimation is not practical. Under the condition of the inaccurate channel information, the performance of the proposed algorithms are analyzed when the channel is overestimated or underestimated. The analysis and simulations show that the proposed algorithms can still keep tolerable performance based on some given QoS requirements when the channel estimation is not ideal. Since the proposed algorithms have the tolerance to the channel estimation errors, i.e., ± 1 and ± 2 dB, the channel estimation methods with lower complexity can be applied. Thus, the potential complexity problem of the adaptive system is reduced.

Generally, it has been concluded that the proposed adaptive OFDM schemes are efficient and robust methods for transmitting data at high rates.

Chapter 1

Introduction

1.1 Motivation

To face the challenge of the high data throughput requirements for modern communications, extensive research efforts have been made on broadband modulation. Orthogonal frequency division multiplexing (OFDM) technique, a specific multicarrier modulation, has emerged as a popular technique to combat ISI (Inter-Symbol Interference) channels. Conventionally, ISI is avoided by inserting the interval guard, the length of which is longer than the multipath delay spread. As a multi-carrier system, in order to improve the utilization of the whole channel, the decision of the modulation scheme on the individual subchannel is a critical problem. In addition, OFDM in its primary form is considered as a digital modulation technique, and not a multi-user channel access technique, since it is utilized for transferring one bit stream over one communication channel using one sequence of OFDM symbols. However, OFDM can be combined with multiple access schemes in time, frequency or code domain to separate the users.

1.1.1 Adaptive modulation

It was reported that the bit error probability of different OFDM subcarriers transmitted in time dispersive channels depends on the frequency domain channel transfer function [2]. The occurrence of bit errors is normally concentrated on a set of severely faded subcarriers. If the subcarriers that exhibit high bit error probabilities can be identified and assigned fewer bits or excluded from data transmission, the overall BER can be substantially improved at the cost of a slight loss of the overall system throughput. As the frequency fading deteriorates the signal-to-noise ratio (SNR) of certain subcarriers and at the same time improves others' above the average SNR value, the potential loss of throughput due to the exclusion of faded subcarriers can be mitigated by employing higher-order modulation techniques on the subcarriers exhibiting high SNR values. Conventionally, the modulation schemes on subchannels are unchanged during the transmission time regardless of the time-varying channel. However, with the higher requirements of the transmission service and the system capacity, the adaptive scheme can perform the allocation and adjustment on subcarriers and bits loaded following the changes of the subchannel states, which utilizes the frequency diversity efficiently.

Intensive research interests have been in adaptive modulation techniques for broadband transmission over wireless channels supporting multimedia services. One important issue on efficiently supporting these applications is the ability to combat intersymbol interference (ISI) in wideband transmission over multipath fading channels. Multicarrier modulation technique, such as OFDM [2–5], appears to be a promising solution to this problem. Although more complexity of the process occurs, the adaptive algorithm shows much better performance than the traditional non-adaptive scheme, especially when channel states vary much with the time and frequency bands.

For the single-service transmission, adaptive algorithms of bit and subcarrier allocation have been studied in several aspects. Some reported work focused on improving the network performance by maximizing the transmission data rates

[6–9] to meet high throughput requirements with the increased demands in video and high-speed data transmissions. Adaptive resource allocation was investigated in [10] to achieve both multiuser diversity and fairness with maximum utilization. Recently, there has been an increasing demand for saving the transmission power of the whole system. The minimization of total transmission power in multiuser systems was attempted by using a multiuser adaptive OFDM scheme [11]. In [12], a suitable modulation scheme is proposed for subcarriers on the basis of a cost function with the expected BERs on each subcarrier. The two methods in [11] and [12] were found to be more suitable to multi-service transmissions in multiuser OFDM systems because fixed data rates and BER requirements could be satisfied. However, with the urgent demand for the system to accommodate more users, it is significant to improve the system capacity and guarantee the quality of service (QoS) of this service transmission under the condition of the limited channel resource and power. Therefore, in order to reach this objective, a novel adaptive modulation for single-service transmission is necessary and worthwhile to be developed in multiuser systems.

For the multi-service transmission, although multi-service transmission is becoming increasingly important to various applications, however, most previously reported work for OFDM systems ([6,11–13], for example) focused only on the resource allocation and bit loading without sufficiently considering efficient support of different services, such as simultaneous voice and data transmissions, which generally have different requirements on the BER and delay tolerance. In general, voice transmission does not need rigid requirements on the transmission rate and BER, but has stringent realtime constraints, which are just opposite to the requirements for most data services. This suggests that fixed-rate transmission combined with adaptive bit loading on low quality subcarriers is well suited to voice transmission to meet the transmission requirements, while variable-rate transmission, which maximizes the total throughput and obtain low BER, is best suited to data communications. Therefore, it is indispensable to propose a new reliable subcarrier allocation and bit loading algorithm with limited transmission power and frequency resources for transmitting voice and data simultaneously.

1.1.2 Combination of OFDM and CDMA

In multiuser systems using static TDMA or FDMA as multiple access schemes, OFDM with adaptive modulation is applied by allocating each user a predetermined time slot or frequency band. Consequently, as a result of adaptive modulation, these unused subcarriers within the allocated time slot or frequency band of a user are wasted and because they are not used by other users. Although the subcarriers appear in deep fade to one user, they may not be in deep fade for other users. In fact, as the fading parameters for different users are mutually independent, it is quite unlikely that a subcarrier will be in deep fade for all users. This motivates us to consider an appropriate system for the adaptive multiuser subcarrier allocation and bit loading schemes.

As one of the multiple access schemes, Code-division multiple-access (CDMA) has become a promising technique as compared with other multiple access techniques, such as frequency division multiple access (FDMA) [14] and time division multiple access (TDMA) [14]. Viterbi Qualcomm Inc. was one of the first to use Code Division Multiple Access (CDMA) [15] for civilian mobile communications, which eventually led to the North American IS-95 standard [16, 17]. In FDMA and TDMA, users are multiplexed by orthogonal frequency bands and orthogonal time slots, respectively. In CDMA, however, users are multiplexed by distinct codes. All users can transmit at the same time and utilize the entire available frequency spectrum. This unique feature of CDMA results in a soft capacity limit [18]. Conventional FDMA and TDMA have hard capacity limits, since they use a finite number of orthogonal resources. One of the important merits of CDMA in cellular environments is its near-unity frequency reuse factor [19]. Each user is assigned a pseudo-random code that is orthogonal to the codes of all the other users, or that has appropriate cross-correlation properties that minimize the multiple access interference (MAI) [15, 20, 21].

In the direct-sequence (DS) CDMA scheme, as one of the major categories of spread-spectrum techniques, the digital data are directly coded at a much higher rate. The code is generated pseudo-randomly and denoted by pseudo-noise (PN) sequence. The receiver will reproduce the same code and correlate the received signal with that code to extract the data. DS-CDMA applies spreading sequences in the time domain and uses rake receivers to optimally combine the time-dispersed energy in order to combat the effects of multipath fading. However, in indoor wireless environments, the time dispersion is low, of an order of nano seconds, and hence a high chip rate, of an order of tens of MHz, is required for resolving the multipath components [4]. This implies a high clock-rate, high power consumption as well as implementation difficulties. In order to overcome these difficulties, several techniques have been proposed, which combine DS-CDMA and OFDM to exploit the wideband channel's inherent frequency diversity by spreading each symbol across multiple subcarriers [22–28]. Therefore, the adaptive algorithms proposed in this thesis will be based on the OFDM/CDMA systems.

1.2 Objectives

The main objectives of the research work in this thesis are to find bit loading and subcarrier allocation algorithms for the adaptive multimedia OFDM transmission.

For single-service transmission, it is known from the pervious related work of adaptive modulation and subcarrier allocation algorithms that the adaptive methods pursue the maximum data rate, minimum BER or minimum transmission power. However, the single-service transmission with the given values of data rates and BER should also be considered when the transmission power is limited. Therefore, one of our objectives is to develop adaptive modulation techniques for the single-service with the given quality of service (QoS). The major problem we will attempt to deal with is interference power resulting from each user in the OFDM/CDMA system.

When two kinds of signals, such as voice and data, are transmitted simultaneously, some algorithms proposed previously did not consider their different transmission requirements sufficiently. Especially, voice is sensitive to the transmission delay and tolerant to low transmission rates, while data transmission requires strict BER performance, high data rates and high power consumption. Therefore, another objective of the thesis is to design an efficient modulation and subcarrier allocation method for voice and data transmissions based on their delay tolerances, BER requirements and transmission rates. Additionally, with guaranteeing the realtime voice transmission, we will try to maximize the transmission rate of data service.

1.3 Major contributions of the Thesis

The major contributions are listed below:

(1) **Performance analysis of OFDM/CDMA and other OFDM-related systems**
Based on each user's requirements of the data rate, BER and transmission power, in Chapter 3, it is shown that the multiuser OFDM/CDMA system can support better performance than the other multiuser OFDM systems, such as OFDM Interleaved-FDMA and OFDM Group-FDMA, which are applied in many recent research work in adaptive OFDM algorithms [8,11,29]. Therefore, for the multiuser OFDM systems with the given transmission requirements of each user, OFDM/CDMA is more suitable.

(2) **Interference minimization by the adaptive bit loading algorithm**
In Chapter 4, an adaptive bit loading algorithm (ABLA) is proposed when users try to transmit a single service, i.e., voice or data, with the requirements of the BER and transmission rate. With the CDMA technique in multiuser systems, the interference from sharing same subchannels by multiple users would occur inevitably. According to channel quality with the

constraints of transmission power and data rates, the problem of the interference minimization for each user is optimized and the number of bits on each user's subcarriers are obtained. Furthermore, we also derive a bit allocation adjustment among all subcarriers for one user to reduce the interference further. Since more bits on subcarriers of one user will lead to more interference power to the other users who are also using these subcarriers, each user decides its suitable numbers of bits loaded on its subcarriers to obtain minimum interference to others. With this algorithm, the OFDM system can support higher transmission rates and more users to meet the higher system capacity, compared with other related methods.

(3) **Simultaneous Voice and Data transmissions by the adaptive transmission algorithm**

For the multi-service transmission, a novel adaptive subcarrier and bit loading (A-SABL) is proposed in Chapter 5. The algorithm allocates appropriate subcarriers and chooses the modulation schemes for the voice transmission first to guarantee its realtime transmission. One or two bits are generally loaded for low-rate voice transmission with loose BER requirements, the selected subcarriers are generally in low channel gains. Then the remaining subcarriers are loaded with a number of bits to achieve the maximum throughput of the data transmission. In this way, the subcarriers in low channel gains are used for voice transmission and those with good quality are allocated for data transmission. Because the transmission power generally exponentially increases with the number of loaded bits [30], the subcarrier for voice transmission has a low power consumption. Consequently, most transmission power can be used for the maximization of data throughput efficiently. The improved performance obtained by the proposed scheme results from more efficient utilization of the total transmission power to support much higher data rates.

1.4 Organization of the Thesis

The rest of this thesis is organized as follows: Chapter 2 shows the detailed description of the OFDM technique and the OFDM/CDMA systems. And we make a brief literature review about recent developments of the adaptive single- and multi-service OFDM systems. In Chapter 3, the analysis of the data rates supported by OFDM/CDMA, OFDM Interleaved-FDMA and OFDM Group-FDMA systems is made. Chapter 4 gives the adaptive bit loading algorithm for single-service in multiuser OFDM/CDMA systems. Adaptive multi-service transmission is described in Chapter 5. According to the channel estimation errors, Chapter 6 gives some analysis on the performance of the above two algorithms and finally, Chapter 7 concludes the research and describes the future works.

Chapter 2

Literature review

2.1 Concepts and fundament of OFDM

To overcome the impairment of the wireless channel due to multi-path propagation, Orthogonal Frequency Division Multiplexing (OFDM) appears to be quite an attractive technique. OFDM is the modulation technique for European standards such as the Digital Audio Broadcasting (DAB) [31] and the Digital Video Broadcasting (DVB) [32] systems. As such it has received much attention and has been proposed for many other applications, including local area networks [33] and personal communication systems [34]. OFDM is a type of multichannel modulation that divides a given channel into many parallel subchannels or subcarriers, so that multiple symbols are sent in parallel. Earlier overviews of OFDM can be found in [35–39].

The first multichannel modulation systems appeared in the 1950's as military radio links, best characterized as frequency-division multiplexed systems. The first OFDM schemes were presented by [40] and [41]. Actual use of OFDM was limited and the practicability of the concept was questioned. However, OFDM was made more practical through the work of [42–45]. OFDM uses the discrete Fourier transform (DFT) and inverse DFT (IDFT) [43] with a cyclic prefix [45]. In practice, DFT is implemented by performing the fast Fourier transform (FFT). The FFT/IFFT and the cyclic prefix have made OFDM both practical and attractive to the radio link designer. A similar multichannel modulation scheme, discrete multitone (DMT) modulation, has been developed for static channels such as the digital subscriber loop [46]. DMT also uses DFT and the cyclic prefix but has the additional feature of bit-loading which is generally not used in OFDM, although related ideas can be found in [47].

2.1.1 Orthogonality of OFDM

In OFDM systems, the "orthogonality" means a precise mathematical relationship between subcarriers. These subcarriers are specially arranged so that the sidebands of the individual subcarriers overlap in quest of the better bandwidth utilization, which is an outstanding advantage of OFDM. Although the spectra of the subbands are overlapped, the signals can still be received without adjacent carrier interference because of the orthogonality.

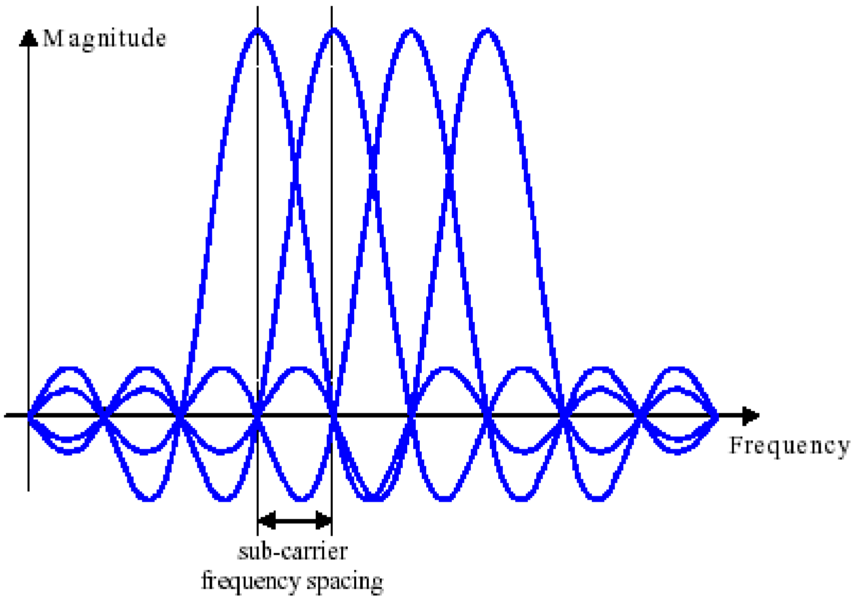


Figure 2.1: The OFDM spectrum.

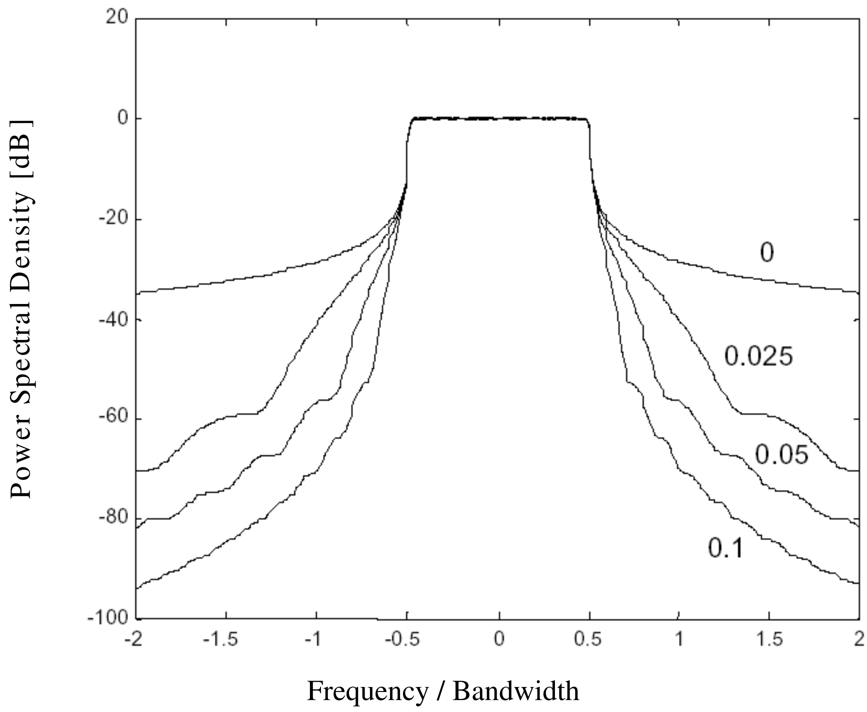


Figure 2.2: The OFDM spectrum with different roll-off factors.

Mathematically, it is assumed that there is a set of signals $\{\varphi_n\}_{n=1}^{N}$, where N can be considered as the number of subcarriers. Then these signals are orthogonal if and only if

$$\int_0^T \varphi_n(t)\varphi_{n'}^*(t)dt = \begin{cases} T, & n = n'; \\ 0, & \text{otherwise.} \end{cases} \tag{2.1}$$

where $(.)^*$ denotes the complex conjugate operator and T is the duration of one symbol. A general set of orthogonal waveform can be expressed as

$$\varphi_n(t) = \begin{cases} \frac{1}{\sqrt{T}} e^{j\omega_n t}, & t \in [0, T]; \\ 0, & \text{otherwise.} \end{cases} \tag{2.2}$$

with $\omega_n = \omega_0 + n\Delta\omega$, and $n = 0, 1, \cdots, N-1$. $f_n = \frac{\omega_n}{2\pi}$ is the frequency of the nth subcarrier and $f_0 = \frac{\omega_0}{2\pi}$ is the lowest frequency used. The spacing between the adjacent subcarriers is $\Delta f = \frac{\Delta\omega}{2\pi} = \frac{W}{N}$, where W is the whole bandwidth. The orthogonality of the different OFDM subcarriers can be shown by the OFDM spectrum in Fig. 2.1. Due to the closely packed nature of subcarriers, the neighboring subbands overlap. But these overlapping subcarriers do not interfere with each other at center frequency because all other subcarrier spectra are zero at the maximum of each subcarrier spectrum. Since all subcarriers are arranged closely in the frequency domain, the spectrum of OFDM looks like “rectangle”. To more quickly reduce the power of out-of-band subcarriers, the OFDM symbol is multiplied by a raised-cosine window before transmission. Fig. 2.2 shows spectra for 64 subcarriers with different values of the roll-off factor of the raised cosine window. Larger roll-off factor would bring high spectral efficiency, but reduces delay spread tolerance.

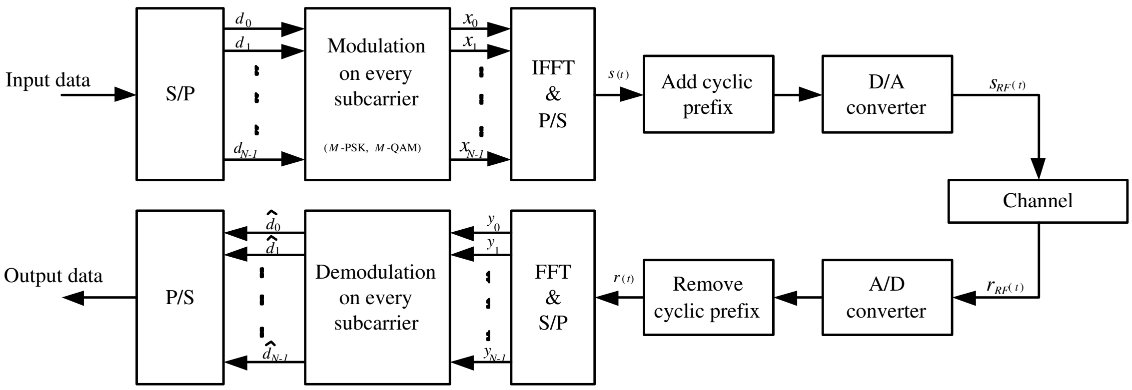


Figure 2.3: Block diagram of an OFDM system.

In the OFDM transceiver, as shown in Fig. 2.3, instead of transmitting many data symbols consecutively over one channel (as in single-carrier modulation systems), the stream of data symbols is split into parallel ones and then transmitted over the available subcarriers. On each subcarrier, the signal is modulated on the frequency band, orthogonal to the others, which can be implemented through the use of IDFT/IFFT. The use of the inverse discrete Fourier transform (IDFT) to replace the banks of sinusoidal generators and the demodulators, suggested by Weinstein and Ebert [43] in 1971, significantly reduces the implementation complexity of OFDM modems. The reduction of the implementation complexity was attributable to a simple realization. The DFT uses a set of harmonically related sinusoidal and cosinoidal basis functions with an integral multiple of the lowest nonzero frequency of the set, which is referred to as the basis frequency. These harmonically related frequencies can hence be used as the set of carriers for the OFDM systems. Instead of carrying out the modulation/demodulation on a subcarrier by subcarrier basis, as in Hirosaki's early proposal [44, 48], all OFDM subcarriers are modulated/demodulated in a single IDFT/DFT step. And replacing IDFT/DFT with IFFT/FFT reduces the amount of calculations by exploiting the regularity of the operations in IDFT/DFT greatly. Finally, the coefficients of the IDFT constitute an OFDM symbol for the further transmission. Since the harmonically related and the modulated individual OFDM subcarriers can be conveniently visualized as the spectrum of the signal to be transmitted, it is the IDFT, rather than DFT, that is invoked in transforming the signal's spectrum to the time domain for transmission over the channel. Recent developments of CMOS technologies allow efficient DSP chips to be used for implementation of IFFT/FFT to calculate the IDFT/DFT.

2.1.2 OFDM system

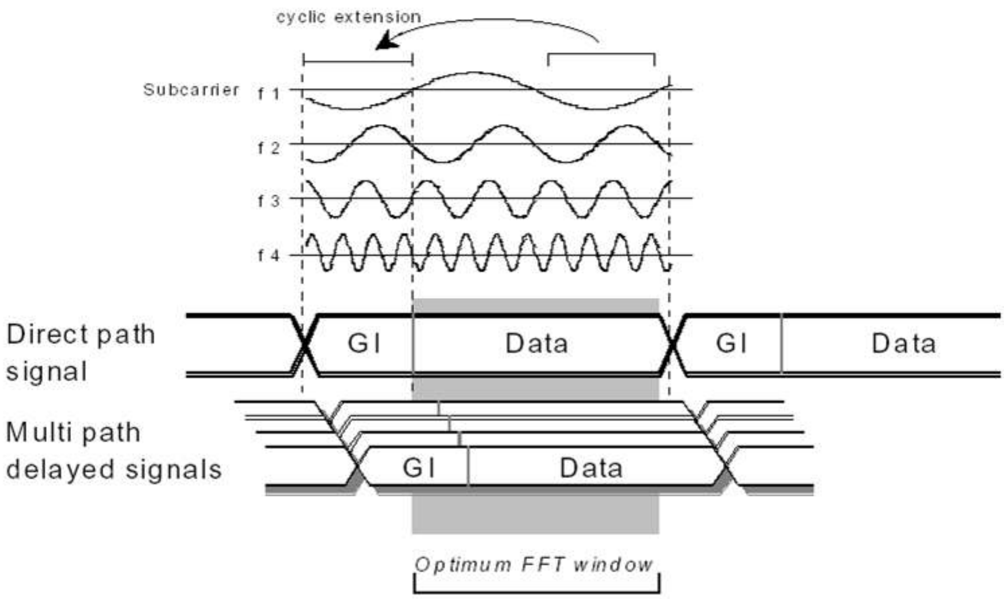


Figure 2.4: The structure of the OFDM symbol.

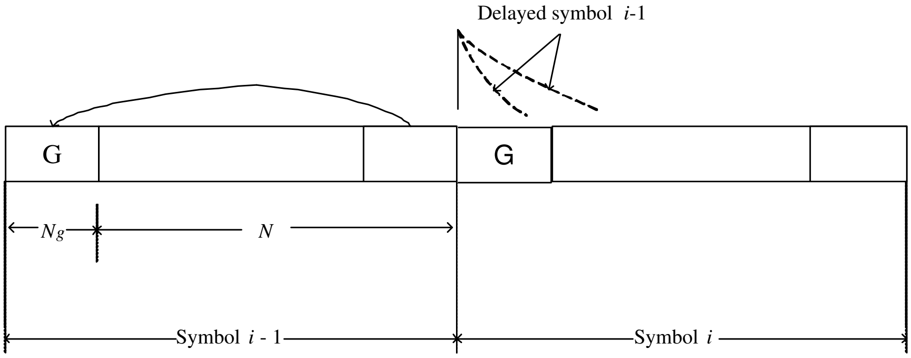


Figure 2.5: The OFDM time-domain signal with a cyclic prefix of N_g samples.

2.1.2.1 System structure

There is a particular property of the OFDM system, which is that each narrow-band subcarrier can be modulated using different modulation methods, such as Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), M-ary Quadrature Amplitude Modulation (QAM) and other higher-order modulations. This is generally known as "symbol mapping (modulation)", as shown in Fig. 2.3. This adaptive modulation technique is known as **adaptive bit loading**, to be described in the following chapters.

The underlying assumption in the context of the OFDM upon invoking the IFFT for modulation is that, although frequency-domain samples produce time-domain samples (by the IFFT), both signals are assumed to be periodically repeated over an infinite time-domain and frequency-domain interval, respectively. Practically, however, it is sufficient to repeat the time-domain signal periodically for the duration of the channel's memory, i.e., for a duration that is comparable to the length of the CIR (Carrier-to-Interference Ratio) [4]. This is the required time interval and the channel's transient response dies down in this duration after exciting the channel with a time-domain OFDM symbol. Its output is constituted by its steady-state response constituted by the received time-domain OFDM symbol once the channel's transient response time has elapsed. In order to ensure that the received time-domain OFDM symbol is demodulated from the channel's steady-state rather than from its transient-response, each time-domain OFDM symbol is extended by the so-called cyclic prefix (used as Guard interval in Fig. 2.3). It is used to overcome the inter-OFDM symbol interference due to the multipath signals. The samples of the cyclic prefix are copied from the end of the time-domain OFDM symbol (referring to Fig. 2.4) and are discarded at the receiver. Clearly, the samples of the cyclic prefix in time-dispersive environments reduce the efficiency of the OFDM transmission because of a factor of $N/(N+N_g)$ (seen in Fig. 2.5) and the duration N_g of the necessary cyclic prefix is decided according to the channel's memory. In general, it is complicated and difficult for a system to change N_g with the instantaneous channel's states. When the channel is in poor quality, the delay of an OFDM symbol may be larger than the length of the cyclic prefix. Additionally, it is unnecessary to set a large N_g when the channel is not in severe fading. Fig. 2.5 illustrates that one delayed previous symbol $i-1$ is covered by the cyclic prefix while the other one is not.

2.1.2.2 OFDM signal

At the transmitter shown in Fig. 2.3, the serial input data are converted to N parallel data, $d_0, d_1, \cdots, d_{N-1}$, to be modulated to M-PSK or M-QAM signals. Then an IFFT is performed on these modulated signals, $x_0, x_1, \cdots, x_{N-1}$. The resulting complex baseband OFDM signal, excluding the cyclic prefix part, from IFFT can be written as

$$s(t) = \sum_{n=0}^{N-1} x_n \exp\left(\frac{j2\pi nt}{T}\right), \quad 0 \leq t < T \tag{2.3}$$

where t is the discrete time index and T is the OFDM symbol duration.

The received signal, $r(t)$, is the sum of a linear convolution with the discrete channel impulse response $h(\tau)$ and the additive white Gaussian noise $\eta(t)$. It is assumed that the fading is slow enough that channel can be considered as time-invariant in one symbol period, and there is a perfect synchronization between transmitter and receiver and also, cyclic prefix is long enough to accommodate the channel impulse response $h(\tau)$. Then the incoming signal before the IDFT/IFFT process at the receiver can be expressed as

$$r(t) = \sum_{\tau} h(\tau)s(t-\tau) + \eta(t). \tag{2.4}$$

The received signal is sampled at the rate N/T and the sample of the received signal r_k is [49]

$$r_k = r(t)|_{t=k\frac{T}{N}}. \tag{2.5}$$

Hence, at the receiver, the M-PSK or M-QAM signal, y_n can be obtained by DFT/FFT process,

$$y_n = \frac{1}{N}\sum_{k=0}^{N-1} r_k \exp\left(-\frac{j2\pi}{N}nk\right). \tag{2.6}$$

Accordingly, the desired parallel data $\hat{d}_0, \hat{d}_1, \cdots, \hat{d}_{N-1}$ can be demodulated from $y_0, y_1, \cdots, y_n$ by corresponding M-PSK or M-QAM demodulation schemes.

The main advantages of an OFDM based system are listed as follows:

- Very good at mitigating the effect of multipath delay
- Scalable to high data rates
- High bandwidth efficiency
- Excellent resistance to Inter-Carrier Interference(ICI)
- Flexible and adaptive modulation techniques such as BPSK, QPSK, QAM and other higher-order modulation schemes
- Easily adopted to severe channel conditions without complex equalization
- Robust against narrow-band co-channel interference
- Robust against inter-symbol interference and fading caused by multipath propagation

- High channel utilization
- Efficient implementation by IFFT/FFT
- Low sensitivity to time synchronization errors
- Tuned sub-channel receiver filters are not required (compared with conventional FDM)
- Facilitates single frequency networks, i.e. transmitter macro-diversity.

Meanwhile, the OFDM technique also has its drawbacks. Firstly, before transmitting the OFDM signals with RF of the transmitter, all independently modulated data on subcarriers are added together. Thus, it is possible that the composite signal has a high-peak power larger than the average power, which would require more complicated amplifiers, the research in this area can be found in [50–52]. Secondly, the OFDM technique is sensitive to Doppler shift [53–56]. Thirdly, it is sensitive to frequency synchronization problems [57–60]. Fourthly, the great improvement of performance is based on some algorithms including adaptive bit loading, subcarrier allocation and so on, which definitely increases the implementation complexity. However, some negative effects can be reduced when useful techniques, such as frequency offset compensating, subcarrier coding and power clipping, are employed [61–65].

2.2 Three types of OFDM-CDMA systems

The OFDM-CDMA systems have been pioneered by Yee. Linnartz and Fettweis [22], by Chouly, Brajal and Jourdan [23], as well as by Fettweis, Bahai and Anvari [24]. And the convolutional coding in conjunction with OFDM-CDMA was investigated by Fazel and Papke in [25]. As a whole, there are three types of OFDM-CDMA systems, such as "Multi-Carrier (MC)-CDMA [22,23,25]", "Multi-Carrier Direct Spread (DS)-CDMA [27]" and "Multi-Tone (MT)-CDMA [28]".

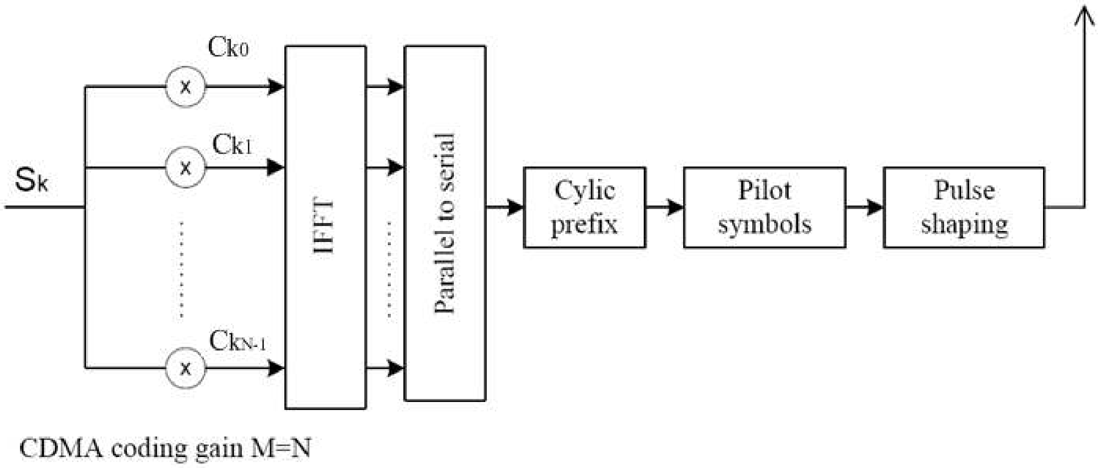


Figure 2.6: MC-CDMA system structure.

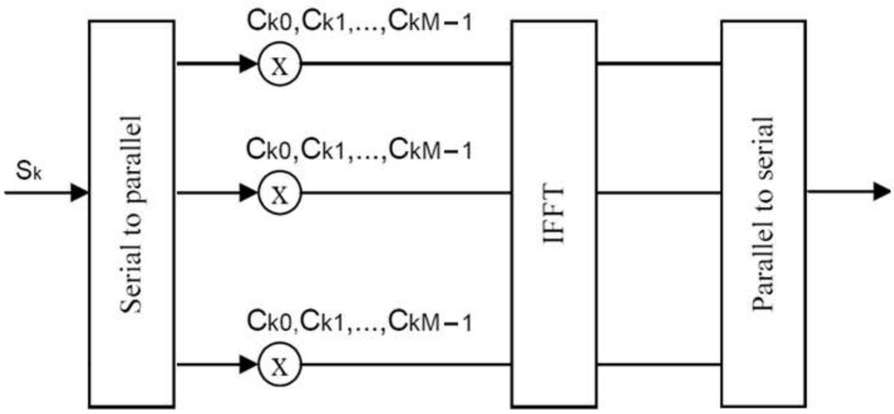


Figure 2.7: MC-DS-CDMA system structure.

In [66], Prasad and Hara reviewed the three types of OFDM-CDMA schemes, and discussed their advantages and disadvantages in terms of the transmitter and receiver structures, the spectral efficiency and the downlink bit error rate (BER) performance. Like non-spread OFDM transmission, OFDM-CDMA methods suffer from high peak-to-mean power ratios, which are dependent on the frequency domain spreading scheme, as investigated by Choi, Kuan and Hanzo [67]. In the dissertation, the second scheme, Multi-Carrier DS-CDMA, is selected since it works well in the uplink communications and is efficient in the establishment of quasi-synchronized channels [26]. As shown in Fig. 2.6, parallel signals are assigned

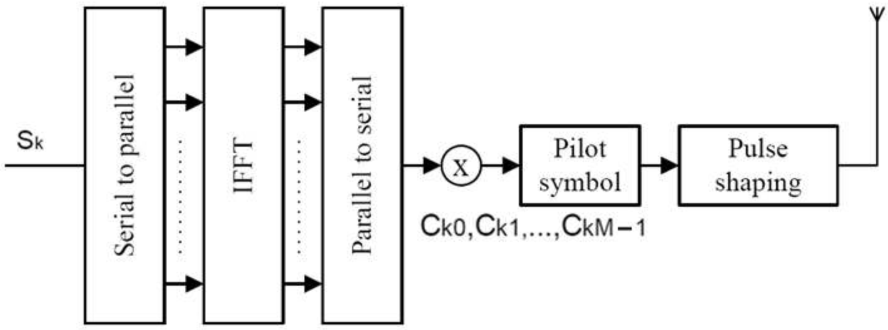


Figure 2.8: MT-CDMA system structure.

on corresponding subcarriers and modulated by each chip respectively in the first type of system, knows as MC-CDMA system. S_k is the serial sequence from user k. This implies that the processing gain, M, should be equal to the number of the subcarriers, N, and each subcarrier conveys a narrowband waveform rather than a direct-sequence waveform. In other words, the resulting signal has a PN coded structure in the frequency domain.

The second type of the systems, known as MC-DS-CDMA and shown in Fig. 2.7, is originally proposed for an uplink communication channel, because the introduction of OFDM signalling into DS-CDMA scheme is effective for the establishment of a quasi-synchronous channel. The proposed algorithms in the thesis are based on this type of system. In MC-DS-CDMA, the available frequency spectrum is divided into N bands of equal width to transmit different signals.

For the third type system as shown in Fig. 2.8, the MT-CDMA transmitter spreads the data streams after the conversion from serial to parallel signals, using a given spreading code in the time domain, so that the spectrum of each subcarrier prior to spreading operation can satisfy the orthogonality condition with the minimum frequency separation [28]. Therefore, the resulting spectrum of each subcarrier no longer satisfies the orthogonal condition. The MT-CDMA scheme uses longer spreading codes in proportion to the number of subcarriers, as compared with a normal (single carrier) DS-CDMA scheme, therefore, the system can accommodate more users than the DS-CDMA scheme.

The main difference between MC-CDMA and MC-DS-CDMA is how they achieve spreading process. MC-CDMA system performs the spreading operation in the frequency domain, while MC-DS-CDMA system performs the spreading operation in the time domain. Another major difference is the method by which both the systems separate the data from different subcarriers. In the transmitter, the spread baseband data from different users is modulated on subcarriers, and the frequency separation between subcarriers is the same. The modulation signal is summed up to form a multicarrier signal. The complex baseband multicarrier signal is in fact nothing more than the inverse Fourier transform of the input symbols.

2.3 Adaptive OFDM

Adaptive OFDM is a new research area on the OFDM scheme combining adaptive modulation, adaptive subcarrier allocation, adaptive coding and adaptive antenna with the OFDM technique. A variety of approaches have been proposed for adaptive OFDM recently [68–72]. In this chapter, a review of well-known adaptive OFDM approaches on adaptive modulation and subcarrier allocation is presented.

2.3.1 Adaptive systems

Adaptive modulation and subcarrier allocation are only suitable for duplex communications between the mobile station and the base station. The adaptive information would be exchanged as shown in Fig. 2.9 and Fig 2.10. If both mobile station (MS) and base station (BS) estimate the channel quality, as shown in Fig. 2.9, in the uplink, the mobile station (MS) will estimate the channel quality and decide the modulation scheme and subcarriers allocation, and the adaptive information will be sent to the base station for correct demodulations. On the contrary, the base station (BS) also does the same work in the downlink. However, if channel estimation and adaptive algorithms are applied in the mobile station, the design of the MS would be more complicated. Additionally, more power will be provided

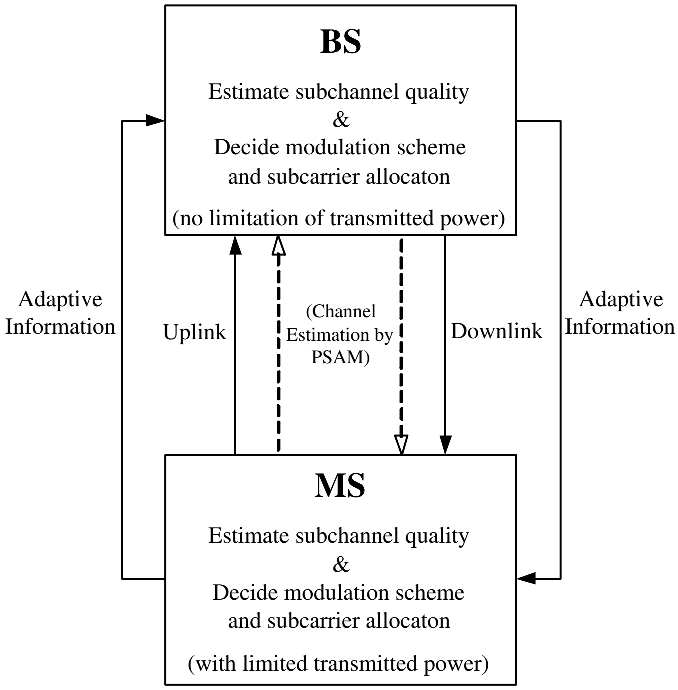


Figure 2.9: Both BS and MS perform channel estimation and adaptive algorithms.

to complete the realization of the complicated algorithms. In the system based on Fig. 2.10, the channel estimation and adaptive modulation and subcarrier allocation are performed only by BS, since BS can support much more power than MS. Therefore, the mobile phone can be designed economically and with less radiation. But, the channel estimation would be not more accurate than that in Fig. 2.9 since the characteristics of uplink and downlink channels have much difference normally. The performance of adaptive modulation and subcarrier allocation algorithms is based on the accurate channel estimation.

Fig. 2.11 shows a normal adaptive multiuser OFDM system. We assume that the system has K users and the kth user has a data rate equal to R_k bits per OFDM symbol. At the transmitter, the serial data from the K users are fed into the subcarrier and bit allocation block which allocates the number of bits for different users to different subcarriers. We assume that each subcarrier has a bandwidth that is much smaller than the coherence bandwidth of the channel and that the instantaneous channel gains on all the subcarriers of all the users are known to the transmitter. Using the channel information, the transmitter applies the combined

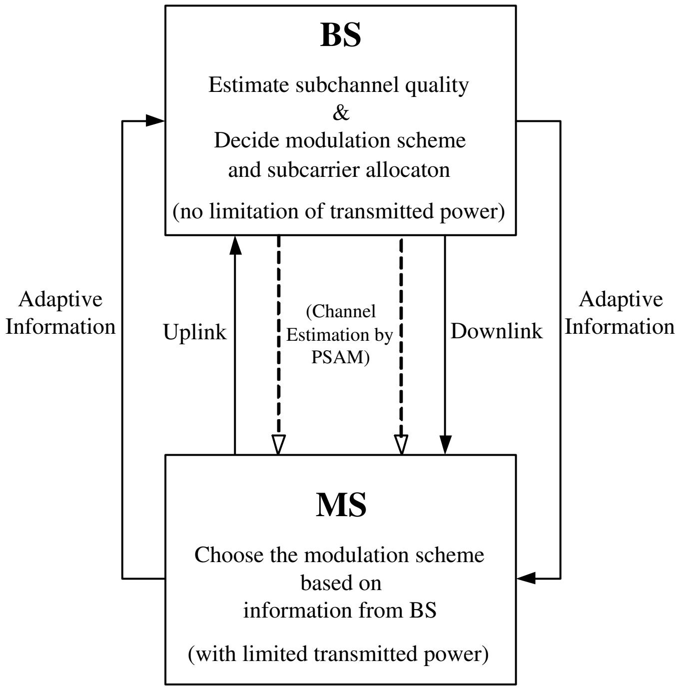


Figure 2.10: Only BS performs channel estimation and adaptive algorithms.

subcarrier, bit, and power allocation algorithms to assign subcarriers to different users and the numbers of bits/OFDM symbol to be transmitted on each subcarrier. Depending on the number of bits assigned to a subcarrier, the adaptive modulator will use a corresponding modulation scheme, and the transmission power level will be adjusted adaptively according to the combined subcarrier, bit, and power allocation algorithms.

As a technique combined with OFDM, adaptive transmission is very helpful to improve the performance of an OFDM system in the aspects of bit error rate (BER), system capacity and capability of supporting high data rates, which will also be demonstrated subsequently. Adaptation of the transmission parameters is based on the transmitter's perception of the channel conditions in the forthcoming time slot. It is necessary that each received signal or training symbols must be detected to obtain the estimation of the future channel parameters.

According to the channel conditions on a time slot, the adapting transmission technique for serial modems in narrowband fading channels has been shown to

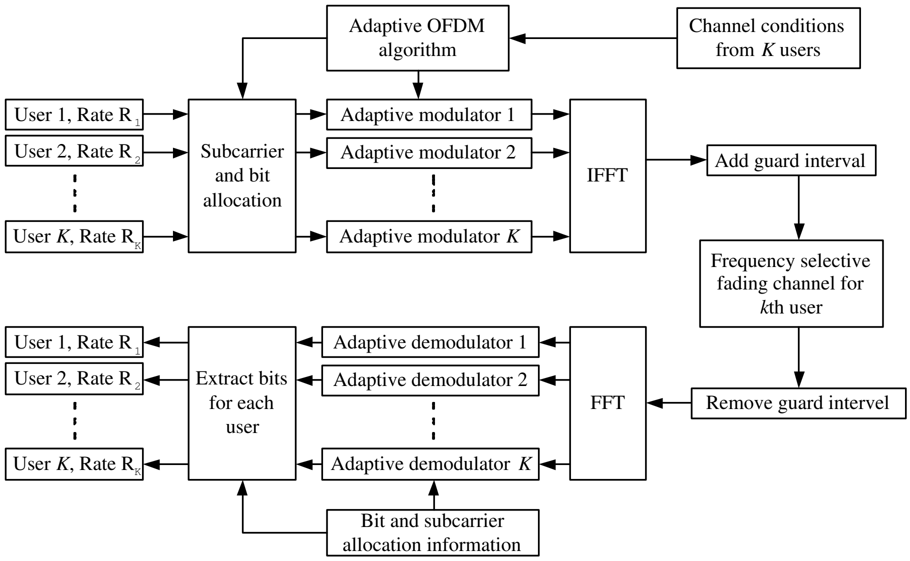


Figure 2.11: A normal multiuser OFDM system with adaptive subcarrier and bit allocations.

considerably improve the BER performance for time division duplex (TDD) systems [73]. However, the Doppler fading rate of the narrowband channel has a strong effect on the achievable system performance [53–56]. If the fading is rapid, then the prediction of the channel condition for the next transmission time slot is inaccurate and the wrong set of transmission parameters may be chosen. Therefore, the adaptive modulation mode can not change rapidly and can only be suitable to the average channel quality. In contrast, if the channel varies slowly, then the data throughput of the system is varying dramatically over time. That is because the modulation control regime changes the adaptive modulation modes in an effort to obey the channel quality as accurately as possible and all adaptive modulation modes have different throughputs. This may require a large buffer to smoothen these bit rate fluctuations in order to ensure a constant data rate. For time-critical applications, such as interactive speech transmission, the potential delays can become problematic. A given single-carrier adaptive system in narrowband channels will therefore operate efficiently only in a limited range of channel conditions. The combination of the adaptive technique with OFDM can ease the problem of slow time-varying channel since the variation of the signal quality can be exploited in both the time and frequency domains. The channel conditions have to be monitored based on the received OFDM symbols and relatively slowly varying channels have to be assumed because adaptive OFDM transmissions are not well suited to rapidly varying channel conditions [2].

2.3.2 Previous adaptive algorithms

2.3.2.1 Adaptive bit loading and subcarrier allocation for single-service

Fixed threshold adaptation algorithm

The fixed threshold algorithm was derived from the adaptation algorithm proposed for serial modems [73]. In the case of a serial modem, the channel quality is assumed to be constant during a symbol time slot, and hence the channel has to be slowly varying in order to allow accurate channel quality prediction easily. Under these circumstances, the same modulation modes, chosen according to the predicted SNR, are employed by all data symbols in the transmission time slot. The SNR thresholds for a given long-term target BER were determined by Powell optimization [74]. It was assumed that two uncoded target BERs: 10^{-2} for a high data rate "speech" system, and 10^{-4} for a higher integrity, lower data rate "data" system. Table 2.1 gives the SNR thresholds l_n for activating a given modulation mode M_n in a slowly Rayleigh fading narrowband channel. Specifically, the corresponding modulation mode M_n is selected if the instantaneous channel SNR exceeds the switching level l_n. This adaptation algorithm assumes a constant instantaneous SNR over all of the block's symbols, but the channel quality varies between the different subcarriers in the case of an OFDM system over a frequency selective channel. For subband adaptive OFDM transmission, this implies that the above switching algorithm cannot be employed if the subband width is wider than the channel's coherence bandwidth.

A more detailed analytically motivated discussion on the optimization of the mo-

Table 2.1: Optimized switching levels for adaptive modulation over Rayleigh fading channels for the "speech" and "data" systems

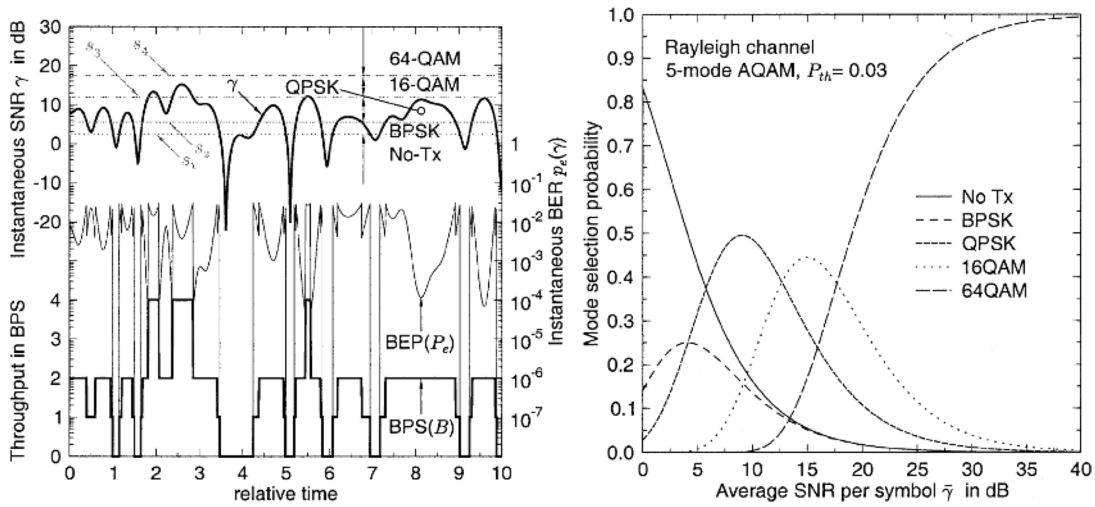
	l_0	l_1	l_2	l_4
speech system	$-\infty$	3.31	6.48	11.61
data system	$-\infty$	7.98	10.42	16.76

dem mode switching thresholds was provided based on Fig. 2.12 in [1]. A five-mode AQAM system was studied. The operation of the five-mode AQAM scheme is illustrated in Fig. 2.12 when communicating over a typical narrow-band Rayleigh-fading channel scenario. The channel-quality related SNR regions are divided by the modulation mode switching levels s_k. The peak instantaneous BER (iBER) limiting scheme [75] was used for deriving the switching levels used in Fig. 2.12(a). It is assumed that the peak iBER is $P_{th} = 3 \times 10^{-2}$ and the associated instantaneous bit-per-symbol (BPS) throughput b is also depicted, using the thick stepped line at the bottom of Fig. 2.12(a). Then it can be observed that the throughput varies from 0 BPS, when the no-transmission (No-Tx) AQAM mode was chosen, to 4 BPS, when the 16-QAM mode was activated. During the depicted observation window, the 64-QAM modulation mode was not activated. The instantaneous BER, depicted as a thin line using the middle trace of Fig. 2.12(a), is limited by the peak instantaneous BER of $P_{th} = 3 \times 10^{-2}$. Fig. 2.12(b) shows the variation of the modulation selection probability with the average SNR.

The algorithm with fixed thresholds checks the channel SNR and then decides the modulation scheme, the process time of which is less than other complicated methods. So it can be realized easily. However, choosing the modulation schemes based on the SNR regions does not consider the limitation of power consumption and transmission rates.

Adaptation algorithm by minimizing the transmission power

In [11], multiuser frequency selective fading is utilized to allocate subcarriers and the number of bits for users. When OFDM with adaptive modulation is applied in



(a) (b)

Figure 2.12: Various characteristics of the five-mode AQAM scheme communicating over a Rayleigh-fading channel employing the specific set of switching levels designed for limiting the peak instantaneous BER to $P_{th} = 3 \times 10^{-2}$. (a) The evolution of the instantaneous channel SNR γ is represented by the thick line at the top of the graph, the associated instantaneous BER $p_e(\gamma)$ by the thin line in the middle and the instantaneous BPS throughput $b(\gamma)$ by the thick line at the bottom. The average SNR is $\bar{\gamma} = 10$ dB. (b) As the average SNR increases, the higher order AQAM modes are selected more often [1].

a frequency selective fading channel, a significant portion of the subcarriers may not be used.

Its objective is to minimize the overall transmission power by allocating the subcarriers to the users and determining the number of bits and the power level transmitted on each subcarrier based on the instantaneous fading characteristics of all users. The multiuser subcarrier, bit, and power allocation problem is formulated as [11]

$$P_T^* = \min_{c_{k,n} \in D} \sum_{n=1}^{N} \sum_{k=1}^{K} \frac{1}{\alpha_{k,n}^2} f_k(c_{k,n}) \tag{2.7}$$

and the minimization is subjected to the constraints:
1) $R_k = \sum_{n=1}^{N} c_{k,n}$, $k \in \{1, \cdots, K\}$;
2) If there exists k' with $c_{k',n} \neq 0$, then $c_{k,n} = 0$, $\forall k \neq k'$,
where $D = \{0, 1, 2, \cdots, V\}$ and V is the maximum number of information bits/OFDM symbol that can be transmitted by each subcarrier. $\alpha_{k,n}$ is the magnitude of the channel gain of the nth subcarrier as seen by the kth user. $f_k(c)$ is the required received power in a subcarrier for reliable reception of c information bits/symbol when the channel gain is equal to unity. The adaptive subcarrier, bit and power allocation algorithm is proposed based on (2.7).

By minimizing the total power of a group of users, the algorithm obtains the limited data rate of each user. But the limitation of single user's transmission power should be considered since this issue is important to the reduction of the interference between users and the design of the mobile phone.

Adaptation algorithm by maximizing the data throughput

In the multiuser OFDM system, the total data rate is viewed as the sum of all the users' data rate, the total data rate of the multiuser OFDM system may be represented by

$$R = \sum_{k=1}^{K}\sum_{n=1}^{N}\frac{1}{T}\log_2(1+\frac{\gamma_{k,n}}{\Gamma}) = \frac{B}{N}\sum_{k=1}^{K}\sum_{n=1}^{N}\log_2(1+\frac{\gamma_{k,n}}{\Gamma}) \quad (2.8)$$

where T is the OFDM symbol duration which is given as $T = 1/B_n = N/B$, B is the total bandwidth and $\gamma_{k,n}$ is the SNR of the subcarrier used by user k. Additionally, the power constraint of the system is written as

$$\sum_{k=1}^{K}\sum_{n=1}^{N} P_{k,n} = P_T \quad (2.9)$$

where P_T denotes the total transmission power.

Since the subcarrier which appears in deep fade to a particular user may not be in deep fade to other users, two or more users would have the same best subcarrier simultaneously. In [8], a proof of the fundamental assumption in [11] and [76] is provided that a subcarrier is exclusively assigned to only one user to obtain the maximization of the overall data rate before proposing the adaptive algorithm. Thus, the multiuser OFDM system can be viewed as a FDMA system with dynamic subcarrier allocation, which means that each user has its own set of subcarriers to carry information bits. Consequently, the multiuser OFDM system can be treated as a single user OFDM system virtually for maximizing overall data rate. Then, the total rate and the total transmission power constraint may be rewritten as [8]

$$R = \frac{B}{N}\sum_{n=1}^{N}\log_2\left(1+P_{k_n^*}\right)|\alpha_{k_n^*}|\frac{N}{N_0 B\cdot\Gamma}, \quad (2.10)$$

where $k_n^* = \arg_k \max\{|\alpha_{1,n}|^2, |\alpha_{2,n}|^2, \cdots, |\alpha_{K,n}|^2\}$, $\Gamma = -\ln(5BER)/1.5$ for $n = 1, 2, \cdots, N$ and

$$\sum_{n=1}^{N} P_{k_n^*} = P_T. \quad (2.11)$$

One of the contributions of this research is that users cannot share the same subcarriers if we want to maximize the sum of the data rates of all users. However, satisfying the requirements of each user's data rate should be considered since each user also has his own demand for the service transmission.

Constant throughput adaptive OFDM

The time-varying data throughput of an adaptive OFDM modem operating with either of the two adaptive algorithms discussed above makes it difficult to employ such a scheme in a wide variety of applications. In order to accommodate the variable data rate, Torrance [73] studied the system implications of variable-throughput adaptive modems in the context of narrow-band channels, stressing the importance of data buffering at the transmitter. The required length of the buffer is related to the Doppler frequency of the channel. With a slowly varying channel, slowly varying data throughput is obtained, and therefore a high buffer capacity is needed. Realtime audio or video transmission is very sensitive to the delay, and therefore different adaptation algorithms are needed for such applications.

The constant throughput adaptive OFDM scheme proposed in [12] exploits the frequency selectivity of the channel, while offering a constant transmission rate. Again, subband adaptivity is assumed in order to simplify the signaling or the associated blind detection of the modulation schemes.

Based on the expected bit error rate in each subband, the modulation scheme allocation of the subbands is performed on the basis of a cost function. For each subband n and each possible modulation scheme mode, s, the expected number of bit errors, $e_{n,s}$, is calculated on the basis of the estimated channel transfer function $\hat{H}$, as well as a function of the number of bits transmitted per subband and modulation scheme, $b_{n,s}$.

Each subband is assigned a state variable s_n holding the index of a modulation scheme. Each state variable is initialed to "0", meaning "no transmission". A set of cost values, $c_{n,s}$, is calculated for each subband n and state s as follows:

$$c_{n,s} = \frac{e_{n,s+1} - e_{n,s}}{b_{n,s+1} - b_{n,s}} \tag{2.12}$$

for all but the highest level modulation index s. If the modulation scheme having the next higher index is used instead of index in subband, this cost value is related to the expected increase in the number of bit errors, divided by the increase of throughput. In other words, (2.12) quantifies the expected incremental BER of the state transition $s \rightarrow s+1$ in subband n.

The modulation scheme adaptation is performed to reach the target number of bits by searching for the block n having the lowest value of $c_{n,s}$, and incrementing its state s_n. This process is repeated until the total number of bits in the OFDM symbol reaches the target number of bits. The total number of bits may exceed the target because of the granularity in bit numbers introduced by the subbands. In this case, the data is padded with dummy bits for transmission.

This constant throughput adaptive OFDM scheme selects a modulation scheme for subcarriers on the basis of a cost function with the expected BERs on each subcarrier. It is suitable to a particular service transmission in multiuser OFDM systems because fixed data rates and BER requirements could be satisfied. But its process time would be long because the modulation scheme on each subcarrier is decided after checking the cost function repeatedly for many subcarriers, which may not be appropriate for the realtime processing.

2.3.2.2 Adaptive bit loading and subcarrier allocation for multi-service

The multi-service traffic consists of different messages that have different QoS requirements. For example, the voice service requires a realtime transmission with the tight delay constraint at low data rates, while the data service requires a higher data rate with less severe delay constraints. Additionally, voice transmission endures higher BER, but the data is very sensitive to BER.

Adaptive BPSK/M-AM scheme

To cope with the difference in BER requirements, adaptive hybrid binary phase shift keying (BPSK)/M-amplitude modulation (AM) is proposed in [77]. It transmits voice over quadrature (Q) channel with BPSK and transmits data over inphase (I) channel with M-ary AM. The power allocated to voice signal is set to just meet the target BER for voice, BER_v, and the remaining power is dynamically assigned to the I channel to support the M-ary AM modulation and to operate below the target data BER, BER_d. Since voice service has higher priority, only voice can be transmitted when signal-to-noise ratio (SNR) is too low to support both voice and data. As SNR grows higher, more power can be assigned to I channel to transmit data at a higher data rate.

Adaptive uniform M-QAM scheme

Since M-ary AM in [77] is less spectrally efficient than that of M-ary quadrature amplitude modulation (QAM), adaptive BPSK/M-AM scheme tends to be spectrally inefficient at high SNRs. A more efficient method is proposed to employ adaptive QAM for both data and voice services with different priorities and switching thresholds in [78].

The proposed method does not send any traffic when the SNR is too low to meet the required BER_v for voice. In this case, voice outage is declared. When the SNR is larger than $\gamma_0 = [\text{erfc}^{-1}(2BER_v)]^2$ (obtained from the exact BER expression of BPSK), it starts to send voice traffic with BPSK modulation. If the SNR is not large enough to transmit signals with 4QAM, data outage is declared. Assuming that V is the maximum number of bits carried by each transmitted symbol, the data SNR range is divided into V regions, and the constellation size of $M = 2^{v+1}$ (v is the number of transmitted data bits in a symbol) is allocated to the vth region ($v = 1, 2, \cdots, V$). When the channel SNR is in vth region, 2^{v+1}-QAM symbol is transmitted carrying 1-bit voice and v-bit data. This is called switching threshold method. Voice is always transmitted by BPSK modulation. In this scheme, both voice and data transmissions are strict with the BER requirements of data, BER_d. The switching threshold for both voice (1 bit) and data (v bits) is obtained as

$$\begin{cases} \gamma_v = \frac{1-2^{v+1}}{1.5} \ln(5\, BER_d), \\ \gamma_{V+1} = \infty. \end{cases} \tag{2.13}$$

Due to the use of uniform M-QAM modulation, the voice bits get unnecessary extra protection at the expenses of spectral efficiency at the region with low SNRs and outage probability for data transmission. The efficiency of multi-service transmission is affected.

Adaptive multi-rate services transmission

In [79], the author proposed adaptive bit loading for multi-rate services. First, this algorithm assigns corresponding service according to modulation level of each subcarrier based on the adaptive selection curves in Fig.2 in [79]. If the modulation level is $B_0 = \{0\}$, no service is assigned. If the modulation level is $B_1 = \{1, 2\}$, one or two bits are assigned to the low-rate service, such as voice service. $B_2 = \{3, 4\}$ is for high-rate service, such as data service. This algorithm is similar to the fixed threshold adaptive algorithm except that two kinds of services are considered in this algorithm.

Dual service optimization

Dual services in [80] mean that the transmissions for two services have different QoSs. The QoS requirement of one kind of service is generally more strict than the others. Both data rates of two services would be maximized in [80]. It tries to obtain the maximum date rate of the other service transmission after guaranteeing the maximization of the service with higher QoS. Its objective is met by finding the optimal tone assignment S and the energy E to the optimization problem of simultaneously providing services with different QoS.

However, it is not appropriate to use the QoS alone as the optimization parameters for the voice/data systems. It is known that, the QoS of data service, generally requires more strict requirements of higher data rates than the voice service, and the delay requirement of voice service is much more critical than the data service, which should be sufficiently considered for channel resource allocation.

2.3.3 Transmission of adaptive information between BS and MS

For performing the demodulation successfully, the adaptive OFDM receiver has to be informed of the modulation schemes used for the different subbands. This information can either be conveyed using signaling subcarriers in the OFDM symbol itself, or the receiver can employ blind detection techniques in order to estimate modulation schemes used for transmissions, as seen in Fig. 2.9 and 2.10.

Signaling

The simplest way of signaling the modulation scheme employed in a subband is to replace one data symbol by an M-PSK symbol, where M is the number of possible modulation schemes [12]. In this case, the reception of each of the constellation points directly signals a particular modulation scheme in the current subband. In our case, for four modulation schemes with the assumption of the perfect phase recovery, the probability of a signaling error $p_s(\gamma)$ is the symbol error probability of QPSK when employing one signaling symbol. Then the correct subband mode signaling probability is

$$(1 - p_s(\gamma)) = [1 - p_{b,QPSK}(\gamma)]^2 , \tag{2.14}$$

where $p_{b,QPSK}(\gamma)$ is the bit error probability for QPSK

$$p_{b,QPSK}(\gamma) = Q(\sqrt{\gamma}) = \frac{1}{2} \cdot \operatorname{erfc}\left(\sqrt{\frac{\gamma}{2}}\right) , \tag{2.15}$$

which leads to the expression for the modulation scheme signaling error probability of [12]

$$p_s(\gamma) = 1 - \left[1 - \frac{1}{2} \cdot \operatorname{erfc}\left(\sqrt{\frac{\gamma}{2}}\right)\right]^2 . \tag{2.16}$$

The signaling error probability can be reduced by employing multiple signaling symbols and maximum ratio combining of the received signaling symbols $R_{s,n}$, in order to generate the decision variable R'_s prior to decision

$$R'_s = \sum_{n=1}^{N_{sym}} R_{s,n} \cdot \hat{H}^*_{s,n} \tag{2.17}$$

where N_{sym} is the number of signaling symbols per subband; $R_{s,n}$ is the received symbols in the signaling subcarriers and $\hat{H}^*_{s,n}$ is the estimated values of the frequency domain channel transfer function at the signaling subcarriers. Assuming perfect channel estimation and constant values of the channel transfer function across the group of signaling subcarriers, the signaling error probability for N_{sym} signaling symbols can be expressed as [12]

$$p'_{\gamma,N_{sym}} = 1 - \left(1 - \frac{1}{2} \cdot \operatorname{erfc}\left(\sqrt{\frac{N_{sym}\gamma}{2}}\right)\right)^2 . \tag{2.18}$$

The signaling symbols for a given subband can be interleaved across the entire OFDM symbol bandwidth in order to benefit from frequency diversity in fading wideband channels.

Blind detection by SNR estimation

For the blind detection by SNR estimation, the receiver has no knowledge of the modulation scheme employed in a particular received subband. It would estimate this parameter by quantizing the de-faded (i.e., fading-compensated) received data symbols $R_n/\hat{H}_n$ in the subband to the closest symbol $\hat{R}_{n,m}$ for all possible modulation schemes for each subcarrier index n in the current subband. The decision-directed error energy for each modulation scheme is calculated according to [12]

$$e_m = \sum_n (R_n/\hat{H}_n - \hat{R}_{n,m})^2 \tag{2.19}$$

and the modulation scheme, which minimizes e_m, is chosen for the demodulation of the subband at the receiver.

2.3.4 Summary

With the QoS requirements of single-service and multi-service transmissions, more appropriate adaptive algorithms are needed to meet those requirements and adapted to the increasing traffic transmission in the future, compared with the previous research.

In terms of the combination of CDMA and OFDM techniques, adaptive OFDM technique is a promising scheme for next generation wireless communications. Since the status of subchannels is always changing with the environment and time, the channels can be utilized better with the adaptive algorithms, which are based on the investigation of the information of all subchannels.

However, the adaptive system becomes more complicated because the transceivers must exchange adaptive information by some methods every time the algorithms are performed. Additionally, accurate channel estimation is also needed. More research has been done in these two aspects, which can support the adaptive algorithms greatly.

Chapter 3

Performance analysis of OFDM/CDMA and other OFDM systems

In this chapter, the OFDM/CDMA, OFDM-TDMA, OFDM-FDMA, OFDM Interleaved-FDMA and OFDM Group-FDMA systems are described and the performance of data rates of each user in the OFDM/CDMA, OFDM Interleaved-FDMA and OFDM Group-FDMA systems is analyzed. Based on the data rate requirement of each user, the theoretical and simulated results show that the performance of the OFDM/CDMA system is better than the other OFDM system for multiuser transmissions with the data rate and transmission power requirements for each user.

3.1 Introduction

In many transmission scenarios, e.g., for wireless communications, transmission systems have to cope with time-varying frequency-selective channels due to multipath propagation. If, as usual, the channel is slowly time-varying compared to the transmitted symbol time, multicarrier modulation, which is often denoted as OFDM [3, 4, 38, 43], is an attractive transmission technique. By using OFDM, the actual dispersive channel is partitioned into frequency-non-selective narrow-band channels, the so-called tones or subcarriers.

OFDM is considered as a digital modulation technique, rather than a multiuser channel access technique, since it is utilized for transferring one bit stream over one communication channel using one sequence of OFDM symbols. Therefore, OFDM can be combined with multiple access schemes using time, frequency or coding separation of the users for multiuser transmissions. The OFDM/CDMA (MC-DS-CDMA) [81] allows all users to share all subcarriers to transmit their data. Spreading codes are used to distinguish different users at the receiver. Each user has a wide bandwidth for the transmission to obtain high data rates. However, the cross-correlation would interfere with the quality of each subband. In [82–84], OFDM is considered in combination with a TDMA scheme for a cellular mobile communication system. In an OFDM-TDMA transmission system, it is assumed that the total bandwidth is exclusively allocated to each user, i.e., all subcarriers, inside a single TDMA frame, which covers some OFDM symbols. The number of OFDM symbols per TDMA frame can be varied, according to the demands of each user. In the considered system, duplex traffic is accomplished by a TDD approach, using subsequent frames for up- and downlink. In the OFDM-FDMA system described in [85], each user is assigned a predetermined band of subcarriers and can only use those subcarriers exclusively in every OFDM symbol. However, there is a high correlation between the channel gains of adjacent subcarriers in a frequency selective fading channel. In order to avoid the situation where all subcarriers of a user are in deep fade, the OFDM Interleaved-FDMA scheme was proposed.

A traditional multiuser OFDM Interleaved-FDMA system is described in [11]. It is the same as OFDM-FDMA except that subcarriers assigned to a user are interlaced with other users' subcarriers in the frequency domain. However, the interleaving of subcarriers among users is fixed regardless of the time-varying channel. Consequently, the utilization efficiency of the whole channel is low. In the multiuser OFDM system described in [8], which can be considered as an enhanced OFDM Interleaved-FDMA system, each user's subcarriers are interlaced dynamically according to the channel state of each user during different symbol periods. For one user, the subcarrier which has highest channel gain seen by this user would be assigned. Hereby, the frequency diversity of each user is utilized sufficiently. The OFDM Interleaved-FDMA system to be discussed in this chapter is based on the dynamic interleaving of users' subcarriers. In this kind of OFDM system, the interference between users resulting from the share of the subbands is eliminated, but fewer subcarriers are used by each user. Besides, individual subcarrier is assigned to one user according to the time-varying channel information in each symbol. Thus, this mode of assigning subcarriers gives rise to more complexity. Especially for the realtime system with so many subcarriers, it looks impractical. In order to reduce the complexity of the system, OFDM Group-FDMA scheme [29] divides the available subcarriers into a number groups and the groups with the highest average channel gain for one user are allocated to this user. However, situations may arise that two or more users may attempt to select the same subcarrier or group for the OFDM Interleaved-FDMA and OFDM Group-FDMA systems, which leads to the conflicts of the subcarrier allocation. Compared with the OFDM/CDMA system, each user in the OFDM Interleaved-FDMA and OFDM Group-FDMA systems can only be assigned fewer subbands for data transmissions if more and more users are required in the system.

This chapter presents that the importance of the OFDM/CDMA system for the high-rate transmission with the demand of each user's data rate. Though the multiuser interference occurs, which results from sharing same subcarriers by multiple users, high efficiency of using the whole bandwidth will make OFDM/CDMA to be more practical and promising.

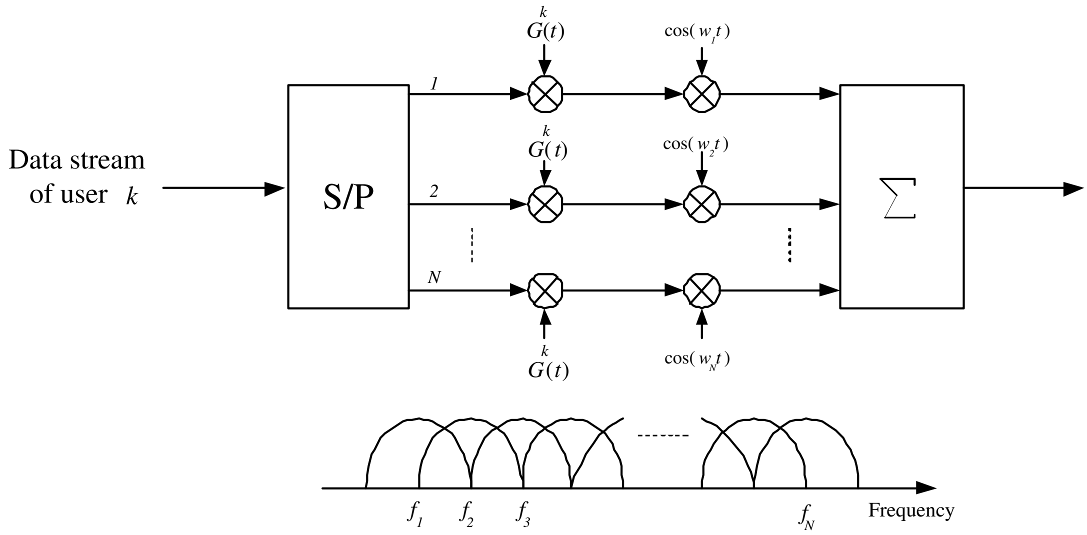


Figure 3.1: Block diagram of the transmitter of multiuser OFDM/CDMA (MC-DS-CDMA) system.

3.2 Descriptions of OFDM-related schemes

The transmitter of the multiuser OFDM/CDMA (MC-DS-CDMA) in a single cell is shown in Fig. 3.1. Spreading codes $\{G^k(t)\}$, such as Gold-Codes [86], are used to distinguish different users at the receiver. Parallel data streams are put onto the orthogonal subcarriers with the frequencies $f_1,\ f_2,\ f_3, \cdots, f_N$, where $\omega_n = 2\pi f_n$. User k ($k = 1, 2, \cdots, K$) can use all N subcarriers to transmit data. Actually, the process that the parallel data are put on those orthogonal subcarriers is done by inverse fast Fourier transform (IFFT) process. At the receiver, inverse processes, such as decorrelation of spreading codes and fast Fourier transform (FFT), will be performed to obtain the original data.

The block diagram of the transmitter of multiuser OFDM-TDMA system and an example of a TDMA frame (4 users) are given in Fig. 3.2 and Fig. 3.3. After the data stream is converted to be parallel, mapping to TDMA frames is performed on subcarriers of each user. Fig. 3.4 shows the scheme of multiuser OFDM-FDMA. Each user is allocated some subcarriers and the subcarriers assigned to users are not changed during the data transmission. In Fig. 3.5, the transmitter of the

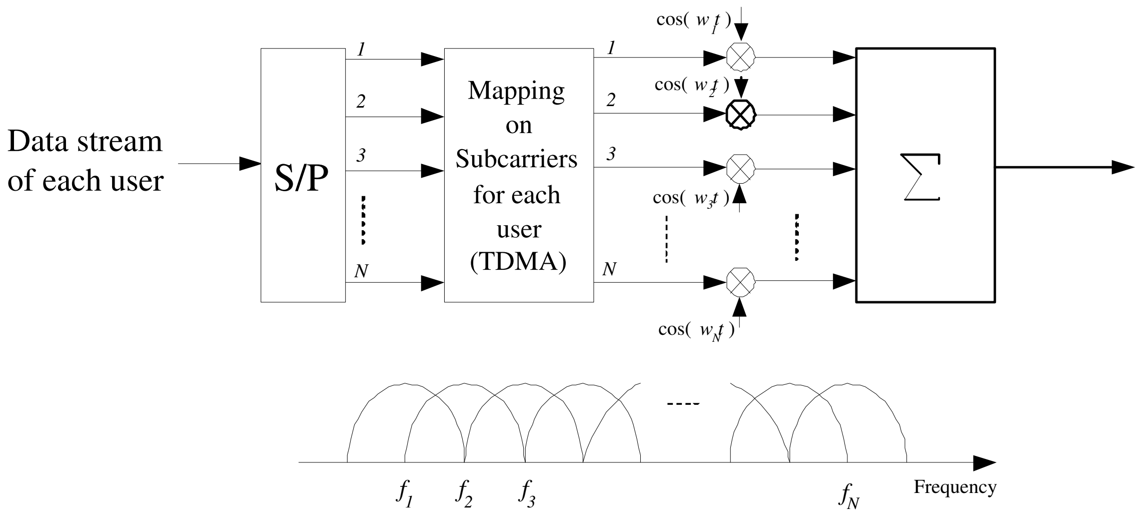


Figure 3.2: Block diagram of the transmitter of multiuser OFDM-TDMA system.

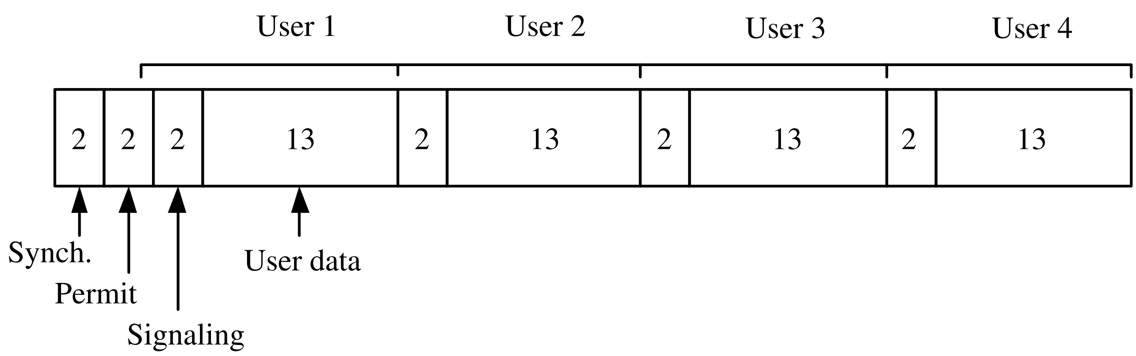


Figure 3.3: Example of a TDMA frame for an OFDM transmission system (the numbers denote OFDM symbols).

multiuser OFDM Interleaved-FDMA system is shown. Subcarriers can not be shared by users. For one user, the choice of the subcarriers would change with the instantaneous channel information. The subcarrier which has highest channel gain seen by this user would be assigned. For example, the third and Nth subcarriers have the highest channel gains for user 2. Then, the numbers of bits are loaded by adaptive algorithms on every subcarrier individually. For the scheme named as OFDM Group-FDMA, subcarriers are partitioned into some groups. The group with the highest average channel gain for one user are allocated to this user, as shown in Fig. 3.6. The subcarriers in one group will carry the same numbers of bits. After the partition, the number of subcarrier groups is much less than

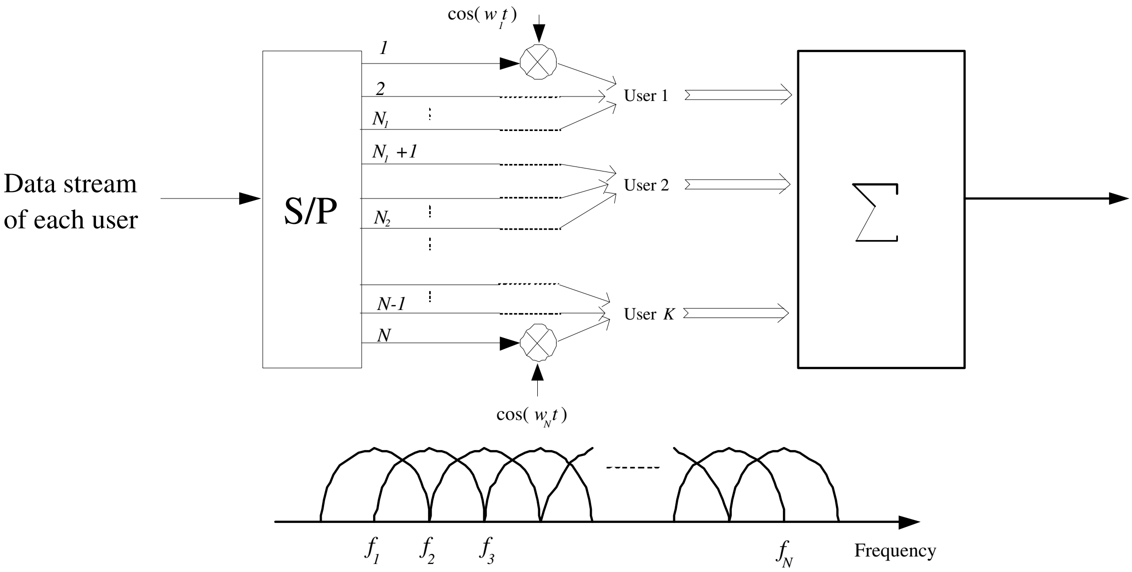


Figure 3.4: Block diagram of the transmitter of multiuser OFDM-FDMA system.

that of subcarriers, so the complexity of the adaptive algorithm of the subcarrier allocation becomes easier for each user. Thus, the processing time cost by the algorithm and the complexity is reduced, which is more suitable for realtime data transmissions. The instantaneous channel information of all users must be taken into account and the type of modulation scheme employed is dependent on the average channel gain of a group.

3.3 System model

Consider an OFDM signal represented in the time domain as

$$x(t) = \sum_{n} s[n]e^{j2\pi f_n t}, \quad 0 \leq t \leq T \tag{3.1}$$

where T is the symbol duration, $s[n]$ is the modulated signal by M-PSK or M-QAM, $f_n = f_0 + n\Delta f$ is the frequency of the nth subcarrier and $\Delta f = 1/T$. Since the transmission channel in frequency-selective fading is divided into many narrow subchannels, which are transmitted in parallel. Therefore, each subchannel can be assumed as flat fading. For flat fading conditions, the channel-impulse response

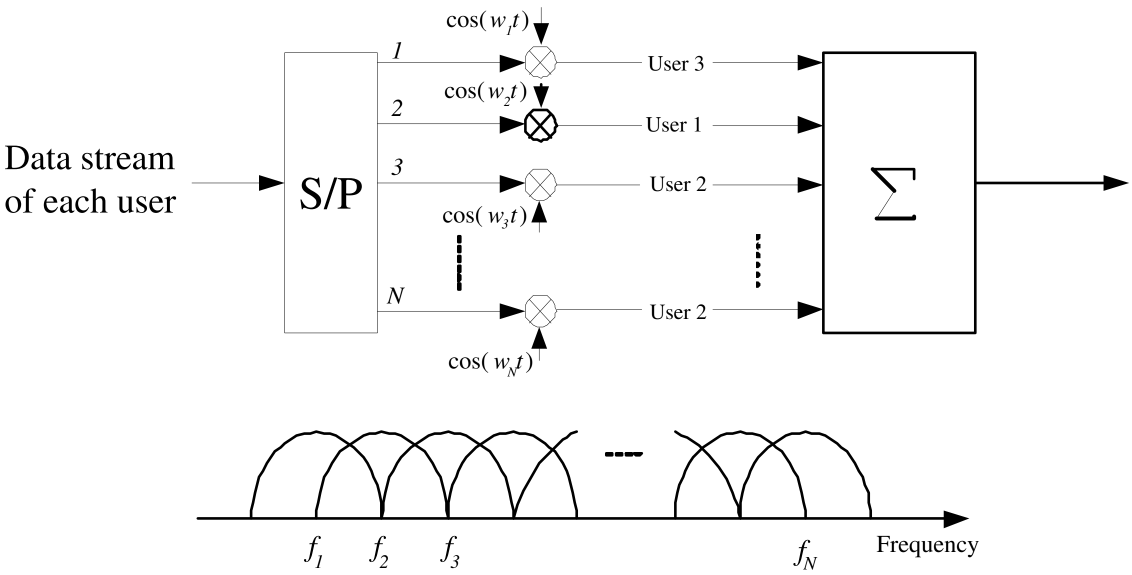


Figure 3.5: Block diagram of the transmitter of multiuser OFDM Interleaved-FDMA system.

can be represented as

$$h(t, \tau) = r(t)\delta(\tau) \tag{3.2}$$

where $r(t)$ is a wide-sense stationary stochastic process with zero mean and unit variance. For the classical Jakes' Doppler spectrum [87], the spectral density of $r(t)$ is

$$P_J(f) = \begin{cases} \frac{1}{\pi f_d} \frac{1}{\sqrt{1-\left(\frac{f}{f_d}\right)^2}}, & \text{if } |f| < f_d; \\ 0, & \text{Otherwise.} \end{cases} \tag{3.3}$$

where f_d is the maximum Doppler frequency. The Jakes' model popularizes the Doppler spectrum associated with Rayleigh fading, and, as a result, this Doppler spectrum is often termed Jakes' spectrum. Due to the frequency offset, the inter-carrier interference (ICI) from other subcarriers is caused by the loss of orthogonality between the subchannels. At the output of the IFFT process, we add a cyclic prefix to protect the OFDM symbols from inter-symbol interference (ISI) due to multipath spreads and against timing-offset efforts at the receiver. Then ISI can be mitigated.

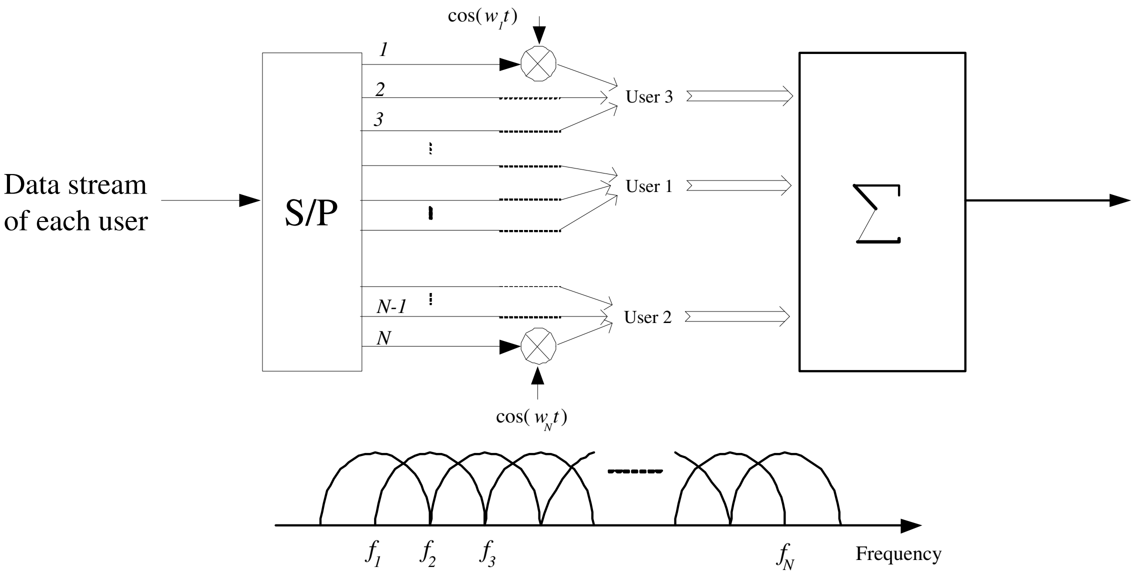


Figure 3.6: Block diagram of the transmitter of multiuser OFDM Group-FDMA system.

At the receivers of OFDM Interleaved-FDMA and OFDM Group-FDMA systems, the demodulated signal of user i on the n_1th subcarrier in one symbol duration is [88]

$$\begin{aligned}\tilde{y}_i[n_1] &= \frac{1}{T}\int_0^T r(t)\sum_n s_i[n]e^{j2\pi f_n t}e^{-j2\pi f_{n_1} t}dt + \eta \\ &= \sum_n \left[\frac{1}{T}\int_0^T r(t)e^{-j2\pi(f_{n_1}-f_n)t}dt\right] s_i[n] \\ &= a_0 s_i[n_1] + \sum_{n\neq n_1} a_{n_1-n}s_i[n] + \eta, \qquad (3.4)\end{aligned}$$

where η is an independent Gaussian random variable with variance equal to σ^2, a_0 represents the attenuation and phase shift of the desired signal and the a_l represents the channel gain of the interfering signal for $l \neq 0$,

$$a_l = \frac{1}{T}\int_0^T r(t)e^{-j2\pi l\Delta f t}dt. \qquad (3.5)$$

If $a_l \neq 0$ with any time variation in the channel, the ICI occurs, as shown by the second term in the right-hand side of (3.4). The ICI power is defined as [88]

$$P_{i,ICI} = E\left|\sum_{l\neq 0} a_l s_i[n_1 - l]\right|^2. \tag{3.6}$$

In the OFDM/CDMA system, since users will share subcarriers to transmit signals and the spreading codes are used to distinguish each user at the receiver, the cross-correlation would give rise to the interference between users on the same subbands, called as multiple access interference (MAI). The cross-correlation of the spreading codes $\rho_{k,i}$ between the spreading codes $G^i(t)$ and $G^k(t)$, as shown in Fig. 3.1, is described in (3.7). It contributes the interference between users i and k on each subcarrier,

$$\rho_{k,i}(\tau_k) = \frac{1}{T_s}\int_0^{T_s} G^i(t)G^k(t-\tau_k)dt \tag{3.7}$$

where τ_k is the variation of the time shift for user k and T_s is the length of the spreading code. Fig. 3.7(a) shows the autocorrelation of Gold sequence of length 31. The cross-correlation between the spreading codes of different users with various delays τ_k is given in Fig. 3.7(b). So in the multiuser OFDM/CDMA system, the demodulated signal of the ith user on the n_1th subcarrier in one symbol duration is

$$\begin{aligned}
\tilde{z}_i[n_1] &= \frac{1}{T}\int_0^T r(t)\sum_n s_i[n]e^{j2\pi f_n t}e^{-j2\pi f_{n_1} t}dt \\
&\quad + \frac{1}{T}\int_0^T r(t)\sum_{k\neq i} s_k[n_1]e^{-j2\pi f_{n_1} t}\cdot \rho_{k,i}dt + \eta \\
&= a_0 s_i[n_1] + \sum_{n\neq n_1} a_{n_1-n}s_i[n] + \sum_{k\neq i}\hat{a}_{n_1}s_k[n_1]\rho_{k,i} + \eta,
\end{aligned} \tag{3.8}$$

where

$$\hat{a}_n = \frac{1}{T}\int_0^T r(t)e^{-j2\pi f_n t}dt. \tag{3.9}$$

The OFDM/CDMA system suffers from the ICI and MAI simultaneously compared with the OFDM Interleaved-FDMA and OFDM Group-FDMA systems. The MAI power due to sharing the n_1th subcarrier by other users is defined as

$$P_{i,MAI} = E\left|\sum_{k\neq i} \hat{a}_{n_1} s_k[n_1]\rho_{k,i}\right|^2. \tag{3.10}$$

3.4 Data rate analysis for OFDM-related schemes

In [11], it has been shown that OFDM-TDMA has the very similar performance to the traditional OFDM Interleaved-FDMA and outperforms OFDM-FDMA in terms of some aspects, such as average SNR versus root mean square(RMS) delay spread and number of users, BER versus average SNR, and the outage probability versus the distance from transmitter. Therefore, OFDM-TDMA and OFDM-FDMA would be not analyzed here.

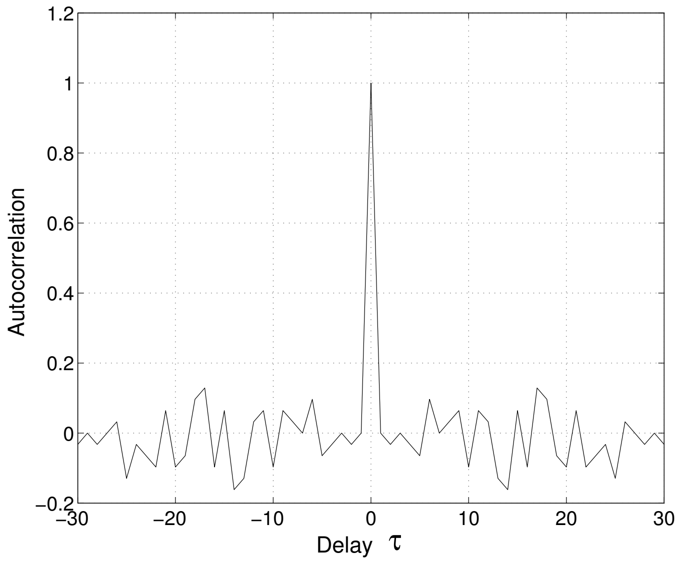
We assume a slowly-varying flat-fading Rayleigh channel at a rate slower than the symbol rate, so that the channel remains roughly constant over each symbol duration. The Rayleigh fading amplitude α follows the probability density function (pdf) [89]

$$f(\alpha) = \frac{2\alpha}{\Omega} e^{-\alpha^2/\Omega}, \quad \alpha > 0 \tag{3.11}$$

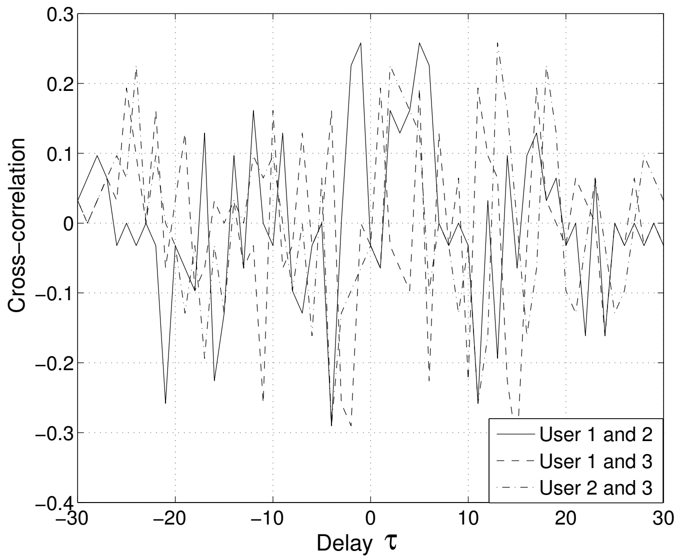
where $\Omega = E\{\alpha^2\}$ is the average fading power.

On the nth subcarrier of user i, the BER expression for the MQAM signal with Gray bit mapping in additive white Gaussian noise (AWGN) is approximately a function of received signal-to-noise ratio (SNR) and constellation size $M = 2^{c_{i,n}}$ expressed as [90, 91]:

$$BER \approx \frac{2}{c_{i,n}}\left(1 - \frac{1}{\sqrt{2^{c_{i,n}}}}\right) \times \operatorname{erfc}\left(\sqrt{1.5\,\frac{\gamma_{i,n}}{2^{c_{i,n}} - 1}}\right) \tag{3.12}$$



(a) Autocorrelation.



(b) Cross-correlation.

Figure 3.7: Autocorrelation of Gold sequence and Cross-correlation between Gold sequences for three users (Length = 31).

where $c_{i,n}$ is the number of loaded bits on the nth subcarrier for user i. The approximation in (3.12) is the tightest with high SNRs. Because the above expression is not easily differentiable or invertible with $c_{i,n}$, assuming that QAM modulation and ideal phase detection are used as in [92], the BER for the nth subcarrier signal of the kth user is bounded by [92]

$$BER \leq \frac{1}{5}\exp\left(\frac{-1.5\gamma_{i,n}}{2^{c_{i,n}}-1}\right), \tag{3.13}$$

Note that the BER bound in (3.13) is valid for $c_{i,n} \geq 2$ and $0 \leq \gamma_{i,n} \leq 30$ dB. For a given BER, (3.13) can be rearranged into the number of bits to be transmitted on the ith user's nth subcarrier

$$c_{i,n} \quad = \quad \log_2\left(1+\frac{\gamma_{i,n}}{\Gamma_i}\right), \qquad n = 1, 2, \cdots, N; \;\; i = 1, 2, \cdots, K, \tag{3.14}$$

where $\Gamma_i = -\ln(5BER_i)/1.5$. Note that Γ_i, which is a function of the required BER, has a positive value larger than 1 in the range of BER $< (1/5)\exp(-1.5) \approx 0.0446$.

The transmission data rates supported by the three types of OFDM systems will be analyzed mathematically in the following parts.

3.4.1 Data rate in the multiuser OFDM/CDMA system

For the multiuser OFDM/CDMA system with K users and N subcarriers, $\alpha_{k,n}$ represents the fading for the nth subcarrier between the base station and the kth user. In OFDM systems, since the total bandwidth B is equally divided into N orthogonal subbands and the subband signals are transmitted in parallel, the bandwidth of the subcarrier signal becomes $B_n = B/N$ for all n and, therefore, the noise variance σ^2 is $N_0B_n = N_0B/N$, where N_0 is the noise power spectral density.

$\tilde{P}_{i,n}$ is assumed to represent the received power of the ith user's nth subcarrier, and the received signal-to-noise ratio (SNR) for the nth subcarrier of user i can be written as

$$\begin{aligned}\gamma_{i,n} &= \frac{\tilde{P}_{i,n}}{\sigma^2 + P_{i,ICI} + P_{i,MAI}} \\ &= \frac{E\left|a_0 s_i[n]\right|^2}{\sigma^2 + E\left|\sum_{l\neq 0} a_l s_i[n-l]\right|^2 + E\left|\sum_{k\neq i} \hat{a}_{n_1} s_k[n]\rho_{k,i}\right|^2}.\end{aligned} \tag{3.15}$$

The interference term between users in the denominator of (3.15) arises from sharing a subcarrier by multiple users. $\gamma_{m,i,n}$ represents the $\gamma_{i,n}$ in the mth symbol duration, and in the multiuser OFDM/CDMA system, the ith user's data rate will be calculated during M-symbol period in the multiuser OFDM/CDMA system, which is represented by

$$\begin{aligned}R_i &= \sum_{m=1}^{M}\sum_{n=1}^{N} c_{i,n} \\ &= \sum_{m=1}^{M}\sum_{n=1}^{N} \log_2\left(1+\frac{\gamma_{m,i,n}}{\Gamma_i}\right) \\ &= \sum_{m=1}^{M}\sum_{n=1}^{N} \log_2 \\ &\quad \left[1 + \frac{1}{\Gamma_i}\cdot\frac{E\left|a_0 s_{m,i}[n]\right|^2}{\frac{N_0 B}{N} + E\left|\sum_{l\neq 0} a_l s_{m,i}[n-l]\right|^2 + E\left|\sum_{k\neq i}\hat{a}_{n_1} s_{m,k}[n]\rho_{k,i}\right|^2}\right].\end{aligned} \tag{3.16}$$

3.4.2 Date rate in the multiuser OFDM Interleaved-FDMA system

According to the same data requirements for users in the OFDM/CDMA and OFDM Interleaved-FDMA systems, the signals to be transmitted on each subcarrier are different between the two OFDM systems. And $s_i'[n]$ represents the signal on the nth subcarrier of user i in the OFDM Interleaved-FDMA system.

The OFDM Interleaved-FDMA system does not allow more than one user to use one subcarrier and the received SNR for the ith user's nth subcarrier signal in the OFDM Interleaved-FDMA system should be

$$\begin{aligned}\gamma'_{i,n} &= \frac{\tilde{P}'_{i,n}}{\sigma^2 + P'_{i,ICI}} \\ &= \frac{E\left|a_0 s'_i[n]\right|^2}{\frac{N_0 B}{N} + E\left|\sum_{l\neq 0} a_l s'_i[n-l]\right|^2}. \end{aligned} \tag{3.17}$$

Since only the subcarrier with the best quality seen by the user will be assigned, we set $p_{m,i,n}$ to be "1" when the nth subcarrier is selected by the ith user during the mth OFDM symbol period and "0" when it is not selected.

$$p_{m,i,n} = \begin{cases} 1, & \text{the } n\text{th subcarrier is selected by the } i\text{th user;} \\ 0, & \text{the } n\text{th subcarrier is not selected by the } i\text{th user,} \end{cases} \tag{3.18}$$

with the condition of

$$\sum_{i=1}^{K}\sum_{n=1}^{N} p_{m,i,n} = N. \tag{3.19}$$

Accordingly, the ith user's data rate obtained by OFDM Interleaved-FDMA during M-symbol period should be

$$\begin{aligned}R'_i &= \sum_{m=1}^{M}\sum_{n=1}^{N} p_{m,i,n}\cdot c_{m,i,n} \\ &= \sum_{m=1}^{M}\sum_{n=1}^{N} p_{m,i,n}\cdot \log_2\left(1+\frac{\gamma'_{m,i,n}}{\Gamma_i}\right) \\ &= \sum_{m=1}^{M}\sum_{n=1}^{N} p_{m,i,n} \\ &\quad \cdot \log_2\left[1+\frac{1}{\Gamma_i}\cdot\frac{E\left|a_0 s'_{m,i}[n]\right|^2}{\frac{N_0 B}{N} + E\left|\sum_{l\neq 0} a_l s'_{m,i}[n-l]\right|^2}\right]. \end{aligned} \tag{3.20}$$

3.4.3 Data rate in the multiuser OFDM Group-FDMA system

In the OFDM Group-FDMA system, the total subcarriers are divided into some groups, and one subchannel group with highest average SNR for one user, will be assigned to this user. It is assumed that the total channel has Y subcarrier groups, each group consists of X subcarriers and $s''_i[n]$ represents the signal transmitted on the nth subcarrier of user i in this system. The data rate is dependent with the average SNR within the yth group, which is

$$\begin{aligned} \gamma''_{i,y} &= \frac{\sum_{n=1}^{X_y} \tilde{P}''_{i,n}}{X\sigma^2 + P''_{i,ICI}} \\ &= \frac{\sum_{n=1}^{X_y} E\left|a_0 s''_i[n]\right|^2}{\frac{X\,N_0 B}{N} + \sum_{n=1}^{X_y} E\left|\sum_{l\neq 0} a_l s''_i[n-l]\right|^2} \end{aligned} \tag{3.21}$$

where X_y represents the number of subcarriers in group y. Since only the subcarrier group with the highest average channel SNR seen by the user will be assigned, we set $p_{m,i,y}$ to be "1" when the yth subcarrier group is selected by the ith user during the mth OFDM symbol period and "0" when it is not selected.

$$p_{m,i,y} = \begin{cases} 1, & \text{the } y\text{th subcarrier group is selected by the } i\text{th user;} \\ 0, & \text{the } y\text{th subcarrier group is not selected by the } i\text{th user.} \end{cases} \tag{3.22}$$

with the condition of

$$\sum_{i=1}^{K} \sum_{y=1}^{Y} X \cdot p_{m,i,y} = N. \tag{3.23}$$

Then the data rate of the ith user in the multiuser OFDM Group-FDMA system during M-symbol period is

$$R''_i = \sum_{m=1}^{M} \sum_{y=1}^{Y} p_{m,i,y} \cdot \sum_{n=1}^{X_y} c_{m,i,n}$$

$$
\begin{aligned}
&= \sum_{m=1}^{M}\sum_{y=1}^{Y} X \cdot p_{m,i,y} \cdot \left[\log_2\left(1+\frac{\gamma''_{m,i,y}}{\Gamma_i}\right)\right] \\
&= \sum_{m=1}^{M}\sum_{y=1}^{Y} X \cdot p_{m,i,y} \\
&\quad \cdot \log_2\left[1+\frac{1}{\Gamma_i}\cdot\frac{\sum_{n=1}^{X_y} E\left|a_0 s''_{m,i}[n]\right|^2}{\frac{X\,N_0 B}{N}+\sum_{n=1}^{X_y} E\left|\sum_{l\neq 0} a_l s''_{m,i}[n-l]\right|^2}\right]. \qquad (3.24)
\end{aligned}
$$

3.4.4 Comparison on data rates

In [8], given the total transmission power of the whole system, the data rates on a subcarrier of the OFDM/CDMA and OFDM Interleaved-FDMA systems are compared under the condition of the same transmission power assigned on a subcarrier. It shows that the total data rate of the multiuser OFDM Interleaved-FDMA system is higher than that in the OFDM/CDMA system only when the subcarrier is assigned to only one user who has the best channel gain for that subcarrier. However, if it is considered that each user has its own requirements of data rates and transmission power, the data rates and transmission power allocated on a subcarrier will be decided based on each user's requirements in different OFDM systems. This is not considered sufficiently in the algorithm proposed in [8].

Appendix A gives the comparison of the number of loaded bits on a subcarrier between the OFDM/CDMA and OFDM Interleaved-FDMA systems with K users. If each user's data rate, BER and transmission power requirements are considered, the transmission power allocated on a subcarrier will be decided based on these requirements. According to Appendix A, we can know that the OFDM Interleaved-FDMA cannot achieve higher data rates on a subcarrier if the transmission power on this subcarrier is allocated less than a threshold. However, although more transmission power is allocated and then more bits can be carried on this subcarrier, less transmission power would be left for other subcarriers. In addition, it is possible that some users in deep fading are not assigned any subcarrier and fail to meet their data rate requirements if all subcarriers have not the best channel gain for these users or all subcarriers have already been occupied by other users to meet their data rate requirements. Or, these users can only be assigned very few subcarriers. Besides, some users would have the same subchannels with the best channel gains, and their priorities to be allocated subcarriers are not considered. Possibly, the sequences of allocating subcarriers to different users will lead to greatly negative effects to the performance of those users whose subcarriers are assigned later.

Therefore, in order to satisfy the data rate requirement of each user, we will not pursue the data rate maximization of the whole system. The data rate requirement of each user will try to be guaranteed. During the performance comparisons between these three OFDM systems in this chapter, the data rate requirement is considered. We set a lower limit of the data rate for each user, R_s, according to the different numbers of subcarriers, as the lowest data rate requirement. The outage of the user with $R_i < R_s$ in the OFDM/CDMA system will be declared. In the OFDM Interleaved-FDMA or OFDM Group-FDMA system, if user i has the data rate with $R_i < R_s$, Table. 3.1 will be performed to improve its data rate at the cost of other users' data rates. From the subcarriers of user j having the highest data rate, we can find the subcarrier with the maximum channel gain seen by user i. Then an appropriate number of bits are loaded according to (3.14). The iteration will be processed until $R_i = R_s$. Meanwhile, we should guarantee $R_j > R_s$. It is noted that the loops will also be stopped when the ith user's transmission power, P_i, becomes more than the power limitation, P_T, $R_i \geq R_s$, or $R_j \leq R_s$. The procedure prevents that overfull subcarriers are occupied by some users and inadequate subcarriers remain for other users to support their requirements. Clearly, in the OFDM Interleaved-FDMA and OFDM Group-FDMA systems, the lowest data rate requirement, set for each user, limits the data rates of some other users by reducing some subcarriers with high channel gains. The outage of user i with $R_i < R_s$, will be declared after Table. 3.1 is performed.

Table 3.1: Adjustment of the number of loaded bits for user i if $R_i < R_s$

```
Loops begin:

/* Find the user having the highest data rate */
j = arg max_k R_k,    (k ≠ i and R_k > R_s);

/* Find the subcarrier with the maximum α_{i,n} in the jth user's subcarriers {n_j} */
n' = arg max_{n_j} α_{i,n};

/* Bit allocation on subcarrier n' for user i */
c_{i,n'} = log_2(1 + γ_{i,n'}/Γ_i);

If (P_i ≥ P_T || R_i ≥ R_s || R_j ≤ R_s)
    Break;
else
    Continue;

Loops End.
```

According to (3.16), (3.20) and (3.24), the expressions of the ith user's data rates of the mth OFDM symbol in the OFDM/CDMA, OFDM Interleaved-FDMA and OFDM Group-FDMA systems, respectively, are

$$R_{m,i} = \sum_{n=1}^{N} \log_2\left(1 + \frac{\gamma_{m,i,n}}{\Gamma_i}\right), \tag{3.25}$$

$$R'_{m,i} = \sum_{n=1}^{N} p_{m,i,n} \cdot \log_2\left(1 + \frac{\gamma'_{m,i,n}}{\Gamma_i}\right), \tag{3.26}$$

and

$$R''_{m,i} = \sum_{y=1}^{Y} X \cdot p_{m,i,y} \cdot \log_2\left(1 + \frac{\gamma''_{m,i,y}}{\Gamma_i}\right). \tag{3.27}$$

Therefore, the difference, $\Delta R'_{m,i}$, between $R_{m,i}$ and $R'_{m,i}$ is

$$\begin{aligned} \Delta R'_{m,i} &= R_{m,i} - R'_{m,i} \\ &= \sum_{n=1}^{N} \log_2 \frac{\Gamma_i + \gamma_{m,i,n}}{\Gamma_i} - \sum_{n=1}^{N} \left(p_{m,i,n} \cdot \log_2 \frac{\Gamma_i + \gamma'_{m,i,n}}{\Gamma_i} \right). \end{aligned} \tag{3.28}$$

And the difference, $\Delta R''_{m,i}$, between $R_{m,i}$ and $R''_{m,i}$ is

$$\begin{aligned} \Delta R''_{m,i} &= R_{m,i} - R''_{m,i} \\ &= \sum_{n=1}^{N} \log_2 \frac{\Gamma_i + \gamma_{m,i,n}}{\Gamma_i} - \sum_{y=1}^{Y} X \cdot p_{m,i,y} \cdot \log_2 \frac{\Gamma_i + \gamma''_{m,i,y}}{\Gamma_i} \end{aligned} \tag{3.29}$$

For the analysis of $\Delta R'_{m,i}$, it is assumed that the average channel SNRs for the ith user are $\bar{\gamma}_{m,i}$ and $\bar{\gamma'}_{m,i}$ for the OFDM/CDMA and OFDM Interleaved-FDMA systems respectively during the mth symbol period. Accordingly, we get

$$\sum_{n=1}^{N} \log_2 \frac{\Gamma_i + \gamma_{m,i,n}}{\Gamma_i} = N \cdot \log_2 \frac{\Gamma_i + \bar{\gamma}_{m,i}}{\Gamma_i}, \tag{3.30}$$

and

$$\sum_{n=1}^{N} \left(p_{m,i,n} \cdot \log_2 \frac{\Gamma_i + \gamma'_{m,i,n}}{\Gamma_i} \right) = \left(\sum_{n=1}^{N} \hat{p}_{m,i,n} \right) \cdot \log_2 \frac{\Gamma_i + \bar{\gamma'}_{m,i}}{\Gamma_i}, \tag{3.31}$$

where $\hat{p}_{m,i,n} \in [0, 1]$ represents the probability that the ith user choose the nth subcarrier in the mth OFDM symbol duration of the OFDM Interleaved-FDMA system, with the condition of

$$\sum_{n=1}^{N} \hat{p}_{m,i,n} = \sum_{n=1}^{N} p_{m,i,n}. \tag{3.32}$$

So, referring to (3.28),

$$\Delta R'_{m,i} = N \cdot \log_2 \frac{\Gamma_i + \bar{\gamma}_i}{\Gamma_i} - \left(\sum_{n=1}^{N} \hat{p}_{m,i,n} \right) \cdot \log_2 \frac{\Gamma_i + \bar{\gamma'}_i}{\Gamma_i} \tag{3.33}$$

is obtained. In terms of $\Delta R'_{m,i}$ in (3.33), we can define,

$$U'_{m,i} = \sum_{n=1}^{N} \hat{p}_{m,i,n} - \frac{\log_2(\Gamma_i + \bar{\gamma}_{m,i}) - \log_2 \Gamma_i}{\log_2(\Gamma_i + \bar{\gamma}'_{m,i}) - \log_2 \Gamma_i} \cdot N \,. \tag{3.34}$$

In the OFDM Interleaved-FDMA system, based on (3.34) and the whole channel information for users, $U'_{m,i}$ will increase with the number of subcarriers assigned to the user, $\sum_{n=1}^{N} \hat{p}_{m,i,n}$. Possibly $U'_{m,i} \geq 0$ can be obtained and $\Delta R'_{m,i}$ will be negative for a particular user i when many subcarriers are assigned to user i. However, the improvement of the ith user's performance will lead to the reduction of the number of subcarriers, $\sum_{n=1}^{N} \hat{p}_{m,k,n}$, $(k \neq i)$, to be assigned to other users, and the lowest data rate requirement, R_s, will not be satisfied for other users. Especially if user i has the highest priority to occupy the subcarriers, all other users with their own requirements of data rates will be affected greatly, such as $\Delta R'_{m,k} < 0$, $(k \neq i)$. Besides, if more new users are required in the OFDM Interleaved-FDMA system, $\sum_{n=1}^{N} \hat{p}_{m,k,n}$ will decrease further based on the limited number of total subcarriers, N. Whereas, the users in the OFDM/CDMA system can always be allocated to all subcarriers for the data transmission regardless of the users' priorities.

Similarly, referring to (3.34), for the analysis of $\Delta R''_{m,i}$, $U''_{m,i}$ can be defined as

$$U''_{m,i} = X \cdot \sum_{y=1}^{Y} \hat{p}_{m,i,y} - \frac{\log_2(\Gamma_i + \bar{\gamma}_{m,i}) - \log_2 \Gamma_i}{\log_2(\Gamma_i + \bar{\gamma}''_{m,i}) - \log_2 \Gamma_i} \cdot N, \tag{3.35}$$

where $\bar{\gamma}''_{m,i}$ is the average channel SNR for the ith user during the mth symbol period in the OFDM Group-FDMA system and $\hat{p}_{m,i,y} \in [0,1]$ is the probability that the ith user chooses the yth subcarrier group with

$$\sum_{y=1}^{Y} \hat{p}_{m,i,y} = \sum_{y=1}^{Y} p_{m,i,y} \,. \tag{3.36}$$

Since the subcarrier group allocation scheme in the OFDM Group-FDMA system is similar to that in the OFDM Interleaved-FDMA system, the OFDM Group-FDMA system is also facing the problems mentioned above. Additionally, the OFDM Group-FDMA system has lower utilization efficiency of frequency diversity for each user, but it is less complicated than the OFDM Interleaved-FDMA system.

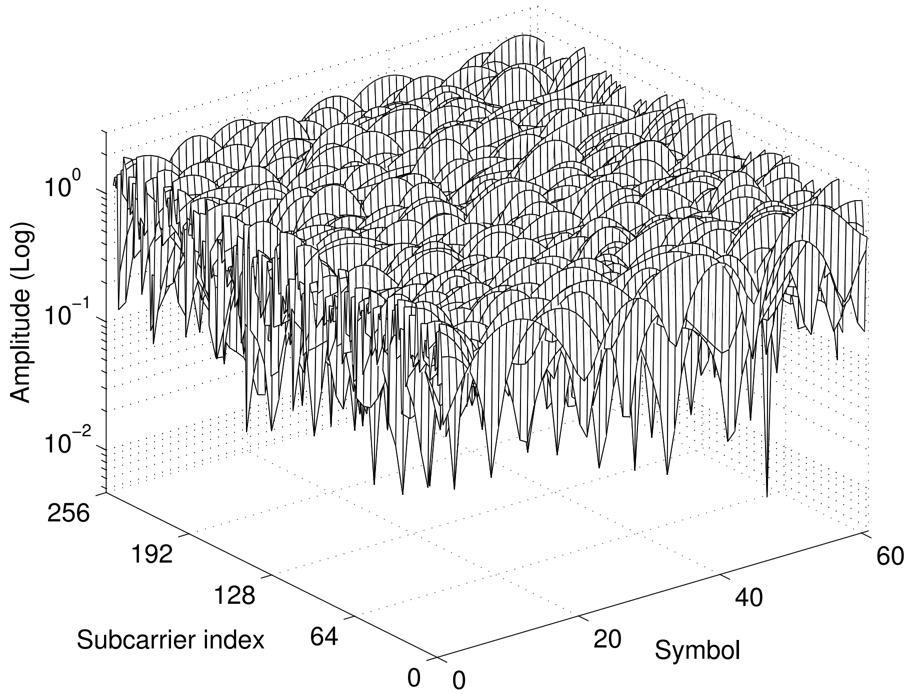
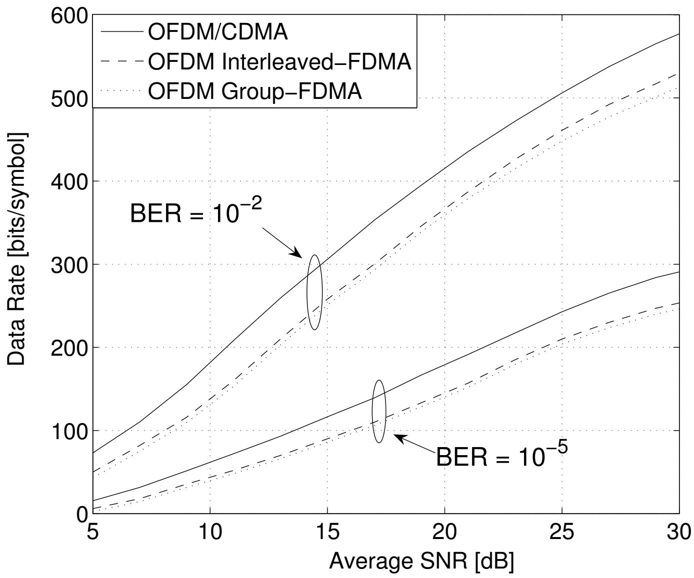


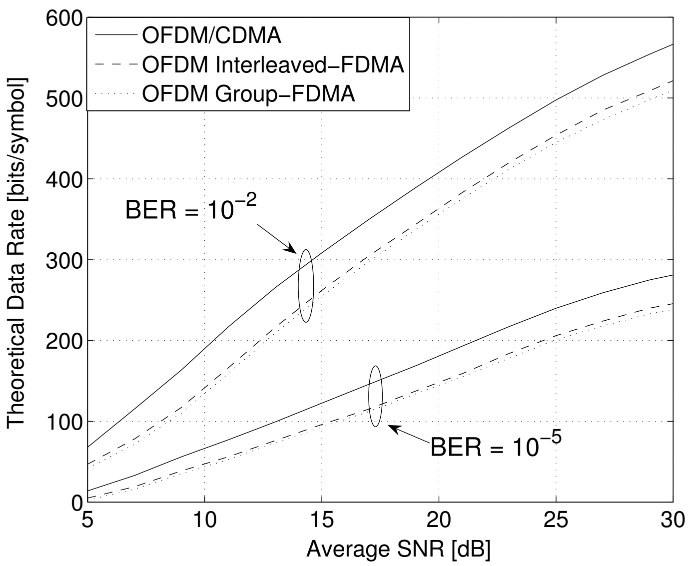
Figure 3.8: The channel amplitudes of subcarriers of user i in different symbol periods.

3.5 Performance analysis

To ensure a fair comparison of these OFDM schemes, we use the optimal bit allocation (OBA) [11] for each user on the assigned subcarriers. Based on the mathematical analysis on the data rates of these subcarrier allocation schemes for multiuser systems, the simulation results will be shown in this section. Fig. 3.8 shows the channel model, which has $N = 256$ subcarriers during $M = 60$ symbols. In each symbol period, 256 subcarriers have different channel amplitudes because of the frequency selective fading. However, when the whole bandwidth is divided into 256 narrow subbands, each subband follows the flat fading. The channel fading obeys a Rayleigh distribution of a maximum Doppler frequency of $f_d = 111$ Hz in a wireless system with the carrier frequency of 2.4 GHz and a vehicular velocity of 50 km/h. Each user's data is sent by the transmitter of



(a) Simulated data rates.



(b) Theoretical data rates.

Figure 3.9: The comparison of the average data rates in the OFDM/CDMA, OFDM Interleaved-FDMA and OFDM Group-FDMA systems at different average SNRs when the data services with BER = 10^{-2} and BER = 10^{-5} are transmitted in the three-user system with 256 subcarriers (R_s = 20 bits/symbol).

the OFDM system set up with these configurations, and the transmitted signals can be demodulated at the receiver. Since the summation of each user's data rate during M symbols period is too large, the average data rate calculated for each user during one symbol period would be the parameter as the performance comparison between these schemes. In the multiuser OFDM system, each user has its own data rate, BER and transmission power requirements. And the lower limit of each user's data rate is set as $R_s = 20$ bits/symbol. The transmission power of each user, i.e., 23 dBm [1], is applied as a threshold, which takes account of limiting the transmission power of each user as well as the power interference to other users. The performance is analyzed for each user's data rate, instead of the total data rates of the whole system. It is assumed that a three-user system is considered, Gold-Codes (Length = 31) are used as spreading codes in the OFDM/CDMA scheme and each group has 4 subcarriers ($X = 4$) for the OFDM Group-FDMA scheme. In terms of the system model and the analysis of data rates in the three systems, the following results show that OFDM/CDMA scheme can obtain better performance in supporting higher data rates and system capacity.

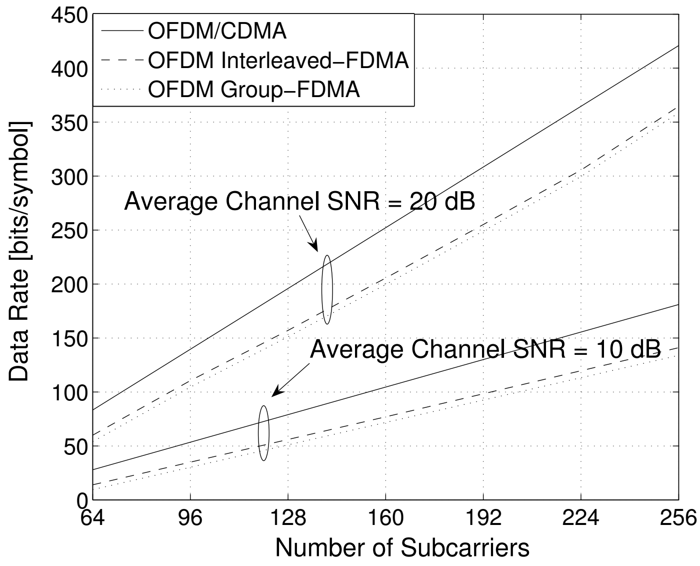
With $R_s = 20$ bits/symbol, Fig. 3.9(a) and (b) give us the comparison of data rates obtained from a three-user system with BER $= 10^{-2}$ and BER $= 10^{-5}$ based on simulations and theoretical analysis. If the required BER is 10^{-2}, the OFDM/CDMA scheme can get nearly $25 \sim 50$ bits/symbol more than the other two schemes when the average SNR varies from 5 to 30 dB. When the data service is transmitted with the required BER of 10^{-5}, the user can get 175 bits/symbol with the subcarrier allocation of OFDM/CDMA scheme, while the other two only can get around 140 bits/symbol at the average SNR of 20 dB. Therefore, for the multiuser transmission with different BER requirements, OFDM/CDMA outperforms the other two schemes in supporting higher data rates. For the OFDM Interleaved-FDMA and OFDM Group-FDMA, though the data rate is lower by the latter than the former, such a little difference can be tolerant because the OFDM Group-FDMA scheme

[1] In the absence of any justification, the transmission power would be 200 mW ($10 \lg 200 = 23$ dBm), the maximum level for many CDMA mobile handsets.

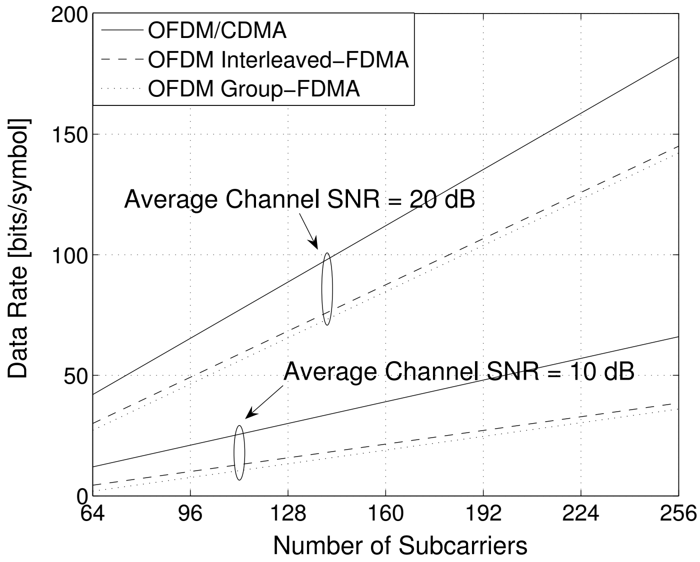
has less complexity and less process time.

In the OFDM systems with different numbers of subcarriers, Fig. 3.10(a) and (b) give the the rates in the three systems with the conditions of BER = 10^{-2} and BER = 10^{-5}. When the average SNR is 10 dB and BER is 10^{-2}, the OFDM/CDMA scheme can get 55 bits/symbol, while OFDM Interleaved-FDMA and OFDM Group-FDMA can get 35 and 30 bits/symbol in the 96-subcarrier system. For the 160-subcarrier system with the average SNR = 20 dB, the data rate of 253 bits/symbol is supported by the OFDM/CDMA system, and the other two can get around 205 bits/symbol. When the required BER is 10^{-5}, it is certain that this condition will support lower data rates than that with BER = 10^{-2}, as shown in Fig. 3.10(b). When the OFDM system has 96 subcarriers, OFDM/CDMA can support only 27 bits/symbol if the average SNR is 10 dB. And this value of the data rate is around and below 10 for the user in the OFDM Interleaved-FDMA and OFDM Group-FDMA systems. When the average SNR is 20 dB in an 160-subcarrier system, the OFDM/CDMA scheme can support 112 bits/symbol, OFDM Interleaved-FDMA and OFDM Group-FDMA get nearly 87 bits/symbol.

In terms of the difference of the data rates, $\Delta R'_{m,i}$ and $\Delta R''_{m,i}$ will increase with the number of users in the OFDM system based on the limited number of subcarriers. As shown in Fig. 3.11(a) with BER = 10^{-2} and the average SNR of 20 dB, the differences between OFDM/CDMA, OFDM Interleaved-FDMA and OFDM Group-FDMA, $\Delta R'_{m,i}$ and $\Delta R''_{m,i}$, reach nearly 70 bits/symbol when the OFDM systems are supporting ten users with 256 subcarriers. For a required data rate of 350 bits/symbol at the average SNR of 20 dB, one more user can be supported by the OFDM/CDMA system than the other two systems. In Fig. 3.11(b), at the average SNR of 10 dB, the data service with BER = 10^{-5} cannot be transmitted with very high rates in the systems with limited subcarriers since many subchannels in deep fading are discarded. It is difficult for the some users in the three OFDM systems to support the data service transmission with $R_s = 20$ bits/symbol if more than nine users are supported, especially for the OFDM Interleaved-FDMA and



(a) BER = 10^{-2}.



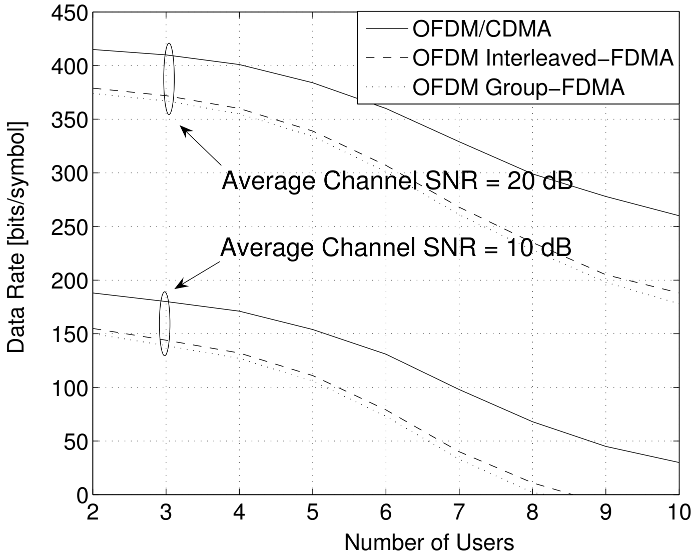
(b) BER = 10^{-5}.

Figure 3.10: The comparison of the average data rates obtained by OFDM/CDMA, OFDM Interleaved-FDMA and OFDM Group-FDMA with different numbers of subcarriers when the data service is transmitted at the average channel SNRs of 10 and 20 dB in the three-user system (R_s = 20 bits/symbol).

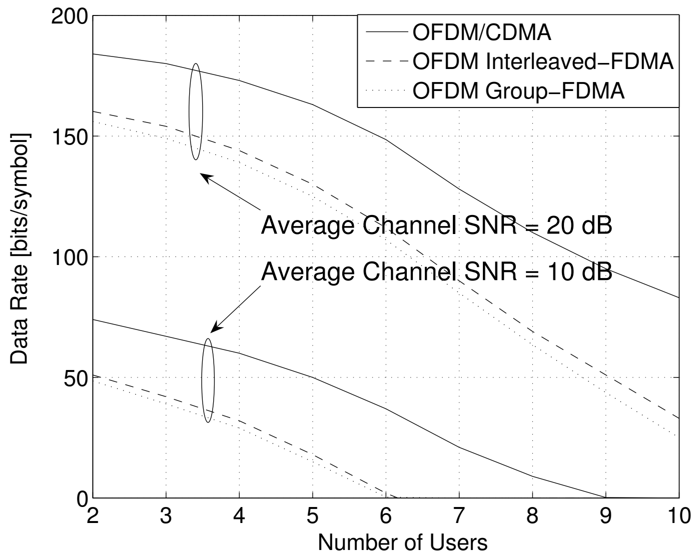
OFDM Group-FDMA systems. Since many subcarriers are in deep fading, only few subcarriers are assigned to each user with the limited number of subchannels, while eight users in the OFDM/CDMA system can still share all the available subcarriers to transmit data even when the whole channel does not have high channel gain.

3.6 Conclusion

In this chapter, five subcarrier allocation schemes for multiuser OFDM systems are described in detail and the performance of OFDM/CDMA, OFDM Interleaved-FDMA and OFDM Group-FDMA are analyzed. Based on the satisfaction of each user's data rate requirement, the results show that the OFDM/CDMA scheme outperforms OFDM Interleaved-FDMA and OFDM Group-FDMA on different situations, such as different average SNRs, BER requirements, numbers of subcarriers and users. OFDM/CDMA is more suitable and promising for the multimedia service in the multiuser systems with high data rates, lower BER requirements and high system capacity in the future.



(a) BER = 10^{-2}.



(b) BER = 10^{-5}.

Figure 3.11: The comparison of the average data rates obtained by OFDM/CDMA, OFDM Interleaved-FDMA and OFDM Group-FDMA with different numbers of users when the data service is transmitted at the average channel SNRs of 10 and 20 dB in the 256-subcarrier system.

Chapter 4

Adaptive bit allocation algorithms for multiuser OFDM/CDMA systems

An adaptive bit allocation algorithm is proposed for the multiuser transmission in OFDM/CDMA systems. The proposed scheme takes advantage of frequency diversity to dynamically allocate a suitable number of bits/per symbol on subcarriers of each user based on the objectives of the required transmission rate and BER. A suboptimal solution to the problem of the bit allocation on subcarriers for each user is derived by minimizing the interference power from each user. Then an algorithm for adjusting the number of allocated bits is used to further reduce the interference without changing the total transmitted data rate. The performance obtained by minimizing the interference resulting from each user is studied in terms of bit error rate, transmission data rate and the system capacity supporting multiple users. The theoretical analysis and simulation results show that the proposed algorithm substantially outperforms those reported previously.

4.1 Introduction

Intensive research interests have been in adaptive modulation techniques for broadband transmission over wireless channels to efficiently support multimedia services, Internet access and future generation mobile communications. One important issue is the ability to combat intersymbol interference (ISI) in wideband transmission over multipath fading channels. Multicarrier modulation technique, such as OFDM, appears to be a promising solution to this problem.

This chapter considers efficient multiuser transmission in multicarrier DS-CDMA (MC-DS-CDMA) systems [81]. The MC-DS-CDMA systems generally perform well and are efficiently used for quasi-synchronized channels [26]. It was reported that with the known instantaneous channel characteristics or transfer functions, the use of adaptive bit allocation algorithms could achieve significant performance improvements in terms of the transmission power, channel throughput and BER [6–13, 93–96]. In general, a higher order modulation scheme is used to load more bits per symbol on subcarriers with large channel gains or signal-to-noise ratios (SNRs) for higher transmission throughput and a low order modulation scheme is employed to allocate one or zero bit per symbol on the subcarriers with low channel gains. It is necessary to achieve a good compromise between the BER performance and system throughput. As the frequency fading deteriorates the SNRs of certain subcarriers and improves the SNRs of other subcarriers, the potential loss of transmission throughput due to the exclusion of deeply faded subcarriers can be mitigated by employing higher order modulation techniques on the subcarriers that have high SNRs.

Adaptive algorithms of bit and subcarrier allocation have been studied in several aspects. Some reported work focused on improving the network performance by maximizing the transmission data rates [6–9] or spectral efficiency [93, 94]. Adaptive resource allocation was investigated in [10] to achieve both multiuser diversity and fairness with maximum utilization. The minimization of total transmission power of a group of users in multiuser systems was attempted by using a multiuser adaptive OFDM scheme (MAO-OFDM) [11] or one user in single-user systems [13, 95, 96]. Though MAO-OFDM tried to minimize the total transmission power of all users in a cell, users cannot transmit data with the whole bandwidth, which substantially reduces the channel efficiency. In [12], constant throughput adaptive OFDM (CTAO-OFDM) selects a suitable modulation scheme for subcarriers on the basis of a cost function (see Equation (3) in [12]) with the expected BERs on each subcarrier. The two methods in [11] and [12] were found to be more suitable to single-service transmissions with the data rate and BER requirements in multiuser OFDM systems because fixed data rates and BER requirements could be satisfied. For multiuser systems, it is very important to minimize the interference power among different users because all users share all subcarriers with different spreading codes. The adaptive bit loading (or allocation) algorithm (ABLA-OFDM) proposed in this chapter deals with the minimization of the interference from each user in the cell. Our theoretical analysis and experimental simulations show that the minimization of the interference resulting from each user provides significant improvements on BER performance, data throughput and the number of users supported by the system. It is clear that there is a certain amount of transmission overhead as the base station (BS) has to inform users about the number of loaded bits assigned to each subcarrier and channel information of other users. However, this overhead can be relatively small, especially if the channels vary slowly (e.g., in an indoor low mobility environment), and the assignment is done once for every OFDM symbol. To further reduce the overhead, we can assign a contiguous band of subcarriers with similar fading characteristics as a group, instead of assigning each individual subcarrier [11].

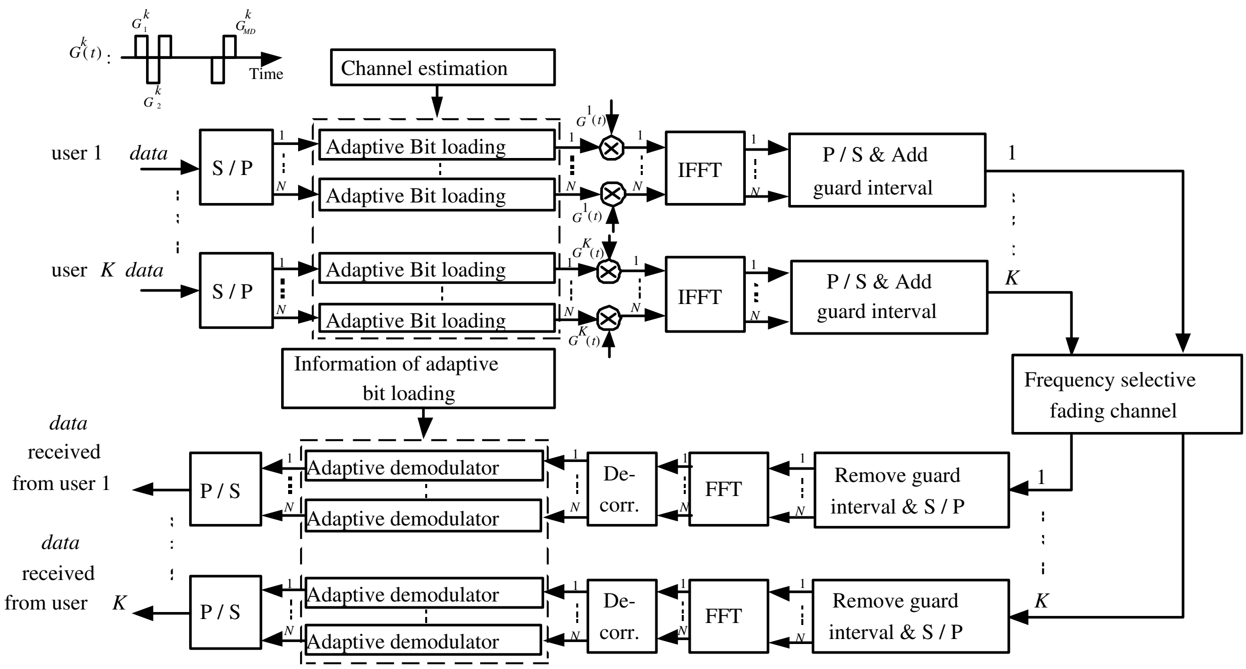


Figure 4.1: Block diagram of a multiuser adaptive OFDM/CDMA system.

4.2 Adaptive bit loading algorithm for single service transmission

4.2.1 Adaptive multiuser single-service system

The multiuser adaptive OFDM/CDMA system in a single cell with adaptive bit allocation facilities for the transmission is shown in Fig. 4.1. It is assumed that the cell has K users sharing N subcarriers with CDMA techniques. The kth user has a data rate R_k bits per OFDM symbol [1]. Spreading codes $\{G^k(t)\}$, such as Gold-Codes with a processing gain G_{MD} [86], are used to distinguish different users at the receiver (or base station). In this system, each subcarrier has a much smaller bandwidth than the coherence bandwidth of the channel. Sequential data of users are converted to be parallel and processed by the adaptive bit loading algorithm for each subcarrier. The modulation scheme is selected among BPSK, QPSK or

[1]In the rest of the thesis, "OFDM symbol" is simplified to be "symbol"

M-ary QAM which uses $c_{i,n}$ bits per symbol loaded on the nth subcarrier of the ith user. It is also assumed that the value of $c_{i,n}$ is in the set $D = \{0, 1, 2, \cdots, V\}$, where V is the maximum number of bits per symbol that can be transmitted by a subcarrier. After the data are encoded by their respective Gold-Codes, inverse fast Fourier transform (IFFT) is performed. The receiver performs the inverse processing, such as decorrelation and demodulation, to obtain the original signals. We will assume the instantaneous (or at least block based) subcarrier fading gains of the OFDM subcarriers in frequency selective fading channels are known and the channel gains are constant during the received time slot. The channel estimation on the basis of the received symbol can be performed by pilot symbol assisted modulation (PSAM) [97, 98].

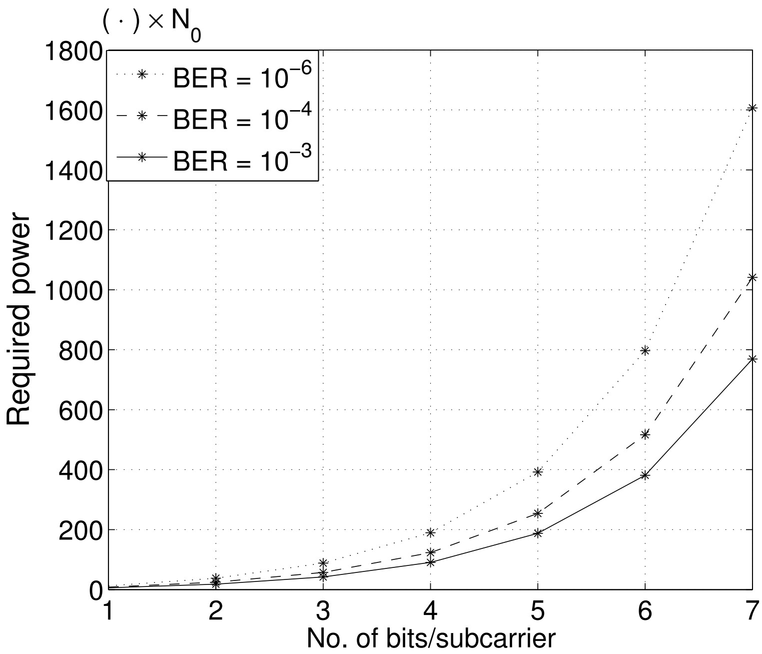
Let us define that $\alpha_{i,n}$ is a random variable representing the fading magnitude of the nth subchannel between the base station and the ith user, and $\tilde{P}_{i,n}(c_{i,n})$ is the required power function in terms of the energy per symbol for a subcarrier to reliably carry information at the rate of $c_{i,n}$ bits per symbol when the channel gain is equal to unity. It is noted that the power function depends on user index i and different users are allowed to achieve different quality-of-service (QoS) requirements with their own coding and modulation schemes. In order to maintain the required QoS at the receiver, the transmission power for the nth subcarrier of the ith user must be [11]

$$P_{i,n}(c_{i,n}) = \tilde{P}_{i,n}(c_{i,n})/\alpha_{i,n}^2, \tag{4.1}$$

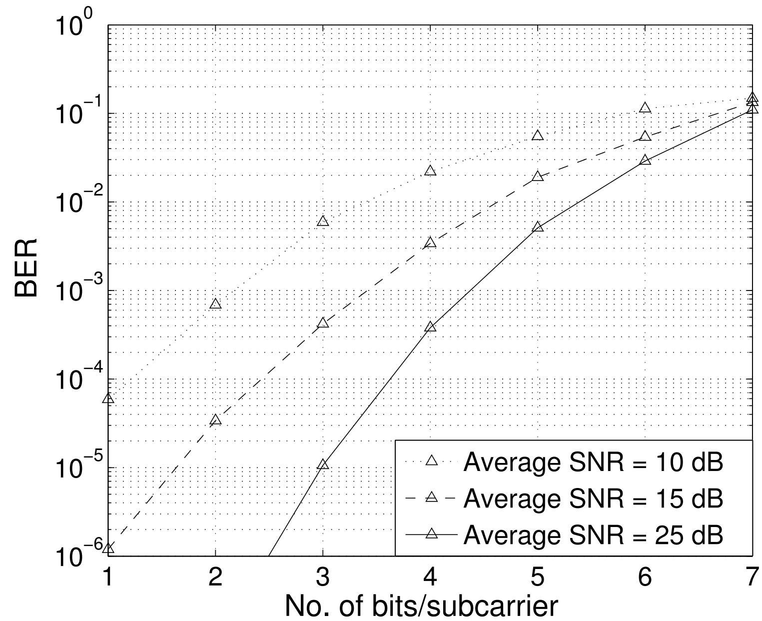
where $i = 1, 2, \cdots, K$, $n = 1, 2, \cdots, N$, and the received power at the receiver is [11]

$$\tilde{P}_{i,n}(c_{i,n}) = \frac{N_0}{3}\left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2 (2^{c_{i,n}} - 1), \tag{4.2}$$

where N_0 is the noise power spectral density (PSD), BER_i is the required bit error rate for the ith user and $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-t^2/2}dt$. The derivation of (4.2) is based on the approximate BER for M-ary QAM [30]. From (4.1) and (4.2),



(a) The required power with various BERs



(b) BER of a subcarrier with various loading conditions in a single-user system

Figure 4.2: Effects of the number of allocated bits on transmission power and BERs.

it is easy to see that $P_{i,n}(0) = 0$ and $P_{i,n}(c_{i,n})$ is a convex function increasing with $c_{i,n}$, which essentially means that transmission power is not needed when zero bit is allocated on the subcarrier and additional power is required when $c_{i,n}$ increases, i.e., $P_{i,n}(c_{i,n}+1) - P_{i,n}(c_{i,n}) > 0$. Thus, the conditions for the standard optimization techniques [99] can be satisfied. It is important to note that the difference, $P_{i,n}(c_{i,n}+1) - P_{i,n}(c_{i,n})$, also increases with $c_{i,n}$. Based on (2), Fig. 4.2 (a) shows that the required power for signals increase exponentially with various number of allocated bits to achieve the given BERs, and Fig. 4.2 (b) illustrates that the BER per subcarrier increases with the number of allocated bits for different average SNRs.

The subcarriers are orthogonal to each other and the intercarrier interference (ICI) is eliminated in OFDM systems. However, the time variations of the channel fading within an OFDM symbol lead to a loss of carrier orthogonality, which, in turn, yields ICI. According to [100, 101], ICI can be modelled as an additional Gaussian random process with zero mean for large N. And some research on ICI cancellation have been done [102–104]. For the application of the adaptive algorithms proposed in the thesis, it is assumed that the ICI cancellation schemes are applied to eliminate the ICI part in the received signals at the receiver. Therefore, in this system, if the transmitted signal from the ith user is detected by the receiver, the decision statistic $z_{i,n}$ for the data symbol of the ith user on the nth subcarrier can be written as [8]

$$z_{i,n} = b_{i,n}\sqrt{P_{i,n}}\alpha_{i,n} + \sum_{\substack{k=1 \\ k\neq i}}^{K} b_{k,n}\sqrt{P_{k,n}}\alpha_{k,n}\rho_{k,i} + \eta_n \tag{4.3}$$

where $b_{i,n}$ is a data symbol from the ith user on the nth subcarrier and is assumed to be an independent random variable with zero mean and unit variance for all i and n, η_n denotes the additive white Gaussian noise (AWGN) with zero mean and variance σ^2, and $\rho_{k,i}$ is the cross-correlation between the spreading codes $G^i(t)$ and $G^k(t)$, as shown in Fig. 4.1, which was described in Chapter 3.

The first term in the right-hand side of (4.3) is the desired signal and the second term is the sum of the interferences from all other users on the nth subcarrier to user i. The interference power, i.e., the first term in (4.3), from user i to all other users on the nth subcarrier is

$$\begin{aligned} I_{i,n} &= E_\alpha\left[\left|\sum_{\substack{k=1\\k\neq i}}^{K} b_{i,n}\sqrt{P_{i,n}}\alpha_{i,n}\rho_{i,k}(\tau_k)\right|^2\right] \\ &= \sum_{\substack{k=1\\k\neq i}}^{K} P_{i,n}\alpha_{i,n}^2\rho_{i,k}^2(\tau_k) \\ &= P_{i,n}\alpha_{i,n}^2\sum_{\substack{k=1\\k\neq i}}^{K}\rho_{i,k}^2(\tau_k) \end{aligned} \tag{4.4}$$

where $E_\alpha[\cdot]$ denotes the expectation operation conditioned on α and the data symbols for all i and n are assumed to be independent random variables with the zero mean and unit variance [8]. So the total interference power from the ith user is written as

$$\begin{aligned} I_i &= \sum_{n=1}^{N} I_{i,n} \\ &= \sum_{n=1}^{N} P_{i,n}(c_{i,n})\alpha_{i,n}^2\sum_{\substack{k=1\\k\neq i}}^{K}\rho_{i,k}^2(\tau_k). \end{aligned} \tag{4.5}$$

Based on the discussion above, the interference from each user in the multiuser OFDM/CDMA system can be minimized if the number of allocated bits, $\{c_{i,n}\}_{n=1}^{N}$, is appropriately selected by the adaptive bit allocation algorithm which is to be described in the next section.

4.2.2 ABLA-OFDM algorithm

This section presents the adaptive bit loading (or allocation) algorithm (ABLA-OFDM) for the multiuser OFDM system. The criteria for the adaptive process is to minimize the total interference power from each user to achieve the required transmission data rate with a given transmission power in a single cell. The first step of the process is to minimize the interference I_i from user i by using a sub-optimal procedure to assign the number of loaded bits onto each subcarrier of the user. The second step makes adjustment on the number of bits allocated by the first step to achieve a further reduction of I_i.

(a). Interference minimization

The basic idea of the first step is to allocate a suitable number of bits to each subcarrier to support the desired data rate and at the same time to produce the minimum interference to other users. In this chapter, the total interference power from each user is to be minimized individually. Let us consider, for example, the minimization of I_i, $0 \le i \le K$, from user i, which is formulated as

$$\min_{\{c_{i,n}\}_{n=1}^{N}} I_i = \min_{\{c_{i,n}\}_{n=1}^{N}} \left\{ \sum_{n=1}^{N} \alpha_{i,n}^2 P_{i,n}(c_{i,n}) \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) \right\}, \quad i = 1, 2, \cdots, K, \tag{4.6}$$

subject to the constraints

$$\sum_{n=1}^{N} P_{i,n} = \frac{P_T}{\bar{\alpha}_i^2}, \tag{4.7}$$

and

$$\sum_{n=1}^{N} c_{i,n} = R_i, \tag{4.8}$$

where $\bar{\alpha}_i$ is the average amplitude of the fading channel from user i to the base station. According to the dynamic power control theory of the CDMA system, the received power from each user, say P_T, at the base station should be as equally distributed as possible [16]. The first constraint in (4.7) ensures the received power from all subcarriers supporting a particular user to be as close to P_T as possible. For the data rate constraint, we try to satisfy it based on the given transmission power and bandwidth. R_i represents the transmission rate threshold of a service, such as voice or data service, and is set depending on the power, bandwidth and service types. In general, R_i cannot be a very large value if the frequency and power resources are limited and it has an upper bound R^T affirmatively. The transmission power should be adjusted based on the known channel state. If the channel gain becomes larger, which means that the channel condition becomes better, the transmission power can be accordingly deduced. To achieve the minimization, it is necessary to relax $c_{i,n} \in D$ to be a real number within the interval $[0, V]$. With the standard optimization techniques [99], we define

$$\begin{aligned} T_i &= I_i - \lambda_i \left(\sum_{n=1}^{N} P_{i,n} - \frac{P_T}{\bar{\alpha}_i^2} \right) - \beta_i \left(\sum_{n=1}^{N} c_{i,n} - R_i \right) \\ &= I_i - \lambda_i \left\{ \frac{N_0}{3} \sum_{n=1}^{N} \left[Q^{-1} \left(\frac{BER_i}{4} \right) \right]^2 (2^{c_{i,n}} - 1)/\alpha_{i,n}^2 - \frac{P_T}{\bar{\alpha}_i^2} \right\} \\ &\quad - \beta_i \left(\sum_{n=1}^{N} c_{i,n} - R_i \right) \end{aligned} \tag{4.9}$$

where $i = 1, 2, \cdots, K$, λ_i and β_i are the Lagrangian multipliers for the two constrains in (4.7) and (4.8), respectively. Let us define

$$\mathbf{T} = [T_1,\ T_2,\ \cdots,\ T_K]. \tag{4.10}$$

The number of allocated bits that leads to the minimization of interference $\{I_1, I_2, \cdots, I_K\}$ can be obtained by

$$\nabla \mathbf{T} = \left[\frac{\partial T_1}{\partial c_{1,n}},\ \frac{\partial T_2}{\partial c_{2,n}},\ \cdots,\ \frac{\partial T_K}{\partial c_{K,n}} \right] = 0, \qquad n = 1, 2, \cdots, N. \tag{4.11}$$

Let us define $S_{i,n}$ to represent $[\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k)]$ in (4.6) and

$$L_i = \frac{N_0 \ \ln 2}{3}\left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2, \quad i = 1, 2, \cdots, K. \tag{4.12}$$

After differentiating T_i with respect to $c_{i,n} \in [0, V]$,

$$\begin{aligned}
\frac{\partial T_i}{\partial c_{i,n}}\,|_{c_{i,n}=\hat{c}_{i,n}} &= \left\{\frac{\partial I_i}{\partial c_{i,n}} - \lambda_i \frac{\partial P_{i,n}}{\partial c_{i,n}} - \beta_i\right\}|_{c_{i,n}=\hat{c}_{i,n}} \\
&= \left\{\frac{\partial P_{i,n}}{\partial c_{i,n}} \cdot \alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i \cdot \frac{\partial P_{i,n}}{\partial c_{i,n}} - \beta_i\right\}|_{c_{i,n}=\hat{c}_{i,n}} \\
&= \left\{\frac{N_0 \ \ln 2 \cdot \left[Q^{-1}\left(BER_i/4\right)\right]^2 \, 2_{i,n}^c}{3} \cdot \alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k)\right\}|_{c_{i,n}=\hat{c}_{i,n}} \\
&\quad - \left\{\lambda_i \cdot \frac{N_0 \ \ln 2 \cdot [Q^{-1}(BER_i/4)]^2 \, 2_{i,n}^c}{3} - \beta_i\right\}|_{c_{i,n}=\hat{c}_{i,n}} \\
&= \left\{\frac{2^{c_{i,n}} \, L_i}{\alpha_{i,n}^2}\left(S_{i,n} - \lambda_i\right) - \beta_i\right\}_{|c_{i,n}=\hat{c}_{i,n}} \\
&= 0
\end{aligned} \tag{4.13}$$

for $i = 1, 2, \cdots, K$, we have

$$\begin{aligned}
\hat{c}_{i,n} &= \log_2\left[\frac{\beta_i \ \alpha_{i,n}^2}{(S_{i,n} - \lambda_i)L_i}\right] \\
&= \log_2\left\{\frac{\beta_i \ \alpha_{i,n}^2}{\frac{N_0 \ \ln 2}{3}\left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2 \left[\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i\right]}\right\}, \\
& \qquad i = 1, 2, \cdots, K; \qquad n = 1, 2, \cdots, N
\end{aligned} \tag{4.14}$$

as the number of bits to be allocated on the nth subcarrier for the ith user. For a fixed set of Lagrangian multipliers $\{\lambda_i, \beta_i\}$ $(i = 1, \cdots, K)$, $\{\hat{c}_{i,n}\}_{i=1}^K$ for each user can be determined by (4.14). An iterative searching algorithm [11] is used to find the set of $\{\lambda_i, \beta_i\}$ such that the constraints for each user can be satisfied.

This algorithm converges because for a given i, the value of $\{c_{i,n}\}$ for all n increases as $\{\lambda_i, \beta_i\}$ increases. As long as the total transmission rate is smaller than VN bits/symbol, which is the total number of bits possibly transmitted within an OFDM symbol, the algorithm will converge to a solution that satisfies all constraints. Similarly, the numbers of loaded bits, $\{\hat{c}_{1,n}, \hat{c}_{2,n}, \cdots, \hat{c}_{K,n}\}_{n=1}^{N}$, for K users are calculated. In this way, the interference power for a particular subcarrier is minimized and the transmission power in (4.7) and data rate in (4.8) for each user are also satisfied. Since the optimization is a problem over a convex set and the set of necessary conditions is also sufficient, the solution that satisfies all the necessary conditions is unique.

The solution $\hat{c}_{i,n}$ obtained from (4.14) is a real number and has to be converted into the nearest integer because $c_{i,n}$ has to be a positive integer. When $\hat{c}_{i,n} < 0$, $c_{i,n}$ is set to be 0. Consequently, the actual data rate to support each user may be smaller or larger than that given in (4.8). Two procedures, as shown in Table 4.1, are used to eliminate the difference between the desired and achieved data rates. Procedure 1 in Table 4.1 deals with the under loaded situation, i.e., $\sum_{n=1}^{N} c_{i,n} < R_i$. It is necessary to allocate one more bit on the nth subcarrier that requires the least additional transmission power. This procedure is repeated until the condition in (4.8) is satisfied. It is possible that more channel bandwidth should be provided when the required data rate is too high for Procedure 1 to satisfy the power constraint in (4.7). For the overloaded situation, i.e., $\sum_{n=1}^{N} c_{i,n} > R_i$, Procedure 2 in Table 4.1 removes one bit from the nth subcarrier from which the most power reduction can be made. Thus, these procedures guarantee to achieve the required data rate and minimize power consumption. In this way, the interference I_i in (4.5) is also reduced.

(b). Bit allocation adjustment

The above proposed algorithm of adaptive bit allocation is based on minimizing the interference from each user with the constraints of transmission power and the required bit rate. However, the optimal results are changed due to the integer rounding procedures. Now let us consider some details of the algorithm when most subcarriers do not suffer severe fading, for example, SNR $>$ 10 dB. In general, the number of bits allocated on the subcarriers should be minimized because both the required power and BER increase with the number of allocated bits, as shown in Fig. 4.2(a) and (b), respectively. According to the proposed algorithm in Section 4.2.2 (a), it is possible that some subcarriers are not used because their channel qualities are relatively worse than that of other subcarriers. However, these unused subcarriers may still be good enough to support applications that do not need very low BERs. For example, telephone services for speech communications have a reasonably good quality with a BER of 10^{-3}. To avoid wasting these unused subcarriers, it is possible to unload one bit from a subcarrier that is already allocated with a large number of bits and reallocate this bit onto an unused subcarrier. Without changing the total transmission rate, this unloading and reallocation adjustment can further reduce the interference from some user and achieve a better performance. This is the reason that the solution presented in (4.14) is considered to be suboptimal. To illustrate the concept of the adjustment, let us assume that 4 bits are allocated on a subcarrier with SNR $=$ 25 dB and BER $< 10^{-3}$. One bit can be unloaded from this subcarrier and reallocated on an unused subcarrier with SNR $=$ 10 dB. It can be seen from Fig. 4.2(b) that after the adjustment, the BERs of both subcarriers are below 10^{-4} and at the same time, the required power is also decreased according to Fig. 4.2(a). Therefore a further reduction of I_i in (4.5) is achieved.

Based on the discussion above, the second step is an adjustment process described in Table 4.2. A limit Δ_i can be set to represent the difference between the maximum and the minimum numbers of bits loaded on the subcarriers for user i. Referring to Table 4.2, one bit is unloaded by Procedure 1 from subcarrier n_1 with the worst channel gain among all subcarriers having the same maximum number of allocated bits. Then the load of this particular subcarrier is alleviated. This unloaded bit is assigned to subcarrier n_2 with the best channel gain among those subcarriers $\{\widetilde{n}\}$

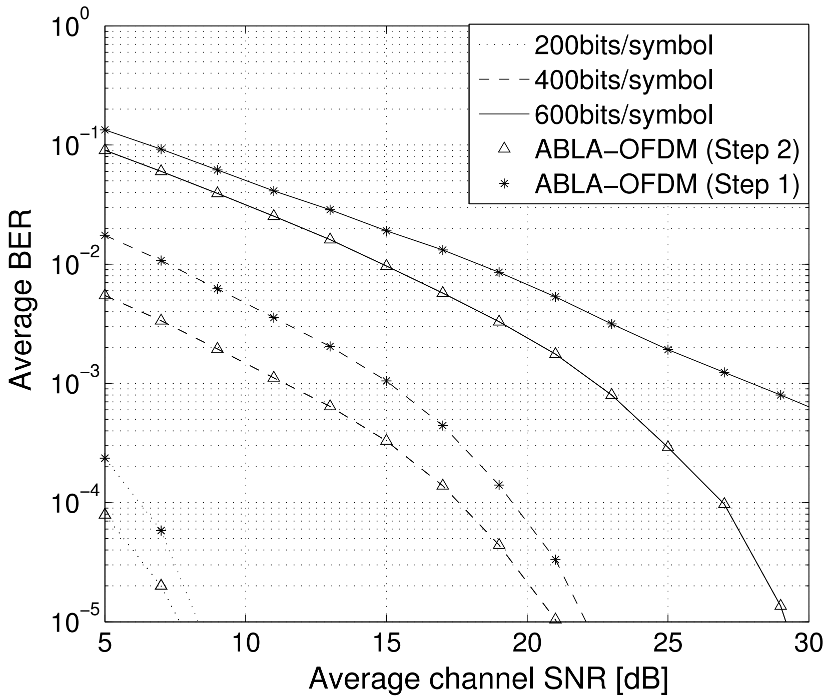


Figure 4.3: Comparison of BERs achieved in Step 1 and Step 2 for a system of three users.

having the same minimum number of allocated bits. This process is performed for Q times, which is the number of those subcarriers having the same $\max_n\{c_{i,n}\}$ before Table 4.2 is used. In this way, a limit is enforced on the maximum difference Δ_i in the numbers of loaded bits.

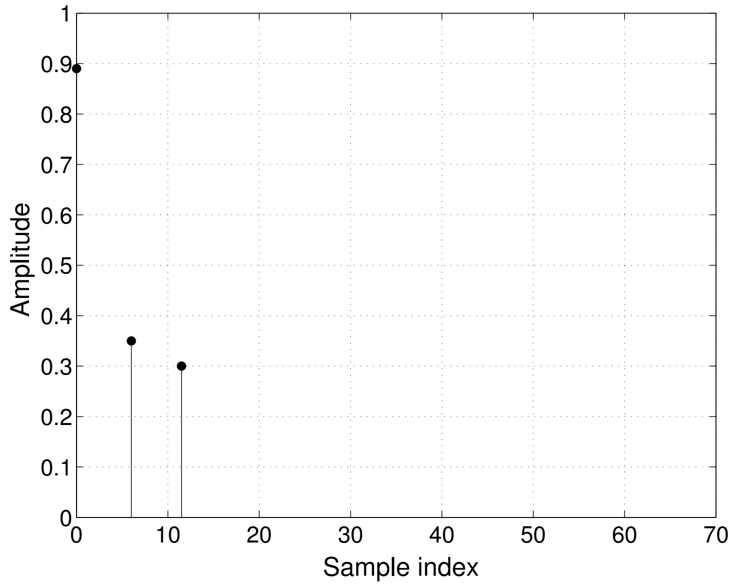
Procedure 2 in Table 4.2 performs the adjustment of the allocated bits among all the subcarriers so that the unused subcarriers, which have zero bit, are to be utilized. It unloads one bit from the subcarrier that has the worst channel gain among subcarriers having a maximum number of allocated bits. Then the corresponding bit is loaded onto one of the unused subcarriers. It should be explained that Procedure 2 is not necessary if the minimum of $\hat{c}_{i,n}$ is larger than zero, which indicates that the system is already properly loaded. In fact, the adjustment algorithm is equivalent to reduction of Δ_i. Appendix B shows that the interference reduction ΔI_i from user i can be obtained based on Δ_i.

In a three-user system, Fig. 4.3 shows that the adjustment process in the second step achieves substantial improvement compared to the BER achieved in the first step without using Table 4.2, especially for a relatively high data rate R_i, such as 600 bis/symbol. For example, when each of the three users are supported with 400 bits/symbol, nearly 2 dB SNR reduction is achieved for the BER of 10^{-4}.

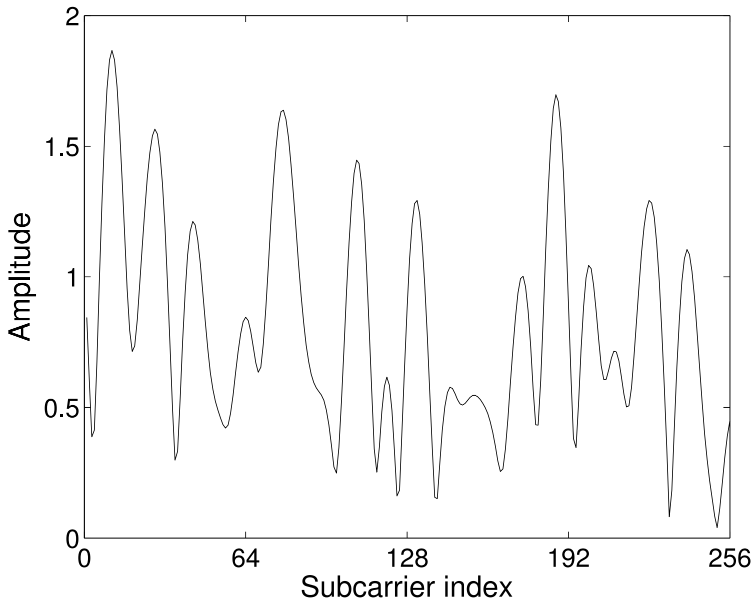
The proposed algorithm attempts to make the best use of all subcarriers for multiuser transmissions in the OFDM system when the quality of subchannels is not very bad. In the case of the subcarrier allocation for the multi-service transmission, however, some subcarriers may not be utilized due to the stringent service requirement and deep fading channel. This case is not considered here.

4.3 Performance comparison based on the theoretical analysis and simulations

The channel is assumed to be modelled by a finite impulse response (FIR) filter with time-varying coefficients as shown in Fig. 4.4(a). The impulse response for the experiments was generated on the basis of the symbol-rate impulse response by fading each of the impulses with a Rayleigh distribution of a maximal Doppler frequency of $f_d = 111$ Hz. The value of f_d corresponds to a wireless local area network (WLAN) channel experienced by a modem transmitting at a carrier frequency of 2.4 GHz with a vehicular velocity of 50 km/h. The channel fading in frequency domain is shown in Fig. 4.4(b). It is also assumed that the OFDM/CDMA system has 256 subcarriers and quasi-synchronized. The system performance achieved by the proposed algorithm is to be analyzed and compared with those obtained by CTAO-OFDM [12] and MAO-OFDM [11] in terms of the BER, system capacity and data rates. It is noted that the CTAO-OFDM algorithm in [12] is carried out based on the same OFDM/CDMA system as the ABLA-OFDM algorithm. As for the comparison with the MAO-OFDM algorithm, it will also be shown that the combination of OFDM and CDMA outperforms that of OFDM and FDMA when

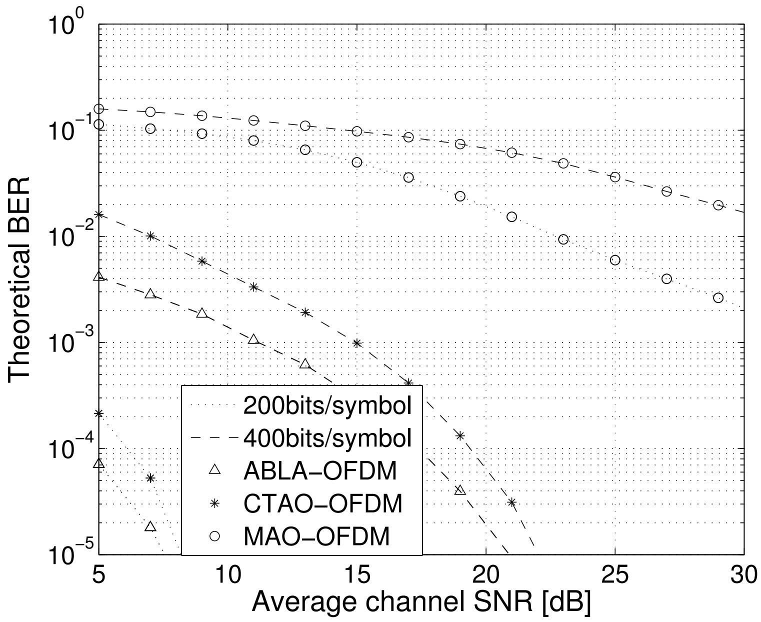


(a)

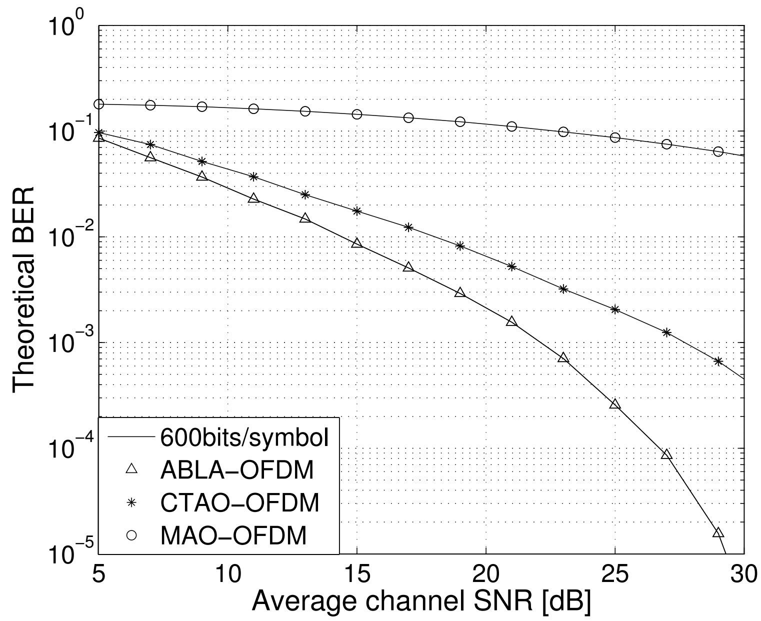


(b)

Figure 4.4: Wideband channel: (a) unfaded symbol spaced impulse response and (b) corresponding frequency domain channel fading.

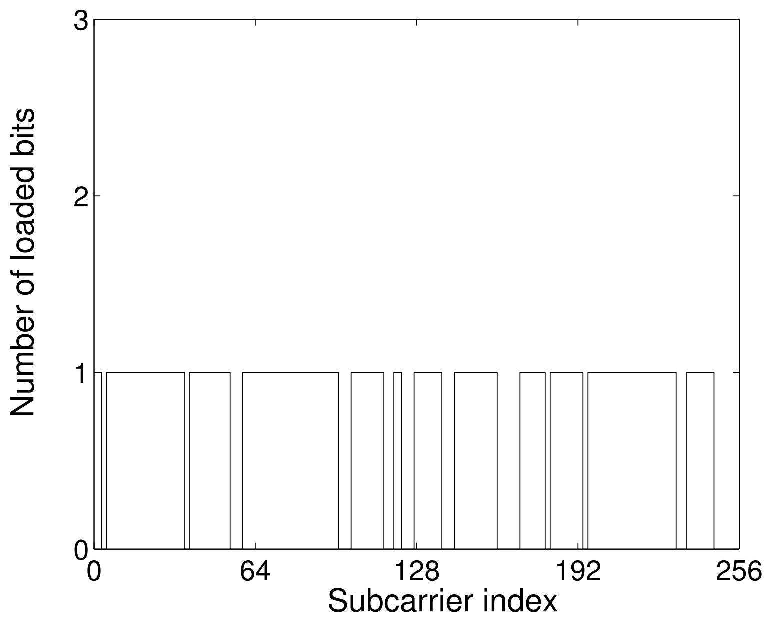


(a) Theoretical BERs of the three users with the same data rates simultaneously, 200 and 400 bits/symbol.

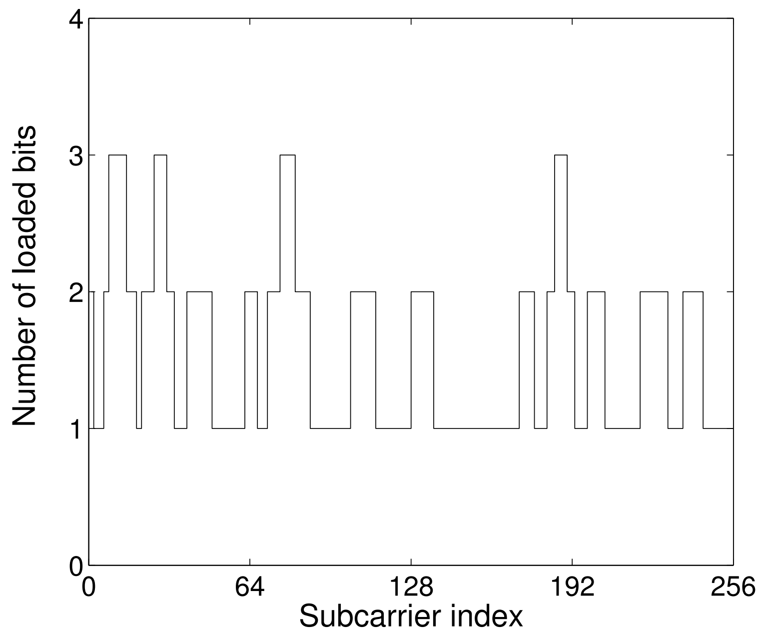


(b) Theoretical BERs of the three users with the same data rates, 600 bits/symbol

Figure 4.5: Comparison of theoretical BERs of a three-user system.

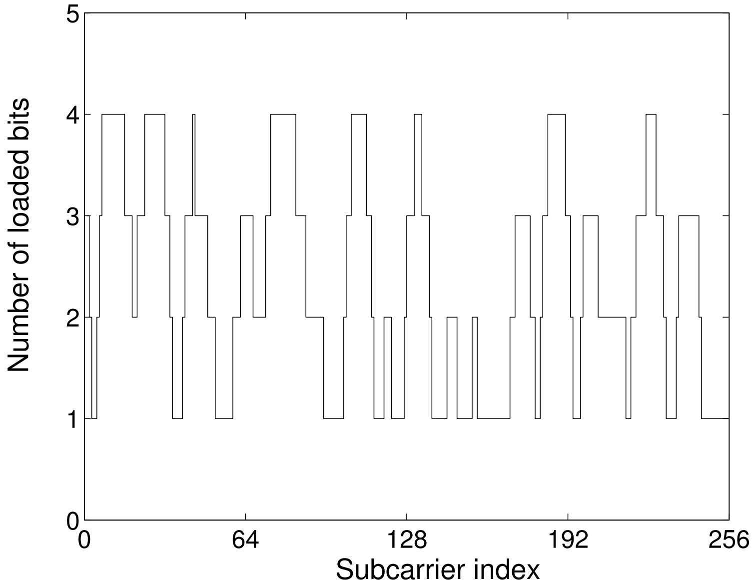


(a) Transmission data rate is 200 bits/symbol

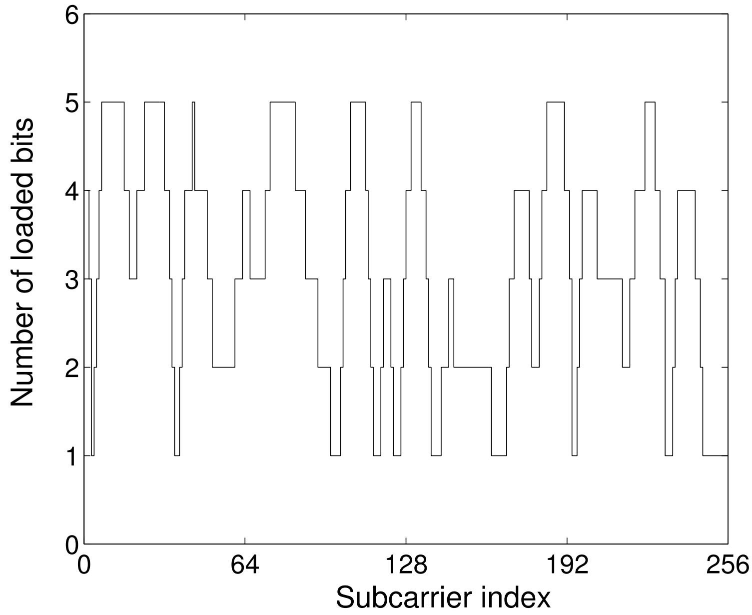


(b) Transmission data rate is 400 bits/symbol

Figure 4.6: The number of loaded bits based on the channel model in Fig. 4.4 (b) when the transmission data rates are 200 and 400 bits/symbol and the average SNR is 20 dB.

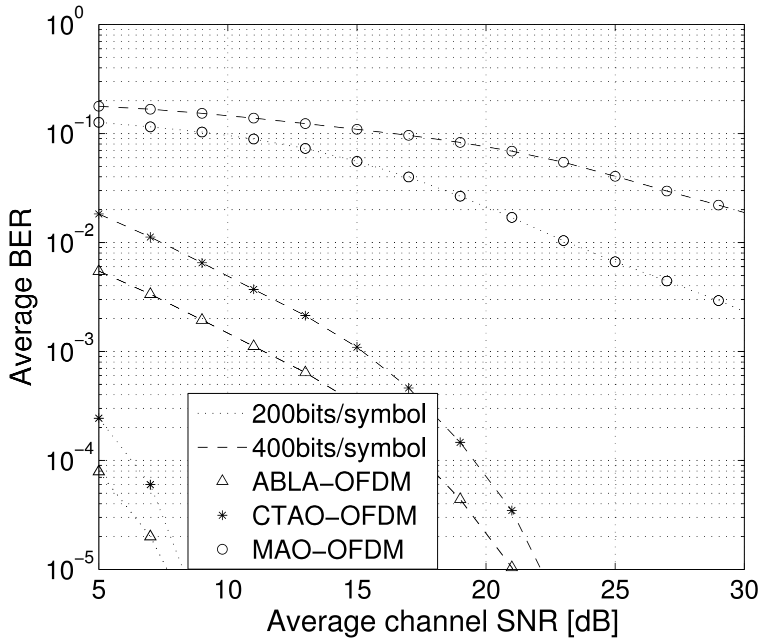


(a) Transmission data rate is 600 bits/symbol

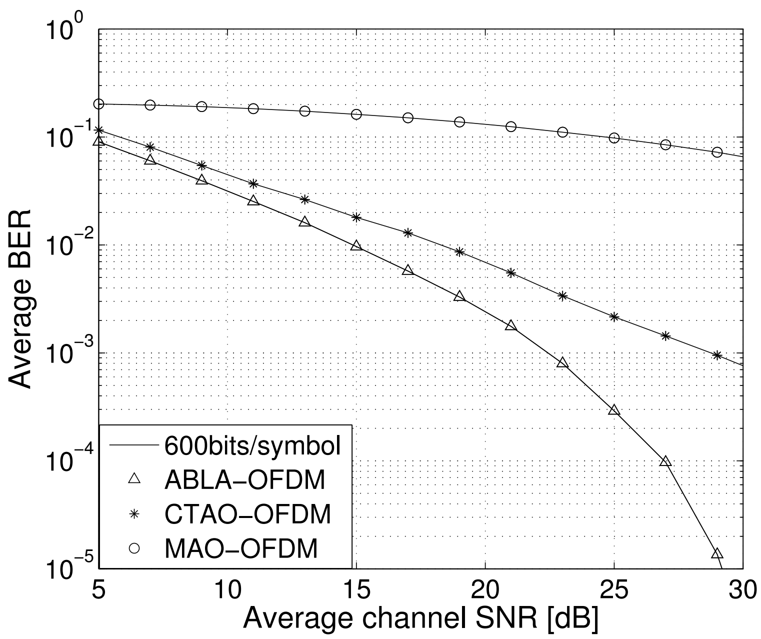


(b) Transmission data rate is 800 bits/symbol

Figure 4.7: The number of loaded bits based on the channel model in Fig. 4.4 (b) when the transmission data rates are 600 and 800 bits/symbol and the average SNR is 20 dB.



(a) Average BERs of the three users with the same data rates simultaneously, 200 and 400 bits/symbol.



(b) Average BERs of the three users with the same data rates, 600 bits/symbol

Figure 4.8: Comparison of BERs obtained from simulations of a three-user system.

the quasi-synchronization [105–107] of the spreading codes is performed.

(a). Theoretical BER

On the nth subcarrier of user i, the BER expression of MQAM with Gray bit mapping in AWGN as a function of received SNR, $\gamma_{i,n}$, and constellation size $M = 2^{c_{i,n}}$ $(c_{i,n} \geq 2)$ is approximately [90, 91]

$$BER_{i,n}^{MQAM} \approx \frac{2}{c_{i,n}} \left(1 - \frac{1}{\sqrt{2^{c_{i,n}}}}\right) \times \text{erfc}\left(\sqrt{1.5 \frac{\gamma_{i,n}}{2^{c_{i,n}} - 1}}\right) \tag{4.15}$$

where the approximation is the tightest at high SNRs. For BPSK modulation $(c_{i,n} = 1)$, the bit BER is given by [108]

$$BER_{i,n}^{BPSK} = \frac{1}{2}\text{erfc}\left(\sqrt{\gamma_{i,n}}\right). \tag{4.16}$$

Base on (4.3), the interference term may be treated as Gaussian noise by the central limit theorem [109], and the received SNR for the ith user's nth subcarrier signal can be written as

$$\begin{aligned} \gamma_{i,n} &= \frac{E_\alpha\left[|b_{i,n}\sqrt{P_{i,n}}\alpha_{i,n}|^2\right]}{E_\alpha\left[\left|\sum_{\substack{k=1\\k\neq i}}^{K} b_{k,n}\sqrt{P_{k,n}}\alpha_{k,n}\rho_{k,i}(\tau_k) + \eta_n\right|^2\right]} \\ &= \frac{\alpha_{i,n}^2\, P_{i,n}}{\sum_{\substack{k=1\\k\neq i}}^{K} \alpha_{k,n}^2 \rho_{k,i}^2(\tau_k) P_{k,n} + \sigma^2}, \quad i = 1, 2, \cdots, K, \end{aligned} \tag{4.17}$$

where $\sigma^2 = N_0\, B/N$. Appendix C derives the theoretical BER based on (4.15) for a particular user i. According to our proposed ABLA-OFDM and the assumption of multichannel parameters, we obtain $\{c_{i,n}\}_{n=1}^{N}$, which is the number of the allocated bits for each user. By (4.15), (4.16) and (23), the theoretical BER for each user is achieved. For a system of three users, Fig. 4.5 shows the theoretical BER performance achieved by ABLA-OFDM, CTAO-OFDM and MAO-OFDM. For a transmission with $BER = 10^{-5}$ and 10^{-4}, the ABLA-OFDM algorithm achieves at least 1 and 2 dB SNR reduction, when the data rate of each user is 400 bits/symbol, compared to the CTAO-OFDM. When the data rate is 600 bits/symbol, it is clear that the data rate is too high for CTAO-OFDM to support, and consequently its BER performance becomes much worse than ABLA-OFDM. Since only some subcarriers are allocated to each user [11], MAO-OFDM cannot support three users with 400 bits/symbol when the total number of subcarriers is limited to 256.

(b). Simulation results

Simulations were carried out to transmit data stream in the system shown in Fig. 4.1. According to ABLA-OFDM bit loading algorithm, Fig. 4.6 and Fig. 4.7 show the numbers of loading bits when the transmission data rates are different at the average SNR of 20 dB. The number of loaded bits on each subchannel varies with the quality of each subchannel. If the subchannel is in severe fading, it only can carry only 0 or 1 bit. That the number of bits is equal to zero means this subcarrier is too bad to support any bits and will be discarded, and meanwhile the data rate requirement is already satisfied, as shown in Fig. 4.6(a). More bits can be supported on the subcarriers which show high amplitudes in Fig. 4.7. Based on the same channel, the maximum number is 1 when the data rate is 200 bits/symbol while the maximum value is 3, 4 or 5 when the data rate is 400, 600 or 800 bits/symbol, as shown in Fig. 4.6 and Fig. 4.7. Accordingly, for the data rates of 600 and 800 bits/symbol, the system will have more power consumption.

Fig. 4.8(a) and (b) show the comparisons among BERs achieved by the ABLA-OFDM algorithm and other schemes with various average SNRs. For transmission of voice signals with a given BER, i.e., 10^{-2}, the ABLA-OFDM algorithm achieves at least 3 and 4 dB SNR reductions, when the transmission data rates of each user are 400 and 600 bits/symbol compared to the CTAO-OFDM algorithm. For transmission of video signals with BER of 10^{-5}, the ABLA-OFDM algorithm achieves nearly 1 dB SNR reduction compared to the CTAO-OFDM algorithm when the transmission data rate is 400 bits/symbol. With the increase of the transmission data rates, such as 600 bits/symbol, ABLA-OFDM achieves a much lower BER when the average SNR is 30 dB. Although we cannot say that MAO-OFDM is useless for this case, the curves in Fig. 4.8(b) indicate that more bandwidth (or subcarriers) is needed to support high rate multiple users with better BERs.

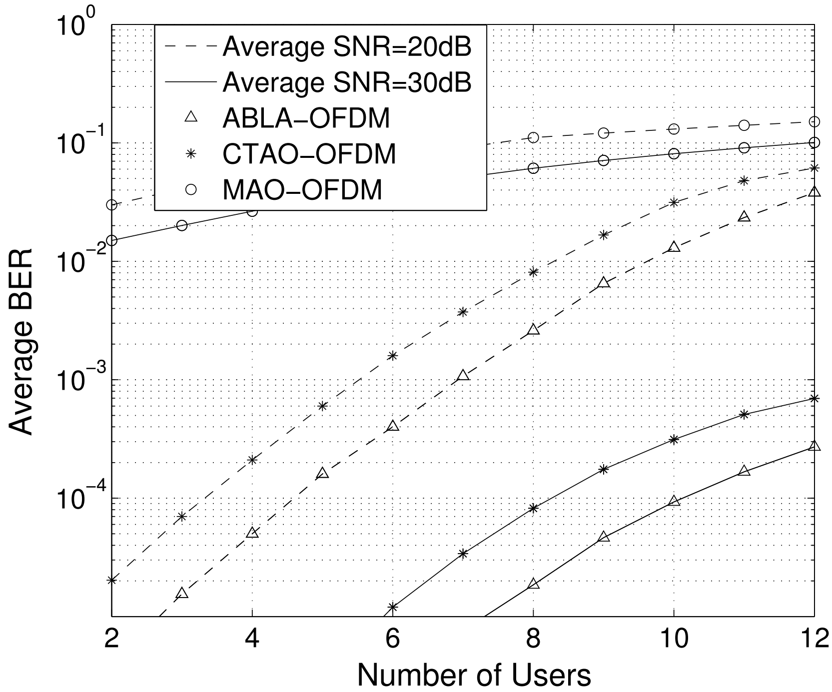
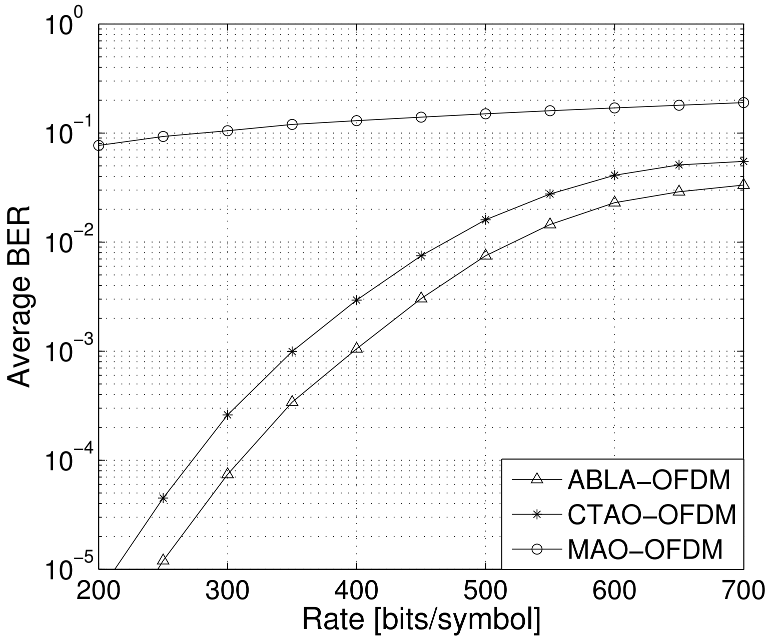
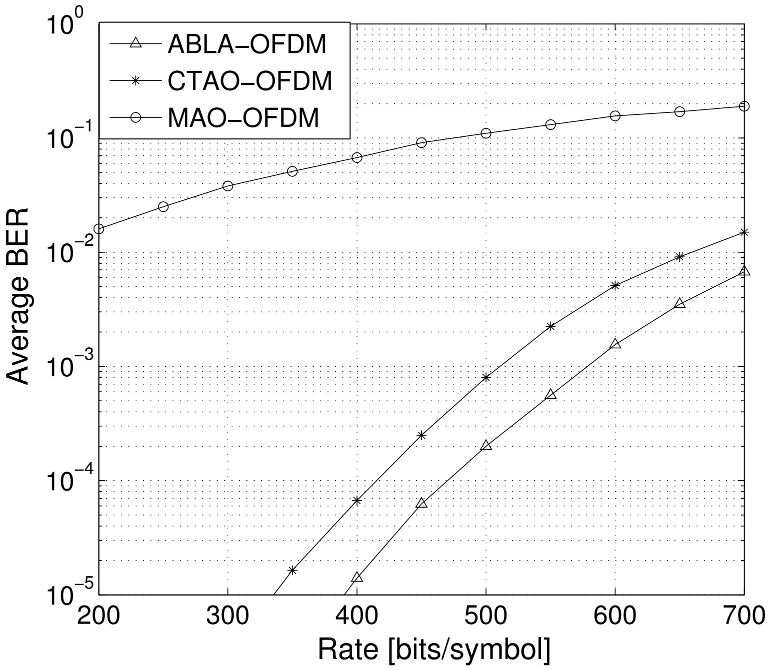


Figure 4.9: Comparison of simulated system capacity with the data rate of 400 bits/symbol.

The benefit of reducing the interference by each user provided by the proposed algorithm can be also explained in terms of the system capacity. Fig. 4.9 shows, when the average SNR is 30 dB and the data rate is 400 bits/symbol, the system using the proposed algorithm is able to accommodate one more user compared with the CTAO-OFDM for video transmission with BER of 10^{-5}. For voice transmission with SNR = 20 dB and BER = 10^{-2}, one more user can be supported compared to that supported by CTAO-OFDM. The proposed ABLA-OFDM algorithm is particularly useful for the transmission with high data rates. At the BERs of 10^{-3} and 10^{-5} and average SNR of 10 dB, for example, Fig. 4.10(a) shows that the ABLA-OFDM algorithm supports 60 and 50 bits/symbol data rates higher than the CTAO-OFDM algorithm respectively. When the average SNR is 20 dB, Figure 4.10(b) shows 70 and 50 more bits/symbol supported by ABLA-OFDM, respectively, compared to the CTAO-OFDM algorithm. However, these advantages

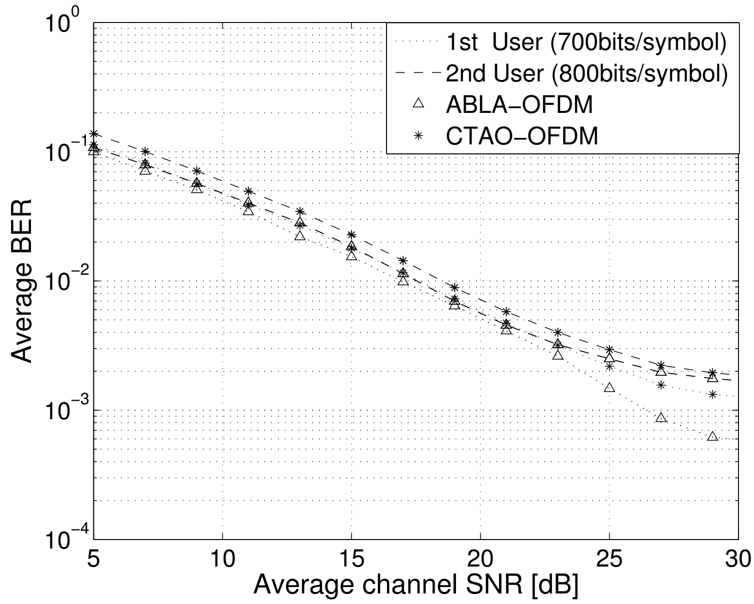


(a) Average SNR = 10 dB

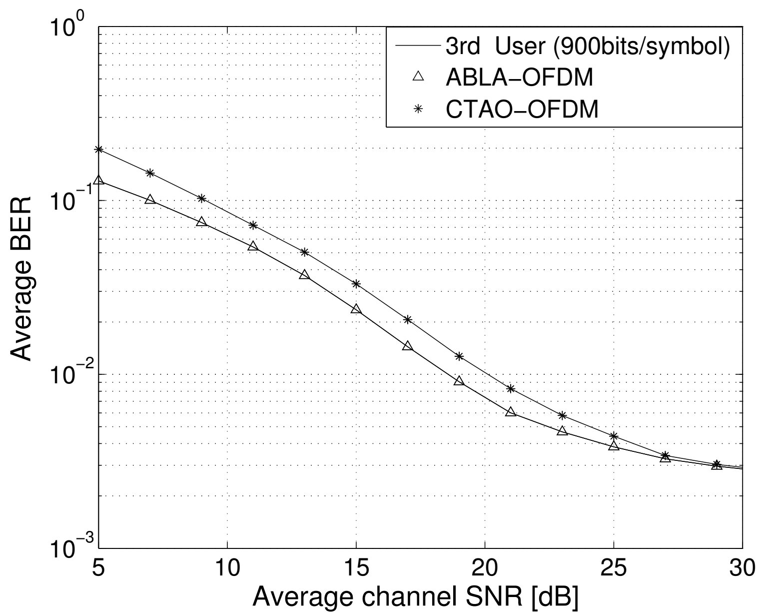


(b) Average SNR = 20 dB

Figure 4.10: Comparison of average BER among ABLA-OFDM, CTAO-OFDM and MAO-OFDM in a three-user system at the average SNR of 10 dB and 20 dB (the three users in the system have the same data rate).



(a) Average BER of the first and second user with 700 and 800 bits/symbol respectively.



(b) Average BER of the third user with 900 bits/symbol

Figure 4.11: Limitation of ABLA-OFDM and CTAO-OFDM algorithms.

become diminished when the data rate becomes more than 700 bits/symbol in this system that has 256 subcarriers. Both ABLA-OFDM and CTAO-OFDM obtain similarly poor performance. In the system of three users with the data rates of 700, 800 and 900 bits/symbol, respectively, Fig. 4.11 shows that at the average SNRs of 25 and 30 dB, the BERs achieved by using ABLA-OFDM and CTAO-OFDM are in the range of $10^{-3} \sim 10^{-2}$, which is only able to support the voice transmission. Referring to Fig. 4.9, Fig. 4.10 and Fig. 4.11, in order to support more users and higher data rates, the only feasible solution is to increase the number of subcarriers or equivalently the channel bandwidth based on the algorithms.

Each algorithm has its complexity. To obtain (4.14), the calculated number of bits to be assigned to the nth subcarriers, at least five multipliers, K adders, one divider and logarithm are used in one loop of searching the appropriate $\{\lambda, \beta\}$. The complexity increases with total number of subcarriers and the convergence speed of searching $\{\lambda, \beta\}$ linearly. In the implementation of the procedures shown in Table 4.1 and Table 4.2, the multipliers and adders can be shared with other process. For the CTAO-OFDM algorithm under different channel conditions, the adaptive modulation scheme is performed by repeatedly searching for the subcarrier having the lowest cost value and incrementing its state. This process is repeated until the target number of bits is reached. The total processing time depends on the number of loops of searching cost values and the required data rates. During the adjustment process in ABLA-OFDM, the numbers of loaded bits on subcarriers are checked, analyzed and further adjusted. The number of loops is only related to the number of the subcarriers which have the maximum and minimum bits. The process time is much less than CTAO-OFDM. Comparatively, MAO-OFDM has the least complexity and may be used in the some environments which need the fast process.

4.4 Conclusion

An adaptive bit allocation algorithm, known as ABLA-OFDM, is reported for the single-service transmission in a single cell of the multiuser OFDM/CDMA system. The criterion is to minimize each user's interference in the cell by allocating the appropriate number of bits on each subcarrier according to the channel quality with the constraints of the transmission power and data rate, based on the assumption of the perfect knowledge of the subcarrier during the received time slot. Both the theoretical analysis and experimental simulations confirm that the proposed ABLA-OFDM algorithm performs better in terms of the BER, system capacity and data rates to be supported compared with other reported algorithms.

Table 4.1: Procedures to support the required data rate for user i

Procedure 1	**If** $\sum_{n=1}^{N} c_{i,n} < R_i$**,** $D = R_i - \sum_{n=1}^{N} c_{i,n}$, /* The difference of data rates */ /* ***Reloading Operation*** */ Loops begin: /* For D Loops */ For all n and $c_{i,n}$, $\triangle P_{i,n} = [P_{i,n}(c_{i,n}+1) - P_{i,n}(c_{i,n})]/\alpha_{i,n}^2$; /* Find the smallest power increase among all subcarriers */ $\hat{n} = \arg\min_n \triangle P_{i,n}$; if $\sum_{n=1}^{N} P_{i,n} < P_T/\bar{\alpha}_i^2$, $c_{i,\hat{n}} = c_{i,\hat{n}} + 1$; else $c_{i,\hat{n}}$ will not increase. Loops end.
Procedure 2	**If** $\sum_{n=1}^{N} c_{i,n} > R_i$**,** $D = \sum_{n=1}^{N} c_{i,n} - R_i$, /* The difference of data rates */ /* ***Unloading Operation*** */ Loops begin: /* For D Loops: */ For all n and $c_{i,n}$, $\triangle P_{i,n} = [P_{i,n}(c_{i,n}) - P_{i,n}(c_{i,n}-1)]/\alpha_{i,n}^2$; /* Find the largest power decrease among all subcarriers */ $\hat{n} = \arg\max_n \triangle P_{i,n}$; $c_{i,\hat{n}} = c_{i,\hat{n}} - 1$; Loops end.

Table 4.2: Adjustment on the number of allocated bits for user i

Procedure 1	If $(\max_n\{c_{i,n}\} - \min_n\{c_{i,n}\}) \geq \Delta_i$, Q = Number of the $\max_n\{c_{i,n}\}$; Loops begin: /*For Q loops:*/ $\{\hat{n}\} = \arg\max_n\{c_{i,n}\}$; $\{\widetilde{n}\} = \arg\min_n\{c_{i,n}\}$; $n_1 = \arg\min_{n_1\in\{\hat{n}\}}\ \{\alpha_{i,n}\}$; $n_2 = \arg\max_{n_2\in\{\widetilde{n}\}}\ \{\alpha_{i,n}\}$; /* ***Bit unloading and reallocation*/*** $c_{n_1} = c_{n_1} - 1$; $c_{n_2} = c_{n_2} + 1$; Loops end.
Procedure 2	If $\min_n\{c_{i,n}\} = 0$, Q = Number of the $\min_n\{c_{i,n}\}$; Loops begin: /*For Q loops:*/ $\{\hat{n}\} = \arg\max_n\{c_{i,n}\}$; $\{\widetilde{n}\} = \arg\min_n\{c_{i,n}\}$; $n_1 = \arg\min_{n_1\in\{\hat{n}\}}\ \{\alpha_{i,n}\}$; $n_2 = \arg\max_{n_2\in\{\widetilde{n}\}}\ \{\alpha_{i,n}\}$; /* ***Bit unloading and reallocation*/*** $c_{n_1} = c_{n_1} - 1$; $c_{n_2} = c_{n_2} + 1$; Loops end.

Chapter 5

Adaptive subcarrier allocation and bit loading for Voice and Data transmissions

This chapter presents a new algorithm of adaptive subcarrier allocation and bit loading for simultaneous voice and data transmissions over frequency selective fading channels in a multiuser OFDM system. The subcarriers with low signal-to-noise ratio are assigned to voice with a small number of bits per symbol to guarantee the required bit-error-rate and transmission rate. With the remaining subcarriers and transmission power, the throughput of data transmission is maximized by loading as many bits as possible on each subcarrier to support high transmission rates with the required bit-error-rate. In addition to the theoretical analysis of this algorithm, simulation results show that a better performance is obtained than previously reported schemes.

5.1 Introduction

Adaptive algorithms of subcarrier allocation and bit loading have been studied in several aspects. Although multi-service transmission is becoming increasingly important to various applications, however, most reported work for OFDM systems ([6, 11–13], for example) focused only on the resource allocation and bit loading without sufficiently considering efficiently supporting different services, such as simultaneous voice and data transmissions, that generally have different requirements on the BER and delay tolerance. In [80], algorithms were reported for two services with higher and lower quality-of-service (QoS) in a single-user OFDM system. However, it is not appropriate to use the QoS alone as the optimization parameters for the voice/data systems. It is known that in the voice/data systems, the QoS of data service generally requires higher data rates and lower BERs than the voice service, and the delay requirement of voice service is much more critical than the data service, which should be sufficiently considered for channel resource allocation. Based on single carrier systems, a scheme of adaptive hybrid binary phase shift keying (BPSK)/M-ary amplitude modulation (M-AM) was proposed for voice and data transmissions [77]. Since M-AM is spectrally less efficient than the M-ary quadrature amplitude modulation (M-QAM), an adaptive technique employing variable rate uniform M-QAM (U-MQAM) was reported for integrated voice/data by changing the constellation size dynamically to take advantage of time varying nature of fading [78]. Due to the use of uniform M-QAM constellation, however, the alphabet size is selected such that, on average, the transmission for voice has also to meet the BER requirement for data service. Therefore, the voice transmission achieves unnecessary extra protection at the expense of spectral efficiency at low SNR region and outage probability that means only for data transmission. An adaptive scheme for multi-rate services (A-MRS) [79] was presented for the OFDM systems in which the low-rate service for voice transmission was supported by loading one or two bits per subcarrier and the high rate data transmission was loaded with more bits according to mode-switching methods with the bit selection curve.

This chapter considers the simultaneous transmissions of voice and data in a multiuser OFDM/CDMA system, in which any user can share all available subcarriers by using CDMA technique [26, 81]. In general, voice transmission does not need rigid requirements on transmission rate and BER, but has stringent realtime constraints, which are just opposite to the requirements for most data services. This suggests that the fixed-rate transmission combined with adaptive bit loading on low quality subcarriers is well suited to voice transmission to meet the transmission requirements, while the variable-rate transmission, which maximizes the total throughput and obtains low BER, is best suited to data communications. Since only one or two bits are generally loaded for the low-rate voice transmission with relaxed BER requirement, the selected subcarriers are generally with low channel gains. After the requirements of both BER and transmission rate of voice service are satisfied, the remaining subcarriers are loaded with as many bits as possible to achieve the maximum throughput for the data transmission. In this way, the subcarriers in somewhat low quality are used for voice transmission and those with good quality are allocated for data transmission. The algorithm applies a threshold on the transmission power of each user, i.e., 23 dBm [1], which takes account of limiting the transmission power of each user as well as the power interference to other users. The proposed algorithm guarantees a low power consumption on voice transmission because only a small number of bits are carried by the assigned subcarriers. Consequently, most transmission power and subcarriers with higher channel gains, which are generally use a higher order modulation scheme to support high data rate transmissions, can be used for the maximization of data throughput.

[1] In the absence of any justification, the transmission power would be 200 mW ($10 \lg 200 = 23$ dBm), the maximum level for many CDMA mobile handsets.

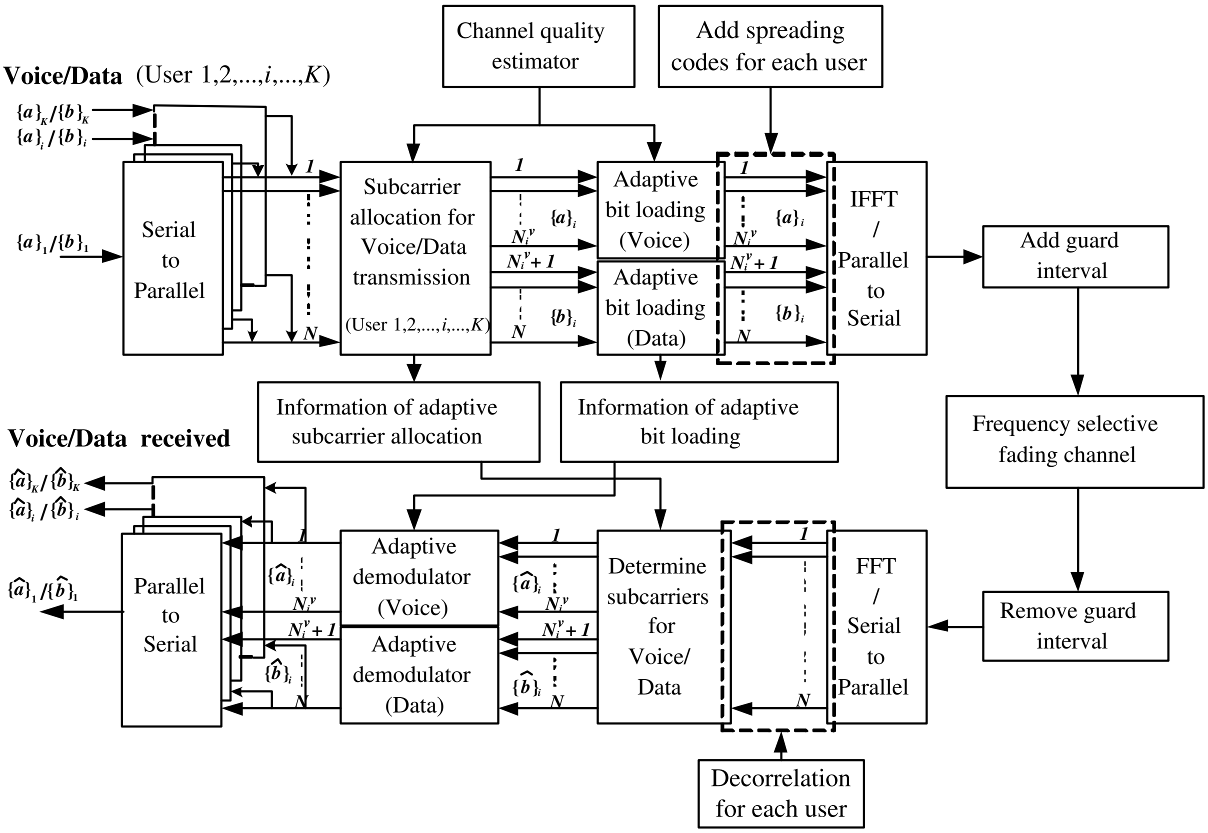


Figure 5.1: Block diagram of adaptive voice/data transmission for multiple users in a multiuser OFDM/CDMA system.

5.2 Adaptive transmission algorithm

5.2.1 Adaptive multiuser multi-service system

The block diagram of adaptive voice/data transmission in a multiuser OFDM/CDMA system is shown in Fig. 5.1, in which each user can use all N subcarriers, and $\{a\}_i$ and $\{b\}_i$ represent the sets of voice and data signals of user i, respectively. The algorithm of subcarrier allocation for voice and data is performed after the serial and parallel format conversion. Based on the estimation of channel gains, the process is adaptively performed to assign a suitable number of bits on the allocated subcarriers for voice and data transmissions. After subcarrier allocation and bit loading, spreading codes are added to signals on each user's subcarriers to distinguish different users with decorrelation operations carried out at the receiver.

Finally, the spread signals on all subcarriers are mixed together for transmission through the fading channel. One main task to be discussed in our presentation is to solve the problem of subcarrier allocation, i.e., determining $\{N_i^v\}_{i=1}^K$, which is the number of subcarriers assigned for voice transmission, by considering the subcarrier conditions of user i and the characteristics of voice/data transmission. With the available information on subcarrier allocation and bit loading from the transmitter, the receiver demodulates the voice and data signals to $\{\hat{a}\}_i$ and $\{\hat{b}\}_i$ on each subcarrier of each user.

At the transmitter, subcarrier allocation and bit loading are performed based on the knowledge of instantaneous subcarriers gains [110]. The fading characteristics of subcarriers are assumed to be constant over one OFDM symbol duration, but vary from symbol to symbol. $P_{i,n}$ is assumed to be the transmission power on the nth subchannel of user k. Then, the received SNR from subchannel n of user i can be written as

$$\gamma_{i,n} = \frac{\alpha_{i,n}^2 P_{i,n}}{\sum_{\substack{k=1\\k\neq i}}^{K} \alpha_{k,n}^2 \rho_{i,k}^2(\tau_k) P_{k,n} + \sigma^2}, \tag{5.1}$$

where $\sum_{\substack{k=1\\k\neq i}}^{K} \alpha_{k,n}^2 \rho_{i,k}^2(\tau_k) P_{k,n}$ is the interference term due to the sharing a subcarrier by K users. It is clear that the total interference power suffered by a particular user increases with the transmission power and the average service rates of the other users in the system. These factors are effectively considered in the denominator of the received SNR of the user in (5.1), where $\rho_{i,k}$ is the cross-correlation between the spreading codes for user i and user k, defined in (3.7).

According to the BER bound in (3.13) for the nth subcarrier signal of the ith user,

$$BER \leq \frac{1}{5} \exp\left(\frac{-1.5\gamma_{i,n}}{2^{c_{i,n}} - 1}\right), \tag{5.2}$$

For a given BER, the above equation can be rearranged into the number of bits to be transmitted on the ith user's nth subcarrier

$$c_{i,n} \quad = \quad \log_2\left(1 + \frac{\gamma_{i,n}}{\Gamma_i}\right), \qquad n = 1, 2, \cdots, N; \;\; i = 1, 2, \cdots, K, \tag{5.3}$$

where $\Gamma_i = -\ln(5BER_i)/1.5$. Because the transmission rate is the sum of the rates supported by all subcarriers, the total transmission rate of user i is represented in terms of "bits/OFDM symbol" as [11],

$$R_i = \sum_{n=1}^{N} c_{i,n} = \sum_{n=1}^{N} \log_2(1 + \frac{\gamma_{i,n}}{\Gamma_i}). \tag{5.4}$$

With the number of the bits, $c_{i,n}$, the corresponding power, $\widetilde{P}_{i,n}$, needed for demodulation at the receiver becomes

$$\widetilde{P}_{i,n}(c_{i,n}) = \frac{N_0}{3}\left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2 (2^{c_{i,n}} - 1), \tag{5.5}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-t^2/2}dt$. Therefore, the power needed at the transmitter of user i is

$$P_{i,n}(c_{i,n}) = \frac{\widetilde{P}_{i,n}}{\alpha_{i,n}^2} = \frac{N_0}{3\alpha_{i,n}^2}\left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2 (2^{c_{i,n}} - 1) \tag{5.6}$$

where $\alpha_{i,n}$ is the gain of the nth subchannel for user i. To meet the requirements of the transmission rate R_T^v for voice service, we first calculate $c_{i,n}^v$, which is the number of bits to be loaded on the nth subcarrier, and N_i^v, which is the number of subcarriers used for voice. Then, the total power at the transmitter of user i for voice service is

$$\begin{aligned} P_i^v &= \sum_{n=1}^{N_i^v} P_{i,n}^v(c_{i,n}^v) \\ &= \sum_{n=1}^{N_i^v} \frac{N_0}{3\alpha_{i,n}^2}\left[Q^{-1}\left(\frac{BER_i^v}{4}\right)\right]^2 (2^{c_{i,n}^v} - 1). \end{aligned} \tag{5.7}$$

Once subcarrier allocation and bit loading for voice transmission are completed, the maximization of data transmission rate, R^d, is performed on the condition of allowable transmission power, $P_i^d = P_T/\bar{\alpha}_i^2 - P_i^v$, where $\bar{\alpha}_i$ is the average amplitude of the subchannel from user i to the base station. According to the dynamic power control theory of CDMA system, the received power from each user, say P_T, at the

Table 5.1: The typical characteristics for voice and data transmissions

	Voice Transmission	Data Transmission
Bit Error Rate Requirement	Low	High
Transmission Rate	Low	High
Delay Requirement	High	Medium
Priority	High	Medium

base station should be the same as possible [16]. The use of remaining power for data transmission by the adaptive subcarrier allocation and bit loading algorithm is to be described in Section 5.2.2 (b).

5.2.2 A-SABL algorithm

This section presents the adaptive subcarrier allocation and bit loading algorithm (A-SABL) to support voice and data transmissions in the multiuser OFDM system. The criteria for the adaptive process is to maximize the data throughput R^d under the condition of achieving the required transmission rate R_T^d with the expected BERs for both data and voice services. Since the data service, with the high transmission rate and low BER, generally consumes most of the power, we assign the transmission power for the voice service as less as possible to meet the required QoS. The first step of the A-SABL algorithm is to assign subcarriers and the number of loaded bits for voice service. With the expected BER, the second step makes the best use of the remaining transmission power and subcarriers to maximize the data throughput. It should be pointed out that the A-SABL algorithm is to achieve the subcarrier allocation and bit loading for both voice and data services with the limited transmission power.

(a). Voice transmission

Based on the typical characteristics of voice and data transmissions, as listed in Table 5.1, higher priority of the subcarrier allocation is given to the voice transmission because of its stringent delay requirement. Since high data rates and low

BERs are generally needed for data service, more subcarriers with more transmission power are generally needed. In general, the number of bits, $c_{i,n}$, to be loaded on a subcarrier is increased with the quality of the subchannel, i.e., the higher the SNR, the larger the number of bits to be loaded on the subcarrier. The power to be consumed on the subcarrier is also increased exponentially with the number of loaded bits.

There exist a few different ways of assigning the voice traffic to the subcarriers. The first one is to arrange the available subchannels in an ascending order according to their channel gains, such as:

$$\alpha_{i,1} \leq \alpha_{i,2} \leq \cdots \leq \alpha_{i,N_i^v} \leq \cdots \leq \alpha_{i,N}, \qquad i = 1, 2, \cdots, K. \tag{5.8}$$

Consequently, the subcarrier allocation process begins from the worst subchannel. Each subcarrier with poor channel gain is loaded with a few bits only, such as $c_{i,n} \leq 2$.

Alternatively, the allocation process can be also performed from the best channel to load a relatively larger number of bits, and the subcarriers are arranged with the descending order of the channel gains as,

$$\alpha_{i,1} \geq \alpha_{i,2} \geq \cdots \geq \alpha_{i,N_i^v} \geq \cdots \geq \alpha_{i,N}, \qquad i = 1, 2, \cdots, K. \tag{5.9}$$

For the fixed throughput of voice service, the former allocation method requires many low quality subchannels and the latter approach uses only a fewer high quality subchannels.

The other possible approach to assign subcarrier for voice is the blind allocation without considering the quality of the subchannels. By reasoning and simulation verification, it is seen that the first approach is used for a better performance because it requires much less transmission power to achieve the same BER and the transmission data rate. It can be easily understood that the transmission power required by a subchannel is exponentially increases with the number of loaded bits.

If the subcarrier arrangement in the descending order is chosen, the subcarriers in good quality, to be used at the beginning will carry many bits. Then much more power would be used since the power increases with the number of bits exponentially. However, much less power would be consumed with the subcarrier allocation in an ascending order, since the subcarriers for voice just carry only one or two bits. The power consumption of the subcarrier allocation in original order is between the former two arrangements. Therefore, the subcarrier allocation with the ascending order of channel gains is chosen.

For verification, a simulation was carried out to observe the required number of subcarriers and the transmission power to support voice rate of 50 bits/symbol under the same channel condition, as shown in Fig. 5.2. It is seen that more subchannels have to be used when the allocation process is started with the subchannels whose gains are in an ascending order, compared to that based on the gains of subchannels in a descending order. The number of subcarriers needed by the blind allocation process without considering the quality of the subchannel is between the numbers of subcarriers needed by the methods based on the other two orders.

Fig. 5.3 shows the comparison of power consumption in terms of normalized power among the three subcarrier allocation arrangements for voice service. With the allocation based on the descending order, the transmission power is always larger than that needed by the other two approaches. It is observed that when the average channel SNR is 27 dB, all the available power is consumed for voice transmission and no power is left for data transmission. Referring to the blind allocation of subcarriers, the voice transmission with only 50 bits/symbol uses as high as 40% of the total power when the average channel SNR is 30 dB. Consequently, it is impossible for the remaining 60% of the total power to support the data transmission of 400 bits/symbol. However, only 4% of the total power is used for voice when the allocation is based on the ascending order in (5.8) when the average channel SNR is 30 dB. Therefore, the subcarrier allocation of our algorithm is based on

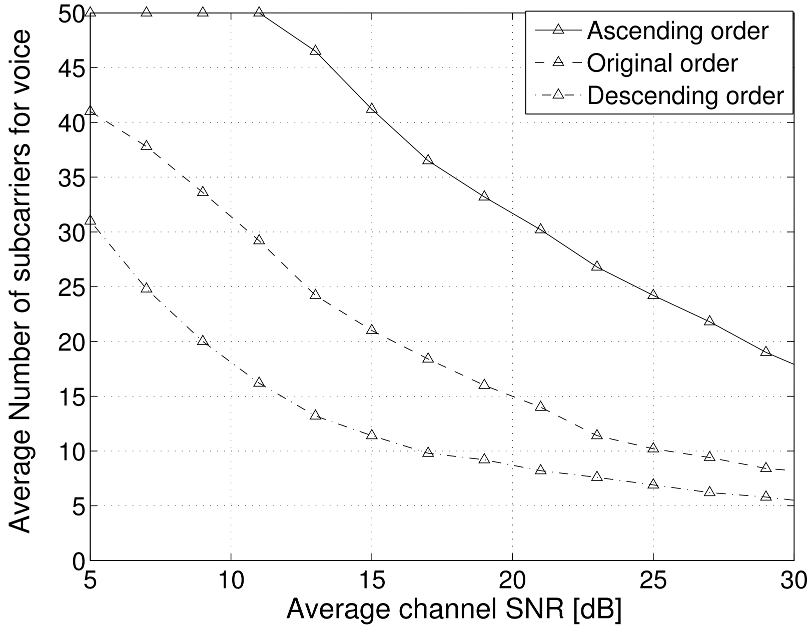


Figure 5.2: Comparison of the number of subcarriers for voice transmission with three subcarrier allocation arrangements ($R^v = 50$ bits/symbol).

the ascending order of the channel gains. Such an arrangement is not only to keep more transmission power for data transmission, but also substantially reduce the multiuser interference as shown in the denominator of (5.1).

Table 5.2 presents the algorithm of subcarrier allocation and bit loading for voice transmission, where U and W are the sets containing the indexes of subcarriers that are to be discarded and to be assigned, respectively. We first exclude the subcarriers in deep fade, as seen by the user, which can not even support BPSK modulation for low BER requirement of voice transmission. Because these subchannels don't have good quality generally, the number of bits, $\hat{c}^v_{i,n}$, loaded on these selected subcarriers are limited within [0, 2]. Subject to the fixed rate R^v_T, the total number of subcarriers, N^v_i, and the corresponding number of loaded bits, $\hat{c}^v_{i,n}$, are determined and stored in the set W. Voice outage is declared when the required power for voice transmission, P^v_i, exceeds a preset threshold, for example, the total or a portion of the total transmission power $P_T/\bar{\alpha}^2_i$.

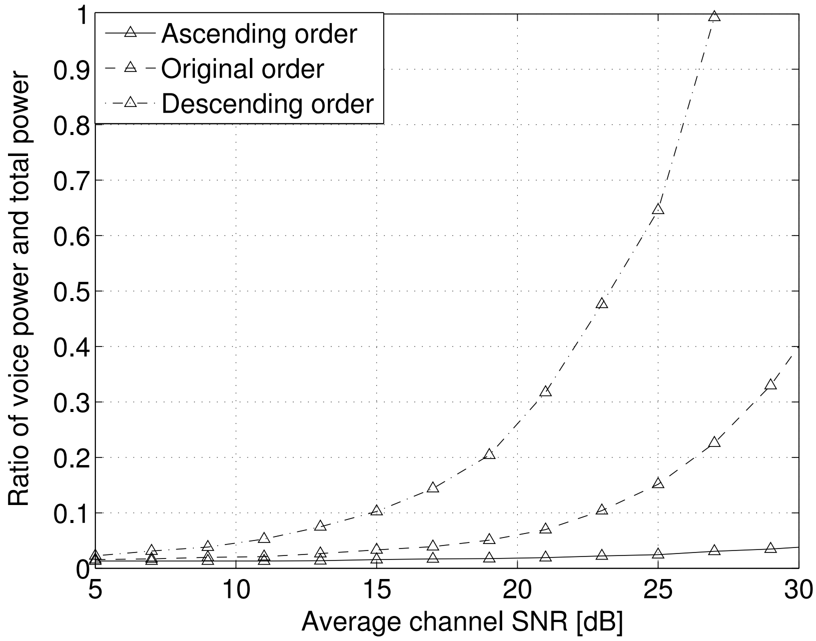


Figure 5.3: Normalized transmission power for voice with three subcarrier allocation arrangements ($R^v = 50$ bits/symbol).

(b). Data transmission

Once the number of subcarriers, i.e., $N_i^d = N - N_i^v$, and their indexes for data transmission are determined, the remaining task is to maximize the total throughput by loading a suitable number of bits onto the available subcarriers. The indexes of the subcarriers usable for data transmission of the ith user are ranked from $N_i^v + 1$ to N. From (5.4), the total throughput for data transmission is

$$\begin{aligned} R_i^d &= \sum_{n=N_i^v+1}^{N} c_{i,n} = \sum_{n=N_i^v+1}^{N} \log_2(1 + \frac{\gamma_{i,n}}{\Gamma_i}) \\ &= \sum_{n=N_i^v+1}^{N} \log_2 \left(1 + \frac{\alpha_{i,n}^2 P_{i,n}/\Gamma_i}{\sum_{\substack{k=1 \\ k\neq i}}^{K} \alpha_{k,n}^2 \rho_{i,k}^2(\tau_k) P_{k,n} + \sigma^2} \right), \\ & \qquad i = 1, 2, \cdots, K. \end{aligned} \tag{5.10}$$

Then the maximization of data throughput

$$\max_{c_{i,n}^d} R_i^d = \max_{c_{i,n}^d} \sum_{n=N_i^v+1}^{N} \log_2 \left(1 + \frac{\alpha_{i,n}^2 P_{i,n}/\Gamma_i}{\sum_{\substack{k=1\\k\neq i}}^{K} \alpha_{k,n}^2 \rho_{i,k}^2(\tau_k) P_{k,n} + \sigma^2} \right) \tag{5.11}$$

is subject to the power limit,

$$\sum_{n=N_i^v+1}^{N} P_{i,n}^d = P_T/\bar{\alpha}_i^2 - P_i^v \tag{5.12}$$

which is the constraint on the available power for data transmission. To achieve the maximum data throughput, the transmission power allocation for data transmission can be performed based on the number of bits assigned to each available subcarrier. The method of power allocation to maximize the total data rate can be found by using the standard Lagrange multiplier technique [99]. Let us define the Lagrangian function as,

$$\begin{aligned} T_i^d &= \sum_{n=N_i^v+1}^{N} \log_2 \left\{ 1 + \frac{\alpha_{i,n}^2 P_{i,n}^d}{\left[\sigma^2 + \sum_{\substack{k=1\\k\neq i}}^{K} \alpha_{k,n}^2 \rho_{i,k}^2(\tau_k) P_{k,n}\right] \Gamma_i} \right\} \\ &\quad - \lambda_i \left[\sum_{n=N_i^v+1}^{N} P_{i,n}^d - (P_T/\bar{\alpha}_i^2 - P_i^v) \right], \end{aligned} \tag{5.13}$$

where λ_i is a Lagrange multiplier. By solving $\partial T_i^d / \partial P_{i,n}^d = 0$ to maximize the total rate of the data transmission, the transmission power allocated to the nth subcarrier of the ith user is

$$\begin{aligned} \hat{P}_{i,n}^d &= \frac{1}{\lambda_i \ln 2} - \frac{\left[\sigma^2 + \sum_{\substack{k=1\\k\neq i}}^{K} \alpha_{k,n}^2 \rho_{i,k}^2(\tau_k) P_{k,n}\right] \Gamma_i}{\alpha_{i,n}^2} = \frac{1}{\lambda_i \ln 2} - \frac{\Psi_{i,n} \Gamma_i}{\alpha_{i,n}^2}, \\ & n = N_i^v + 1, N_i^v + 2, \cdots, N; \quad i = 1, 2, \cdots, K, \end{aligned} \tag{5.14}$$

where $\Psi_{i,n}$ is the interference power to the nth subcarrier of user i due to the additive Gaussian noise and the multiple access. For a fixed set of Lagrangian multipliers $\{\lambda_i\}$ $(i = 1, \cdots, K)$, $\{\hat{P}^d_{i,n}\}^K_{i=1}$ on each subcarrier can be determined by (5.14). By starting from a large value of λ_i and guaranteeing a positive $\hat{P}^d_{i,n}$, an iterative searching algorithm can be used to find the set of $\{\lambda_i\}$ such that the constraints of each user's power for data service can be satisfied, i.e., $\sum_{N^d} \hat{P}^d_n = P_T/\bar{\alpha}^2 - P^v$. This algorithm converges because for a given i, the values of $\{\hat{P}^d_{i,n}\}$ for all n increase as $\{\lambda_i\}$ decrease. As long as the data transmission power of each user is smaller than $P_T/\bar{\alpha}_i^2 - P^v$, which is the total data transmission power, the algorithm will converge to a solution that satisfies the power constraint. Similarly, the numbers of loaded bits, $\left\{\hat{c}^d_{1,n}, \hat{c}^d_{2,n}, \cdots, \hat{c}^d_{K,n}\right\}$, on the subcarriers for the data service transmission for K users are calculated as,

$$\hat{c}^d_{i,n} = \log_2 \left\{ 1 + \frac{3\hat{P}^d_{i,n}}{N_0 \left[Q^{-1}\left(\frac{BER^d_i}{4}\right)\right]^2} \right\}$$

$$n = N^v_i + 1, N^v_i + 2, \cdots, N; \quad i = 1, 2, \cdots, K, \qquad (5.15)$$

which maximizes the total throughput of data transmission.

In practice, $\hat{c}^d_{i,n}$ should be rounded to the nearest integer, $\check{c}^d_{i,n}$, for the corresponding modulation schemes. Consequently, the power allocated on the subcarriers would change into $\check{P}^d_{i,n}$ due to the rounding process of the numbers of bits loaded. It is assumed that F_i represents the floor integer of $\sum^N_{n=N^v_i+1} \hat{c}^d_{i,n}$. After the numbers of bits are rounded to the nearest integers, if $\sum^N_{n=N^v_i+1} \check{c}^d_{i,n} < F_i$, some transmission power will remain, while the transmission power for data, $P_T/\bar{\alpha}_i^2 - P^v_i$, will not be enough to support the numbers of loaded bits if $\sum^N_{n=N^v_i+1} \check{c}^d_{i,n} > F_i$. Therefore, a scheme is needed to perform the adjustment of the transmission power on subcarriers. In order to meet the power condition, two procedures, as shown in Table 5.3, are used to meet the transmission power requirement for data service. Procedure 1 in Table 5.3 deals with the situation of $\sum^N_{n=N^v_i+1} \check{c}^d_{i,n} < F_i$. In order to utilize the transmission power assigned to data service efficiently, it is necessary to allocate one more bit on the nth subcarrier that requires the least additional transmission power. This procedure is repeated until the the transmission power for data service is used up. For the situation of $\sum_{n=N_i^v+1}^{N} \check{c}_{i,n}^d > F_i$, Procedure 2 in Table 5.3 removes one bit from the nth subcarrier from which the most power reduction can be made until the numbers of loaded bits can be supported by $P_T/\bar{\alpha}_i^2 - P_i^v$. Since the data rate is not limited to a certain value, the effect to the system by the rounding and adjustment process will not be considered. As a result, the subcarriers with $\check{c}_{i,n}^d = 0$ are to be discarded. If the total calculated data rate $R_i^d = \sum_{n=N_i^v+1}^{N} \check{c}_{i,n}^d$ is smaller than R_T^d, it means that the transmission power for data service is not enough to support the data rate R_T^d and then the data outage of user i is declared.

According to A-SABL algorithm, different users can share all subchannels, which provides more channel resource to increase the transmission capacity. The ascending arrangement of subcarriers for voice transmission makes best use of those subcarriers with low quality and consumes less power. Since different subcarriers which appear in good quality to one user may not be in good quality for other users, mostly one user is transmitting voice while another one is transmitting data. Each user will find the most suitable subcarriers to it for voice and data transmissions dynamically based on the fading of all subchannels. Consequently, this avoids that some subcarriers are always assigned to one user whatever their fading conditions are.

For maximizing the data rate, it does not mean that the maximized data rate by this proposed algorithm must be higher than the result of other rate-maximization algorithms, since the premise of data rate maximization here is different. Therefore, the comparison with other algorithms in data rate maximization is not necessary.

In this chapter, firstly, voice transmission satisfying its requirement should be guaranteed. Secondly, we want to make best use of the remaining channel and power resource to maximize the data rate. Some papers have already proposed some schemes to maximize the data rate in the OFDM system. The typical one for multiuser system is proposed in [8]. This paper states that the data rate for a specific subcarrier can be maximized when the subcarrier is assigned to only one user who has the best channel gain for that subcarrier. However, in this system, voice and data are transmitted simultaneously and the priority of voice transmission is higher than data transmission. Because it is not necessary to maximize the voice rate, CDMA technique provides the good way to use the subcarriers very efficiently. Otherwise, much more frequency resource will be wasted if the user is assigned only some subcarriers. Besides, if the CDMA technique is only be used in voice transmission and the proposed scheme [8] by Jiho will be used in data transmission, it is not practical, since the premise of Jiho's scheme is that the subcarriers cannot be shared by others, however, the subcarriers have been already assigned to other users for voice transmission.

5.3 Performance comparison based on the theoretical analysis and simulations

We now evaluate the performance of the proposed subcarrier allocation and bit loading algorithm according to Table 5.2, (5.15) and Table 5.3 by computer simulations. The channel is assumed to be modelled by a finite impulse response (FIR) filter with time-varying coefficients. The impulse response for the experiments was generated on the basis of the symbol-spaced impulse response shown in Fig. 4.4 (a) by fading each of the impulses with the Rayleigh distribution of a maximal Doppler frequency of $f_d = 111$ Hz in a wireless system with the carrier frequency of 2.4 GHz and a vehicular velocity of 50 km/h. The channel fading in frequency domain is shown in Fig. 4.4(b).

Let us consider the voice/data OFDM/CDMA system that has 256 subcarriers. Because the higher priority is given to voice transmission, subcarriers are assigned to support voice service first and the remaining subcarriers are used for data transmission. With the A-SABL algorithm, studies are to be made on the performance of voice/data transmission in multiuser systems. Simulation results of the average BERs, service rates and outage probability obtained by the A-SABL method are presented for various average channel SNRs and numbers of users. These results are compared with those of the adaptive multi-rate services (A-MRS) [79] and the uniform M-QAM (U-MQAM) [78], which are extended to be used in the same multiuser OFDM/CDMA system. We assume that the total transmission power is 20 dBm and the required BER for voice, BER^v, and that for data, BER^d, are 10^{-2} and 10^{-5}, respectively. The voice rate requirement R_T^v for the first simulation is assumed to be 50 bits/symbol and R_T^d is 400 bits/symbol.

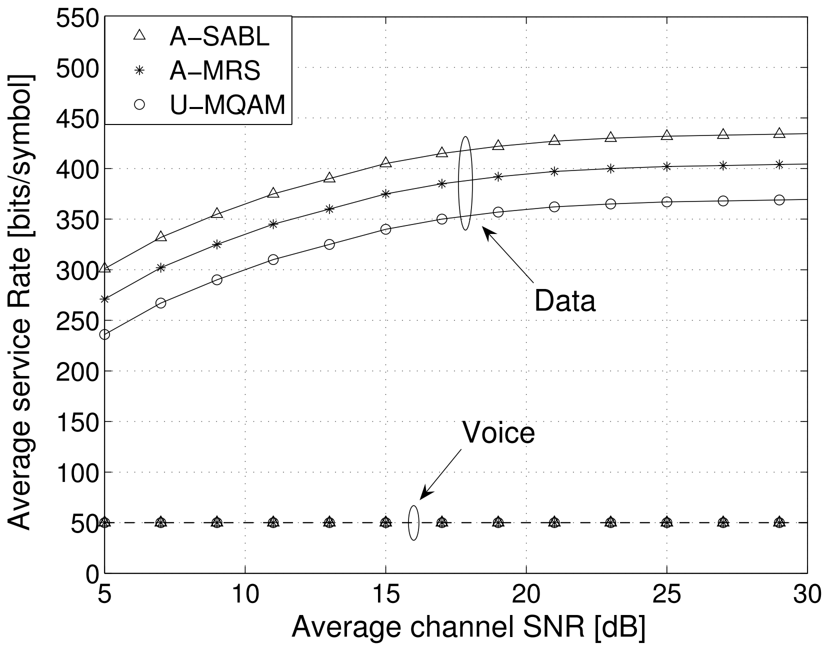


Figure 5.4: Comparison of average voice and data rates in a three-user system.

In terms of the average service rates, Fig. 5.4 shows the voice and data rates supported by the three algorithms with different average channel SNRs in a three-user system. The required voice rate of 50 bits/symbol is guaranteed by A-SABL, A-MRS and U-MQAM. For the data rate, the proposed algorithm, A-SABL, can support 70 bits/symbol more than U-MQAM and nearly 26 bits/symbol more than A-MRS. On the same condition with the same data rate of 400 bits/symbol, the average BER of three users are shown in Fig. 5.5. The voice BERs obtained by the three schemes have similar changes and the BER requirement of 10^{-2} is satisfied when the average channel SNR is more than 16 dB. To achieve BER =

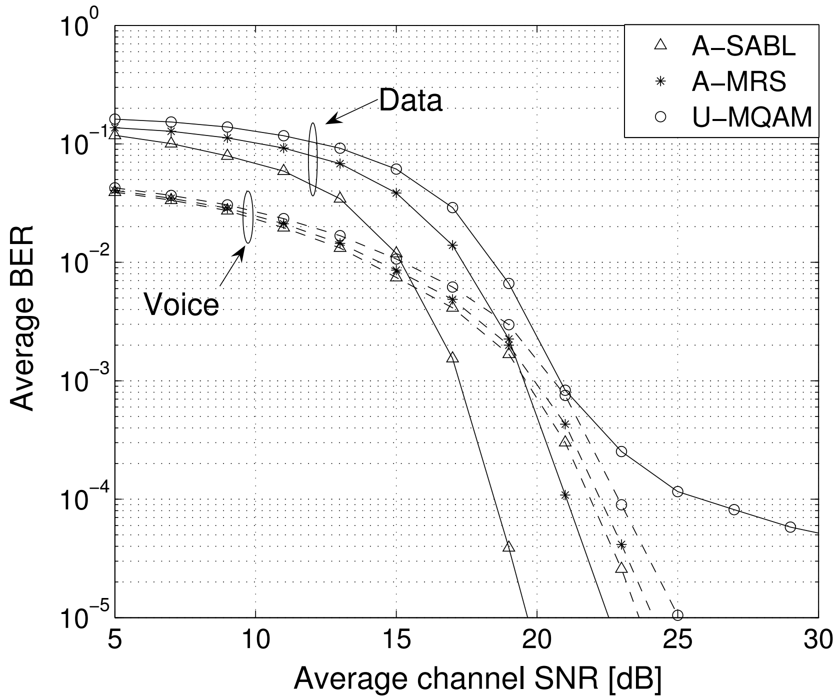
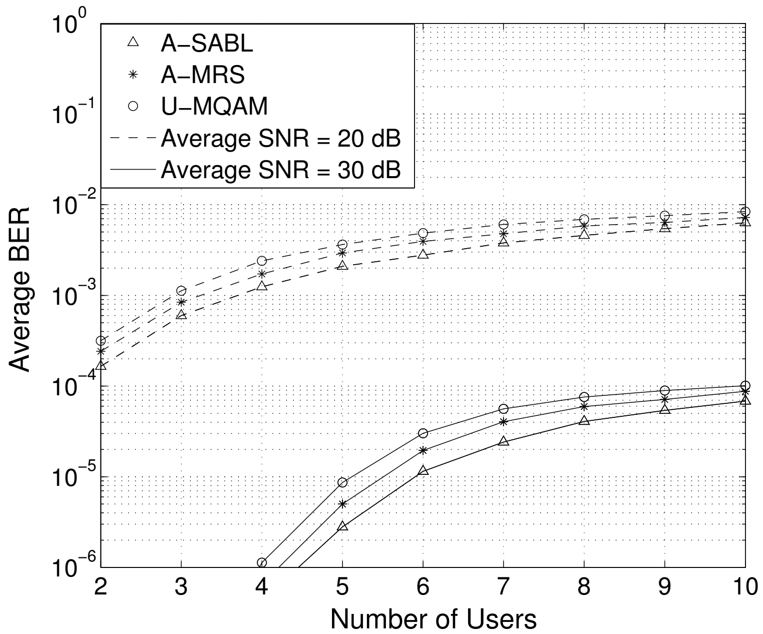


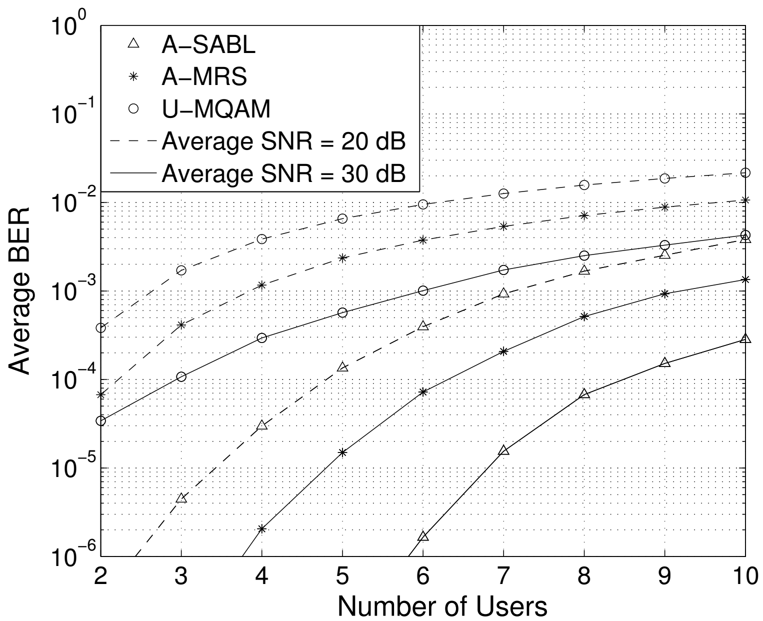
Figure 5.5: Comparison of BERs obtained from simulations of a three-user system.

10^{-5} requirement for data service, the A-SABL must have an average SNR of 19 dB, which is about 3 dB lower than the A-MRS. For the U-MQAM scheme, 400 bits/symbol cannot be possibly supported on this condition to achieve the average BER of 10^{-5}.

Since users in multiuser systems share all the subchannels, the interference among different users has significant effects on the BERs. Fig. 5.6(a) presents the performance of voice service when the average channel SNRs are 20 and 30 dB, respectively. For A-SABL, A-MRS and U-MQAM, the achieved average BERs for voice service have a similar tendency as the numbers of users in the multiuser OFDM/CDMA system is increased. It is seen that when 10 users are in the system, BER requirement of 10^{-2} can be still achieved when the average SNR is 20 dB and the voice rate $R_T^v = 50$ bits/symbol. For data service with the BER requirement of 10^{-5} and rate requirement of 400 bits/symbol, Fig. 5.6(b) shows that the A-SABL algorithm can support 2 more users than the A-MRS as the average channel SNR is 30 dB. For BER requirement of data transmission to be 10^{-4}, the



(a) Voice service.



(b) Data service.

Figure 5.6: Comparison of BERs performance of voice and data services in the system accommodating different numbers of users.

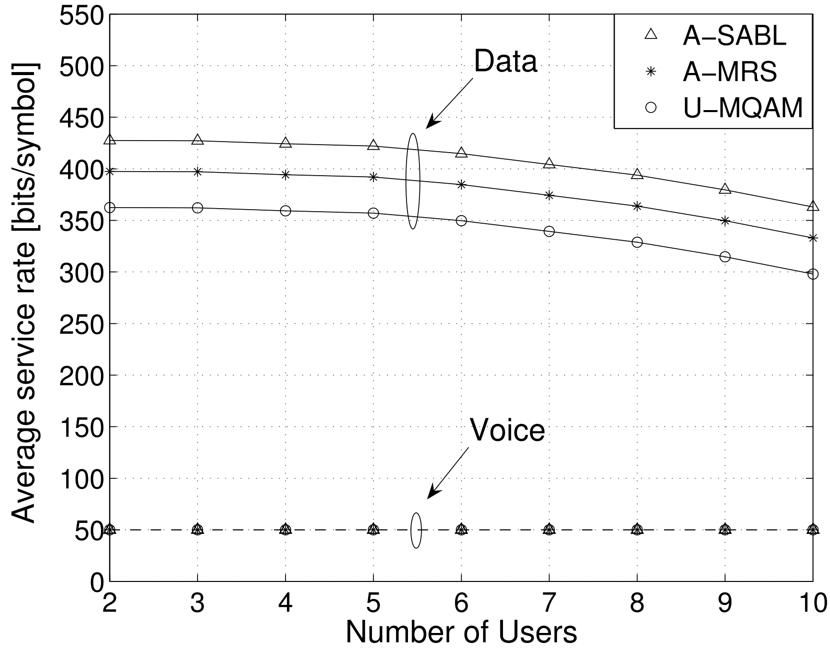


Figure 5.7: Comparison of average voice/data rates in the system accommodating different numbers of users when the average SNR is 20 dB.

proposed algorithm supports at least 3 more users than the A-MRS and U-MQAM, respectively, when the average channel SNR is 20 dB. In general, the BER performance of the A-SABL is degraded when the number of users in the system is increased due to the limited frequency resource. Alternatively, the effect of increasing the number of users can be compensated by reducing the data rates supported by the subcarriers. Fig. 5.7 shows that, at the average channel SNR of 20 dB, the data rate in the system with A-SABL changes from 427 to 365 bits/symbol when the number of users increases from 2 to 10, while the data rates in the system with A-MRS and U-MQAM decrease from 395 to 336 bits/symbol and from 365 to 297 bits/symbol, respectively. However, the voice rates are guaranteed at 50 bits/symbol by the three schemes.

Based on the target BER performance and rate requirements, Appendices D and E derive the outage probability of data service. Since the voice outage is declared when the transmission power for voice exceeds the assigned transmission power, the outage probability of voice service can be obtained from calculating the

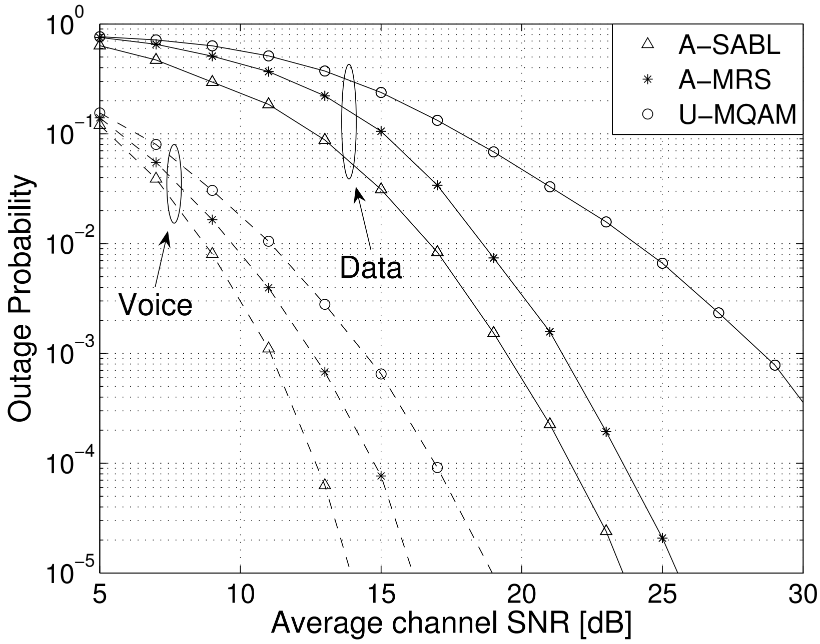


Figure 5.8: Comparison of outage probabilities for voice/data versus average SNR in a three-user system with $R_T^v = 50$ bits/symbol, $R_T^d = 400$ bits/symbol and $BER^v = 10^{-2}$, $BER^d = 10^{-5}$.

transmission power for voice directly. Fig. 5.8 shows the comparison of outage probability for voice/data versus average SNR in a three-user system. With the outage probability of 10^{-3}, the A-SABL achieves 1.5 dB and 4 dB SNR reduction compared with A-MRS and U-MQAM for voice transmission, and nearly 2 dB SNR reduction compared with the A-MRS for data service to achieve the outage probability of 10^{-5}. Due to the poor BER performance of U-MQAM, as shown in Fig. 5.5, it gets much higher outage probability when the data rate requirement is 400 bits/symbol. It is also observed that the performance of the proposed A-SABL algorithm becomes degraded for the high data rate transmission. When the transmission rate for data services reaches 430 bits/symbol, for example, in a three-user system, higher outage probability occurs as shown in Fig. 5.9, which means that the system is too congested and a wider bandwidth is needed for acceptable QoS requirements.

Let us now consider the effects of increasing the transmission rate for voice service

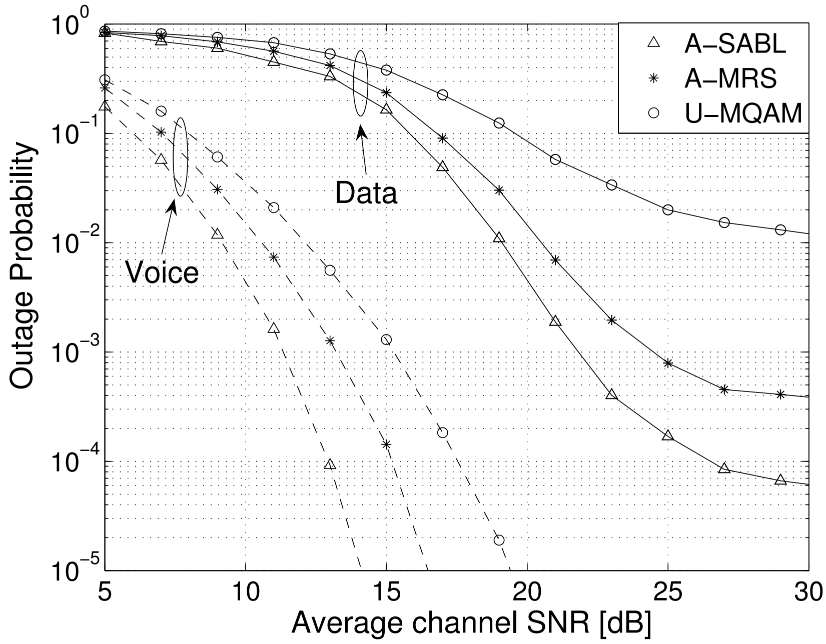


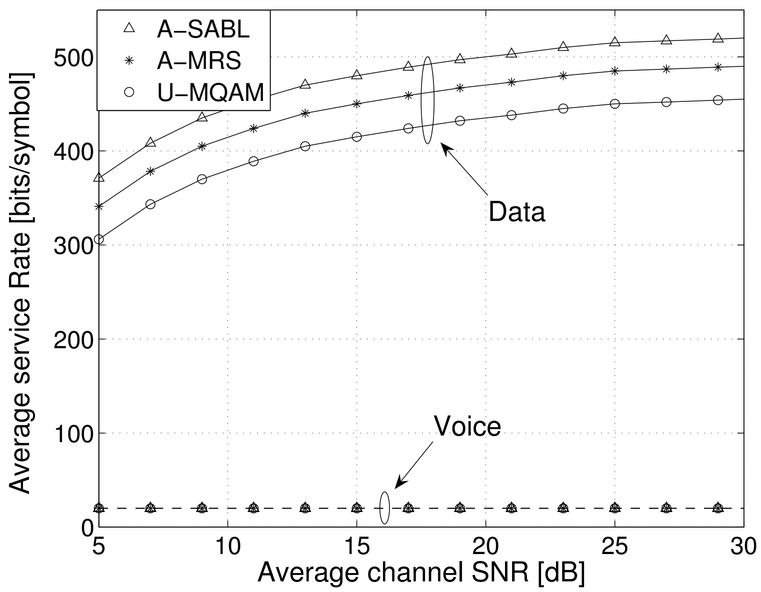
Figure 5.9: Comparison of outage probabilities for voice/data versus average SNR in a three-user system with R_T^v = 50 bits/symbol , R_T^d = 430 bits/symbol and $BER^v = 10^{-2}$, $BER^d = 10^{-5}$.

relative to that for data service. Fig. 5.10(a) and (b) show the effects on the achievable data rates when the voice rate requirements R_T^v are 20 and 80 bits/symbol, respectively. In comparison, the increment of 60 bits/symbol brings the decrement of data rates by nearly 120 bits/symbol since more subcarriers are used for voice transmission. When the voice service requires higher rates, the data rate supporting data service is accordingly reduced since more power and subcarriers have to be used for voice transmission, as shown in Fig. 5.11(a) and (b) for the cases R_T^v = 140 and 200 bits/symbol. When R_T^v = 200 bits/symbol, it is very difficult to support the data rate that is higher than 150 bits/symbol. For more comprehensive observation, Fig. 5.12 shows the decrease of the data rate with the increase of the voice rate at the different average SNRs. When the voice rate reaches 230, 282 and 330 bits/symbol, there would be no data transmission at the average SNR of 5, 10 and 30 dB, respectively. For data transmission, adding one more bit on the subcarriers may consume much more transmission power to guarantee lower BER. Therefore, the total transmission rate decreases when the voice rate increases as shown in Fig. 5.13. Let us consider the case that the system has to only support voice transmission when the voice rate continues increasing. At the average SNR of 5 dB, the maximum voice rate supported is 300 bits/symbol as its curve stops when $R^v = 300$ bits/symbol. This value is 341 at the average SNR of 10 dB. Since most of subcarriers are in good quality at the average SNR of 30 dB, 500 bits/symbol of voice rate can be supported.

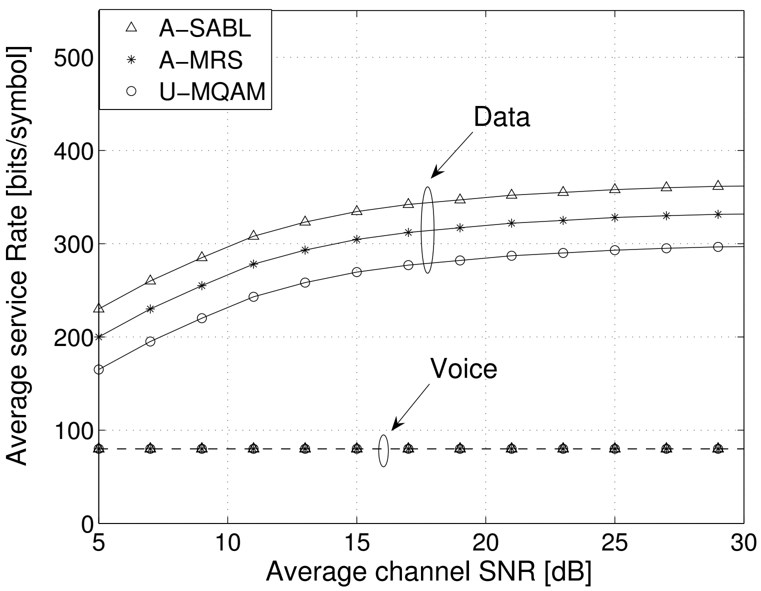
In the aspect of the computational complexity, the voice transmission is processed at first, and at least N loops will be done with nearly $2 \times N_v$ adders. To get the calculated results of the adaptive data transmission, (5.14) and (5.15), N_d loops are to be performed with nine multipliers, two dividers, $(K+1)$ adders and one logarithm in one loop. The power adjustment procedure for the data transmission shown in Table 5.3 would be processed for N_d loops and N_d adders can be shared with other process. Possibly the adaptive data transmission would be delayed since it is performed after the adaptive voice transmission. For the A-MRS algorithm, it is simpler than the proposed algorithm. Once the SNR of each subcarrier from the channel estimation is obtained, it just loads the corresponding number of bits by checking the Bit-SNR table, regardless of the subcarrier order arrangement. U-MQAM is simpler than A-MRS and A-SABL algorithm. U-MQAM combines the voice bit and data bits together. For example, if 4 bits are loaded on one subcarrier, 1 bit will be used for voice and 3 bits will be used for data.

5.4 Conclusion

This chapter proposes an adaptive subcarrier allocation and bit loading algorithm for integrated voice and data transmissions in a multiuser OFDM/CDMA system. The objective is to meet the realtime requirement and the QoS for voice transmission and maximize the transmission throughput for data service and achieve the target BER with the given total transmission power. Since the signal symbols in the OFDM system are transmitted in parallel through a number of orthogo-

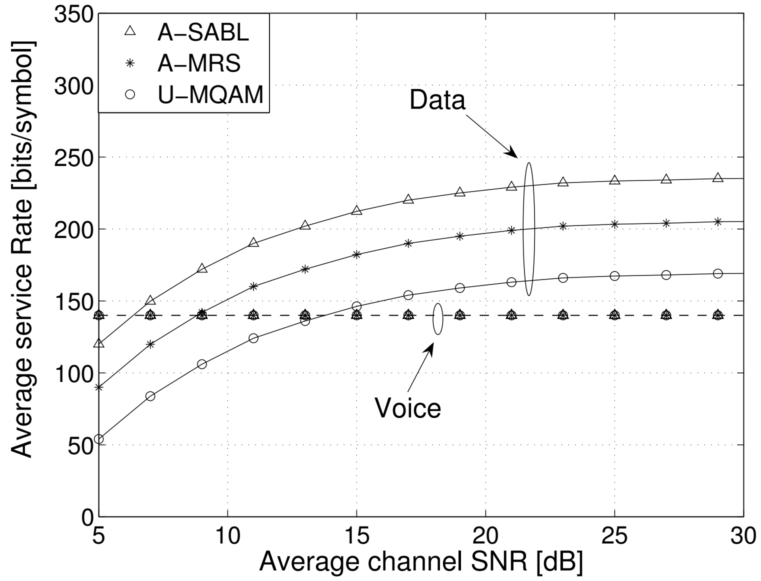


(a) $R_T^v = 20$ bits/symbol

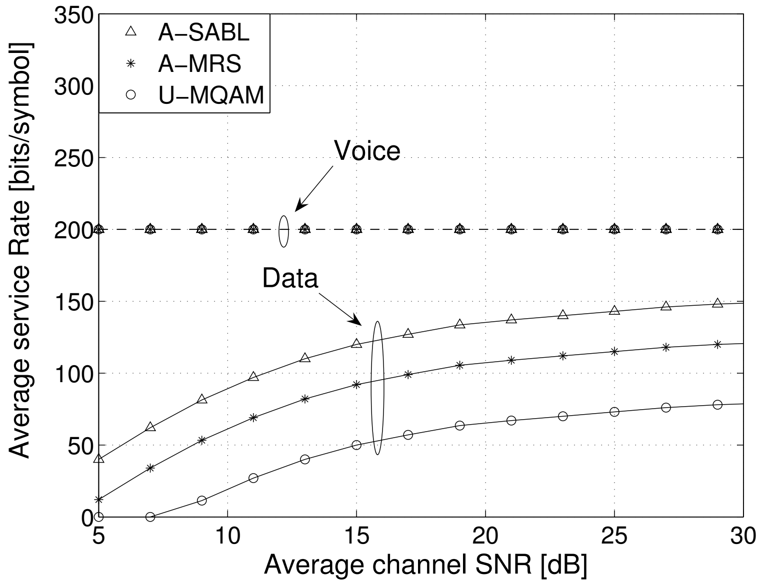


(b) $R_T^v = 80$ bits/symbol

Figure 5.10: Comparison of average voice and data rates in a three-user system ($BER^v = 10^{-2}$ and $BER^d = 10^{-5}$).



(a) $R_T^v = 140$ bits/symbol



(b) $R_T^v = 200$ bits/symbol

Figure 5.11: Comparison of average voice and data rates in a three-user system ($BER^v = 10^{-2}$ and $BER^d = 10^{-5}$).

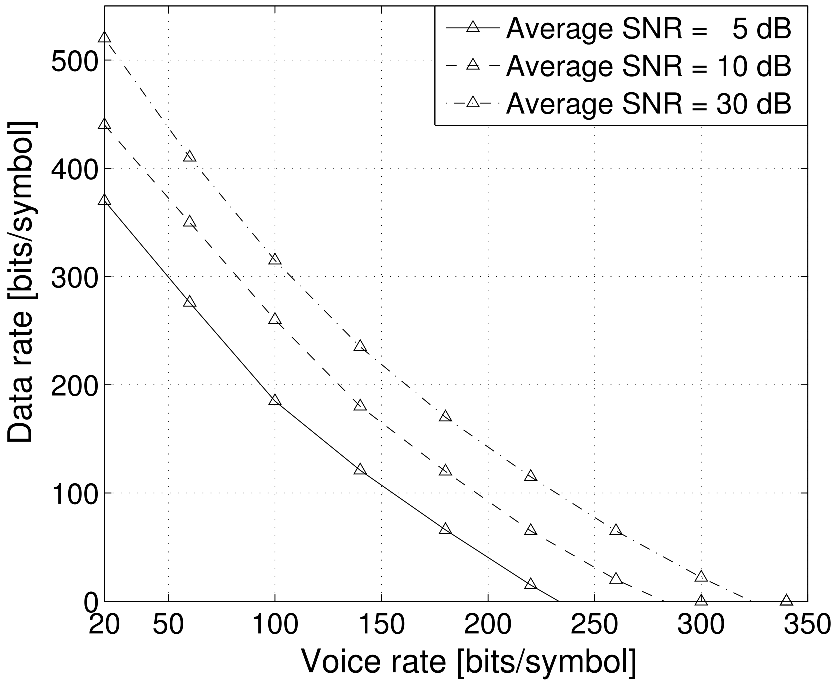


Figure 5.12: Date rate versus Voice rate at different average SNRs in a three-user system ($BER^v = 10^{-2}$ and $BER^d = 10^{-5}$).

nal subcarriers simultaneously, the spectral diversity may be exploited using the proposed adaptive transmission scheme.

The adaptive scheme is derived via two steps. The first one is the subcarrier allocation and bit loading for voice transmission due to the stringent realtime constraints of the voice transmission. The second step is to make the best use of the remaining transmission power and subcarriers to support the maximum data rate according to the variable-rate data transmission requirement. The improved performance obtained by the A-SABL scheme results from more efficient utilization of the total transmission power to support much higher data rate. The simulation results show that the proposed algorithm achieves significantly better performance in terms of supporting data rate, BER and outage probability than that achieved by the A-MRS and U-MQAM methods. The results reported in this chapter are obtained under the assumption of available channel information.

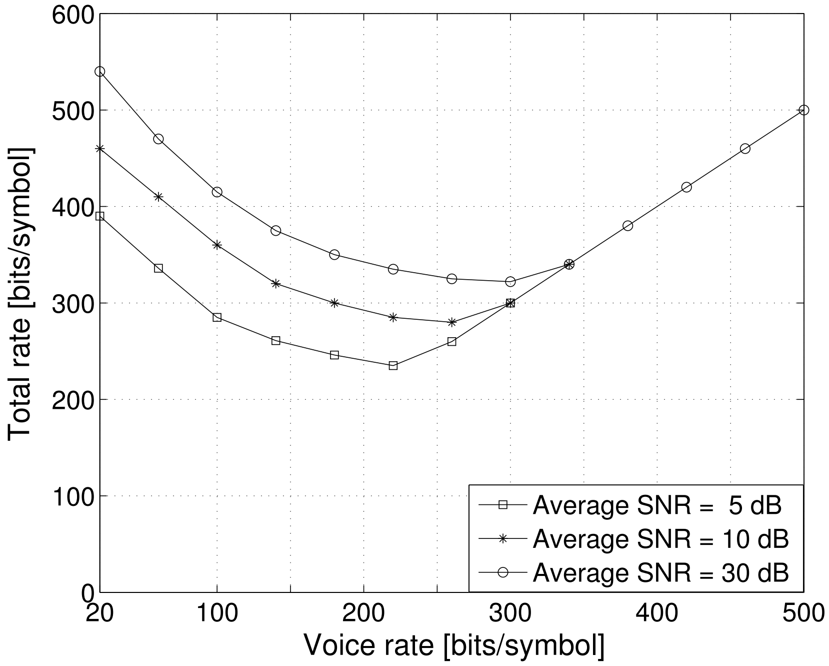


Figure 5.13: Total rate versus Voice rate at different average SNRs in a three-user system ($BER^v = 10^{-2}$ and $BER^d = 10^{-5}$) .

Table 5.2: Algorithms of subcarrier allocation and bit loading for voice transmission of user i

1	Initialization For user i, $\alpha_{i,1} \leq \alpha_{i,2} \leq \cdots \leq \alpha_{i,N}$, $i = 1, 2, \cdots, K$ Let $N_i^v = 0$; $R_i^v = 0$; $W = \{\phi\}$; / * W includes used subcarriers for Voice * / $U = \{\phi\}$; / * U includes discarded subcarriers * / $U \cup V = \{1, \cdots, N\}$; $U \cap V = \{\phi\}$

2	for $n = 1$ to N
	{
	$c_{i,n}^v = 1$; / * BPSK Modulation * /
	$BER_{i,n}^v = \frac{1}{2}\text{erfc}(\sqrt{\gamma_{i,n}})$ [77]; / * According to $\gamma_{i,n}$ in (5.1) * /
	if $BER_{i,n}^v > BER_{i,n}^v$
	{ $U = U \cup n$;
	continue; }
	}
	Obtain V based on U. / * V includes available subcarriers * /

3	for $n = V(1)$ to N / * Start Loading from subcarrier $V(1)$ * /
	{
	$c_{i,n}^v = \log_2\left(1 + \frac{\gamma_{i,n}}{\Gamma_i}\right)$;
	if $c_{i,n}^v > 2$
	{ $c_{i,n}^v = 2$;
	$R_i^v = R_i^v + c_{i,n}^v$; }
	if $R_i^v \leq R_T^v$
	{ $W = W \cup n$;
	$N_i^v = N_i^v + 1$; }
	else
	break;
	}
	$P_i^v = \sum_{n=1}^{N_i^v} P_{i,n}^v(c_{i,n}^v)$; / * Transmission power for Voice * /
	if $P_i^v > P_T/\bar{\alpha}_i^2$
	{ Voice outage occurs; }
	else
	$\{P_i^d = P_T/\bar{\alpha}_i^2 - P_i^v;\}$ / * Transmission power for Data * /

Table 5.3: Adjustment of the transmission power on subcarriers for user i

Procedure 1	**If** $\sum_{n=N_i^v+1}^{N} \check{c}_{i,n}^d < F_i$, /* ***Reloading Operation*** */ Loops begin: For all n and $\check{c}_{i,n}^d$ for data service, $\triangle\check{P}_{i,n}^d = [\check{P}_{i,n}^d(\check{c}_{i,n}^d + 1) - \check{P}_{i,n}^d(\check{c}_{i,n}^d)]/\alpha_{i,n}^2$; /* Find the smallest power increase */ $\hat{n} = \arg\min_n \triangle\check{P}_{i,n}^d$; if $\sum_{n=N_i^v+1}^{N} \check{P}_{i,n}^d < P_T/\bar{\alpha}_i^2 - P_i^v$ $\check{c}_{i,\hat{n}}^d = \check{c}_{i,\hat{n}}^d + 1$; else $\check{c}_{i,\hat{n}}^d$ will not increase; break; Loops end.
Procedure 2	**If** $\sum_{n=N_i^v+1}^{N} \check{c}_{i,n}^d > F_i$, /* ***Unloading Operation*** */ Loops begin: For all n and $\check{c}_{i,n}^d$ for data service, $\triangle\check{P}_{i,n}^d = [\hat{P}_{i,n}^d(\check{c}_{i,n}^d) - \check{P}_{i,n}^d(\check{c}_{i,n}^d - 1)]/\alpha_{i,n}^2$; /* Find the largest power decrease */ $\hat{n} = \arg\max_n \triangle\hat{P}_{i,n}^d$; if $\sum_{n=N_i^v+1}^{N} \check{P}_{i,n}^d > P_T/\bar{\alpha}_i^2 - P_i^v$ $\check{c}_{i,\hat{n}}^d = \check{c}_{i,\hat{n}}^d - 1$; else $\check{c}_{i,\hat{n}}^d$ will not decrease; break; Loops end.

Chapter 6

System performance with inaccurate channel estimation

In Chapter 4 and Chapter 5, two algorithms for ABLA-OFDM for single-service transmission and A-SABL for multi-service transmission, are proposed. However, these algorithms are based on the assumption that the channel information is known by the transceiver. In this chapter, the system performance based on the two proposed algorithms would be analyzed when the channel information obtained by the receiver is inaccurate.

6.1 Introduction

Adaptive modulation in OFDM systems is an attractive technique for high-speed wireless data transmissions. Two adaptive algorithms are put forward to allocate subcarriers and load a suitable number of bits on selected subcarriers, such as the adaptive bit allocation algorithm for the multiuser OFDM/CDMA systems, and the adaptive subcarrier allocation and bit loading for the simultaneous voice/data transmission. The former is suitable to the system in which users would transmit only one kind of service with the fixed data rate, while the latter is used in the

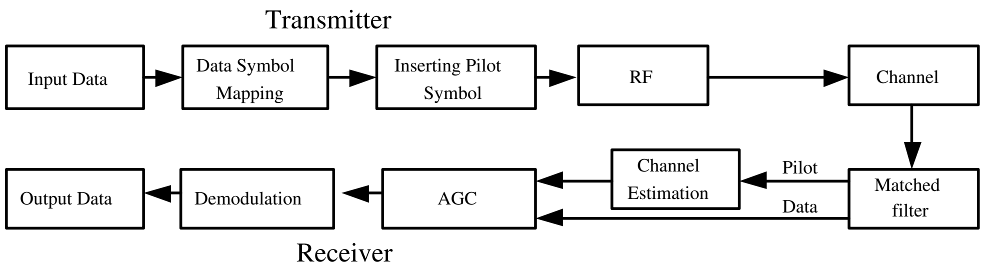


Figure 6.1: System block diagram of the PSAM communication system.

multi-service system with variable data rates.

However, the severe amplitude and phase fluctuations inherent to wireless channel significantly degrade the BER performance of M-QAM. That is because the demodulator must scale the received signal to normalized channel gain so that its decision regions correspond to the transmitted signal constellation. This scaling process is called automatic gain control (AGC) [111]. The AGC improperly scales the received signal if the channel gain is estimated with errors. This can lead to incorrect demodulation even in the absence of noise. Thus, accurate fading compensation techniques at the receiver are required by the reliable communication with M-QAM. Channel estimation of wireless channels is a very effective technique to precisely compensate for inevitable channel amplitude and phase distortion. Channel estimation by pilot symbol assisted modulation (PSAM) were studied in [112–114].

6.2 Pilot Symbol Assisted Modulation (PSAM)

A block diagram of the PSAM communication system is shown in Fig. 6.1. Pilot symbols are periodically inserted into the data symbols at the transmitter for the channel parameters, such as the amplitude α and the phase shift θ, to be extracted and interpolated at the channel estimation stage. These estimated parameters are given by $\breve{\alpha}$ and $\breve{\theta}$, respectively. At the receiver, the received signal goes through the AGC, which compensates for the channel fading by dividing the received signal

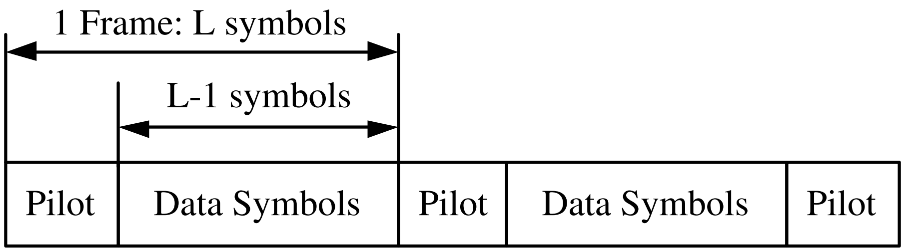


Figure 6.2: Frame format using pilot symbols.

with the fading estimate $\alpha e^{j\theta}$. The demodulated data bits can be obtained by the decision device after the AGC process.

We assume that the channel changes very slowly over each symbol duration. The Rayleigh fading amplitude α follows the probability density function (pdf) [89]

$$f(\alpha) = \frac{2\alpha}{\Omega} e^{-\alpha^2/\Omega}, \quad \alpha > 0 \tag{6.1}$$

where $\Omega = E\{\alpha^2\}$ is the average fading power. The joint distributions $f(\alpha, \check{\alpha})$ and $f(\theta, \check{\theta})$ will be described later. Specifically, as shown in Fig. 6.2, the data is formatted into frames of L symbols, with the first symbol in each frame used for the pilot symbol.

After matched filtering and sampling with perfect symbol timing at the rate of $1/T_s$, a baseband T_S-spaced discrete-time complex-valued signal is obtained as

$$y_k = z_k x_k + n_k. \tag{6.2}$$

The sequence x_k represents complex M-QAM (or M-PSK) and pilot symbols. The sequence z_k represents the fading, which is a complex zero-mean Gaussian random variable for Rayleigh channel, and n_k is AWGN with variance $\sigma^2 = N_0/2$. At the receiver, channel fading at the pilot symbol duration is extracted by dividing the received signal with the known pilot symbols denoted by x,

$$\check{z}_j = \frac{y_j}{x} = z_j + \frac{n_j}{x}. \tag{6.3}$$

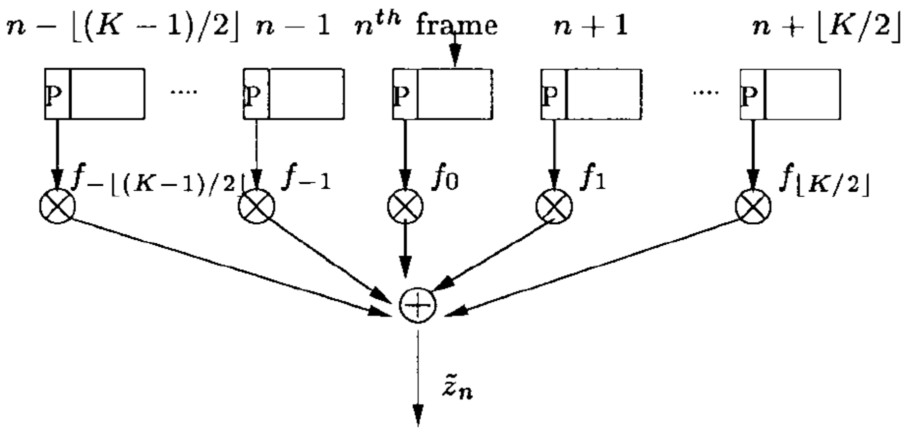


Figure 6.3: Fading interpolation in PSAM.

where z_j is the fading during the pilot symbol in the jth frame. The receiver estimates the fading at the lth data symbol time in the nth frame from the K nearest pilot symbols. For example, as illustrated in Fig. 6.3 [115], the receiver uses $[(K-1)/2]$ pilot symbols from pervious frames, the pilot symbol from the current frame, and the pilot symbols from the $[K/2]$ subsequent frames. Thus, the fading estimate is given by

$$\tilde{z}_n^l = \sum_{k=-[(K-1)/2]}^{[K/2]} f_k^l \tilde{z}_{n+k} \, , \tag{6.4}$$

where $l = 1, 2, \cdots, L-1$ is the data symbol index within each frame, and f_k^l are real interpolation coefficients. Fig. 6.4 shows the pilot pattern within one OFDM symbol. The pilots are inserted into the subcarriers with an interval, the value of which has the inverse ratio to the channel quality. If the channel is good, this interval could be enlarged and the number of pilots is reduced, which can increase the efficiency of the system. While the channel is in deep fading, more pilots should be inserted among subcarriers crowdedly in order to obtain the estimation with fewer errors. As a result, the number of subcarriers for the data transmission would decrease.

Since the estimated fading $\tilde{z}$ is a weighted sum of zero-mean complex Gaussian random variables, it is also a zero-mean complex Gaussian random variable. Thus,

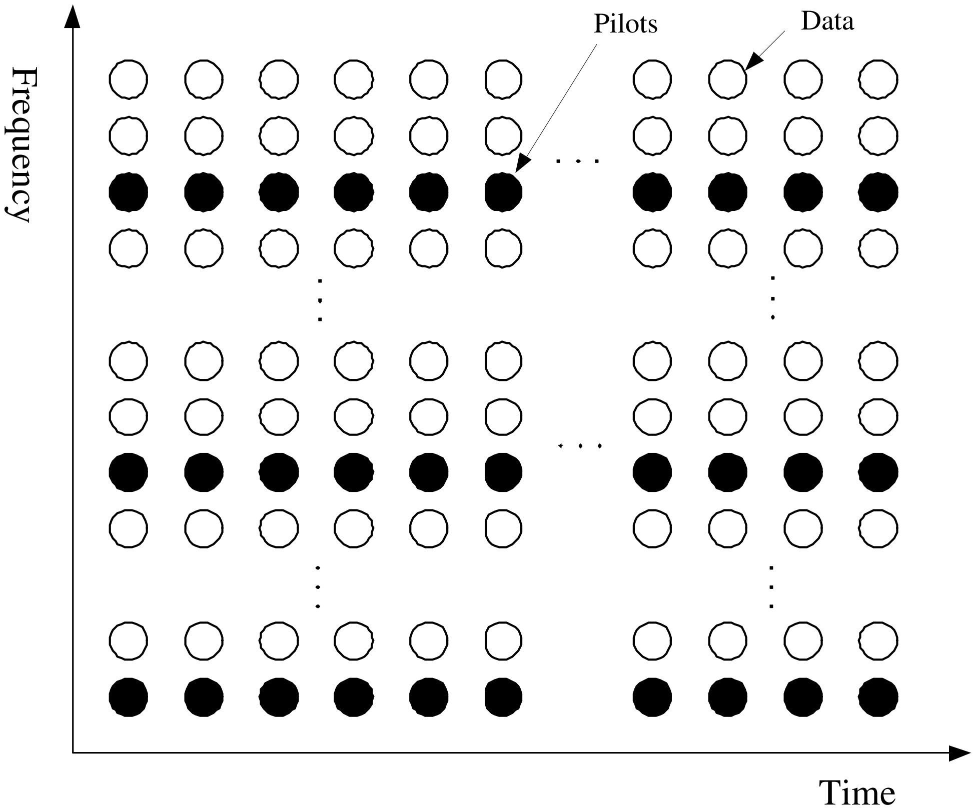


Figure 6.4: Pilot pattern in an OFDM symbol.

the channel amplitude $\alpha = |z|$ and its estimate $\check{\alpha} = |\tilde{z}|$ have a bivariate Rayleigh distribution given by [116]

$$\begin{aligned} f(\alpha, \check{\alpha}) &= \frac{4\alpha\check{\alpha}}{(1-\varphi)\Omega\check{\Omega}} I_0 \left(\frac{2\sqrt{\varphi}\alpha\check{\alpha}}{(1-\varphi)\sqrt{\Omega\check{\Omega}}} \right) \\ &\quad \cdot \exp\left[-\frac{1}{1-\varphi} (\frac{\alpha^2}{\Omega} + \frac{\check{\alpha}^2}{\check{\Omega}}) \right], \end{aligned} \tag{6.5}$$

where $\varphi = (cov(\alpha, \check{\alpha})/\sqrt{var(\alpha^2)var(\check{\alpha}^2)}$, $0 \leq \rho < 1$, is the correlation coefficient between α^2 and $\check{\alpha}^2$, $\Omega = E\{\alpha^2\}$, $\check{\Omega} = E\{\check{\alpha}^2\}$, and I_0 is the zeroth-order modified Bessel function. The phase θ and its estimate $\check{\theta}$ have a joint distribution similar to Eq. (8.106) in [116] given by

$$f(\theta,\check{\theta}) \;=\; \frac{1-\varphi}{4\pi^2}\left[\frac{(1-q^2)^{1/2}+q(\pi-cos^{-1}q)}{(1-q^2)^{3/2}}\right],\ \theta\geq 0,\ \ \check{\theta}\leq 2\pi \tag{6.6}$$

where $q = \sqrt{\varphi}cos(\theta-\check{\theta})$. The derivation of three parameters: φ, Ω and $\check{\Omega}$ are given in [115].

6.3 Estimation error analysis

In the proposed algorithms described in the previous two chapters, such as adaptive bit allocation for multiuser OFDM/CDMA systems and adaptive subcarrier allocation and bit loading for simultaneous voice/data transmission in the multiuser OFDM systems, the channel estimation is assumed to be made perfectly by PSAM. It means that the channel amplitude $\check{\alpha}_n = \alpha_n$ and the phase $\check{\theta}_n = \theta_n$ for each subcarrier. We now relax our earlier assumptions about the estimation errors in the two algorithms. Because the power is proportional to the square of the amplitude, we get the estimation error, $\epsilon = 10\,|lg\,(\check{\alpha}_n^2/\alpha_n^2)| \neq 0$ (in dB) [117]. The effect of estimation error will be dramatic on systems with Rayleigh fading. The channel model is the same as that in the previous chapters. Fig. 6.5(a) shows the amplitudes of subchannels affected by the channel gain overestimation, $\epsilon > 0$. And the effect to the subchannels by the channel gain underestimation is shown in Fig. 6.5(b). Our adaptive subcarrier allocation and modulation schemes use the channel estimation at the base station since the base station can provide more power and complexity for the channel estimation algorithms than the mobile station. At the transmitter, the channel estimation is used to determine the subcarriers assigned and signal constellation and power to be sent. At the receiver, the channel estimation is used to determine which signal constellation and power are sent, and also to scale the decision regions of the MQAM demodulator corresponding to the constellation and power. Note that the channel estimation used to determine the signal constellation and power must be strictly causal since the transmitter must adapt to the time-varying channel. However, the channel estimation used to scale the decision regions can be noncausal (i.e., it can interpolate between past and future channel estimates or pilot symbols), although this will introduce delay in the decoding.

The estimation error therefore affects the BER of the adaptive system in two ways. The transmission power and the number of loaded bits on the nth subcarrier will be adapted as $P(\breve{\alpha}_n)$ and $c(\breve{\alpha}_n)$ instead of $P(\alpha_n)$ and $c(\alpha_n)$, which may cause a change in the target data rates and BERs. In the following parts, the effects of the channel estimation errors for a particular user will be analyzed.

6.3.1 Estimation error analysis for Case 1: ABLA algorithm

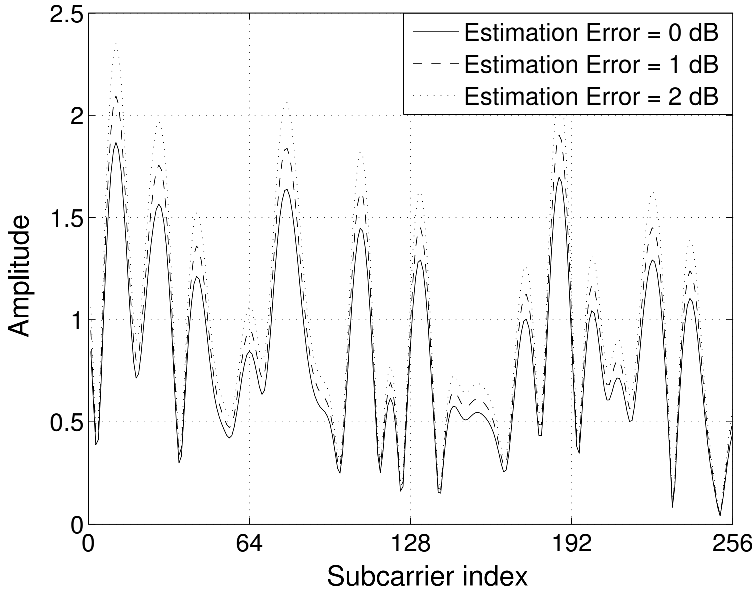
For this case, the adaptive bit allocation algorithm for the multiuser OFDM/CDMA system (ABLA-OFDM), the estimated subchannel amplitude $\breve{\alpha}_n$ should be

$$\breve{\alpha}_n^2 \quad = \quad 10^{\pm\epsilon/10} \cdot \alpha_{i,n}^2, \tag{6.7}$$

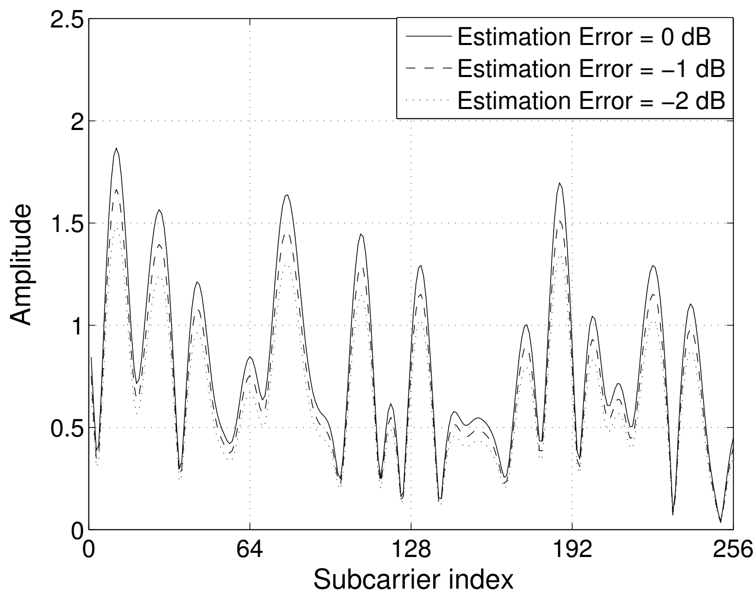
if ϵ is defined in dB. When the channel estimation error is $\{1, -1\}$ or $\{2, -2\}$ dB, $\breve{\alpha}/\alpha$ would be $\{1.12, 0.89\}$ or $\{1.26, 0.79\}$ respectively. Based on (4.14) and the channel estimation errors, we calculate the number of bits loaded on the nth subcarrier of user i,

$$\breve{c}_{i,n} \quad = \quad \log_2 \left\{ \frac{10^{\pm\epsilon/10} \cdot \beta_i' \, \alpha_{i,n}^2}{\frac{N_0 \ln 2}{3} \left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2 \left[10^{\pm\epsilon/10} \, \alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i'\right]} \right\}, \tag{6.8}$$

where $\beta_i' = \{\beta_{i,+\epsilon}', \beta_{i,-\epsilon}'\}$ $\lambda' = \{\lambda_{+\epsilon}, \lambda_{-\epsilon}\}$. Because of the channel estimation error ϵ, the bits loaded on the nth subcarrier becomes more (when $\breve{\alpha}_n > \alpha_n$, called



(a) $\epsilon = 0$, 1 and 2 dB.



(b) $\epsilon = 0$, -1 and -2 dB.

Figure 6.5: Wideband channel with different channel estimation errors.

overestimation) or less (when $\check{\alpha}_n < \alpha_n$, called underestimation) than the ideal $c_{i,n}$, which is the number of bits obtained in terms of the perfect channel estimation. Based on the constraint in (4.8), we have

$$\sum_{n=1}^{N} \check{c}_{i,n} = R_i, \tag{6.9}$$

and

$$\sum_{n=1}^{N} c_{i,n} = R_i. \tag{6.10}$$

Therefore, referring to (6.8), (6.9) can be rewritten as,

$$\begin{aligned} R_i &= \sum_{n=1}^{N} \check{c}_{i,n} \\ &= \sum_{n=1}^{N} \log_2 \left\{ \frac{10^{\pm\epsilon/10} \cdot \beta_i' \, \alpha_{i,n}^2}{\frac{N_0 \ln 2}{3} \left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2 \left[10^{\pm\epsilon/10} \, \alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i'\right]} \right\} \\ &= \log_2 \prod_{n=1}^{N} \left\{ \frac{10^{\pm\epsilon/10} \cdot \beta_i' \, \alpha_{i,n}^2}{\frac{N_0 \ln 2}{3} \left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2 \left[10^{\pm\epsilon/10} \, \alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i'\right]} \right\} \\ &= \log_2 \frac{10^{\pm\epsilon\, N/10} \cdot {\beta'}_i^N \, \alpha_{i,n}^2}{\left\{\frac{N_0 \ln 2}{3} \left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2\right\}^N} \\ &\qquad \cdot \prod_{n=1}^{N} \left[10^{\pm\epsilon/10} \, \alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i' \right]. \end{aligned} \tag{6.11}$$

Correspondingly, we get (6.12) from (6.10),

$$R_i = \sum_{n=1}^{N} c_{i,n}$$

$$= \log_2 \frac{\beta_i^N \, \alpha_{i,n}^2}{\left\{\frac{N_0 \ln 2}{3}\left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2\right\}^N} \cdot \prod_{n=1}^{N}\left[\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i\right]. \quad (6.12)$$

Then in terms of (6.11) and (6.12),

$$\log_2 \frac{10^{\pm\epsilon N/10} \cdot {\beta'}_i^N \, \alpha_{i,n}^2}{\left\{\frac{N_0 \ln 2}{3}\left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2\right\}^N} \cdot \prod_{n=1}^{N}\left[10^{\pm\epsilon/10}\,\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda'_i\right]$$
$$= \log_2 \frac{\beta_i^N \, \alpha_{i,n}^2}{\left\{\frac{N_0 \ln 2}{3}\left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2\right\}^N} \cdot \prod_{n=1}^{N}\left[\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i\right], \quad (6.13)$$

we derive

$$\beta'_i = 10^{\pm\epsilon/10}\,\beta_i \cdot \left[\prod_{n=1}^{N} \frac{10^{\pm\epsilon/10}\,\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda'_i}{\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i}\right]^{\frac{1}{N}}. \quad (6.14)$$

After replacing β'_i in (6.8), we have

$$\check{c}_{i,n} = \log_2 \left\{ \frac{10^{\pm\epsilon/10} \cdot 10^{\pm\epsilon/10}\,\beta_i \cdot \left[\prod_{n=1}^{N} \frac{10^{\pm\epsilon/10}\,\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda'_i}{\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i}\right]^{\frac{1}{N}} \alpha_{i,n}^2}{\frac{N_0 \ln 2}{3}\left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2 \left[10^{\pm\epsilon/10}\,\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda'_i\right]} \right\}$$
$$= \log_2 \left\{ \frac{\beta_i \, \alpha_{i,n}^2}{\frac{N_0 \ln 2}{3}\left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2 \left[\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i\right]} \right\}$$
$$+ \log_2 \left\{ \frac{10^{\pm 2\epsilon/10} \left[\prod_{n=1}^{N} \frac{10^{\pm\epsilon/10}\,\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda'_i}{\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i}\right]^{\frac{1}{N}}}{\frac{10^{\pm\epsilon/10}\,\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda'_i}{\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i}} \right\}$$

$$= \quad c_{i,n} + \log_2 \left\{ \frac{10^{\pm 2\epsilon/10} \left[\prod_{n=1}^{N} \frac{10^{\pm\epsilon/10}\, \alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i'}{\alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i} \right]^{\frac{1}{N}}}{\frac{10^{\pm\epsilon/10}\, \alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i'}{\alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i}} \right\}. \qquad (6.15)$$

The second term of (6.15) shows the effect by the error estimation. If the condition below,

$$10^{2\epsilon/10} \cdot \left[\prod_{n=1}^{N} \frac{10^{\epsilon/10}\, \alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i'}{\alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i} \right]^{\frac{1}{N}} > \frac{10^{\epsilon/10}\, \alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i'}{\alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i}, \qquad (6.16)$$

is met, the channel is overestimated and the calculated number of loaded bits would be larger than the that when the channel estimation is perfect, $\check{c}_{i,n} > c_{i,n}$. And if

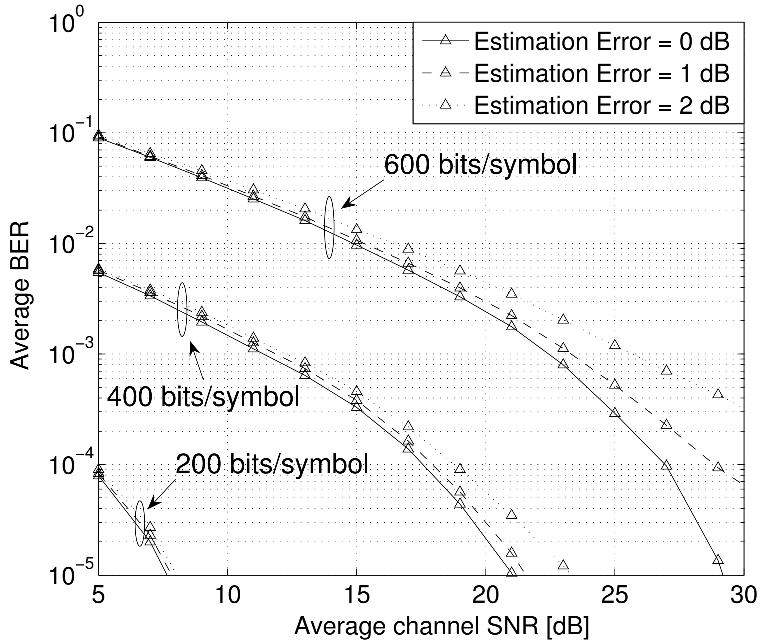
$$10^{-2\epsilon/10} \cdot \left[\prod_{n=1}^{N} \frac{10^{-\epsilon/10}\, \alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i'}{\alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i} \right]^{\frac{1}{N}} < \frac{10^{-\epsilon/10}\, \alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i'}{\alpha_{i,n}^2 \sum_{\substack{k=1 \\ k\neq i}}^{K} \rho_{i,k}^2(\tau_k) - \lambda_i}, \qquad (6.17)$$

the channel is underestimated and fewer number bits would be calculated, such as $\check{c}_{i,n} < c_{i,n}$. After the number of bits loaded on the nth subcarrier is calculated loaded on the nth subcarrier, it should be rounded to the nearest integer. Consequently, the actual data rate to support each user may be smaller or larger than the given data requirement. Then Table 4.1 will be used to deal with this problem and the number of loaded bits will be adjusted by Table 4.2.

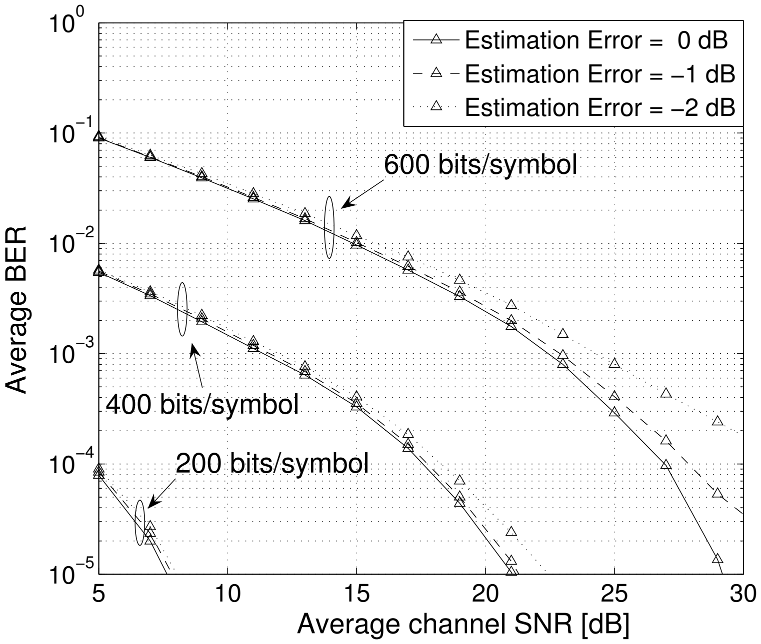
Normally, when the channel is overestimated, $\check{\alpha}_n > \alpha_n$, the obtained number of bits on subcarriers based on the algorithm will be more than those obtained from the perfect channel estimation. Consequently, the BER will increase with the number of bits on subcarriers accordingly. However, in the ABLA-OFDM algorithm, based on the requirements of the transmission power and the data rate, these constraints can clamp the number of bits on subcarriers, which prevents the substantial increase of BER. When the channel is underestimated, these constraints would "remind" the algorithm that some remaining power should be fully used to achieve the data rate requirement. Accordingly, more bits are to be loaded based on the ABLA-OFDM algorithm. In addition, based on Table 4.1 and Table 4.2, the procedures in the two tables guarantee the required transmission rates and the efficient utilization of the transmission power. The self-adjustment procedures reduce the impairments further on the adaptive system due to the channel estimation errors.

Although some procedures in the ABLA-OFDM algorithm try to reduce the effects by the channel estimation errors, the impairment to the system performance cannot be eliminated. When the channel is estimated perfectly, the number of bits are obtained in (4.14) by the suboptimal scheme in the ABLA-OFDM algorithm, which is the premise on which the bit adjustment procedures in Table 4.1 and Table 4.2 are applied. However, this premise, $\check{c}_{i,n}$, is changed, as shown in (6.15), if the channel is estimated with errors. As a result, the whole performance of the system would be affected.

Fig. 6.6(a) and (b) give us the comparison of BER obtained from simulations of a three-user system with same data rates, such as 200, 400 and 600 bits/symbol when the channel estimation errors are 0, ±1 and ±2 dB respectively. When the average SNR varies between 5 and 20 dB, the required SNR for the systems, with three different data rates, increases less than 1 dB when $\epsilon = \pm1, \pm2$ dB, as shown in Fig. 6.6(a) and (b). When the average SNR is larger than 20 dB and the required BER is 10^{-5}, more negative effects resulting from ϵ occur with the increase of the supported data rates. When the average SNR increases, the difference between the

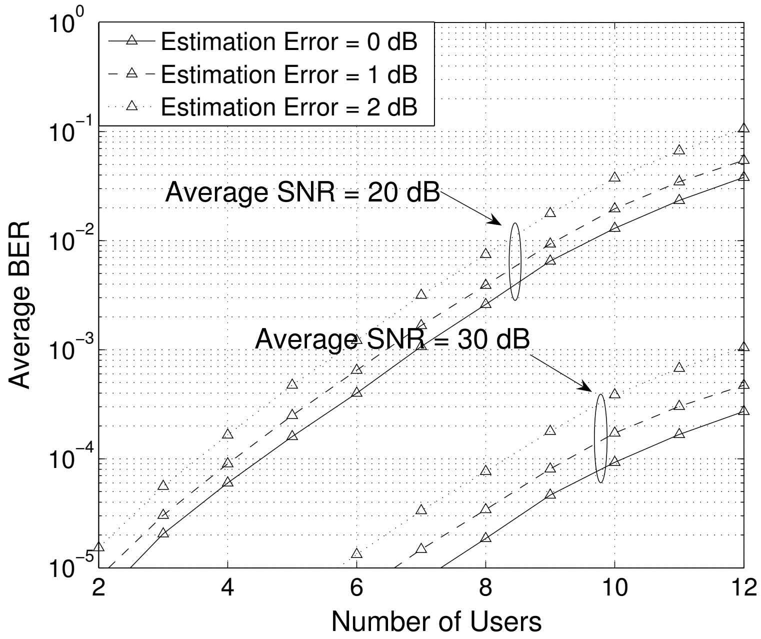


(a) ϵ = 0, 1 and 2 dB.

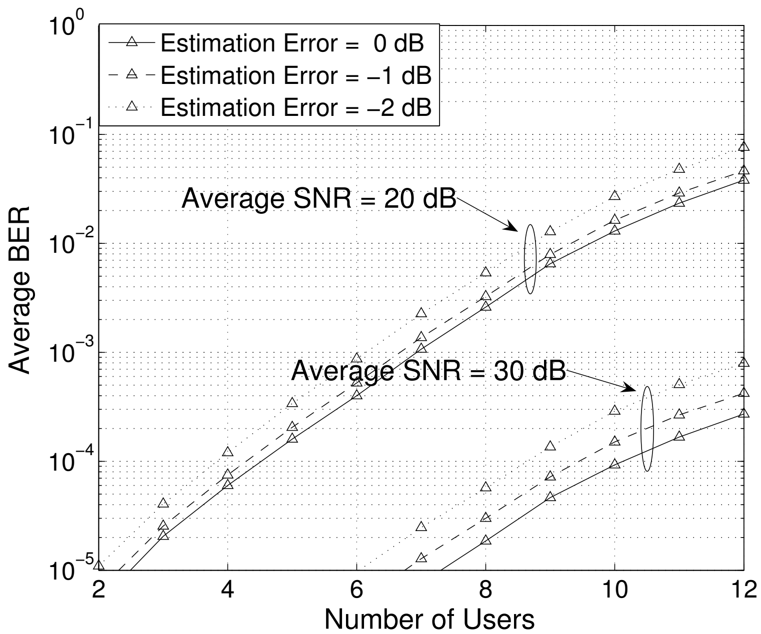


(b) ϵ = 0, -1 and -2 dB.

Figure 6.6: Average BERs of the three users with the different average SNRs. (Case 1)

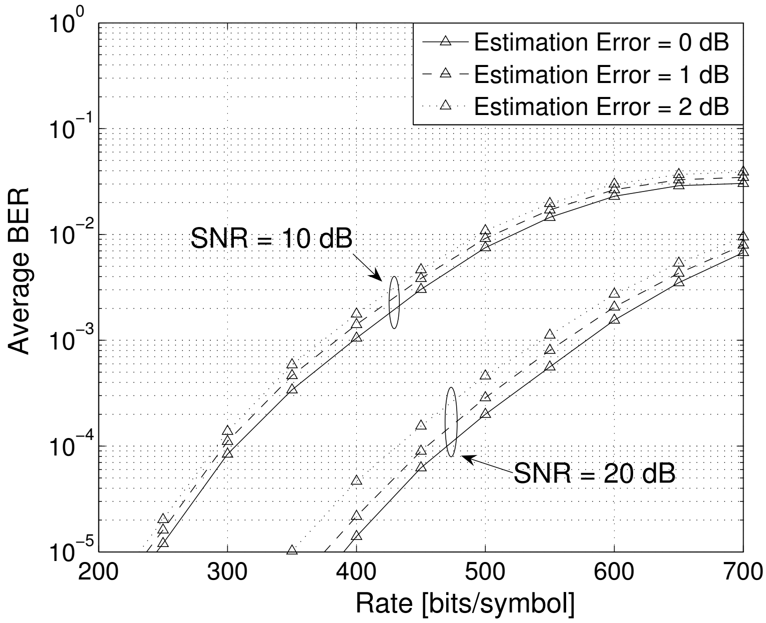


(a) $\epsilon = 0$, 1 and 2 dB.

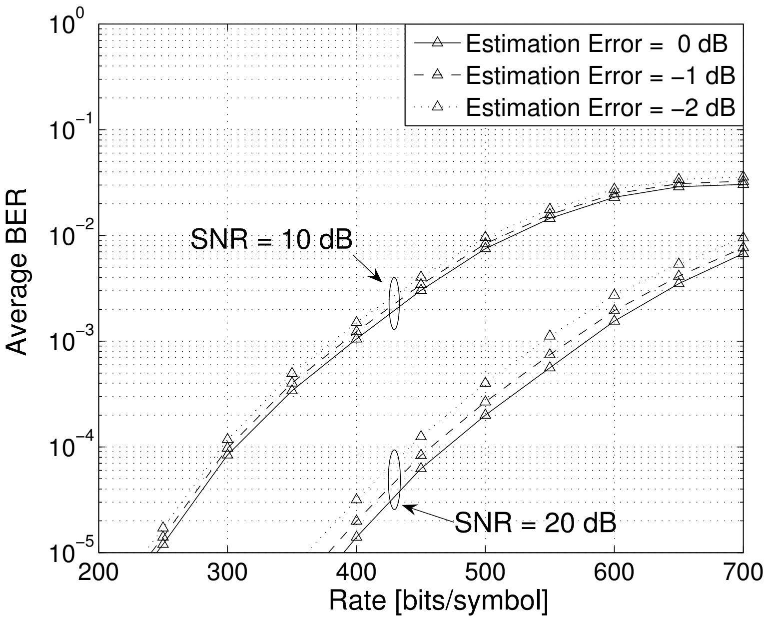


(b) $\epsilon = 0$, -1 and -2 dB.

Figure 6.7: Average BERs with the different number of users supported when the supported data rate is 400 bits/symbol. (Case 1)



(a) $\epsilon = 0$, 1 and 2 dB.



(b) $\epsilon = 0$, -1 and -2 dB.

Figure 6.8: Average BERs of the three users with the different data rates supported. (Case 1)

affected transmission performance by ϵ would increase since more bits are loaded and then the effects to the number of loaded bits by the estimation errors increase accordingly at a higher average channel SNR. The effects by the channel estimation errors can be also explained in terms of the system capacity. Fig. 6.7(a) shows, when the average SNR is 20 dB and the data rate is 400 bits/symbol, the system, affected by $\epsilon = 2$ dB, accommodates 6 users with BER $= 10^{-3}$, while 7 users can be supported by the system with perfect channel estimation. When ϵ is -2 dB, the required BER is 10^{-5} and the average SNR is 30 dB, the system capacity is decreased in one user, compared with the system with $\epsilon = 0$ dB. For $\epsilon = 1$ dB, only little negative effect on the system performance occurs. As for the performance of the transmission with high data rates, in Fig. 6.8(a) and (b), only 40 bits/symbol is reduced at most because of the inaccurate channel estimation with ±1 and ±2 dB when the average SNR is 10 or 20 dB. For the effect to the system performance, there is some difference between the channel overestimation and underestimation. Compared with the channel underestimation, more bits are already loaded on some subcarriers when the algorithm begins since the subchannel gains are overestimated. This leads to higher BERs on these subcarriers, although the data rate requirement clamp the number of bits on some subcarriers. Whereas, in order to meet the data rate requirement if the channel underestimation occurs, the inadequate number of bits will be loaded at last. Therefore, the BER performance with channel underestimation is better than with channel overestimation.

As a whole, the simulation results show little impairment on the adaptive algorithm by the channel estimation errors. Due to the constraints of the data rate and transmission power, and self-adjustment procedures in the ABLA-OFDM algorithm, the effects on the adaptive system performance by the inaccurate channel estimation is reduced, which is significant for the application of the adaptive algorithm with less strict channel estimation.

6.3.2 Estimation error analysis for Case 2: A-SABL algorithm

The effect to the performance is different between the Case 1 (ABLA-OFDM for single-service) and Case 2 (A-SABL for multi-service) when the inaccurate channel estimation occurs. If the subchannel amplitude estimated is higher than the actual one, the number of bits on subcarriers for the voice service would increase and some subcarriers with low channel gains, to be discarded, may be allocated some bits. Thus, much more transmission power will be consumed to support more bits on subcarriers, especially those with low channel gains, to meet the BER requirement of voice service. Although the transmission rate of the voice service is satisfied, a little more remaining subcarriers may not support better performance for the data service since less power remains. If the subchannel amplitude estimated is lower than the actual one, more subcarriers would be allocated to the voice to guarantee its transmission rate requirement. Consequently, the maximization of the data rate is interfered with since the data service gets fewer subcarriers according to its strict BER requirement.

For the voice transmission, the subcarrier allocation and bit loading scheme allocates the number of bits according to the estimated subchannel SNRs at the receiver, as shown in Procedure 2 and 3 of Table 5.2. Due to the estimation errors, the number of subcarriers in Group $\{U\}$, to be discarded, will decreases or increases when the channel is overestimated or underestimated.

For the data transmission, based on the power allocation in (5.14) and the channel estimation errors, $\pm\epsilon$, for user i, the transmission power allocated on the nth subcarrier of user i can be written as,

$$\check{P}^{d}_{i,n} = \frac{1}{\lambda'_i \ln 2} - \frac{\Psi_{i,n}\,\Gamma_i}{10^{\pm\epsilon/10}\alpha^2_{i,n}}, \qquad (6.18)$$

where $\lambda'_i = \{\lambda'_{i,+\epsilon}, \lambda'_{i,-\epsilon}\}$. Then the same iterative searching algorithm described in Chapter 5 will be applied to determined the value of $\hat{P}^d_{i,n}$. With the channel estimation errors, the number of bits loaded to the nth carrier for data transmission of user i can be calculated according to (5.15),

$$\begin{aligned}\check{c}^d_{i,n} &= \log_2\left\{1+\frac{3\,\check{P}^d_{i,n}}{N_0\left[Q^{-1}(\frac{BER^d_i}{4})\right]^2}\right\}\\ &= \log_2\left\{1+\frac{3\left(\frac{1}{\lambda'_i\ln 2}-\frac{\Psi_{i,n}\,\Gamma_i}{10^{\pm\epsilon/10}\alpha^2_{i,n}}\right)}{N_0\left[Q^{-1}(\frac{BER^d_i}{4})\right]^2}\right\}.\end{aligned} \tag{6.19}$$

In practice, $\check{c}^d_{i,n}$ should be rounded to the nearest integers to use the corresponding modulation schemes based on the power adjustment in Table 5.3.

Overestimation

According to the result of A-SABL algorithm, if the channel is overestimated, $\check{\alpha_n} > \alpha_n$, the number of bits on subcarriers for the voice service would increase and some subcarriers with low channel gains, to be discarded, may be allocated one or two bits. Thus, much more transmission power will be consumed to support more bits on subcarriers, especially those with low channel gains, to meet the BER requirement of voice service, as analyzed in Appendix F. And less transmission power remains for the data transmission. Although the number of sucarriers, N^d, for data service increases, the increment is slight for data transmission with high data rates when the overestimation error is within [0, 2]. That is because the voice rate is only 50 bits/symbol and the number of bits loaded on a subcarriers is limited to 2.

Fig. 6.9 shows the BER performance of the voice and data transmissions with different channel overestimation errors, $R^v_T = 50$ bits/symbol and $R^d_T = 400$ bits/symbol. As the voice has the lower transmission rate, the negative impact by ϵ is not much and its BER requirement can be satisfied. The impairment to the performance of the voice transmission results from that some subcarriers suffering severe fading are chosen. When ϵ is 2 dB, more transmission power is used by voice service and less power remains for data. Thus, to meet the same data rate, higher BERs occurs and the performance of the data service decreases more than that with $\epsilon = 1$ dB. The BER of 10^{-5} only can be reached at the average SNR of 28.7 dB. Fig. 6.10 shows the outage comparisons of the outage probabilities of the voice and data transmissions when the channel estimation errors are 1 and 2 dB, R_T^v is 50 bits/symbol and R_T^d is 400 bits/symbol. There is a little effect to the voice service ($\epsilon = 1$ and 2 dB) and much effect to the data service, especially when $\epsilon = 2$ dB. However, the outage probability of 10^{-4} can still be obtained when the average SNR is near 30 dB. Although there is much effect to the data transmission when the channel estimation error is 2 dB, the voice transmission with higher priority can still be guaranteed. Additionally, the data rate to be supported is also affected due to the channel overestimation. As shown in Fig. 6.11, about 18 bits/symbol is reduced when the estimation error is 1 dB and the data rate gets more than 50 bits/symbol reduction with $\epsilon = 2$ dB. However, the voice rates are always guaranteed as $R_T^v = 50$ bits/symbol.

Underestimation

If the estimation error, $-\epsilon$, occurs, which means $\check{\alpha_n} < \alpha_n$, the number of bits on subcarriers chosen for the voice service would decrease. Additionally, more subcarriers suffering severe fading may be discarded because they are underestimated. Thus, the number of subcarriers for the voice transmission would increase to meet the fixed transmission rate, R_T^v, according to Table. 5.2. Since more subcarriers are used to support the total voice rate, the total transmission power for voice decreases referring to Fig. 4.2(a) and Appendix G. Accordingly, more power can be assigned to data service.

However, the benefit from the increment of the transmission power can be ignored for data service to support high data rates with reduced number of subcarriers.

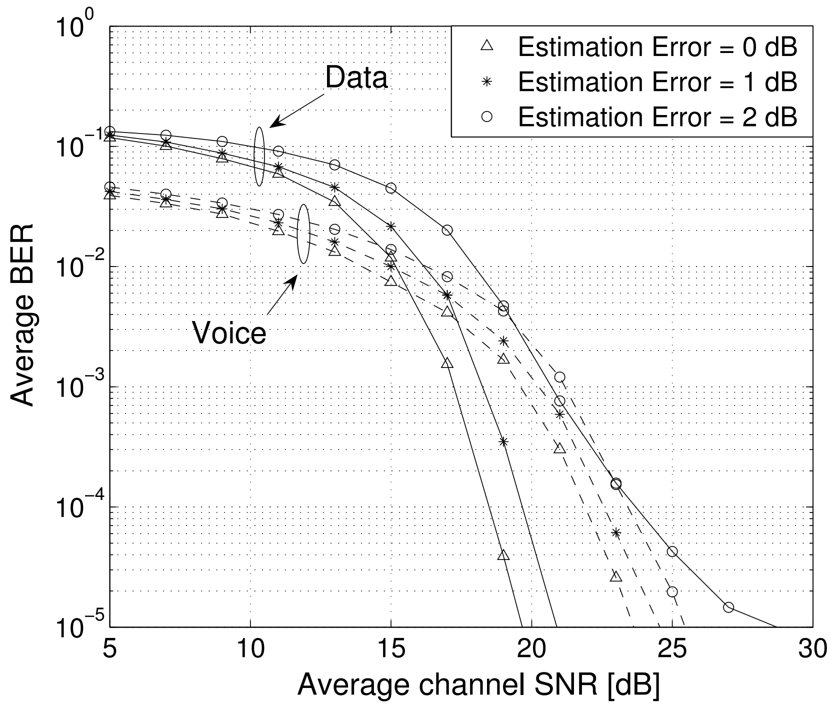


Figure 6.9: Comparison of BER for voice/data versus average SNRs with different channel overestimation errors. Note: $R_T^v = 50$ bits/symbol and $R_T^d = 400$ bits/symbol. (Case 2)

For the voice transmission with the BER of 10^{-3} and the data transmission with the BER of 10^{-6}, the required power to support c_n bits with $BER^v = 10^{-3}$ is much less than the power to support c_n bits with $BER^d = 10^{-6}$. For example, 1 bit are reduced from one subcarrier having 3 bits originally for voice due to the underestimation. And the reduced power is used to support this bit on another subcarrier and then the remaining is assigned for data service. As show in Fig. 4.2(a), the power reduction for voice is only $14N_0$, while the additional power of $50N_0$ and $250N_0$ are required to support only one and two more bits respectively on a subcarrier having 3 bits originally for data service. As a whole, with the reduced number of bits and slightly increased transmission power, the performance of the data transmission is affected by the channel underestimation in terms of BERs, outage probabilities and data rates.

Due to the reduction of the number of the subcarriers and little power increment

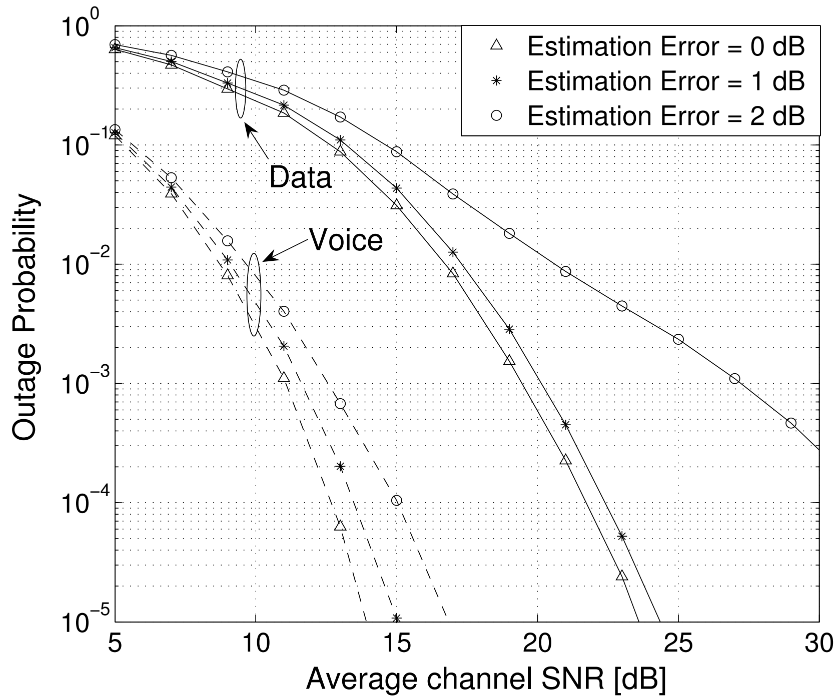


Figure 6.10: Comparison of outage probabilities for voice/data versus average SNRs with different channel overestimation errors. Note: $R_T^v = 50$ bits/symbol and $R_T^d = 400$ bits/symbol. (Case2)

for the data transmission, the impairment to the data service performance by the channel underestimation is more than that by the channel overestimation. However, the voice performance becomes better since more subcarriers with higher channel gains are allocated. Fig. 6.12 shows the BER performance of the voice and data transmissions with different channel overestimation errors, $R_T^v = 50$ bits/symbol and $R_T^d = 400$ bits/symbol. We can see the BER of voice performance is improved and 1 dB SNR reduction is obtained for $\epsilon = -2$ dB compared with that for $\epsilon = 0$ dB. On the contrary, the performance of the data transmission by the channel underestimation is worse than that by the channel overestimation shown in Fig. 6.9. When ϵ is 2 dB, more subcarriers with high channel gains are used by the voice service and less remains for data. Thus, to meet the same data rate, higher BERs occurs and the performance of the data service is downgraded. At the average SNR of higher than 30 dB, the BER of 10^{-5} can be reached. In terms of the outage probabilities, Fig. 6.13 shows that low outage probabilities are

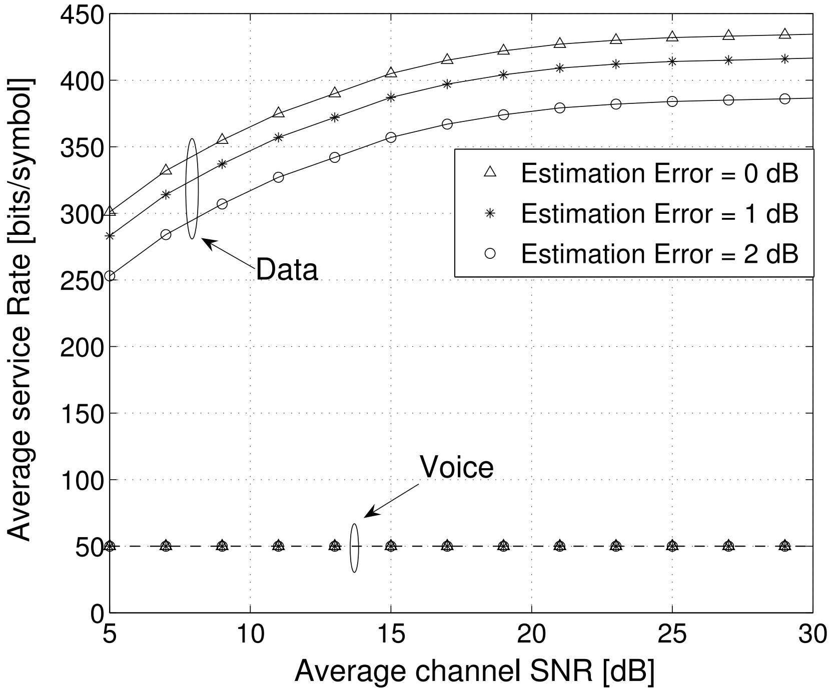


Figure 6.11: The transmission rates of voice/data service supported with different channel overestimation errors. Note: $R_T^v = 50$ bits/symbol. (Case 2)

obtained for the voice service (ϵ = -1 and -2 dB) and the outage probabilities are affected much to the data service, especially when ϵ is 2 dB. the outage probability of 10^{-3} can be obtained when the average SNR is 30 dB. Although there is much effect to the data transmission when the channel estimation error is -2 dB, the voice transmission with higher priority can still be guaranteed and its transmission performance is improved. Based on the effect to the performance of the BER and outage probability, the trend of the decreasing data rate due to the channel underestimation is shown in Fig. 6.14. Nearly 27 bits/symbol is reduced when the estimation error is -1 dB and the data rate gets more than 68 bits/symbol reduction with ϵ = -2 dB. And the voice rates are always guaranteed as $R_T^v = 50$ bits/symbol. In order to support higher data rates on the situation of higher channel estimation errors, the number of subcarriers or equivalently the channel bandwidth can be increased.

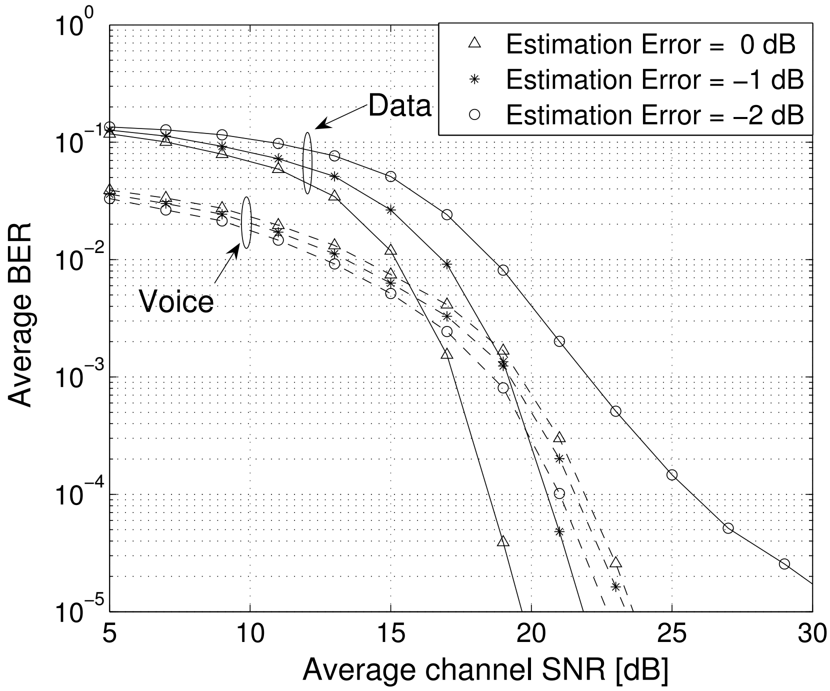


Figure 6.12: Comparison of BER for voice/data versus average SNRs with different channel underestimation errors. Note: $R_T^v = 50$ bits/symbol and $R_T^d = 400$ bits/symbol. (Case 2)

6.4 Conclusion

In the previous two chapters, two adaptive subcarrier allocation and bit loading algorithms were proposed based on the perfect channel estimation. However, 0 dB channel estimation error is not practical. The adaptive modulation system has much dependency to the channel estimation. The complexity and process time of the channel estimation algorithm would affect the performance and application of the adaptive algorithms directly. Under the condition of the inaccurate channel information, the performance of the proposed algorithms, ABLA and A-SABL, are analyzed when the channel is overestimated and underestimated. The analysis and simulations show that the proposed algorithms can still keep tolerable performance based on some given QoS requirements when the channel estimation is not ideal. It is known that the accurate channel estimation is at the cost of the complexity of the estimation algorithms. Therefore, since the proposed algorithms have the

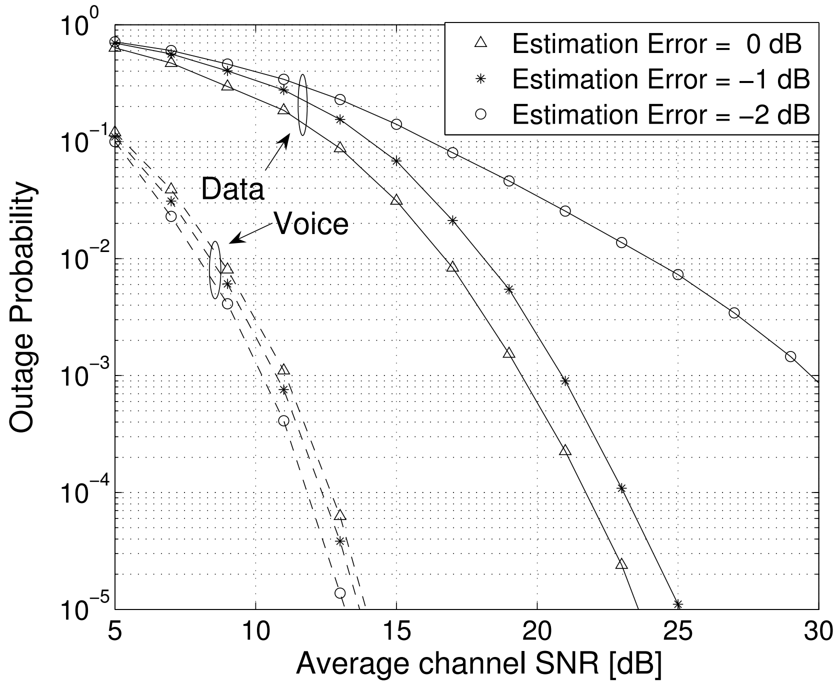


Figure 6.13: Comparison of outage probabilities for voice/data versus average SNRs with different channel underestimation errors. Note: $R_T^v = 50$ bits/symbol and $R_T^d = 400$ bits/symbol. (Case 2)

tolerance to the channel estimation errors, i.e., ±1 and ±2 dB, the channel estimation methods with lower complexity can be applied in the adaptive system. Thus, the potential complexity problem of the adaptive OFDM system is reduced.

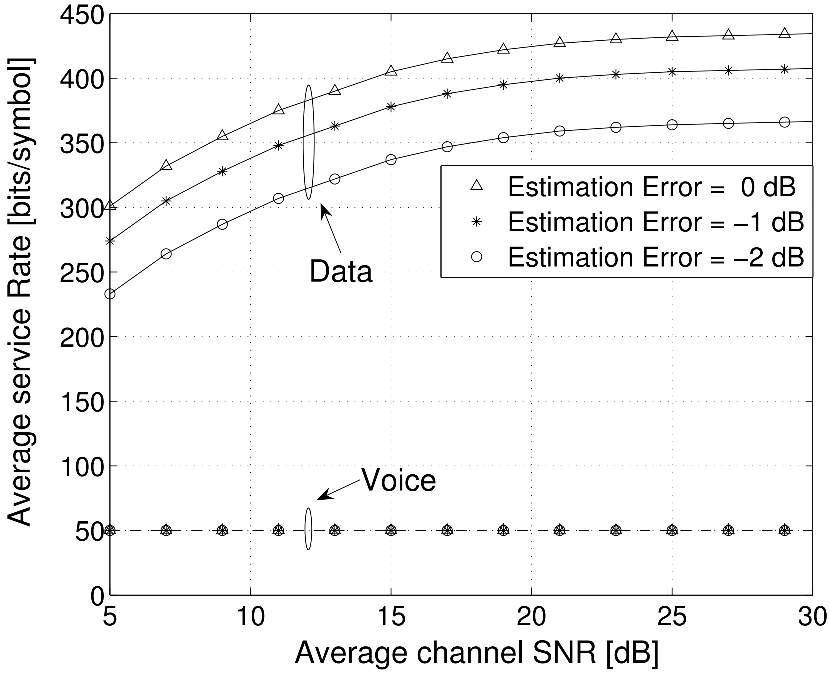


Figure 6.14: The transmission rates of voice/data service supported with different channel underestimation errors. Note: $R_T^v = 50$ bits/symbol. (Case 2)

Chapter 7

Conclusions and recommendations for future work

In this chapter, we draw the conclusions of the thesis. The contents of the previous chapters are reviewed. Some recommendations for future work are provided.

7.1 Conclusions

This thesis deals with the problem of adaptive modulation and subcarrier allocation methods for single- and multi-service transmissions with constrained transmission power in the Multi-Carrier DS-CDMA (called OFDM/CDMA in this thesis) system. Several methods are developed for both cases of the service transmissions in order to improve the performance of the adaptive transmission based on limited frequency and power resources.

The comparison of the OFDM/CDMA, OFDM Interleaved-FDMA and OFDM Group-FDMA has been analyzed for the data transmission. Because of the near-unity reuse factor, one of the important merits of CDMA, the combination of OFDM and CDMA brings substantial increase in the transmission data rate per unit bandwidth when the frequency resources are limited. Even though the multiple access interference exists in OFDM/CDMA systems, better performance can still be achieved than that in other OFDM systems.

A novel adaptive bit loading algorithm (ABLA) for single-service transmission has been presented for the multiuser OFDM/CDMA system. The interference from sharing same subchannels by multiple users would occur inevitably by using the CDMA technique in multiuser systems. With the satisfaction of the transmission requirements for one type of service, in the first step, a suboptimal solution to minimize the interference from each user is put forward. Then the bit allocation adjustment scheme in the second step is presented to make the best use of the subchannels and reduce the interference further. The performance of the proposed ABLA-OFDM is examined by simulations in the frequency-selective fading channel, in which each subchannel is in flat fading. The comparisons are made with the previous related methods, such as CTAO-OFDM and MAO-OFDM, in the single-service transmission with the given BERs and data rates. The simulation results show the proposed ABLA-OFDM algorithm achieves substantial improvement on the BER performance, system capacity and data rates.

An efficient adaptive subcarrier allocation and bit loading algorithm (A-SABL) has been developed for the multi-service (Voice and Data) transmission in the multiuser OFDM/CDMA system. The previous methods for multi-service transmissions is not efficient in application to the realtime voice transmission, because the voice transmission, very sensitive to delay, is not set as higher priority. In order to deal with the problem, the subcarrier allocation and bit loading are adopted for the voice transmission at first. Then an adaptive modulation scheme for the data transmission is developed to maximize the data rate of each user according to the remaining subchannels and transmission power. The performance of the proposed A-SABL algorithm is examined and compared with other previous algorithms. The simulation results demonstrate that the A-SABL algorithm outperforms other methods with similar channel conditions and multi-service transmission requirements.

The adaptive modulation system has much dependency to the channel estimation.

The complexity and process time of the channel estimation algorithm would affect the performance of the adaptive algorithms directly. Under the condition of the inaccurate channel information, the performance of the proposed algorithms are analyzed when the channel is overestimated and underestimated. The analysis and simulations show that the performance of the proposed algorithms can still maintain fairly good performance when the channel estimation errors occur, i.e., ± 1 and ± 2 dB. It is known that the accurate channel estimation is at the cost of the complexity of the channel estimation algorithms. Therefore, the proposed algorithms, tolerant to the channel estimation errors, the channel estimation methods with lower complexity can be used. Thus, the complexity of the adaptive OFDM system is reduced.

If the two proposed algorithms are put into practice, the complexity of the transmitter will increase much and the main work that the receiver should do is only to demodulate the signals based on the adaptive modulation information transmitted from the transmitter. If the transmitter cannot perform the channel estimation due to the design and computational complexity, such as the mobile phone design, the channel estimation algorithm can be done at the receiver. However, the channel estimation information maybe not accurate since the uplink and downlink channels are somewhat different. In order to reduce the cost and design complexity of the transmitters greatly, such as mobile phone with the design, power and cost limitations, all these calculations can be done at the base station and the base station will only send the the number of bits on each subcarrier and the index of the allocated subcarriers to the mobile phone by the overhead or a contiguous band of subcarriers. As a result, more delay occurs and more efficient techniques are needed to transmit the information accurately.

Since there are many limitations on the hardware design, transmission power and cost in the mobile phone, it is better to implement the simple algorithms in the mobile phone design and the complicated algorithms in the base station.

7.2 Recommendations for future work

This thesis has solved some of the problems in the adaptive subcarrier allocation and modulation for single- and multi-service transmissions in the OFDM/CDMA system. The research and development in this area have been and will be one of the most active and vibrant branches of the adaptive systems for a long period. And so far there are still many unsolved problems in these topic which need further investigation, and much more work should be done to develop better algorithms to deal with these problems. Based on the present work, future research work can be recommended as follows.

Transmission of the adaptive information

Based on the proposed algorithms, the transmitter performs the adaptive subcarrier allocation and modulation to transmit signals. The receiver has to be informed the adaptive bit loading information, including the location of the assigned subcarriers and the set of demodulator parameters employed for the receiver packet. This information can either be conveyed within the packet at the cost of losing useful data bandwidth, or the receiver can attempt to estimate the parameters employed at the transmitter by means of signalling and blind detection mechanisms. Future research should be conducted on the effective methods that are efficient for the accurate transmission of the adaptive information with the minimum cost of useful data bandwidth.

Suitable channel estimation schemes for the adaptive OFDM

In this thesis, the proposed adaptive algorithms cannot work properly without the efficient channel estimation algorithms. Channel estimation is necessary before the process of adaptive OFDM algorithms, which is performed according to the instantaneous channel information. However, different channel estimation schemes would result in different performance of the adaptive algorithms. More accurate estimation with higher complexity may not be practical for the application of the realtime adaptive systems. So a tradeoff between the precision of channel estimation and the complexity of both channel estimation schemes and adaptive OFDM algorithms should be analyzed and suitable channel estimation schemes for the proposed adaptive algorithms are essential.

Efficient schemes to reduce the high Peak-to-Average power ratio

At the transmitter in the adaptive OFDM system, high peaks in power (up to N times the average, where N is amount of subcarriers) result in irregular envelopes, consequence of using independently modulated subcarriers. High peak-to-average ratio power cuts down the system performance. In order to avoid the extremely high back-offs and costly amplifiers, occasional clipping and/or soft threshold must be allowed. This phenomenon leads to in-band distortion that increases the BER and to spectral widening that increases adjacent channel interference. Therefore, the development of the efficient schemes to reduce the high peak-to-average power ratio is an interesting further research direction for supporting the ability of the adaptive OFDM/CDMA system in service transmissions.

Appendices

Appendix A. Comparison of data rates on a subcarrier

The discussion in the appendix is based on that the transmission power assigned to a specific subcarrier is decided by the data rate and BER requirements of users in the OFDM system. In a K-user OFDM/CDMA system, the data rate for a specific subcarrier n can be represented as

$$\begin{aligned} r_n &= \sum_{i=1}^{K} \log_2 \left(1 + \frac{\gamma_{i,n}}{\Gamma_i}\right) \\ &= \sum_{i=1}^{K} \log_2 \left(1 + \frac{\tilde{P}_{i,n}}{\sigma^2 + P_{i,ICI} + P_{i,MAI}} \frac{1}{\Gamma_i}\right). \end{aligned} \quad (1)$$

In a K-user OFDM Interleaved-FDMA system, the data rate for a specific subcarrier n, assigned to user i, can be represented as

$$\begin{aligned} r'_n &= \log_2 \left(1 + \frac{\gamma'_{i,n}}{\Gamma_i}\right) \\ &= \log_2 \left(1 + \frac{\tilde{P}'_{i,n}}{\sigma^2 + P'_{i,ICI}} \frac{1}{\Gamma_i}\right). \end{aligned} \quad (2)$$

If we define

$$\Delta r_n = r_n - r'_n, \tag{3}$$

then Δr_n can be described by (4)

$$\begin{aligned}\Delta r_n &= \sum_{i=1}^{K} \log_2 \left(1 + \frac{\tilde{P}_{i,n}}{\sigma^2 + P_{i,ICI} + P_{i,MAI}} \frac{1}{\Gamma_i}\right) - \log_2 \left(1 + \frac{\tilde{P}'_{i,n}}{\sigma^2 + P'_{i,ICI}} \frac{1}{\Gamma_i}\right) \\ &= \log_2 \frac{\prod_{i=1}^{K} \left(1 + \frac{\tilde{P}_{i,n}}{\sigma^2 + P_{i,ICI} + P_{i,MAI}} \frac{1}{\Gamma_i}\right)}{1 + \frac{\tilde{P}'_{i,n}}{\sigma^2 + P'_{i,ICI}} \frac{1}{\Gamma_i}}.\end{aligned} \tag{4}$$

If we subtract the denominator from the numerator of the operand in the log function in (4) and set it as

$$\Psi_n = \prod_{i=1}^{K} \left(1 + \frac{\tilde{P}_{i,n}}{\sigma^2 + P_{i,ICI} + P_{i,MAI}} \frac{1}{\Gamma_i}\right) - \left(1 + \frac{\tilde{P}'_{i,n}}{\sigma^2 + P'_{i,ICI}} \frac{1}{\Gamma_i}\right), \tag{5}$$

then Ψ_n becomes a function with respect to the variable $\tilde{P}'_{i,n}$. And

$$\Psi_n|_{\tilde{P}'_{i,n}=0} = \prod_{i=1}^{K} \left(1 + \frac{\tilde{P}_{i,n}}{\sigma^2 + P_{i,ICI} + P_{i,MAI}} \frac{1}{\Gamma_i}\right) - 1 > 0. \tag{6}$$

Also, we may observe that the derivative of Ψ_n with respect to $\tilde{P}'_{i,n}$,

$$\frac{\partial \Psi_n}{\partial \tilde{P}'_{i,n}} = -\frac{1}{\sigma^2 + P'_{i,ICI}} < 0. \tag{7}$$

Therefore, Ψ_n has a maximum value when $\tilde{P}'_{i,n} = 0$ and decreases when $\tilde{P}'_{i,n}$ increases. By $\Psi_n > 0$, we can get

$$\tilde{P}'_{i,n} \quad < \quad \Gamma_i(\sigma^2 + P'_{i,ICI}) \left[\prod_{i=1}^{K} \left(1 + \frac{\tilde{P}_{i,n}}{\sigma^2 + P_{i,ICI} + P_{i,MAI}} \frac{1}{\Gamma_i} \right) - 1 \right]. \qquad (8)$$

Based on the condition in (8), the nth subcarrier can carry more bits in a K-user OFDM/CDMA system than that in a K-user OFDM Interleaved-FDMA system. Otherwise, the OFDM Interleaved-FDMA system will get the higher data rate when much more $\tilde{P}'_{i,n}$ is allocated. However, in a multiuser OFDM Interleaved-FDMA system with limited power, too much transmission power assigned to a subcarrier will lead to the inadequate power supply for other subcarriers or users with the given data rate and BER requirements.

Appendix B. Relationship between the interference I_i and Δ_i

This appendix studies the relationship between the interference and Δ_i, which is the difference between the maximum and the minimum numbers of allocated bits onto subcarriers for user i according to the results in Section 4.2.2 (a).

For a voice or data transmission, its QoS should be kept unchanged. When transmitting a service, subcarriers in low quality carry less signal bits and subcarriers with good quality carry more signal bits. The adaptive algorithm adjusts the number of bits on subcarriers and keeps the BER on each subcarriers similar. Therefore, by (4.1) and (4.2), the transmission power for the nth subcarrier of the ith user can be written as

$$P_{i,n}(c_{i,n}) = \frac{\frac{N_0}{3}\left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2 (2^{c_{i,n}}-1)}{\alpha_{i,n}^2}, \quad i = 1, 2, \cdots, K. \tag{9}$$

Based on the definition of n_1 and n_2 in Table 4.2, we have $c_{i,n_1} = max_n\{c_{i,n}\}$, $c_{i,n_2} = min_n\{c_{i,n}\}$ and $\Delta_i = c_{i,n_1} - c_{i,n_2} > 1$. Likewise, $\alpha_{i,n_1} = max_n\{\alpha_{i,n}\}$ and $\alpha_{i,n_2} = min_n\{\alpha_{i,n}\}$. The decrement of the transmission power when unloading one bit from subcarrier n_1 is

$$P_{i,n_1}(c_{i,n_1}) - P_{i,n_1}(c_{i,n_1}-1) = \frac{\frac{N_0}{3}\left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2 2^{c_{i,n_1}-1}}{\alpha_{i,n_1}^2}. \tag{10}$$

Similarly, the increment of the transmission power due to reloading one more bit on the n_2th subcarrier is

$$P_{i,n_2}(c_{i,n_2}+1) - P_{i,n_2}(c_{i,n_2}) = \frac{\frac{N_0}{3}\left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2 2^{c_{i,n_2}}}{\alpha_{i,n_2}^2}. \tag{11}$$

It is assumed that $P'_{i,n_1} = P_{i,n_1}(c_{i,n_1}-1)$, $P'_{i,n_2} = P_{i,n_2}(c_{i,n_2}+1)$ and I'_i is the interference resulting from user i after the bit adjustment by Δ_i. Referring to

(4.5),

$$\begin{aligned}
I_i &= \sum_{n=1}^{N} I_{i,n} \\
&= \sum_{n=1}^{N} P_{i,n}\alpha_{i,n}^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k) \\
&= \sum_{\substack{n=1\\n\neq n_1,n\neq n_2}}^{N} \sum_{\substack{k=1\\k\neq i}}^{K} P_{i,n}\alpha_{i,n}^2\rho_{i,k}^2(\tau_k) + \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k)(\alpha_{i,n_1}^2 P_{i,n_1} + \alpha_{i,n_2}^2 P_{i,n_2}). \quad (12)
\end{aligned}$$

Then

$$\begin{aligned}
\Delta I_i &= I_i - I_i' \\
&= \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k)\alpha_{i,n_1}^2(P_{i,n_1} - P_{i,n_1}') - \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k)\alpha_{i,n_2}^2(P_{i,n_2}' - P_{i,n_2}) \\
&= \frac{N_0}{3}\left[Q^{-1}\left(\frac{BER_i}{4}\right)\right]^2 \sum_{\substack{k=1\\k\neq i}}^{K} \rho_{i,k}^2(\tau_k)(2^{c_{i,n_1}-1} - 2^{c_{i,n_2}}) \quad (13)
\end{aligned}$$

For the reduction of I_i, which is larger than zero, we can derive the conditions:

$$2^{c_{i,n_1}-1} - 2^{c_{i,n_2}} > 0. \quad (14)$$

and

$$2^{\Delta_i - 1} > 1. \quad (15)$$

Since $\Delta_i > 1$, we can obtain the positive reduction of I_i.

Appendix C. Theoretical BER for a particular user i

Since the data rate, R_i, of user i is regarded as the total number of bits during a symbol period and can be considered as the summation of $R_{i,1}$, $R_{i,2}$, $\cdots$, and $R_{i,N}$ on N subcarriers. Anyway, the BERs on each subcarrier are different even though they are similar. So, the number of errors received from N subcarriers are $e_{i,1}, e_{i,2}, \cdots$, and $e_{i,N}$. Therefore the BER on each subcarrier is

$$BER_{i,1} = \frac{e_{i,1}}{R_{i,1}},\ BER_2 = \frac{e_{i,2}}{R_{i,2}},\ \cdots,\ BER_{i,N} = \frac{e_{i,N}}{R_{i,N}}. \tag{16}$$

The BER_i of user i is

$$BER_i = \frac{e_{i,1} + e_{i,2} + \cdots + e_{i,N}}{R_{i,1} + R_{i,2} + \cdots + R_{i,N}}. \tag{17}$$

According to the numbers of loaded bits by the proposed algorithm, such as $c_{i,1}, c_{i,2}, \cdots$, and $c_{i,N}$, the data rates carried by the subcarriers are proportional to the number of loaded bits

$$\frac{R_{i,n}}{R_{i,n-1}} = \frac{c_{i,n}}{c_{i,n-1}}. \tag{18}$$

Then a coefficient matrix is defined as

$$\mathbf{B}_i = \begin{bmatrix} \mathbf{B}_{i,1} \\ \mathbf{B}_{i,2} \\ . \\ . \\ \mathbf{B}_{i,N} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1N} \\ a_{21} & a_{22} & \cdots & a_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ a_{N1} & a_{N2} & \cdots & a_{NN} \end{bmatrix} \tag{19}$$

where

$$a_{mn} = \begin{cases} \frac{R_{i,n}}{R_{i,m}} = \frac{c_{i,n}}{c_{i,m}}, & m \neq n \\ 1, & m = n. \end{cases} \tag{20}$$

Therefore, the overall transmission data rate for user i is

$$\begin{aligned} R_i &= R_{i,1} + R_{i,2} + \cdots + R_{i,N} \\ &= (1 + a_{12} + \cdots + a_{1N})R_{i,1} \\ &= (a_{21} + 1 + \cdots + a_{2N})R_{i,2} \\ &= \cdots\cdots\cdots\cdots\cdots \\ &= (a_{N1} + a_{N2} + \cdots + 1)R_{i,N}, \end{aligned} \tag{21}$$

or R_i is described as

$$R_i = \mathbf{B}_{i,n} \cdot \begin{bmatrix} R_{i,n} \\ R_{i,n} \\ . \\ . \\ R_{i,n} \end{bmatrix}_{N\times 1}, \tag{22}$$

for $n = 1, 2, \cdots, N$. By (19) and (22), (17) can be changed into

$$\begin{aligned} BER_i &= \frac{e_{i,1}}{R_i} + \frac{e_{i,2}}{R_i} + \cdots + \frac{e_{i,N}}{R_i} \\ &= \sum_{m=1}^{N} \frac{e_{i,m}}{\sum_{n=1}^{N} a_{mn} \cdot R_{i,m}} \\ &= \sum_{m=1}^{N} \frac{BER_{i,m}}{\sum_{n=1}^{N} a_{mn}}. \end{aligned} \tag{23}$$

Based on (4.15), (4.16) and (23), the theoretical BER can be obtained.

Appendix D. The outage probability of data transmission

Theorems in [118] [119] are used in the calculations of the probability in Appendices A and B. In this appendix, we assume that all variables are real numbers. Since this appendix derives the outage probability for each user, the subscript i will be ignored for simplicity. Based on (5.14), we have

$$\alpha_n = \sqrt{\frac{\lambda \ln 2 \cdot \Psi_n \Gamma}{1 - \lambda \ln 2 \cdot \hat{P}_n^d}}. \tag{24}$$

Thus, the probability distribution function of $\hat{P}_n^d$ can be represented as

$$\begin{aligned} F_{P_n^d}(\hat{P}_n^d) &= P\left(\frac{1}{\lambda \ln 2} - \frac{\Psi_n \Gamma}{\alpha_n^2} \le \hat{P}_n^d\right) \\ &= P\left(\alpha_n \le \sqrt{\frac{\lambda \ln 2 \cdot \Psi_n \Gamma}{1 - \lambda \ln 2 \cdot \hat{P}_n^d}}\right) \\ &= \int_0^{\sqrt{\frac{\lambda \ln 2 \cdot \Psi_n \Gamma}{1 - \lambda \ln 2 \cdot \hat{P}_n^d}}} p_\alpha(\alpha_n) d\alpha_n, \end{aligned} \tag{25}$$

where $p_\alpha(\alpha_n)$ is the probability density function (pdf) of α_n [89],

$$p_\alpha(\alpha_n) = \frac{2\alpha_n}{\Omega} e^{-({\alpha_n}^2/\Omega)}, \tag{26}$$

and $\Omega = E\{{\alpha_n}^2\}$ is the average fading power. Therefore, the probability density function of $\hat{P}_n^d$ should be

$$\begin{aligned} p_{P_n^d}(\hat{P}_n^d) &= F'_{P_n}(\hat{P}_n^d) \\ &= p_\alpha\left(\sqrt{\frac{\lambda \ln 2 \cdot \Psi_n \Gamma}{1 - \lambda \ln 2 \cdot \hat{P}_n^d}}\right) \cdot \left(\sqrt{\frac{\lambda \ln 2 \cdot \Psi_n \Gamma}{1 - \lambda \ln 2 \cdot \hat{P}_n^d}}\right)' \end{aligned}$$

$$
\begin{aligned}
&= \frac{2}{\Omega}\sqrt{\frac{\lambda \ln 2 \cdot \Psi_n \Gamma}{1-\lambda \ln 2 \cdot \hat{P}_n^d}} \cdot e^{-\sqrt{\frac{\lambda \ln 2 \cdot \Psi_n \Gamma}{\Omega(1-\lambda \ln 2 \cdot \hat{P}_n^d)}}} \\
&\quad \times \frac{1}{2}\left(\frac{\lambda \ln 2 \cdot \Psi_n \Gamma}{\Omega(1-\lambda \ln 2 \cdot \hat{P}_n^d)}\right)^{-\frac{1}{2}} \cdot \frac{\lambda^2 \ln^2 2 \cdot \Psi_n \Gamma}{(1-\lambda \ln 2 \cdot \hat{P}_n^d)^2} \\
&= \frac{\lambda^2 \ln^2 2 \cdot \Psi_n \Gamma}{\sqrt{\Omega}(1-\lambda \ln 2 \cdot \hat{P}_n^d)^2} \cdot e^{-\sqrt{\frac{\lambda \ln 2 \cdot \Psi_n \Gamma}{\Omega(1-\lambda \ln 2 \cdot \hat{P}_n^d)}}}. \qquad (27)
\end{aligned}
$$

According to (5.15), we arrive at the total data rate for data service R^d,

$$
\begin{aligned}
R^d &= \sum_{n=N^v+1}^{N} \hat{c}_n^d \\
&= \sum_{n=N^v+1}^{N} \log_2\left\{1+\frac{3\,\hat{P}_n^d}{N_0\left[Q^{-1}\left(\frac{BER^d}{4}\right)\right]^2}\right\} \\
&= \log_2 \prod_{n=N^v+1}^{N}\left\{1+\frac{3\hat{P}_n^d}{N_0\left[Q^{-1}\left(\frac{BER^d}{4}\right)\right]^2}\right\}. \qquad (28)
\end{aligned}
$$

After assuming Y as 2^{R^d} and

$$
X_n = 1+\frac{3\,\hat{P}_n^d}{N_0\left[Q^{-1}\left(\frac{BER^d}{4}\right)\right]^2}\,, \qquad (29)
$$

(28) is rewritten into

$$
Y = \prod_{n=N^v+1}^{N} X_n. \qquad (30)
$$

The probability distribution function of X_n is

$$
F_{X_n}(x_n) = P\left(1+\frac{3\,\hat{P}_n^d}{N_0\left[Q^{-1}\left(\frac{BER^d}{4}\right)\right]^2} \leq X_n\right)
$$

$$
\begin{aligned}
&= P\left(P_n^d \le N_0\left[Q^{-1}\left(\frac{BER^d}{4}\right)\right]^2 \cdot \frac{x_n - 1}{3}\right) \\
&= \int_0^{N_0\left[Q^{-1}\left(\frac{BER^d}{4}\right)\right]^2 \cdot \frac{x_n - 1}{3}} p_{P_n^d}(\hat{P}_n^d)\, d\hat{P}_n^d\,,
\end{aligned} \tag{31}
$$

and hereby its probability density function would be derived as follows,

$$
\begin{aligned}
p_{X_n}(x_n) &= F'_{X_n}(x_n) \\
&= p_{P_n^d}\left(N_0\left[Q^{-1}\left(\frac{BER^d}{4}\right)\right]^2 \cdot \frac{x_n - 1}{3}\right) \\
&\quad \cdot \left(N_0\left[Q^{-1}\left(\frac{BER^d}{4}\right)\right]^2 \cdot \frac{x_n - 1}{3}\right)' \\
&= p_{P_n^d}\left(N_0\left[Q^{-1}\left(\frac{BER^d}{4}\right)\right]^2 \cdot \frac{x_n - 1}{3}\right) \\
&\quad \cdot \frac{N_0\left[Q^{-1}\left(\frac{BER^d}{4}\right)\right]^2}{3}\,.
\end{aligned} \tag{32}
$$

Since the derivations of P_n^d for $n = N^v + 1, N^v + 2, \cdots, N$ are independent, $\{X_n\}_{n=N^v+1}^{N}$ are independent according to (29). And X_n is limited by

$$
\begin{aligned}
X_n &= 1 + \frac{3\,\hat{P}_n^d}{N_0\left[Q^{-1}\left(\frac{BER^d}{4}\right)\right]^2} \\
&\le 1 + \frac{3\,P^d}{N_0\left[Q^{-1}\left(\frac{BER^d}{4}\right)\right]^2}
\end{aligned} \tag{33}
$$

As a result, the probability density function of Y, $p_Y(y)$, can be obtained based on the conclusion in Appendix B, which educes the distribution function of R^d as

$$
\begin{aligned}
F_{R^d}(R^d) &= P(\log_2 Y \le R^d) \\
&= P(Y \le 2^{R^d})
\end{aligned}
$$

$$= \int_0^{2^{R^d}} p_Y(Y)\, dY. \quad (34)$$

The probability density function of the rate of the data service can be obtained as,

$$p_{R^d}(R^d) = p_Y(2^{R^d}) \cdot 2^{R^d} \ln 2. \quad (35)$$

When R^d is less than the data rate requirement R_T^d, the outage probability of data service is

$$p_{outage}^d = \int_0^{R_T^d} p_{R^d}(R^d)\, dR^d. \quad (36)$$

Appendix E. The probability density function of $Y = \prod_{n=1}^{N} X_n$

This is the problem about the distribution of the function of n-dimension independent random variables with the awareness of the probability density function of each random variables. The derivation will be based on the method to resolve the two-dimension function distribution. Foremost, it is assumed that

$$Z_1 = X_1 X_2, \quad (37)$$

and the probability density function of (X_1, X_2) is $p(x_1, x_2)$. Then the distribution function of Z_1 is

$$F_{Z_1}(z_1) = P(Z_1 \leq z_1)$$

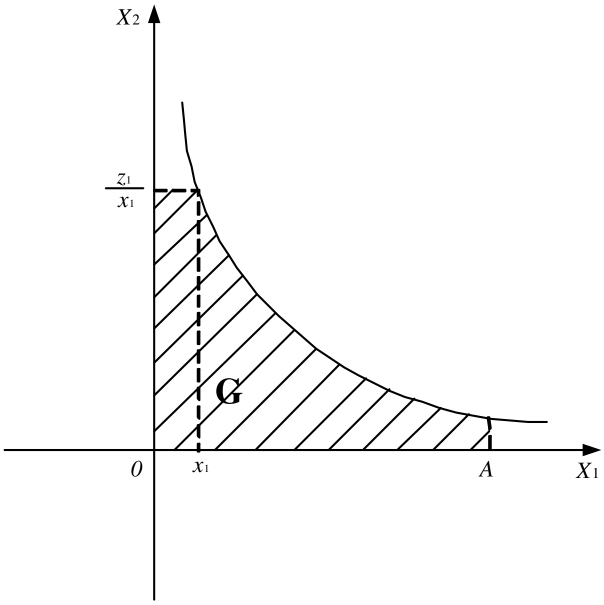


Figure 1: The distribution of the function $Z_1 = X_1 X_2$.

$$= \oint_G p(x_1, x_2) dx_1 dx_2, \tag{38}$$

where G is the shadowed area in Fig. 1 if x_n is positive and limited by A. Therefore,

$$\oint_G p(x_1, x_2) dx_1 dx_2 = \int_0^A \int_0^{\frac{z_1}{x_1}} p(x_1, x_2) dx_1 dx_2. \tag{39}$$

If u is set as $u = x_1 x_2$, we can arrive at

$$\int_0^{\frac{z_1}{x_1}} p(x_1, x_2) dx_2 = \int_0^{z_1} \frac{1}{x_1} p(x_1, \frac{u}{x_1}) du, \tag{40}$$

so

$$\begin{aligned} F_{Z_1}(z_1) &= \oint_G p(x_1, x_2) dx_1 dx_2 \\ &= \int_0^{z_1} \left[\int_0^A x_1 p(x_1, \frac{u}{x_1}) dx_1 \right] du. \end{aligned} \tag{41}$$

Referring to the definition of the probability density function and the independence of X_1 and X_2, the probability density function of Z_1 would be

$$\begin{aligned} p_{Z_1}(z_1) &= \int_0^A x_1 p(x_1, \frac{z_1}{x_1}) dx_1 \\ &= \int_0^A x_1 p_{X_1}(x_1) p_{X_2}(\frac{z_1}{x_1}) dx_1. \end{aligned} \tag{42}$$

Consequently, for the case of $Z_2 = X_1X_2X_3$ and $Z_3 = X_1X_2X_3X_4$, the probability density functions of Z_2 and Z_3 could be obtained based on the conclusion in (42) if $Z_2 = X_3Z_1$ and $Z_3 = X_4Z_2$,

$$p_{Z_2}(z_2) = \int_0^A x_3 p_{X_3}(x_3) p_{Z_2}(\frac{z_2}{x_3}) dx_3, \tag{43}$$

and

$$p_{Z_3}(z_3) = \int_0^A x_4 p_{X_4}(x_4) p_{Z_3}(\frac{z_3}{x_4}) dx_4. \tag{44}$$

As a result, the probability density function of $Y = Z_{N-1} = \prod_{n=1}^{N} X_n$ is derived as

$$\begin{aligned} p_Y(y) &= p_{Z_{N-1}}(z_{N-1}) \\ &= \int_0^A x_N p_{X_N}(x_N) p_{Z_{N-1}}(\frac{z_{N-1}}{x_N}) dx_N. \end{aligned} \tag{45}$$

Appendix F. The effect to the transmission power of voice by channel overestimation in Case 2

This appendix studies the effect to the transmission power of voice by channel overestimation. When the channel overestimation occurs, the number of bits on subcarriers increases, resulting in the reduction of the number of subcarriers used by voice service with the limitation of the voice rate. According to the subcarrier allocation in the ascending order, this reduction is done by moving two bits from the subcarriers with high channel gains to those having zero, one and two bits.

It is assumed that two bits will be removed from the n_xth subcarrier having two bits, which brings the power reduction of

$$\Delta P_x = \frac{\Upsilon(2^2 - 1)}{\alpha_{n_x}^2} = \frac{3\Upsilon}{\alpha_{n_x}^2} \tag{46}$$

according to (5.6), where

$$\Upsilon = \frac{N_0}{3}\left[Q^{-1}\left(\frac{BER}{4}\right)\right]^2. \tag{47}$$

There are four possible ways for the two bits to disperse from the n_xth subcarrier to other subcarriers. The first one is that the two bits are loaded on two subcarriers, n_1 and n_2, both of which have no bits. The second way is that the two bits are loaded on the n_3th subcarrier having no bits. The third way is that one bit is allocated to the n_4th subcarrier having no bits and another bit is loaded on the n_5th subcarrier having one bit. By the last way, the two bits are loaded on two subcarriers, n_6 and n_7, both of which have been loaded one bit. For the subchannel gains among the eight subcarriers, the n_xth subcarrier has the highest α_{n_x}. We can obtain the transmission power increments on the seven subcarriers,

$$\Delta P_1 = \frac{\Upsilon(2^1 - 1)}{\alpha_{n_1}^2} = \frac{\Upsilon}{\alpha_{n_1}^2}, \tag{48}$$

$$\Delta P_2 = \frac{\Upsilon(2^1 - 1)}{\alpha_{n_2}^2} = \frac{\Upsilon}{\alpha_{n_2}^2}, \tag{49}$$

$$\Delta P_3 = \frac{\Upsilon(2^2-1)}{\alpha_{n3}^2} = \frac{3\Upsilon}{\alpha_{n3}^2}, \tag{50}$$

$$\Delta P_4 = \frac{\Upsilon(2^1-1)}{\alpha_{n4}^2} = \frac{\Upsilon}{\alpha_{n4}^2}, \tag{51}$$

$$\Delta P_5 = \frac{\Upsilon(2^2-1)}{\alpha_{n5}^2} - \frac{\Upsilon(2^1-1)}{\alpha_{n5}^2} = \frac{2\Upsilon}{\alpha_{n5}^2}, \tag{52}$$

$$\Delta P_6 = \frac{\Upsilon(2^2-1)}{\alpha_{n6}^2} - \frac{\Upsilon(2^1-1)}{\alpha_{n6}^2} = \frac{2\Upsilon}{\alpha_{n6}^2}, \tag{53}$$

and

$$\Delta P_7 = \frac{\Upsilon(2^2-1)}{\alpha_{n7}^2} - \frac{\Upsilon(2^1-1)}{\alpha_{n7}^2} = \frac{2\Upsilon}{\alpha_{n7}^2}. \tag{54}$$

For the four situations, we have their power increments respectively,

$$(\Delta P_1 + \Delta P_2) - \Delta P_x > \frac{2\Upsilon}{\alpha_{n_2}^2} - \frac{3\Upsilon}{\alpha_{n_x}^2}, \quad (\text{for } \alpha_{n_1} < \alpha_{n_2}), \tag{55}$$

$$\Delta P_3 - \Delta P_x > \frac{3\Upsilon}{\alpha_{n_x}^2} - \frac{3\Upsilon}{\alpha_{n_x}^2} = 0, \tag{56}$$

$$(\Delta P_4 + \Delta P_5) - \Delta P_x > \frac{3\Upsilon}{\alpha_{n_x}^2} - \frac{3\Upsilon}{\alpha_{n_x}^2} = 0, \tag{57}$$

and

$$(\Delta P_6 + \Delta P_7) - \Delta P_x > \frac{4\Upsilon}{\alpha_{n_x}^2} - \frac{3\Upsilon}{\alpha_{n_x}^2} > 0. \tag{58}$$

Except the first situation, the other three situations bring positive increment of the transmission power for voice because of the channel overestimation. In terms of (55), the power increment can be obtained when the following condition exits,

$$\frac{\alpha_{n_2}}{\alpha_{n_x}} \approx 0.8165. \tag{59}$$

However, it is impossible that the n_xth subcarrier can carry two bits while the n_2th subcarrier, α_{n_2} of which is so closed to α_{n_x}, is to be discarded if the channel is perfectly estimated. Therefore, with $\alpha_{n_2} < 0.8165\alpha_{n_x}$, we can have the positive power increment for the first situation. Consequently, for the voice transmission power, we obtain the positive power increment for the four situations due to the channel overestimation.

Appendix G. The effect to the transmission power of voice by channel underestimation in Case 2

This appendix studies the effect to the transmission power of voice by channel underestimation. When the channel underestimation occurs, the number of bits loaded on each subcarrier decreases, and therefore more subcarriers should be assigned to guarantee the fixed rate requirement, R^T. Besides, the reduced number of bits will be assigned to the subcarriers with higher channel gains because the subcarrier allocation obeys the ascending order of subchannel gains.

It is assumed that Δc is the reduced number of bits on the n_1th subcarrier and allocated to a new subcarrier, n_2, with $\alpha_{n_1} < \alpha_{n_2}$. The decrement of the transmission power when unloading Δc bits from subcarrier n_1 is

$$\begin{aligned} \Delta P_1 &= P_{n_1}(c_{n_1}) - P_{n_1}(c_{n_1} - \Delta c) \\ &= \frac{\frac{N_0}{3}\left[Q^{-1}\left(\frac{BER}{4}\right)\right]^2 2^{c_{n_1}-\Delta c}(2^{\Delta c} - 1)}{\alpha_{n_1}^2}. \end{aligned} \tag{60}$$

Similarly, the increment of the transmission power due to reloading Δc bits on the n_2th subcarrier is

$$\begin{aligned} \Delta P_2 &= P_{n_2}(\Delta c) \\ &= \frac{\frac{N_0}{3}\left[Q^{-1}\left(\frac{BER}{4}\right)\right]^2 (2^{\Delta c} - 1)}{\alpha_{n_2}^2}. \end{aligned} \tag{61}$$

Therefore, we have the total power reduction due to the bit reloading,

$$\begin{aligned}\Delta P &= \Delta P_1 - \Delta P_2 \\ &= \frac{\frac{N_0}{3}\left[Q^{-1}\left(\frac{BER}{4}\right)\right]^2 2^{c_{n_1}-\Delta c}(2^{\Delta c}-1)}{\alpha_{n_1}^2} \\ &\qquad -\frac{\frac{N_0}{3}\left[Q^{-1}\left(\frac{BER}{4}\right)\right]^2 (2^{\Delta c}-1)}{\alpha_{n_2}^2} \\ &= \frac{N_0}{3}\left[Q^{-1}\left(\frac{BER}{4}\right)\right]^2 \cdot (2^{\Delta c}-1)\left(\frac{2^{c_{n_1}-\Delta c}}{\alpha_{n_1}^2} - \frac{1}{\alpha_{n_2}^2}\right), \qquad (62)\end{aligned}$$

where $c_{n_1} - \Delta c \geq 1$ is the number of remaining bits on the n_1th subcarrier and $2^{\Delta c} - 1 \geq 1$. Hereby, we have $\Delta P > 0$.

Author's Publications

(1) Hua Zhang, Guoan Bi and Liren Zhang, "New adaptive bit allocation algorithms for multiuser OFDM/CDMA systems", *Wireless Networks*, Springer Netherlands, Aug. 2007.

(2) Hua Zhang, Guoan Bi and Liren Zhang, "Adaptive Subcarrier Allocation and Bit Loading for Simultaneous Voice/Data Transmission in OFDM Systems", accepted for publication in *Wireless Communications & Mobile Computing*, Wiley.

(3) Hua Zhang, Guoan Bi, Qian Yu and Gang Hu, "New adaptive bit loading algorithms for uplink multiuser OFDM/CDMA systems", *Proceedings of the IEEE International Conference on Communications* (ICC'04), Paris, 2004, pp. 4128-4132.

(4) Hua Zhang and Guoan Bi, "Adaptive Subcarrier Allocation and Bit Loading for Simultaneous Voice/Data Transmission in OFDM Systems", *Proc. of IEEE RIUPEEC'05*, HongKong, 2005.

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