Studies on Power Allocation for Multiple Access with Successive Interference Cancellation

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逐次干渉除去を用いた多元接続システムのパワー割り当てに関する研究

論文概要

未来の無線通信ネットワークでは、あらたにIoT(Internet of Things)のような潜在的なアプリケーションが登場することで、接続される端末数が急激に増加し、膨大な数の端末を収容しなくてはならない。そのため、無線アクセスネットワークは、大規模な端末の多元接続と高い周波数利用効率を求められる。情報理論の視点から見ると、直交多元接続は必ずしも最適なプロトコルではない。多元接続の通信路容量の限界を達成するためには、非直交多元接続とマルチユーザー検出(MUD: multiuser detection)技術が必要になる。非直交の符号分割多元接続(CDMA: code-division multiple access)については、複数のMUD技術が提案されている。その中で、逐次干渉除去(SIC: successive interference cancellation)は、その低複雑さと良好な検出性能から、実用化が期待されているMUD方法である。

ランダムアクセスはバースト的なデータを扱うために設計されたプロトコルである。チャネル化された多元接続法と比較すると、遅延特性が改善できる。基地局による集中的な割り当てと違い、端末同士がお互いに自律的に競合してチャネルを占用するため、パケットの衝突が一定の確率で発生する。そのため、トラフィック負荷が高くなった場合は、衝突が増加し、スループットが劣化する。しかし、マルチパケット受信(MPR: multiple packet reception)技術と呼ばれる複雑な検出方法を活用することで、複数のパケットが衝突している受信信号でも複数のパケットを分離して検出することが可能となる。SIC受信機は、逐次的に正しく検出したパケットを受信信号から除去することで、さらに多数のパケットを検出できる可能性を持つ。

増加する無線端末による無線周波数資源の不足に対応するため、ダイナミックな周波数共用を行うコグニティブ無線(CR: cognitive radio)が有望な技術の一つとして期待されている。コグニティブ無線は、プライマリユーザ(PU: Primary

User)が利用する周波数をセカンダリユーザ(SU: Secondary User)が共用することを、プライマリ基地局の干渉量を制限し、プライマリシステムのQoS(Quality of Service)を保護することを条件に認めるものである。この時、セカンダリ基地局への上りリンクで多元接続する際には、干渉量を抑制ため、セカンダリ端末の送信電力の割り当てが不可欠である。

多数の多元接続システムにおいて、送信電力割り当て方法はよく研究されている。基地局が集中的に電力を制御するかどうかにより、電力制御の方法は二つのタイプに分類できる。集中電力割り当て方法は、基地局が下りチャネル通じて端末の送信電力を制御する。分散電力割り当て方法は、端末が与えられた送信電力と分布の情報によって送信電力を自律的に決定する。

本論文では、逐次干渉除去を用いたランダムアクセスシステムの分散電力制御の研究を行う。本論文は全体が6章で構成されており、1章で研究背景を、2章では関連する基礎技術についての説明を行っている。3章ではスループット特性の改善を目指して、衝突状態でも複数のパケットの復号が可能である一般的なSIC受信機のための、分散電力割り当て(DPA: decentralized power allocation)を提案する。4章では、MAC層と物理層双方を考慮して、全体データレートを最大化するための、改良DPAアルゴリズムを提案する。また推定ユーザ数が実際のユーザ数とミスマッチを引き起こした場合の性能評価を行う。5章では、より現実的なモデルの下で、コグニティブ無線における二次ユーザのランダムアクセスのためのDPAアルゴリズムを提案する。さらにフェージング環境における干渉電力低減のための日和見型送信プロトコルを提案する。最後に6章で、本論文をまとめる。

Abstract

In future wireless communication networks, the number of devices is likely to increase dramatically due to potential development of new applications such as the Internet of Things (IoT). Consequently, radio access network is required to support multiple access of massive users and achieve high spectral efficiency. From the information theoretic perspective, orthogonal multiple access protocols are suboptimal. To achieve the multiple access capacity, non-orthogonal multiple access protocols and multiuser detection (MUD) are required. For the non-orthogonal code-division multiple access (CDMA), several MUD techniques have been proposed to improve the spectrum efficiency. Successive interference cancellation (SIC) is a promising MUD techniques due to its low complexity and good decoding performance.

Random access protocols are designed for the system with bursty traffic to reduce the delay, compared to the channelized multiple access. Since the users contend for the channel instead of being assigned by the base station (BS), collisions happen with a certain probability. If the traffic load becomes relatively high, the throughput of these schemes steeply falls down because of collisions. However, it has been well-recognized that more complex procedures can permit decoding of interfering signals, which is referred to as multi-packet reception (MPR). Also, an SIC decoder might decode more packets by successively subtracting the correctly decoded packets from the collision.

Cognitive radio (CR) is an emerging technology to solve the problem of spectrum scarcity by dynamically sharing the spectrum. In the CR networks, the secondary users (SUs) are allowed to dynamically share the frequency bands with primary users (PUs) under primary

quality-of-service (QoS) protection such as the constraint of interference temperature at the primary base station (PBS). For the uplink multiple access to the secondary base station (SBS), transmit power allocation for the SUs is critical to control the interference temperature at the PBS.

Transmit power allocation has been extensively studied in various multiple access scenarios. The power allocation algorithms can be classified into two types, depending on whether the process is controlled by the base station (BS). For the centralized power allocation (CPA) algorithms, the BS allocates the transmit powers to the users through the downlink channels. For the random access protocols, there are also efforts on decentralized power allocation (DPA) that the users select transmit powers according to given distributions of power and probability, instead of being assigned the transmit power at each time slot by the BS.

In this dissertation, the DPA algorithms for the random access protocols with SIC are investigated and new methods are proposed. First a decentralized multilevel power allocation algorithm to improve the MAC throughput performance is proposed, for the general SIC receiver that can decode multiple packets from one collision. Then an improved DPA algorithm to maximize the overall system sum rate is proposed, taking into account of both the MAC layer and PHY layer. Finally, a DPA algorithm for the CR secondary random access is proposed, considering the constraint of interference temperature and the practical assumption of imperfect cancellation. An opportunistic transmission protocol for the fading environment to further reduce the interference temperature is also proposed. For the future work, the optimal DPA for the random access with the SIC receiver is still an open problem. Besides, advanced multiple access schemes that aim to approach the multiple access capacity by combining the advantages of the network coded cooperation, the repetition slotted ALOHA, and the SIC receiver are also interesting.

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ACRONYMS

Acronyms

5G Fifth-generation

ANCC Adaptive network coded cooperation

AWGN Additive white Gaussian noise

BER Bit error rate

BICM Bit-interleaved coded modulation

BP Belief propagation

BS Base station

CDMA Code-division multiple access

CPA Centralized power allocation

CR Cognitive radio

CSI Channel state information

CSMA Carrier sensing multiple access

DE Density evolution

DPA Decentralized power allocation

EXIT Extrinsic information transfer

FDMA Frequency-division multiple access

FER Frame error rate

IDMA Interleave-division multiple access

IoT Internet of things

ACRONYMS

IRSA Irregular repetition slotted ALOHA

LAN Local area network

LDGM Low density generator matrix

LDPC Low density parity check

LT Luby transform

MA Multiple access

MAC Media access control

MAP Maximum a posteriori

MIMO Multiple- input multiple-output

MLPA Multilevel power allocation

MPR Multipacket reception

MUD Multiuser detection

NOMA Non-orthogonal multiple access

OFDMA Orthogonal frequency-division multiple access

OTP Opportunistic transmission protocol

PBS Primary base station

PDF Probability distribution function

PHY Physical

PMF Probability mass function

PU Primary user

QPSK Quadrature phase shift keying

RSA Repetition slotted ALOHA

SBS Secondary base station

SIC Successive interference cancellation

SINR Signal-to-interference-and-noise ratio

SIR Signal-to-interference ratio

SNR Signal-to-noise ratio

SU Secondary user

TDMA Time-division multiple access

WSN Wireless sensor network

XOR Exclusive OR

ACRONYMS

1

Introduction

In this chapter, an introduction for the research on the decentralized power allocation algorithms for the random access with the successive interference cancellation receiver is presented. This chapter is organized as the following. First, in Section 1.1, the research and the application background of the related wireless communication technologies are reviewed. In Section 1.2, the motivation of this research is explained and the problems to be solved are shown. In Section 1.4, the scope of research is shown. Finally, Section 1.5 gives an overview of the whole dissertation.

1.1 Background

A multiple access (MA) system consists of multiple transmitters and one common receiver. The multiple access scenarios can be found in various wireless communication networks, e.g., uplink from users to base station (BS) in cellular network and uplink from terminals to access point (AP) in computer networks. Different from point to point communications, a problem that how the transmitters share the channel resource to transmit their information raises naturally. Multiple access protocol is a method to let the transmitters access the channel efficiently [1, 2, 3, 4].

Depending on behaviors of the transmitters and the receiver, the conventional multiple access protocols can be classified into two types: channelized access and random access. In the channelized access protocols, the channel resource is divided into multiple sub-channel resource blocks. These resource blocks are assigned to the transmitters by the receiver in a coordinated manner. For example, in time-division multiple access (TDMA) protocol, the same frequency band is shared by multiple transmitters by dividing time into different time slots. Since the channel resource allocation is guaranteed by the centralized coordination, the channelized access protocols are especially suitable for voice services in the cellular networks. However, in the communication systems that the dominant traffic is bursty data, such as computer network and sensor network, the channelized protocols result in the delay and the waste of channel resource since each user has to wait for its own assigned sub-channel.

Random access protocols are proposed to solve this problem. In the random access protocols, the transmitters contend for the transmission to the receiver by randomly accessing the channel. For instance, in a slotted ALOHA system, the transmitters synchronize to the time slot and access the channel whenever they have packets to transmit [5, 6, 7]. The slotted ALOHA system runs in an uncoordinated manner, without the centralized channel assignment of the receiver. Moreover, comparing to the TDMA protocol, delay performance can be improved, since the transmitters need not to wait for the assigned time slot. Hence, the random access protocols are suitable for the bursty traffic with delay requirement such as data communications in the computer networks. Carrier sensing multiple access with collision avoidance (CSMA/CA) can be considered as a "polite" version of the ALOHA protocol. The transmitters probe the channel before the transmission. If the channel is sensed busy, then the transmission is deferred for a random interval to reduce the incidence of collision [8, 9, 10, 11]. With such more sophisticated mechanism, the CSMA/CA can achieve superior throughput performance and is widely used in the wireless computer networks.

Although the multiple access protocols for both the cellular networks and the computer networks are becoming maturer with the fast development of the cellular networks and the computer networks, other emerging types of wireless network such as wireless sensor network (WSN), cognitive radio (CR) network, have different requirements on the multiple access protocol [12, 13]. For the coming fifth-generation (5G) cellular network, due to a potential development of the machine to machine (M2M) communication and the Internet of Things (IoT), physical layer issues such as transmission waveforms and multiple-access (MA) schemes should be reconsidered for the requirements of higher spectrum efficiency and supporting massive users [14, 15, 16, 17, 18, 19]. A promising MA scheme is the non-orthogonal multiple access (NOMA) which achieves high spectral efficiencies by using successive interference cancellation (SIC) at the receiver [20]. As shown in Fig. 1.1, in contrast to the conventional orthogonal MA schemes such as TDMA, NOMA can improve the MAC-PHY cross-layer efficiency by simultaneously serving multiple users in the same degrees of freedom by splitting them in the power domain. One conventional implementation of NOMA is non-orthogonal code division multiple access (CDMA) with multiuser detection (MUD), where separate codes are used for different transmitters [21, 22, 23]. Another non-orthogonal multiple access protocol is interleave division multiple access (IDMA), where distinct interleavers are used to separate the transmitters [24, 25].

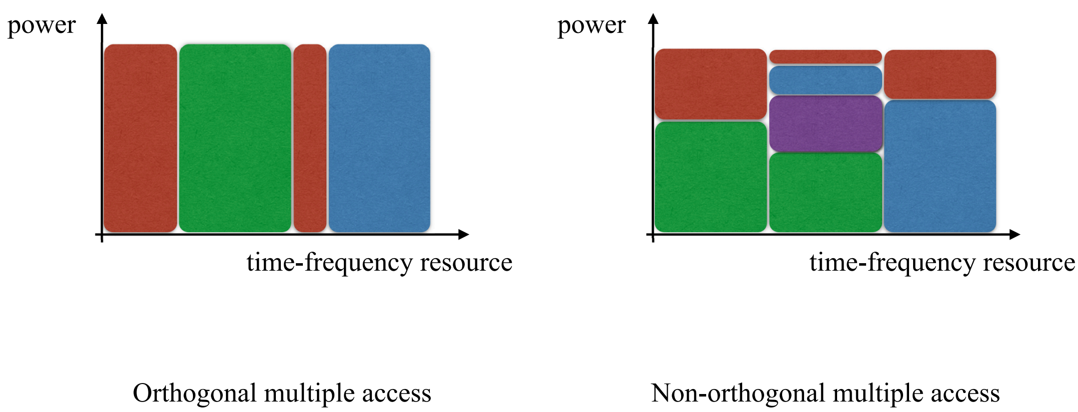

Figure 1.1: Comparison of OMA and NOMA - non-orthogonal power division vs. orthogonal time-frequency division.

In fact, from information theoretic point of view, conventional orthogonal channelized access protocols are suboptimal. For the additive Gaussian white noise (AWGN) channel, to achieve multiple access capacity, all transmitters should occupy all the time and frequency band, just using different codebooks.

The receiver decodes all the received signals jointly. The principle of SIC can be used to explain how to achieve the multiple access capacity [26].

Information theoretic analysis on the random access is more complicated, since the bursty nature of real sources is ignored in the information theory model. In addition, delay is a fundamental quantity in the random access networking, but is ignored as a parameter in the information theory. The gap between the information theory and the network oriented studies has been pointed out by Gallager and well documented by Ephremides and Hajek [27, 28]. In a recent literature, Minero *et al.* proposed an optimal random access strategy for a system of symmetric traffic, where transmitters adjust their data rate according to the arrival rate and number of transmitters [29].

Conventional analysis using the collision model on the random access protocols also has several limitations. The collision model focuses on the media access control (MAC) layer, ignoring the underlying physical (PHY) layer processing. A received packet can be successfully decoded whenever it is the only transmitted packets in that time slot. The received packets are considered as completely destroyed whenever two or more packets are transmitted simultaneously. However, in practical wireless networks, the receiver may fail to decode the only one received packet due to the channel impairment such as fading. In addition, it has been well-recognized in the literature [30, 31, 32, 33, 34, 35, 36, 37] that more complex procedures could permit decoding of interfering signals, which is referred to as *multipacket reception* (MPR). For example, if the power of one of the received packets is sufficiently higher than the other packets in the collision, the strongest one can be correctly decoded while the others are lost, which is known as *capture effect* [30]. Also, a SIC decoder might decode more packets by successively subtracting the correctly decoded packets from the collision [38]. Among the MUD techniques, the SIC has the advantages of relatively low complexity and near-optimal decoding performance in the practical systems [39]. The use of SIC has thus been actively investigated in wireless multiple access scenarios [20, 23, 40, 41, 42]. Besides, recently, the slotted ALOHA-type random access using SIC among time slots has been extensively studied [43, 44, 45].

1.2 Motivation and Problem

To better exploit the benefit of using the SIC receiver in the random access system, designing proper decentralized power allocation (DPA) algorithms is critical and required, since there is no centralized control from the BS or AP. In such decentralized system, each user randomly selects the data rate and the transmit power according to certain probability distributions, independent of the choices of other users. Without the proper designed power allocation, during the random access, there might be too many severe collisions that is unable to be decoded or too many wasted idle time slots. Hence, the problem raises as to find the optimal combination of the data rates, the transmit power levels, and the probability distributions, to maximize the resulted system spectrum efficiency. This problem is still open to be solved.

Power allocation is widely used in the wireless communication networks for various purposes. To show the differences of my studied DPA, here the existing power allocation schemes is explained briefly. The first type is distributed power control schemes among multiple BSs to control the inter-cell interference by adjusting the transmit power levels of users in each cell, which have been proposed in [46, 47]. The second type is centralized optimal power allocation algorithms for the channelized access fading channels in a single BS, which have been proposed and analyzed in [48, 49, 50, 51]. With respect to the special requirement of the cognitive radio, optimal power allocation strategies for the multiple access of the secondary users have been proposed in [52, 53]. The third type is power control in the CDMA systems. For the conventional CDMA systems, open-loop power control and close-loop power control are used to solve the near-far problem by letting the received power of different transmitters the same at the receiver [21, 54, 55]. For the CDMA systems with the SIC receiver, the situation is significantly different, since the interference can be subtracted out of the received signal. The corresponding optimal power allocation algorithm has been proposed in [42]. In these power allocation schemes, the transmitter power levels are controlled by the receiver, which is different from my studied decentralized power allocation.

In this dissertation, first a simplified decentralized power allocation problem for the random access system with SIC is addressed, where the transmission data rates in one time slot of all the users are the same, i.e., all the users employ the same channel code and modulation. This simplification can reduce the transceiver complexity greatly and hence makes the corresponding solution more practical on exiting systems. This universal data rate is denoted as *base code rate* in my research. Then the problem is to find the optimal combination of the transmit power levels and the corresponding probabilities. There are few investigations addressing this issue. As originally pointed out in [30], the power allocation enhances the resulted throughput of the system. In [32, 37], random transmission power control algorithms have been proposed in order to achieve higher throughput assuming that the receiver is able to decode a single packet from the collision. In [56, 57], a decentralized power control for random access with SIC has been proposed; in this system, the discrete power levels are derived, and the optimal probability distribution of power levels is obtained, with the implicit limitation of that, at most, two packets could be decoded from a single collision. Recently, the optimal DPA based on threshold-based water-filling has been proposed for the random access but *without* the SIC receiver [58].

1.3 Contributions and Novelty

This dissertation studies DPA algorithms for random access with a more general SIC receiver that can decode multiple packets from a collision. First, a decentralized multilevel power allocation algorithm is proposed to improve the MAC throughput performance, for the more general SIC receiver. Then, an improved DPA algorithm is proposed to maximize the overall system sum rate, taking into account of both the MAC layer and PHY layer. The performance for the mismatches between the practical number of user and the estimated one is also evaluated. Finally, a DPA algorithm for the CR secondary random access is proposed, considering the constraint of interference temperature and the practical assumption of imperfect SIC. An opportunistic transmission protocol is also proposed for the fading environment to further reduce the interference temperature.

The optimization problem of DPA for random access with the more general SIC receiver is formulated. According to the intractable optimization problem, a per-level iterative process is proposed to obtain the power levels and the corresponding probabilities, iterating from the lowest power level to the highest one. The overall optimization problem is decomposed into tractable subproblems in each power level. Different from the conventional studies of random access protocols focusing only on the MAC layer efficiency, the MAC-PHY cross layer spectrum efficiency is also considered to further improve the algorithm and perform fair comparisons. The application of DPA in CR secondary random access differs from the conventional works that the power allocation is performed in a centralized manner. In addition, to my best knowledge, the idea of opportunistically reducing the interference temperature by dividing SUs into groups in the secondary random access with SIC is novel, according to the existing literatures.

1.4 Scope

Considering the PHY layer, the cross-layer design of a MAC protocol involves various aspects of communication techniques, such as modulation and channel coding of the information blocks, type of MAC protocol, power allocation algorithm, and multiuser detection at the receiver.

This work is mainly on designing the decentralized power allocation algorithms for the random access with the SIC receiver. To focus on the power allocation algorithm, the simple random access protocol of slotted ALOHA type is considered instead of more sophisticated ones. The slotted ALOHA protocol can be consider as the basic of the CSMA/CA protocol, without the carrier sensing function and with reduced volume of protocol overhead. Hence, the slotted ALOHA is more suitable for the scenarios that the users cannot perform carrier sensing or require small volume of protocol over head. In addition, the proposed method can be applied to the more sophisticated protocols but with necessary modifications. The SIC receiver is used due to the good decoding performance and the low complexity. The PHY layer is taking into account but is abstracted without looking into the details of the modulation and channel coding.

1.5 Overview of the Dissertation

The following shows the main content of each chapter and the relations among chapters.

- **Chapter 1** introduces the background, the research scope, the research problems, and the motivation of this dissertation.
- **Chapter 2** provides an overview of the related techniques and works on the power allocation of multiple access communications, including the multiple access protocols, the successive interference cancellation, and the power allocation algorithms for multiple access communications. The purpose of this chapter is to provide preliminaries of the following proposal chapters. Readers who are familiar with these topics can skip into the next chapter.
- **Chapter 3** presents my first proposal of the decentralized multilevel power allocation for the random access with the SIC receiver.
- **Chapter 4** presents an improved DPA algorithm, based on the proposal in Chapter 3. This improved algorithm can achieve superior performance by modifying the methods of power level estimation and probability optimization. The cross-layer system sum rate performance is considered and the performance of a practical case with a mismatch between the practical number of users and the estimated one is shown.
- **Chapter 5** presents the proposal on applying the DPA algorithm proposed in Chapter 4 to the CR secondary random access scenario, considering the practical assumptions such as imperfect SIC cancellation and random number of users. An opportunistic transmission protocol that can further reduce the interference temperature in the CR fading environment is also shown.
- **Chapter 6** concludes this dissertation, summarizing the contributions of the proposals in Chapters 3, 4, and 5. Other works on proposing novel MAC protocols and the future directions are also discussed.

2

Overview of Power Allocation for Random Access with SIC

This chapter is an overview to provide background knowledge of the research work on decentralized power allocation for random access with SIC. Three key techniques are involved: the random access protocols, the SIC, and the power allocation in multiple access. The proposed schemes will be understood better with the corresponding knowledge, since this research is mainly based on these techniques. To give a broader view on the random access protocols, other types of multiple access protocols, such as channelized access protocols, are also explained briefly.

The organization of this chapter is as following. First, Section 2.1 introduces the multiple access protocols, with emphasis on the non-orthogonal multiple access and slotted ALOHA protocol. Then Section 2.2 presents the theory and applications of the SIC technique in MAC. Section 2.3 shows the power allocation algorithms.

2.1 Multiple Access Protocols

Multiple access is one of the most common type of multiuser communication systems. A general model of such a system is depicted in Fig. 2.1. There are widespread applications in various communication systems, such as the uplink from the user devices to the BS in the cellular networks, transmissions in the wireless LAN, the uplink from ground stations to the satellite, and transmissions from sensors to the sink in the WSN [1, 2, 4].

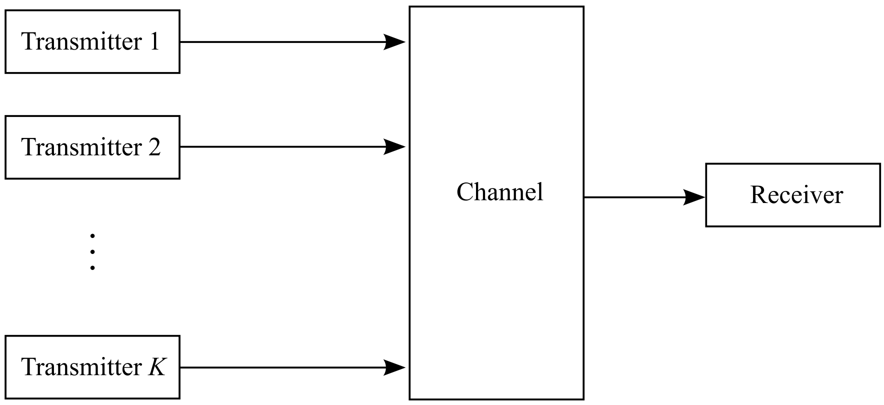

Figure 2.1: Block diagram of the multiple access system - with K transmitters communicating to one receiver.

The multiple access protocol is the method how the multiple transmitters share the common uplink channel to the receiver. As shown in Fig. 2.2, various protocols have been proposed for the multiple access systems with different features for various requirements. One natural idea is to divide the time-frequency spectrum orthogonally and let the BS assign the orthogonal spectrum pieces to the users. For example, frequency-division multiple access (FDMA) subdivides the channel bandwidth into a number of frequency non-overlapping sub-channels and the users access to the channel simultaneously. While TDMA subdivides the time into slots and orthogonal frequency division multiple access (OFDMA) subdivides the time-frequency plane into orthogonal resource grids. An alternative to these orthogonal multiple access protocols is to allow more than one user to share a channel by use of direct-sequence spread spectrum signals. In CDMA, the signal transmissions among the multiple users completely overlap both in time and in frequency [21]. The separation of these signals at the receiver is facilitated by the pseudorandom code sequences with small cross-correlations but could be non-orthogonal. While another non-orthogonal protocol, IDMA, also lets users occupy all the time and the frequency band, but separates the multiple signals by different interleaving patterns assigned to the users [25].

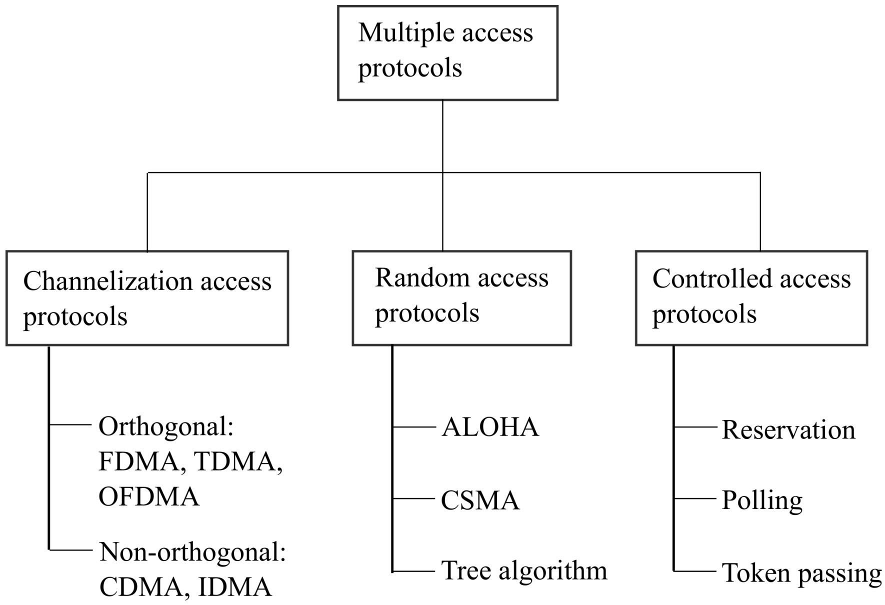

Figure 2.2: Taxonomy of the multiple access protocols - channelization access, random access, controlled access.

Random access communication is one of the approaches to dynamic channel sharing [3]. Without channel assignment by the receiver, the transmitters contend for the channel in a uncoordinated manner. The consequence is that in a duration, the receiver may receive a packet successfully if there is one and only one user transmitting, or the receiver fails to receive due to multiple users transmitting simultaneously (collision), or the channel is idle since no user transmits. The benefit is that the users can transmit soon after traffic arrives and hence save the time to wait for the assigned time slot as in the TDMA protocol. The ALOHA system is the first devised random access protocol [5]. There are basically two types of ALOHA protocols: slotted and unslotted. In a slotted ALOHA system, users transmit to the receiver whenever the packets arrive. In a slotted ALOHA, the packets are transmitted in time slots that have specified beginning and ending times. The users synchronize according to the time slot before transmission.

To improve the throughput performance by avoiding collisions, CSMA has been proposed by exploiting the carrier sensing capability and the sophisticated protocol design [8]. Even without carrier sensing, the tree algorithm can increase the system throughput by the use of feedback from the receiver [59, 60]. The controlled access protocols such as the reservation protocol, the polling protocol, and the token passing protocol, can be considered as random access protocols with a degree of control by the receiver.

2.2 Successive Interference Cancellation

The principle of successive interference cancellation has been used to derive the capacity of the Gaussian multiple-access channel [38]. For the multiuser detection in the multiple access communications, the SIC is based on cancelling the reconstructed interfering signal from the received signal, one at a time as they are detected [2]. Consider the Gaussian multiple-access system consists of K users and one common BS. The corresponding capacity region is described by $2^K - 1$ constraints, where each constraint stands for one possible non-empty subset $\mathcal{K}$ of users:

$$\sum_{k\in\mathcal{K}} R_k < \log\left(1 + \frac{\sum_{k\in\mathcal{K}} P_k}{N_0}\right), \quad \forall\mathcal{K} \subset \{1, 2, \cdots, K\}, \tag{2.1}$$

where P_k is the transmit power of the k-th user and N_0 is the noise power.

To give an intuition, the capacity region of the two-user Gaussian channel is illustrated in Fig. 2.3. Assume that the full transmit power of user 1 and user 2 are P_1 and P_2, respectively. The data rates of user 1 and user 2, (R_1, R_2), must satisfy the following constraints due to the Shannon's capacity theorem:

$$R_1 < \log\left(1 + \frac{P_1}{N_0}\right), \tag{2.2}$$

$$R_2 < \log\left(1 + \frac{P_2}{N_0}\right). \tag{2.3}$$

When the orthogonal multiple access is used, the channel resource is divided orthogonally and assigned to each user. Consider an orthogonal TDMA scheme that assign a portion T_1 of the time to user 1 and the remained portion, $T_2 = 1 - T_1$, to user 2. In this case, the maximum data rate that user 1 can achieve is given by

$$T_1 \log\left(1 + \frac{P_1}{T_1 N_0}\right), \tag{2.4}$$

Similar to the case of user 1, the maximum rate user 2 can achieve is

$$(1 - T_1) \log \left(1 + \frac{P_2}{(1 - T_1)N_0}\right). \tag{2.5}$$

All the data rate pairs can be obtained by varying the value of T_1 in the orthogonal TDMA scheme. However, all such data rate pairs do not approach the Gaussian multiple-access capacity region. Hence, the TDMA scheme and other orthogonal multiple-access schemes are suboptimal.

On the contrast, the optimal data rate region can be achieved by non-orthogonal multi-access and the SIC receiver. In this case, each user encodes its data using a capacity-achieving channel code and all users transmit simultaneously. The SIC receiver decodes the packet from both the users in two steps. In the first step, the SIC receiver decodes the packet of user 2, from noise and the signal of user 2, which can be treated as Gaussian interference. The maximum date rate user 2 can achieve is $R_2^* = \log\left(1 + \frac{P_2}{P_1+N_0}\right)$. Once the SIC receiver decodes the packet from user 2, it can reconstruct user 2's signal and subtract the reconstructed signal from the received signal. The SIC receiver can then continue to decode the packet of user 1 only from the Gaussian noise. Hence, the maximum data rate of user 1 is given by $R_1^* = \log\left(1 + \frac{P_1}{N_0}\right)$. Considering the data rates of all users can achieve, the bound of sum data rate is given by $\log\left(1 + \frac{P_1+P_2}{N_0}\right)$. With this sum data rate bound, all data rate pairs in the capacity region shown in Fig. 2.3 can be obtained by the corresponding capacity-achieving channel codes of the target data rates.

In the practical applications for the wireless communications, the SIC decoder performs as well as a near-optimal decoder while it has much lower linear complexity [39]. The use of SIC has thus been actively investigated in wireless multiple access and broadcast scenarios [20, 23, 40, 41, 42, 61]. Specially, for the random access communications, the SIC can be used to detect signals from the collision in one time slot [30, 37, 56], or even among time slots through the advance protocol designs [44, 45, 62].

Some practical implementation issues should be considered such as the complexity scaling with the number of users, the error propagation, and the imperfect channel estimation. Among these implementation issues, for the uplink multiple

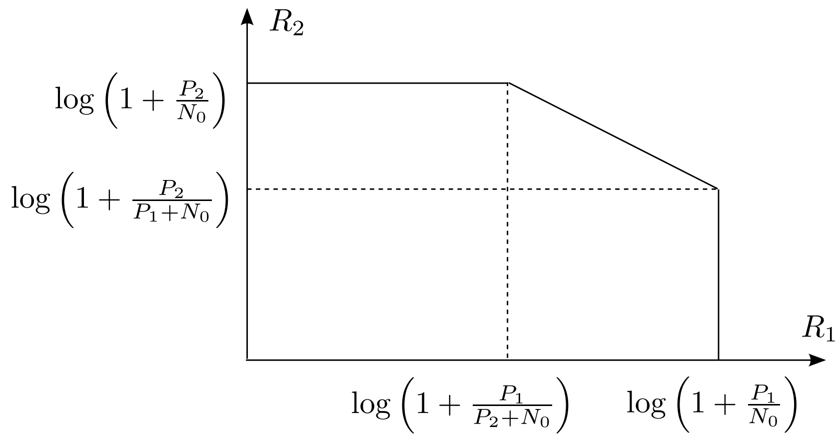

Figure 2.3: Capacity regions of two-user Gaussian multiple-access channel - can be achieved by the SIC decoding.

access with the powerful channel coding, the imperfect channel estimation becomes critical, since to cancel an interference packet from the received signal, the contribution of this interfering packet need to be reconstructed using the decoded information block. For the wireless fading environment, the contribution of the interfering packet depends also on the channel coefficient. Inaccurate estimation of the channel coefficient will lead to cancellation errors that cannot be neglected when designing the power allocation algorithms.

2.3 Power Allocation for Multiple Access

Power allocation or power control for the multiple access is a technology that allocates or controls the uplink transmit power levels, to achieve various performance purposes. The transmit power allocation algorithms have been extensively studied in various multiple access scenarios and can be classified into two types, depending on wether the BS controls the process.

2.3.1 Centralized Power Allocation for Multiple Access

In the centralized power allocation (CPA) algorithms, the BS controls the power allocation process. The BS can optimize the transmit power levels for various targets, including maximizing the system throughput for the data service and maximizing the number of the voice services. Then the BS allocates the transmit power levels to the users through the downlink channel. In the conventional CDMA systems such as the IS95 cellular system that the voice service is dominant, the transmit power control is critical to overcome the *near-far* problem and to keep the received signal-to-interference ratios (SIRs) the same for all the users [21].

The situation is significantly different for the CDMA systems using the SIC. In this case, it is also required that each user experiences the same SIR at the time of decoding. However, interference is being subtracted out of the received signal after each user, so the first user to be decoded sees the most interference, the last user the least. Heuristically, the first user to be decoded should be the strongest user, the weakest user should be decoded last. Hence, the power control method should be different from the one used in the conventional CDMA systems. The optimal CPA algorithm has been proposed for the CDMA with the assumption of the imperfect SIC receiver in [42].

In addition, for the general multiple access system in the fading environment, the power allocation can be used to control the transmit power adaptively according to the fading status. Optimal power allocation strategies have been proposed to achieve the ergodic capacity, the delay-limited capacity, and the outage capacity in [48, 63].

2.3.2 Decentralized Power Allocation for Random Access

In the DPA algorithms used in the random access systems such as the slotted ALOHA, the transmit power levels are not assigned by the BS but are selected by the users in a decentralized manner [32, 37]. Since there is no centralized control, the users have to choose whether or not to transmit, and also the data rate and the transmit power randomly and independently, according to the given probability distribution. Compared to the CPA algorithms in the previous section, in the

DPA schemes frequent feedbacks of power control signalling from the BS to the users are not required. The BS needs to only obtain the transmit power levels and the probabilities offline and broadcast them to the users once at the beginning the communication session. An optimal DPA algorithm has been proposed for the random access with the SIC receiver that can decode at most two packets from one collision, using the MPR model of the SINR [56]. In this scheme, the discrete power levels are first obtained according the constraint that the highest SINR of receiving two packets of different power levels exceeds the decoding threshold. With the obtained power levels, the corresponding probabilities are obtained by the convex optimization to maximize the system MAC throughput.

In this dissertation, to simplify the problem, an assumption that the data rate is the same for all the users is made. The aim of designing the DPA for the random access becomes to obtain the power levels and the optimize the corresponding probability distribution. It should be noted that this study on the power allocation among multiple users in one cell is different from the conventional distributed power control schemes among multiple cells proposed in [46, 47].

2.4 Chapter Summary

This chapter provides the overview for the related techniques including the multiple access protocols, the SIC, and the power allocation for the multiple access communications. It is helpful to understand the content of this chapter, the research in this dissertation is closely related to these techniques.

3

Proposal of Decentralized Multilevel Power Allocation for Random Access

In this chapter, a DPA strategy for random access that has the capabilities of MPR and SIC is introduced. A previous study optimizes the probability distribution for discrete transmission power levels, with implicit limitations on the successful decoding of at most two packets from a single collision. The optimization problem for the general case is formulated, where a base station can decode multiple packets from a single collision, and this depends only on the SINR. A feasible suboptimal iterative per-level optimization process is also proposed by introducing relationships among the different discrete power levels. Compared with the conventional power allocation scheme with MPR and SIC, the proposed method significantly improves the system throughput; this is confirmed by computer simulations.

This chapter is organized as follows. Section 3.2 describes the system model. Section 3.3 proposes the multilevel random access scheme, formulates the optimization problem, introduces the virtual user method, and presents the iterative per-level optimization process. Section 3.4 is devoted to the analysis of the proposed scheme and provides the analytical value of the system MAC throughput. In Section 3.5, the performances are compared by presenting the numerical results from computer simulations. Finally, Section 3.6 summarizes the conclusions.

3.1 Introduction

As originally pointedI out in [30], the power allocation enhances the resulting throughput of the random access system. In [32, 37], a random transmission power control is proposed in order to achieve higher throughput assuming that the receiver is able to decode a single packet from the collision. In [56], a decentralized power control for random access with SIC is proposed; in this system, the discrete power levels are derived, and the optimal probability distribution of power levels is obtained, with the implicit limitation of that, at most, two packets could be decoded from a single collision.

This chapter focuses on a random power allocation to enhance the MPR capability and the use of SIC for the single random access time slot to avoid the large buffer at the receiver side. Specifically, decentralized *multilevel power allocation* (MLPA) is proposed. The users randomly select transmission power levels from the given discrete power levels according to the corresponding probability distribution and the receiver tends to decode more than two packets from a collision. This decentralized power control and optimization are similar to [56] but the proposed approach can be considered as a more general case. A suboptimal per-level iterative optimization method for the AWGN channel is proposed. However, the obtained power levels and the corresponding probabilities also perform well in the fading environment. The main contributions of this chapter are summarized as follows:

- The probability distribution optimization problem of the multilevel power allocation for generalized random access with MPR and SIC is formulated.
- A feasible suboptimal solution using the virtual user method and the per-level iterative optimization process is proposed.
- The theoretical throughput is derived from the optimization results and is used to investigate the improvement of throughput with an increase in the power level.
- The selection of base code is investigated by performing computer simulations.

Table 3.1: Notation in Chapter 1.

Notation	Meaning
K	Number of active users
k	Index of user, $k = 1, 2, \cdots, K$
e_k	Transmission power of user k
L	Number of power levels
l	Index of power level, $l = 1, 2, \cdots, L$
E_l	Value of power level l
p_l	Probability of selecting discrete power E_l
K_l	Number of users with discrete power E_l
R_o	Base rate
ρ	Decoding threshold of base code
ν	$\frac{1}{\rho}$ rounded down to an integer
δ	Margin ratio of decoding threshold, $\delta = \frac{1}{\rho} - \nu$
d_l	Conditional expectation of packet number successfully decoded at level l
D_l	Expectation of packet number successfully decoded from level 1 to level l
D_L	Expectation of packet number successfully decoded from level 1 to level L
T	System MAC throughput
R	System PHY throughput

3.2 System Model

Preliminary to an explanation of the system model treated throughout the paper, the notation is summarized in Table 3.1.

Consider a wireless random access network that consists of one common BS and K users as illustrated in Fig. 3.1. Let $\mathbf{K} = \{1, 2, \cdots, K\}$ denote the set of users and $k \in \mathbf{K}$ is an index of the user. As shown in Fig. 3.2, the information packets are first encoded by sufficiently powerful channel codes, such as turbo codes and low-density parity-check (LDPC) codes, and then the coded packets are modulated to complex signals. The channel coding and the modulation together constitute the *base code* with the data rate R_o.

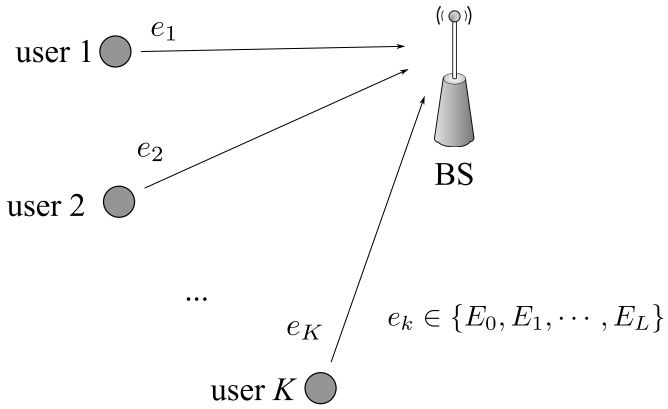

Figure 3.1: System model of the random access system using decentralized power allocation - with K users and one common BS.

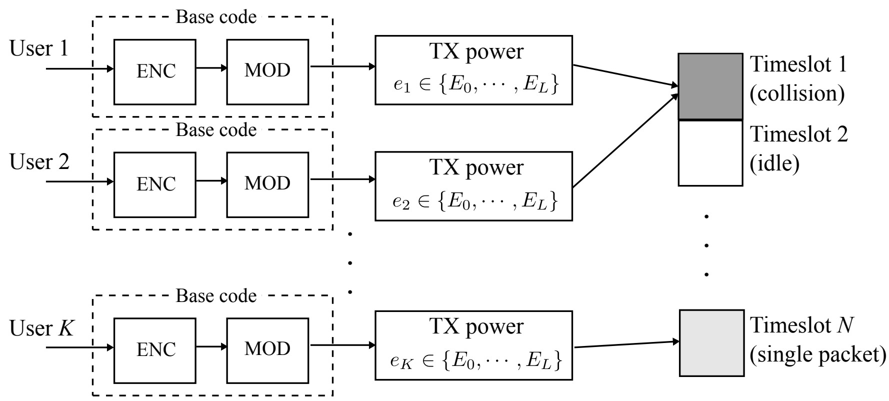

Figure 3.2: Block diagram of the random access system using decentralized power allocation - using the same base code, with K users during N time slots.

At every time slot, each user randomly selects a transmission power and transmits its own coded packet with the chosen power. Namely, user k transmits with power $e_k \in [0, 1]$. If $e_k = 0$, user k is idle during the time slot, and if $e_k = 1$, user k transmits with full power. Note that this can be considered to be a simplified case of the slotted ALOHA, where each user either transmits with full power or keeps idle. Each user selects the transmission power independently in a distributed manner, and none has any knowledge of the transmission power of the other users. The network is assumed to be fully loaded, that is, each user always has a packet to transmit and the buffer is assumed to be sufficient (i.e., the arrival packets are queued in the buffer that is large enough that packets are never discarded).

The received signal y at the BS can be written as

$$y = \sum_{i=1}^{K} h_i \sqrt{e_i} x_i + z, \tag{3.1}$$

where x_i is the transmitted signal of the i-th user with amplitude $\sqrt{e_i}$ and h_i denotes the complex channel coefficient. When AWGN channel is considered, it follows that $h_i = 1$ for $\forall i$. Also, when flat Rayleigh fading channel is considered, the channel coefficient is modelled as a circularly symmetric complex Gaussian random variable $h_i \sim \mathcal{CN}(0, 1)$. Assume that the channel state information (CSI) is ideally available at the BS but not at the users. The noise z is modeled as a circularly symmetric complex Gaussian random variable $z \sim \mathcal{CN}(0, N_0)$. The assumptions that the same average SNR for all users and the flat Rayleigh fading that the channel gain keeps the same during one time slot but may change in the next time slot are made. One of the application scenarios is that the users are located far away from the BS and they are close to each other compared with the distance to the BS. Hence the path loss difference of uplink (user to BS) is not the dominant factor for the decentralized power allocation and is neglected in this chapter.

Then, the SINR corresponding to the user k can be calculated by

$$\mathrm{SINR}_k = \frac{|h_k|^2 e_k}{\sum\limits_{i \in \mathbf{K} \setminus k} |h_i|^2 e_i + N_0}, \tag{3.2}$$

where $\mathbf{K} \setminus k$ denotes the subset of $\mathbf{K}$ from which k is excluded. The BS can decode the packet of user k if and only if SINR_k exceeds the *decoding threshold* ρ which is obviously defined by R_o. The threshold of ideal channel coding $\tilde{\rho}$ is thus given by

$$\tilde{\rho} = 2^{R_o} - 1. \tag{3.3}$$

However, owing to the gap between practical codes and channel capacity, a higher SINR is required to correctly decode the information. Hence, an arbitrary small

$\Delta > 0$ is used to capture this gap. The practical decoding threshold is given by

$$\rho = \left(2^{R_o} - 1\right)(1 + \Delta). \tag{3.4}$$

In a communication system, the packets from different users would correlate each other and significantly degrade the decoding performance. To deal with this problem, bit-interleaved coded modulation (BICM) that originally proposed to improve the decoding performance in the fading environment [64], can be used to eliminate the correlations by letting each packet use statistically independent interleaver. Simulations of transmitting totally correlated packets but without the noise are performed, comparing with the case of AWGN channel that the packet is only corrupted by the noise. As shown in Fig. 3.3, the correlated interferences profoundly degrade the decoding performance. However, with the BICM, the cases that the users using different interleavers achieve close waterfall region to the case of the AWGN channel. In a practical scenario, the users would generate partially correlated packets but the correlation portion is small, and the BICM can further decorrelate the packets. Hence, the decoding threshold is used in the proposed algorithm and the simulations.

Upon decoding the information packet with the highest SINR, the SIC process begins to subtract the corresponding packet from the received signal. The SIC process is repeated in the order of descending SINR until all packets have been decoded except for that none's SINR exceeds the decoding threshold.

3.3 Proposed Method

3.3.1 Problem Statement

Consider the discrete power levels and the corresponding probability mass function (PMF) in a random access system, since it are conjectured in [37, 56] that the optimal power distribution may be of a discrete nature. For each time slot, each user randomly selects a transmission power from a set of discrete power levels $\mathbf{E} = \{E_0, E_1, \cdots, E_L\}$, according to the discrete probability distribution $\mathbf{p} = [p_0, p_1, \cdots, p_L]$. Here $l \in \{0, 1, \cdots, L\}$ is the index of the power levels.

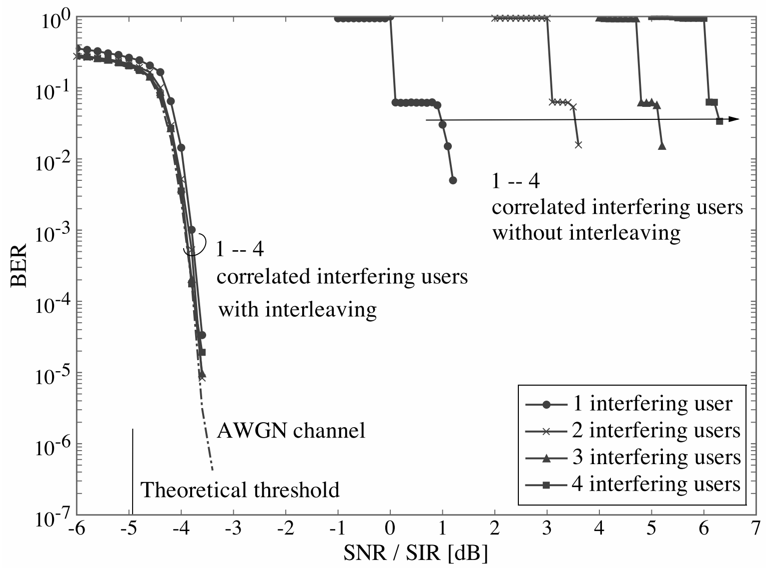

Figure 3.3: Bit error rate performance of the scheme with totally correlated interfering users, using BICM or not using BICM - a turbo code with component code of rate 1/3 RSC code $(15, 17)_8$ in octal form is used. The information size is 1530 bits and quadrature phase shift keying (QPSK) is used.

Taking user k for example, the probability that it transmits with E_l is given by

$$p_l = \Pr(e_k = E_l). \tag{3.5}$$

With the power constraints, the power of the lowest level is $E_1 > 0$ and the power of the highest level is $E_L \leq 1$. Assume that $E_i < E_j, \forall i < j$. When $e_k = E_0 = 0$, it means that the user does not transmit signals, and the corresponding probability is $1 - \sum_{i=1}^{L} p_i \geq 0$; hence $\sum_{i=1}^{L} p_i \leq 1$. The key issues here are how to design the discrete power levels and how to optimize the probability distribution in order to maximize the average number of decodable packets, given the constraint on the transmission power. In the rest of paper, this average number of decodable packets is referred to as *MAC throughput*.

3.3.2 Optimization Problem Formulation

To formulate the problem of maximizing the system MAC throughput, define the event of successful decoding the users with power level l as

$$\mathsf{S}_l = \text{Event[successfully decode } K_l \text{ packets of } l\text{-th level]}, \tag{3.6}$$

where K_l is the number of users transmitting with power E_l, and $\sum_{l=0}^{L} K_l = K$.

For analytical tractability, here consider the AWGN channels, namely $h_i = 1, \forall i$. Consider the decoding of an arbitrary user with the l-th power level in the sufficiently high SNR region where the effect of noise can be neglected. Assuming that the users above the l-th power level have been successfully decoded and ideally subtracted by the SIC process, the probability of successful decoding is given by

$$\begin{aligned} q_l(\mathbf{p}, \mathbf{E}) &= \Pr(\mathsf{S}_l | \mathsf{S}_{l+1}, \ldots, \mathsf{S}_L) \\ &= \Pr\left(\frac{E_l}{(K_l - 1)E_l + \sum_{i=1}^{l-1} K_i E_i} \geq \rho\right), \end{aligned} \tag{3.7}$$

where the other $(K_l - 1)$ signals with the same power E_l and the signals with the lower power levels $\sum_{i=1}^{l-1} K_i E_i$ are considered to be interference. Equation (3.7) shows the condition for successful decoding one user from among K_l users. Upon the successful decoding of the first packet with power level E_l, the interference from the same power level is reduced to $(K_l - 2)E_l$, due to the packet subtraction. Hence with this condition, all K_l users can be successfully decoded.

Assuming the packets of higher levels are successfully decoded and subtracted, for the l-th power level, the conditional expectation of packet number that can be successfully decoded is given by [1]

$$\begin{aligned} d_l(\mathbf{p}, \mathbf{E}) &= \mathbb{E}[K_l q_l] \\ &= \sum_{K_l=1}^{K} K_l \Pr(K_l) \Pr\left(\frac{E_l}{(K_l - 1)E_l + \sum_{i=1}^{l-1} K_i E_i} \geq \rho\right), \end{aligned} \tag{3.8}$$

where K_l is a binomial random variable whose probability is given by

$$\Pr(K_l) = \binom{K}{K_l} p_l^{K_l} (1 - p_l)^{K - K_l}. \tag{3.9}$$

[1] To simplify the notation, $q_l(\mathbf{p}, \mathbf{E})$ will be written as q_l when this will not cause any confusion.

Let $D_L(\mathbf{p}, \mathbf{E})$ denote the expectation of packet number that can be successfully decoded from power level 1 to L. Considering the overall SIC process, the decoding starts from the highest power level L. The throughput contribution of the L-th power level is simply given by d_L, since there is no higher power level. For power levels $l < L$, it is needed to take into account of the probabilities of successfully decoding the higher levels since only when the packets of all the higher levels are subtracted first, the packets of l-th level have the chance to be decoded. Hence the contribution of the l-th power level is given by $d_l \prod_{i=l+1}^{L} q_i$. Finally the overall throughput $D_L(\mathbf{p}, \mathbf{E})$ is a summation of the throughput contributions from all the power levels, as the following

$$\begin{aligned} D_L(\mathbf{p}, \mathbf{E}) &= d_L + \cdots + d_l \prod_{i=l+1}^{L} q_i + \cdots + d_1 \prod_{i=2}^{L} q_i \\ &= d_L + \sum_{j=1}^{L-1} \left(d_j \prod_{i=j+1}^{L} q_i \right). \end{aligned} \tag{3.10}$$

For a general case, let $D_l(\mathbf{p}, \mathbf{E})$ [1] denote the expectation of packet number that can be successfully decoded from power levels 1 to l, assuming the packets of all the higher power levels are subtracted. Similarly D_l is given by

$$D_l(\mathbf{p}, \mathbf{E}) = d_l + \sum_{j=1}^{l-1} \left(d_j \prod_{i=j+1}^{l} q_i \right). \tag{3.11}$$

For the multiple-access network, the system MAC throughput T is used to measure the MAC layer efficiency, which is mathematically defined by

$$T = \frac{\sum_{i=1}^{N} \tilde{D}_L(i)}{N}, \tag{3.12}$$

where N is the number of time slots and $\tilde{D}_L(i)$ is the number of successfully decoded packets in the i-th time slot. According to the definition of T, the optimization of the function $D_L(\mathbf{p}, \mathbf{E})$ is identical to the maximization of the system MAC throughput. Direct formulation of the optimization problem is

[1] $D_l(\mathbf{p}, \mathbf{E})$ will be written as D_l when this will not cause any confusion.

hence given by [65]

$$
\begin{aligned}
\max_{\mathbf{p},\mathbf{E}} \quad & D_L(\mathbf{p},\mathbf{E}) \\
\text{s.t.} \quad & 0 < E_i \le 1, \quad i = 1,\dots,L \\
& E_{i-1} - E_i < 0, \quad i = 1,\dots,L \\
& 0 < p_i < 1, \quad i = 1,\dots,L \\
& \sum_{i=1}^{L} p_i \le 1.
\end{aligned}
\tag{3.13}
$$

3.3.3 Suboptimal per-Level Optimization

Since the number of power levels L is unknown, direct optimizing the target function $D_L(\mathbf{p},\mathbf{E})$ is unfeasible. Moreover, even if L can be derived, it is difficult to prove the concavity of the target function $D_L(\mathbf{p},\mathbf{E})$, which consists of multiple functions of $q_l(\mathbf{p},\mathbf{E})$ and $d_l(\mathbf{p},\mathbf{E})$.

By observing (3.7), notice that the summed interference $\sum_{i=1}^{l-1} K_i E_i$ makes it difficult to derive the successful decoding probability q_l. If this item can be replaced by a function of E_l, it may be possible to obtain a closed form of q_l that depends only on E_l and K_l. Hence to simplify the problem and make the optimization feasible, a suboptimal method that introduces relationships among the power levels is proposed. Specifically, except for the first power level, the relationships among the current l-th power level ($l > 1$) and its lower power levels is given by

$$E_l = \sum_{i=1}^{l-1} K p_i E_i. \tag{3.14}$$

Based on the law of large numbers, for large K, the following approximation can be made:

$$\sum_{i=1}^{l-1} K p_i E_i \approx \sum_{i=1}^{l-1} K_i E_i. \tag{3.15}$$

From (3.14) and (3.15), the total power of all users at lower levels can be treated as a single *virtual user* at the current power level. By introducing this relationship among power levels, the current power level can be obtained by the known values of the lower power levels. In addition, with the approximation, the probability of successfully passing the current power level can be simplified into a tractable simple function. Thus, (3.7) can be rewritten as

$$\begin{aligned} q_l(p_l) &= \Pr\left(\frac{E_l}{(K_l-1)E_l+\sum_{i=1}^{l-1}K_iE_i}\geq\rho\right) \\ &\approx \Pr\left(\frac{E_l}{(K_l-1)E_l+E_l}\geq\rho\right) \\ &= \Pr\left(K_l\leq\frac{1}{\rho}\right)=\Pr\left(K_l\leq\nu\right) \\ &= \sum_{u=0}^{\nu}\binom{K}{u}p_l^u\left(1-p_l\right)^{K-u}, \end{aligned} \tag{3.16}$$

where $\nu=\left\lfloor\frac{1}{\rho}\right\rfloor$. Since K_l is the number of packets, and thus it is always an integer, the equation $\Pr\left(K_l\leq 1/\rho\right)=\Pr\left(K_l\leq\nu\right)$ holds. Hence for $l>1$, at most ν users at the l-th power level can be decoded. With this approximation, for each power level, using (3.7)–(3.11) and (3.16), the target function $D_l(\mathbf{p},\mathbf{E})$ is reduced to a simplified function $D_l(p_l)$, which is given by

$$\begin{aligned} D_l(p_l) &= q_l\left(K_l+D_{l-1}\right) \\ &= \Pr\left(K_l\leq\nu\right)\left(K_l+D_{l-1}\right) \\ &= \sum_{u=0}^{\nu}\left(\binom{K}{u}p_l^u\left(1-p_l\right)^{K-u}\left(u+D_{l-1}\right)\right), \end{aligned} \tag{3.17}$$

where p_l is the only variable and D_{l-1} is set to a constant, since D_{l-1} is maximized for power level $l-1$ and is independent of p_l. As shown in (3.16), the set of power levels $\mathbf{E}$ has no effect on the target function. Finally, for the l-th power level, the optimal p_l^* can be obtained by maximizing the function $D_l(p_l)$, which turns out to be quasi-concave.

Proposition 1. *Function $D_l(p_l)$ is quasi-concave.*

The proof is given in 6.3.3.

Since $D_l(p_l)$ is proven to be quasi-concave, it is known that there is one and only one global maximal for $D_l(p_l)$, and the optimal p_l^* can be obtained by the

Algorithm 1 Obtain $\mathbf{E}$ and $\mathbf{p}^*$

Initialization: $l = 1, E_1$

while 1 **do**

  Optimize D_l and obtain p_l^* using (3.17)

  if $\sum_i^l p_i^* \leq 1$ **then**

    save p_l to $\mathbf{p}^*$, continue.

  else

    discard p_l^*, break.

  end if

  Calculate E_l using (3.14)

  if $E_l \leq 1$ **then**

    save E_l to $\mathbf{E}$, $l = l + 1$, continue.

  else

    discard E_l and p_l^*, break.

  end if

end while

optimization algorithm. Hence the optimization of the multilevel power allocation becomes feasible by using an iterative process from the lowest to the highest power level. For each power level, the optimization problem is simplified to

$$\begin{aligned} \max_{p_l} \quad & D_l(p_l) = \sum_{u=0}^{\nu} \left(\binom{K}{u} p_l^u \left(1 - p_l\right)^{K-u} \left(u + D_{l-1}\right) \right). \\ \text{s.t.} \quad & 0 < p_l < 1. \end{aligned} \tag{3.18}$$

The optimization process begins from the lowest power level $l = 1$, where the minimum required transmission power is $E_1 = N_0\rho$. For higher power levels $l > 1$, the power is calculated by (3.14). The entire process is shown as Algorithm 3. The optimization is calculated iteratively up to the highest power level L, with constraints on the power $E_L \leq 1$ and on the probability $\sum_{i=1}^{L} p_i \leq 1$. Finally, the set of power levels $\mathbf{E}$ and the corresponding optimized discrete probability distribution $\mathbf{p}^*$ can be obtained.

3.3.4 Calculation of Power Levels

This subsection provides a method for choosing the parameters that improve the calculation of E_l by taking into account the effect of noise. For a given SNR, the system MAC throughput depends only on the base rate, since for a given base rate R_o, the decoding threshold ρ and ν are determined. However, notice that $\nu \leq 1/\rho$, and the margin ratio of the decoding threshold is

$$\delta = \frac{1}{\rho} - \nu, \tag{3.19}$$

where $0 \leq \delta < 1$.

In the presence of noise, the condition in (3.16) for successful decoding can be rewritten as

$$\frac{E_l}{(K_l - 1)E_l + E_l + N_0} \geq \rho, \tag{3.20}$$

which can be expressed as

$$K_l \leq \frac{1}{\rho} - \frac{N_0}{E_l}. \tag{3.21}$$

Recalling (3.16), the condition for successful decoding after omitting the noise and excessive interference is $K_l \leq \nu$. The effect of noise can be neglected due to the margin ratio if

$$\nu \leq \frac{1}{\rho} - \frac{N_0}{E_l}. \tag{3.22}$$

For the power levels of $l > 1$, it follows that

$$E_l \geq \frac{N_0}{\delta}. \tag{3.23}$$

These requirements are used to improve the calculation of power for $l > 1$, as follows:

$$E_l = \max\left(\sum_{i=1}^{l-1} K p_i E_i, \frac{N_0}{\delta}\right). \tag{3.24}$$

3.4 Throughput Analysis

This section derives the analytical system MAC throughput from the probabilities $\mathbf{p}^* = [p_0^*, p_1^*, \cdots, p_L^*]$ obtained by the proposed algorithm. The obtained power

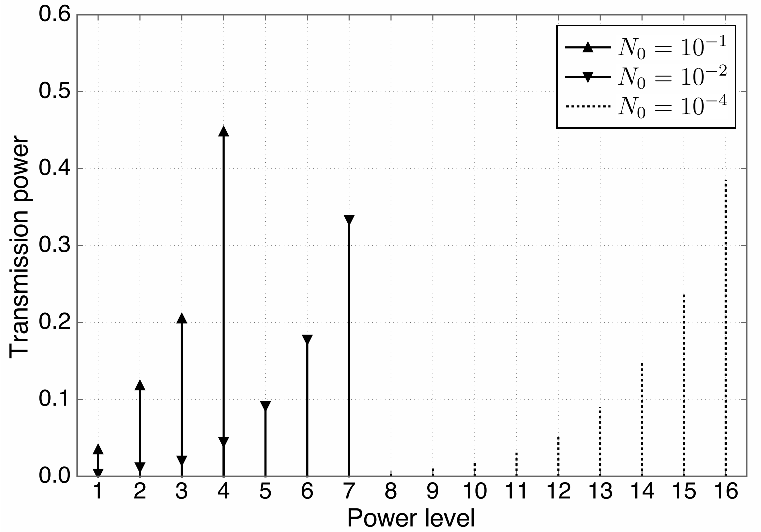

Figure 3.4: Obtained power levels according to various noise power levels - The abscissa axis stands for the index of power levels (real scale of $E_1, E_2, \cdots, E_L$).

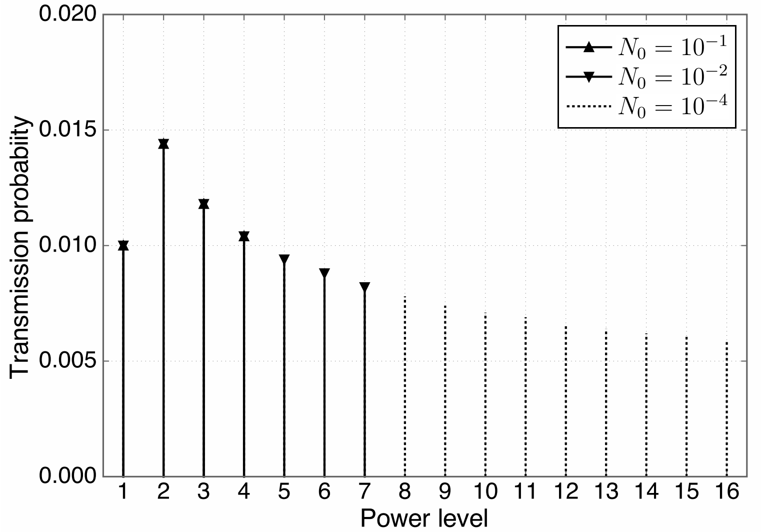

Figure 3.5: Obtained probabilities according to various noise power levels - The abscissa axis stands for the index of power levels ($E_1, E_2, \cdots, E_L$). Note that the sum probability shown in this figure is less than 1, since the power level $E_0 = 0$ (no transmission) is not shown there. In the system, the sum probability of all power levels from E_0 to E_L is 1.

levels and the corresponding probabilities are shown in Fig. 3.4 and Fig. 3.5, respectively.

According to the calculation of D_L in (3.10), the theoretical system MAC throughput D_L^* can be derived. Let q_l^* denote the probability of successful decoding the l-th power level for $l \in \{1, 2, \cdots, L\}$. By replacing p_l with p_l^* in (3.7), q_l^* is derived by the following

$$\begin{aligned} q_l^* &= \Pr(\mathsf{S}_l | \mathsf{S}_{l+1}, \ldots, \mathsf{S}_L, \mathbf{p}^*) \\ &= \sum_{u=0}^{\nu} \binom{K}{u} p_l^{*u} (1 - p_l^*)^{K-u} \\ &\approx \sum_{u=0}^{\nu} \frac{\lambda_l^u e^{-\lambda_l}}{u!} \quad \text{where} \quad \lambda_l = p_l^* K, \end{aligned} \tag{3.25}$$

where if K is sufficiently large, from the fact that a Poisson distribution is an approximated version of the binomial distribution for large K, the above approximation is made.

Let d_l^* denote the MAC throughput contributed by power level l. Similarly, by replacing p_l with p_l^* in (3.8), d_l^* is derived by the following

$$\begin{aligned} d_l^* &= \sum_{u=1}^{\nu} u \binom{K}{u} p_l^{*u} (1 - p_l^*)^{K-u} \\ &\approx \sum_{u=1}^{\nu} \frac{\lambda_l^u e^{-\lambda_l}}{(u-1)!} \quad \text{where} \quad \lambda_l = p_l^* K. \end{aligned} \tag{3.26}$$

Using (3.10), (3.25) and (3.26), the analytical system MAC throughput is given by the following closed-form expression

$$\begin{aligned} & D_L^*(\mathbf{d}^*, \mathbf{q}^*, L) \\ &= d_L^* + \cdots + d_l^* \prod_{i=l+1}^{L} q_i^* + \cdots + d_1^* \prod_{i=2}^{L} q_i^* \\ &= d_L^* + \sum_{j=1}^{L-1} \left(d_j^* \prod_{i=j+1}^{L} q_i^* \right), \end{aligned} \tag{3.27}$$

where $\mathbf{q}^* = [q_1^*, \cdots, q_L^*]$ and $\mathbf{d}^* = [d_1^*, \cdots, d_L^*]$.

As shown in Fig. 3.6, the throughput results from the simulation are tightly bounded by the derived analytical throughput. The suboptimal algorithm is designed with the assumption of low noise power and the noise is neglected in the optimization problem formulation. Hence as the noise power decreases, the numerical throughput by the simulations approaches to the analytical throughput. The reason for the stair curve in Fig. 3.5 is that the MAC throughput performance depends on the obtained numbers of power levels and this number must be a integer. For different regions of SNR, different number of power levels are obtained but the number is the same inside each SNR region. Having the analytical throughput, the performance that the random access system can achieve can well understood, especially for the case of low noise power.

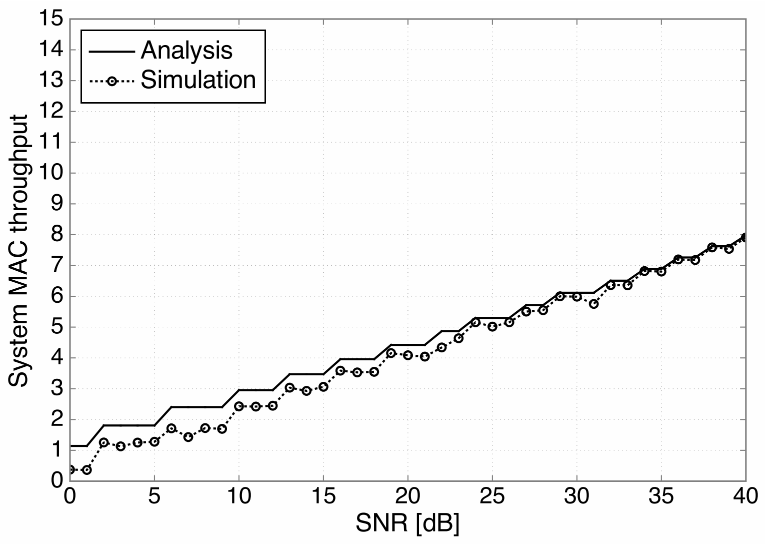

Figure 3.6: Analytical and simulated throughput of the random access system with the decentralized multilevel power allocation - for various $1/N_0$ values with $K = 100$ and $\Delta = 0.1$.

3.5 Numerical Results

Computer simulations are performed and used to verify the effectiveness of the proposed MLPA scheme and to compare it with the existing random access schemes. The simulation parameters are listed in Table 3.2. Simulations with using various data rates are performed and some guidance on selecting the base code is provided.

Table 3.2: Simulation parameters of the random access system with the decentralized multilevel power allocation.

Parameter	Value
Base channel code	1/5 turbo code
Base modulation	QPSK
Base rate R_o	$1/5 \times 2 = 0.4$
Gap of threshold Δ	0.4125
Decoding threshold ρ	0.4467
Noise power N_0	10^{-1}
Fading channel	Flat Rayleigh fading
Number of user K	[4,20]

3.5.1 Throughput Performance Comparisons

The comparisons of the system MAC throughput using the the proposed scheme and the conventional decentralized power allocation schemes are made for various number of user K. Figure 3.7 shows the system MAC throughput performances of various random access schemes including the slotted ALOHA, the SIC scheme with decentralized power allocation (SIC-DPA) in [56], and the proposed SIC scheme with MLPA (SIC-MLPA). Specially, the simulation for the proposed MLPA is also performed with the same constraint as in [56] where at most two packets can be decoded from one collision (SIC-MLPA constrained).

The SIC-DPA scheme achieves superior throughput performance comparing with the slotted ALOHA, since the capability of SIC is exploited by properly allocating transmission power. However, its performance is limited, since at most two collided packets can be decoded, even if the decoding threshold is exceeded. The proposed SIC-MLPA achieves large throughput improvement without the constraint, and the SIC-MLPA constrained scheme still can achieve superior performance but with smaller gain. This indicates that the main gain comes from successful decoding from collisions of more than two packets. Hence to exploit the advantage of the SIC receiver, the proposed scheme is more effective. It can be observed that the throughput of SIC-MLPA with small K is higher and the curve tends to be flat as K becomes large. The reason lies in the optimization process, where the optimization of probabilities $\mathbf{p}$ depends on K. For small K, the resulted probability of being idle p_0 is small. Hence, most of the users transmit with randomly selected non-zero power levels and achieve the higher throughput. On the contrast, the optimization process of the next chapter is independent of K. The trend of performance according to K is different from the one in this chapter.

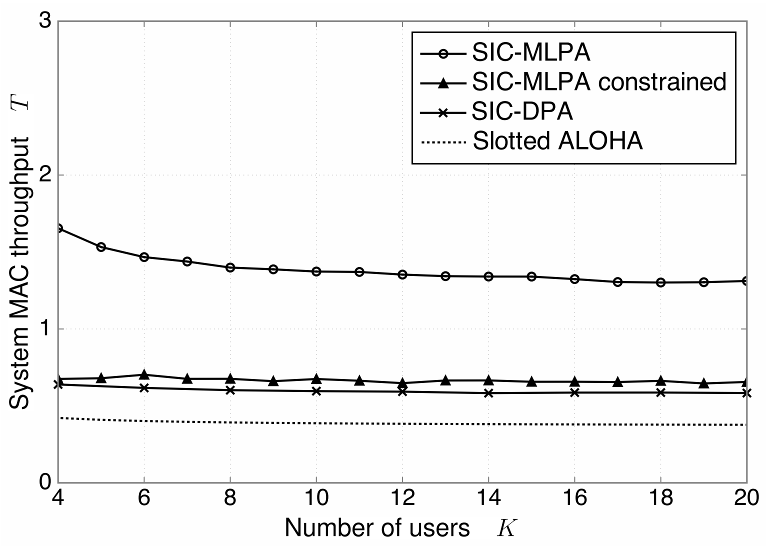

Figure 3.7: Comparison of system MAC throughput for the AWGN channel - for various schemes with different numbers of users.

3.5.2 Throughput Performances in Fading Environment

Figure 3.8 shows the throughput performances of the random access schemes with SIC in the fading environment, using different decentralized power allocation strategies including the proposed SIC-MLPA scheme, the SIC-DPA scheme in [56], and the random access scheme with SIC but without transmission power allocation (the received power is changed randomly by the fading channel). The existing SIC-DPA scheme achieves superior throughput performance comparing with the scheme without power allocation, and the proposed SIC-MLPA further improves the throughput performance. These results show that although the fading affects the power allocation on the received power levels, the power allocation schemes can still outperforms the scheme without power allocation.

Figure 3.9 compares the throughput performances between the fading channel and the AWGN channel. Both the existing SIC-DPA scheme and the proposed SIC-MLPA scheme in the fading environment achieve superior throughput performance. For the proposed scheme, this is because that the random fading coefficient makes the received power levels of the same transmit power level more dynamic and creates additional opportunities of successful decoding.

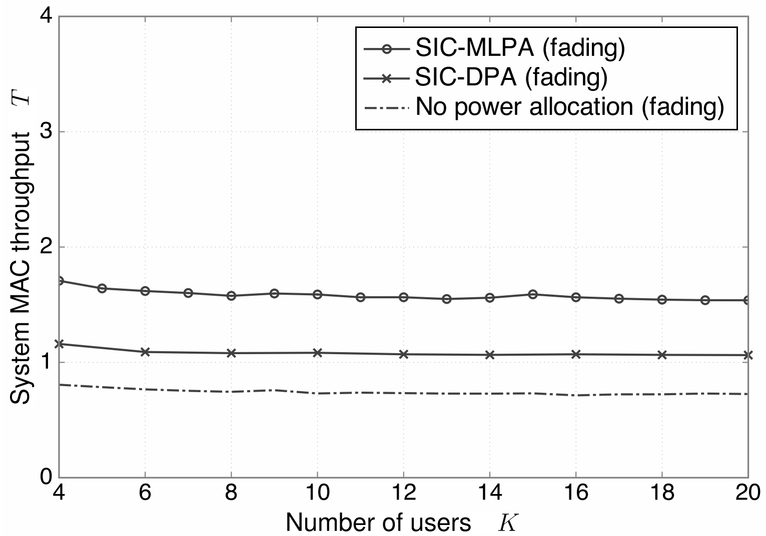

Figure 3.8: Comparison of system MAC throughput in the fading environment - for various schemes with different numbers of users.

3.5.3 Base Code Selection

Since the parameters including ρ, ν, and δ that affect the performance are determined only by the base rate R_o, simulations for various base rates are also performed. The system PHY throughput results for $1/N_0 = 20$ [dB] are listed in Table 3.3. Note that $\Delta = 0.1$ is set for the assumption of even powerful channel code. Here, the system PHY throughput R is used to measure the overall efficiency of both the MAC and PHY layers. Since all of the users adopt the same base code with data rate R_o, the system PHY throughput is $R = R_oT$. According to Table 3.3, for a low-rate base code, the decoding threshold ρ is low, and thus

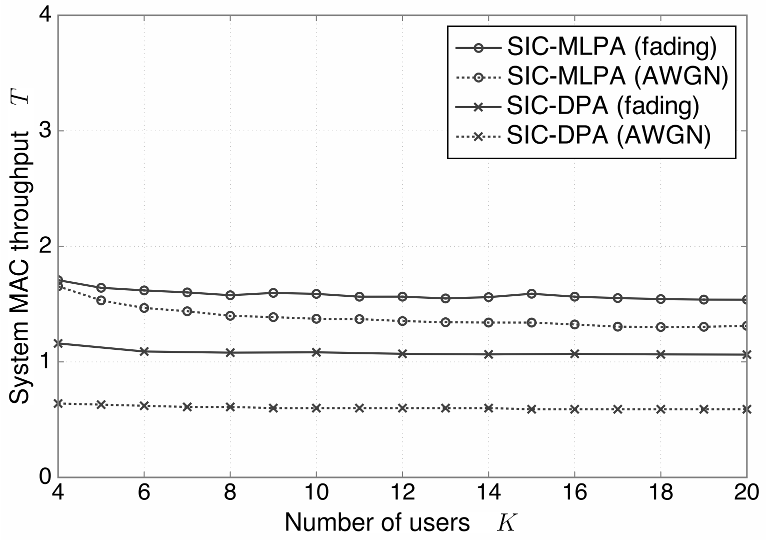

Figure 3.9: Comparison of system MAC throughput in the AWGN environment and in the fading environment - for various schemes with different numbers of users.

more packets of the same power level (larger ν) can be decoded. The margin ratio δ is also important for the system PHY performance, since it makes the system more tolerant of noise and the random interference from lower power levels. Without designing the parameters as in (3.24), the base code of $R_o = 1/7 \times 2$ achieved an inferior system PHY throughput performance ($R^{(1)}$ column) due to the small margin ratio $\delta = 0.15$. The effect of a small δ can be alleviated by the parameter design using (3.24), as shown in the $R^{(2)}$ column of Table 3.3. Hence when selecting the base code, it is needed to avoid one that makes δ small. The base code that maximizes the system PHY throughput R can be found by using the results of the simulations: the base code of $1/8 \times 2$.

3.6 Chapter Summary

In this chapter, the proposed multilevel power allocation for a decentralized random access scheme with the capabilities of MPR and SIC is proposed. The problem of optimizing the discrete power levels and the probability distribution are formulated, and by introducing relationships among the different power levels,

Table 3.3: Summed data rates of various base codes for the selection of the base code.

R_o	ρ	ν	δ	$R^{(1)}$	$R^{(2)}$
1/5×2	0.35	2	0.84	1.60	1.63
1/6×2	0.29	3	0.50	1.57	1.52
1/7×2	0.24	4	0.15	0.98	1.45
1/8×2	0.21	4	0.80	1.82	1.83
1/9×2	0.18	5	0.46	1.61	1.58

a feasible suboptimal iterative per-level optimization process is obtained. Theoretical system MAC throughput from the optimized transmission probabilities is derived. The numerical results confirms that the system MAC throughput of the proposed scheme is better than that of conventional schemes. The proposed optimization method is suboptimal and there are several obstacles to obtain tight optimal results. The first obstacle is that the discrete power levels are unknown without the proposed methods. In addition, the original target function is complicated and the number of power levels is large according to the numerical results. Hence, the convergence is hard to be guaranteed. Differential evolution, one of the genetic optimization algorithms to find the global optimal for the non-convex problems, has been tried but does not work well due to the obstacles aforementioned. One of the future work is to continue to improve the performance of the random access scheme by combining the power allocation for a single time slot and the SIC for multiple time slots.

4

Proposal of A Simple Random Access Scheme with Multilevel Power Allocation

This chapter introduces an improved decentralized power allocation approach for random access with capabilities of MPR and SIC. Considering specific features of SIC, a bottom-up per-level algorithm is proposed to obtain discrete transmission power levels and corresponding probabilities. Comparing with conventional power allocation scheme with MPR and SIC, the proposed approach significantly improves system sum rate; this is confirmed by computer simulations.

This chapter is organized as the follows. Section 4.1 provides an introduction for the proposed scheme. Section 4.2 shows the system model. Section 4.3 illustrates the proposed method. Section 4.4 presents the numerical results obtained via computer simulations. Section 4.5 summarizes this chapter.

4.1 Introduction

Xu *et al.* proposes a decentralized power allocation for random access with SIC [56], using the MPR model of the SINR. The discrete power levels are derived according to the SIC feasible region first, and then the corresponding probabilities are obtained by the MAC throughput optimization. This scheme is suitable for random access applications of high traffic load with difficulty in establishing centralized control. However, this work had a limitation of that two packets, at most, can be decoded from a single collision, and the MAC throughout is affected by this limitation. Moreover, although the data rate of the PHY layer is considered for the deriving of the SIC feasible region, the performance comparison only focused on the MAC throughput.

A multilevel power allocation algorithm for the random access with a more general SIC receiver that can decode multiple packets from one collision is proposed in Chapter 3. That proposal attempts to maximize the MAC throughput by obtaining proper discrete power levels and optimizing the corresponding probabilities. To obtain the power levels, relationships among the power levels are introduced and approximations are used to calculate the current power level from the obtained lower power levels.

This chapter shows an improved DPA algorithm based on the proposal shown in Chapter 3, using the same system model. In this new DPA scheme, instead of introducing relationships among power levels, the current power level is estimated from the power levels and probabilities of the obtained lower levels. The obtained power levels and the corresponding probabilities are more efficient, which is verified by the numerical results. Differing from the conventional works that only focus on the MAC throughput, this proposal explicitly takes into account the data rate of PHY layer, and uses sum data rate of the system to evaluate overall efficiency of both the PHY layer and the MAC layer. With the proposed DPA algorithm, a simple random access scheme of the slotted ALOHA type achieves the superior sum rate performance than the existing MPR-SIC power allocation scheme.

4.2 System Model

Consider a wireless random access network that consists of one common base station (BS) and K users. Let $\mathcal{K} = \{1, 2, \cdots, K\}$ denote the set of users and $k \in \mathcal{K}$ is an index of the user. The information blocks are first encoded by sufficiently powerful channel codes, such as turbo codes, and then the coded packets are modulated to complex signals. The channel coding and the modulation together constitute the *base code* with the data rate R_o.

For each time slot, each user randomly selects a transmit power from a set of discrete power levels $\mathbf{E} = \{E_0, E_1, \cdots, E_L\}$, according to the PMF $\mathbf{p} = [p_0, p_1, \cdots, p_L]$. Here $l \in \{1, \cdots, L\}$ and L are the index and the number of power levels, respectively. Specifically, a user keeps idle during the time slot if $E_0 = 0$ is selected, and the corresponding probability is $1 - \sum_{i=1}^{L} p_i \geq 0$. Here $0 < E_1 < \cdots < E_L \leq 1$ due to the transmission power constraint such that the maximum transmit power of each user is 1. Let e_k denote the transmit power of user k, and the probability that user k transmits with E_l is $p_l = \Pr(e_k = E_l)$. Each user selects the transmit power independently in a distributed manner, and none has any knowledge of the transmit power of the other users. The network is assumed to be fully loaded, that is, each user always has a packet to transmit and the buffer is assumed to be sufficient.

The received signal y at the BS can be written as

$$y = \sum_{i=1}^{K} h_i \sqrt{e_i} x_i + z, \tag{4.1}$$

where x_i is the transmitted signal of the i-th user with unit amplitude, the assigned transmit power is e_i, and h_i denotes the complex channel coefficient. When an AWGN channel is considered, $h_i = 1$ for $\forall i$. Also, when flat Rayleigh fading channel is considered, the channel coefficient is modeled as a circularly symmetric complex Gaussian random variable $h_i \sim \mathcal{CN}(0, 1)$. It is assumed that the CSI is ideally available at the BS but not at the users. The noise z is modeled as a circularly symmetric complex Gaussian random variable $z \sim \mathcal{CN}(0, N_0)$. Since the full transmit power is set to unity, the SNR of a packet at full power is $1/N_0$. Then, the SINR corresponding to the user k can be calculated by

$$\mathrm{SINR}_k = \frac{|h_k|^2 e_k}{\sum_{i \in \mathcal{K} \setminus k} |h_i|^2 e_i + N_0}, \tag{4.2}$$

where $\mathcal{K} \setminus k$ denotes the subset of $\mathcal{K}$ from which k is excluded. The BS can decode the packet of user k iff SINR_k exceeds the *decoding threshold* $\rho = \left(2^{R_o} - 1\right)$. Upon decoding the information packet with the highest SINR, the SIC process begins to subtract the corresponding packet from the received signal. The SIC process is repeated in the order of descending SINR until all packets have been decoded except that none's SINR exceeds the decoding threshold.

4.3 Proposed Method

Let T_l denote the throughput contributed by the l-th power level assuming that the packets at higher power levels are subtracted. Let ζ_i denote the probability that the SIC process successfully continues to a lower power level from the current i-th level (i.e., at the i-th level, the received packet is decoded successfully or no packet is received). The target function is the overall MAC throughput summed over all power levels and the optimization problem is to maximize this function. To obtain this function, the throughput of each power level should be obtained first. In the SIC process, to decode the packets of the current power level, all the higher levels have to be past first. Hence this probability $\prod_{i=j+1}^{L} \zeta_i$ is multiplied. The throughput optimization problem is then formulated as

$$\begin{aligned} \max_{\mathbf{p},\mathbf{E}} \quad & T_L + \sum_{j=1}^{L-1} \left(T_j \prod_{i=j+1}^{L} \zeta_i \right) \\ \text{s.t.} \quad & 0 < E_i \leq 1, E_{i-1} - E_i < 0, \quad i = 1, \ldots, L \\ & 0 < p_i < 1, \sum_{i=1}^{L} p_i \leq 1, \quad i = 1, \ldots, L \end{aligned} \tag{4.3}$$

Since direct optimization is extremely difficult, a bottom-up per-level algorithm is proposed to obtain $\mathbf{E}$ and $\mathbf{p}$. For the lowest power level ($l = 1$), the BS decodes the packet from just the noise, and the power can be simply calculated by $E_1 = N_0\rho$. The same as the slotted ALOHA, the optimal transmit probability is given by $p_1^* = 1/K$, resulting MAC throughput $T_1 = e^{-1}$. For the higher power levels ($l \geq 2$), Algorithm 3 is used to calculate the power and optimize the probability. The details of the algorithm is shown in the following subsections.

4.3.1 Power Calculation

Let K_l denote the number of users that transmit with power level E_l and K_l follows the binomial distribution $K_l \sim B(K, p_l)$. For the sufficient large K, the Poisson distribution can be used to approximate the binomial distribution as follows

$$\Pr(K_l = i) = \frac{e^{-\lambda_l} \lambda_l^i}{i!}, \quad \lambda_l = K p_l. \tag{4.4}$$

Algorithm 2 Obtain $\mathbf{E}$ and $\mathbf{p}$

Initialization: $l = 2, E_0 = 0, E_1 = N_0\rho, p_1^* = 1/K$

while 1 **do**

Calculate E_l using (4.7).

Estimate γ_l using (5.9).

Obtain p_l^* using (5.16).

if $E_l \leq 1$ & $\sum_i^l p_i^* \leq 1$ **then**

Save E_l to $\mathbf{E}$, save p_l^* to $\mathbf{p}$, calculate T_l using (5.13),

$l = l + 1$, continue.

else

Discard E_l and p_l^*, break.

end if

end while

$L = l, p_0^* = 1 - \sum_{i=1}^{L} p_i^*$, save p_0^* to $\mathbf{p}$.

For the l-th power level ($l \geq 2$), to successfully decode the packet from the noise N_0 and the total interference I_l, the power should satisfy the following

$$E_l \geq (I_l + N_0)\,\rho, \tag{4.5}$$

where random variable $I_l = \sum_{i=1}^{l-1} K_i E_i$ is a sum of weighted binomial random variables.

Let γ_l denote the probability of successful decoding when single packet at the l-th level is received and γ_l is given by

$$\gamma_l = \Pr\left(\frac{E_l}{I_l + N_0} > \rho\right), \tag{4.6}$$

where $\zeta_l = \Pr(K_l = 1)\gamma_l + \Pr(K_l = 0)$. With probability of $1 - \gamma_l$, the BS fails to decode the packet and the decoding stops at the l-th level. Hence, the power E_l should make γ_l large enough. It is considered that the randomness mainly comes from the power level $l - 1$ and apply a simple calculation as follows

$$E_l = \left(\sum_{i=1}^{l-2} K p_i E_i + \beta E_{l-1} + N_0\right)\rho, \tag{4.7}$$

where β is an adjustable coefficient to resist the randomness of I_l and can be evaluated by the numerical method. Note that approximations to the sum of weighted binomial random variable ($\sum_{i}^{l-1} K_i E_i$) can be used with the known inequalities such as the Chernoff inequalities. In addition, the concentration inequalities are more suitable for this approximation. However, the bounds provided by all these inequalities are not tight enough. Hence, the adjustable parameter β and the numerical method are used in this proposal.

With this calculation of E_l, the successful decoding probability γ_l can be rewritten as

$$\begin{aligned}\gamma_l &= \Pr\left(\frac{\left(\sum_{i=1}^{l-2} K p_i E_i + \beta E_{l-1} + N_0\right)\rho}{\sum_{i=1}^{l-1} K_i E_i + N_0} > \rho\right) \\ &= \Pr\left(\sum_{i=1}^{l-2} K_i E_i + K_{l-1} E_{l-1} < \sum_{i=1}^{l-2} K p_i E_i + \beta E_{l-1}\right)\end{aligned} \tag{4.8}$$

With the approximation of $\sum_{i=1}^{l-2} K_i E_i \approx \sum_{i=1}^{l-2} K p_i E_i$, γ_l can be approximated in a simple form

$$\Pr\left(K_{l-1} < \beta\right) = e^{-\lambda_{l-1}} \sum_{i=0}^{\beta-1} \frac{\lambda_{l-1}^{i}}{i!}. \tag{4.9}$$

The probability γ_l can be either estimated directly by simulations using (5.9) or approximated by (4.9). [1]

4.3.2 Probability Optimization

Considering the throughput T_{l-1} as a constant, the optimal probability p_l^* can be obtained by maximizing the following target function of MAC throughput

$$\begin{aligned}f_l(\lambda_l) &= \Pr(K_l = 0) T_{l-1} + \gamma_l \Pr(K_l = 1)(1 + T_{l-1}) \\ &= e^{-\lambda_l} T_{l-1} + \gamma_l \lambda_l e^{-\lambda_l}(1 + T_{l-1}).\end{aligned} \tag{4.10}$$

For the given K, obtaining the optimal probability p_l^* is equivalent to obtaining the optimal λ_l^*. The optimization problem is formulated as

$$\lambda_l^* = \arg\max_{0 \le \lambda_l \le K} \{f_l(\lambda_l)\} \tag{4.11}$$

[1]The accuracy of the estimation has been verified via simulation even if it is not shown in the letter due to the page limit.

To obtain λ_l^*, the first order derivative of $f_l(\lambda_l)$ with respect to λ_l is calculated as follows

$$f_l'(\lambda_l) = e^{-\lambda_l}(T_{l-1}\gamma_l + \gamma_l - T_{l-1} - \gamma_l(1 + T_{l-1})\lambda_l). \tag{4.12}$$

Lemma 1. *For the fixed T_{l-1}, there is one and only one λ_l^* that maximizes $f_l(\lambda_l)$.*

If $\gamma_l < T_{l-1}/(1 + T_{l-1})$, λ_l^* becomes negative, which is not allowed since the probability $p_l^* = \lambda_l^*/K$ must be nonnegative. Hence, in consequence

$$\begin{cases} \lambda_l^* = 0 \quad \gamma_l < \frac{T_{l-1}}{1+T_{l-1}} \\ \lambda_l^* = \frac{1+T_{l-1}(1-1/\gamma_l)}{1+T_{l-1}} \quad \frac{T_{l-1}}{1+T_{l-1}} \leq \gamma_l \leq 1. \end{cases} \tag{4.13}$$

By substituting the optimal λ_l^* into (5.13), T_l is given by

$$T_l = f_l(\lambda_l^*) = e^{-\lambda_l^*}T_{l-1} + \gamma_l\lambda_l^* e^{-\lambda_l^*}(1 + T_{l-1}). \tag{4.14}$$

4.4 Numerical Results

To validate the proposed DPA scheme, numerical evaluation is performed via computer simulations. Consider a simple slotted ALOHA type random access with K full-loaded users contending the transmission to one BS, without using the carrier sensing and the backoff mechanism. Both the AWGN and flat Rayleigh fading channels are assumed. All the transmitted packets are encoded using a powerful channel code with data rate $R_o = 2/25$. In every time slot, each user randomly selects the transmit power from the power level set $\mathbf{E}$ according to the corresponding probabilities $\mathbf{p}$, independent of the choices of the other users.

Sum rate defined as $R_{sum} = T \times R$ is used to evaluate the system performance, where T and R stand for the MAC throughput and the data rate of the PHY layer, respectively. In this proposal, the sum rate is given by $T \times R_o$. However, in the conventional MAC protocols such as the slotted ALOHA and the random access scheme with SIC in [56], only the MAC throughput is evaluated and the PHY data rate is ignored. For a fair comparison, assume that the data rates in these two conventional schemes achieve the point-to-point Gaussian channel capacity $C = \log_2(1 + \text{SNR})$, which results in $R_{sum} = T \times C$. Specifically, the ideal R_{sum} is given by $e^{-1} \times C$ and $0.57 \times C$, respectively, for the slotted ALOHA scheme and the random access scheme in [56]. The scheduled orthogonal multiple access such as the time division multiple access (TDMA) achieves $T = 1$, yielding $R_{sum} = 1 \times C$.

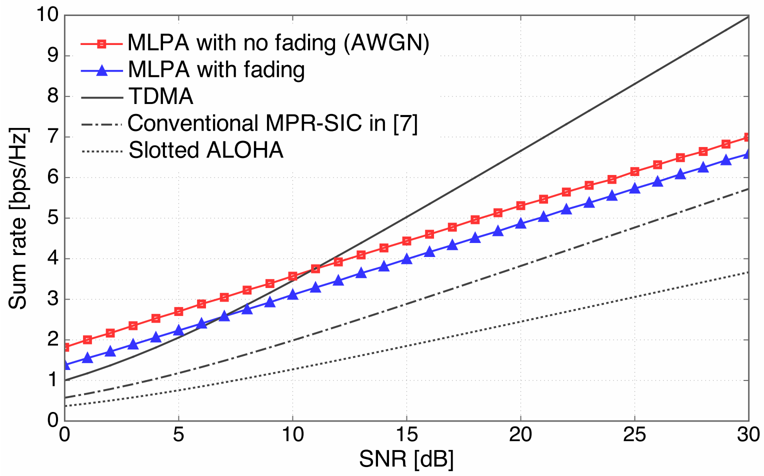

Figure 4.1: Sum rate performance of various schemes for the AWGN channel - with $K = 100$.

Figure 4.1 provides the sum rate results of various schemes according to the SNR. The slotted ALOHA scheme is used as the performance baseline of the random access schemes. The scheme in [56], termed the conventional MPR-SIC, outperforms the slotted ALOHA for all SNR regions, due to the capability of decoding two packets from a collision and the corresponding transmit power optimization. The proposed scheme under the AWGN channel assumption (with $\beta = 6$), termed the MLPA with no fading, outperforms the conventional MPR-SIC scheme for all SNR regions, since the BS can decode multiple packets (could be more than two) from a collision. Because the optimization algorithm is designed for the AWGN channel and the channel status at transmitter is not exploited, the scheme of MLPA with fading underperforms the scheme of MLPA with no fading. The MLPA with no fading scheme even outperforms the TDMA in the low SNR region due to the non-orthogonal feature of MLPA that the sum transmit power can exceed the constraint value of single user transmit power ($\sum_{k=1}^{K} e_k > 1$). In the high SNR region, since the interference from the other packets becomes the dominant factor, the scheduled TDMA scheme outperforms all the random access schemes. Note that the slopes of the TDMA and the proposed scheme are different and the TDMA outperforms the proposal scheme in high SNR region. The reason lies in the same base data rate R_o used for all the SNR regime in the proposed scheme. The difference of the slopes means that the efficiency of MAC layer becomes lower as the SNR increases. This phenomenon requires further investigation such as checking the case of using various R_o for the high SNR region or developing a new joint rate-power allocation algorithm to further improve the sum rate performance.

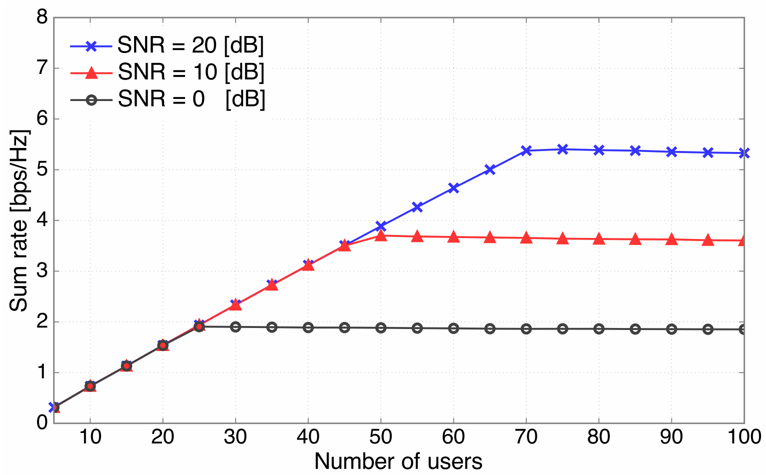

Figure 4.2: Sum rate performance for various number of users - using the proposed power allocation algorithm.

The sum rate results of various values of K for the AWGN channel are shown in Fig. 4.2. From the fact that the performance for small K is limited, the resulting sum rate is still low (note that the maximal sum rate is R_oK). This is due to the use of low rate base code even if all the packets are resolved from the collision. As K increases, the sum rate increases until the number of users causes no limitation. For the scenarios with small number of users, the idea of rate splitting in [40] could be employed to create multiple virtual users within each user, thus leading to an increased total number of users in the system to relieve the constraint.

Figure 4.3 shows the sum rate performance of a practical scenario under the AWGN channel assumption, where the actual number of users, $\widetilde{K}$, may be dif-

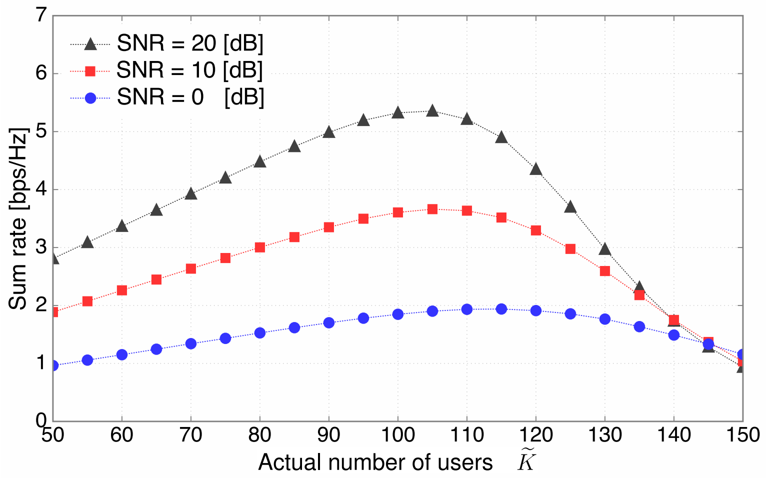

Figure 4.3: Sensitivity of the user number mismatch - between $\widetilde{K}$ and K.

ferent from the estimated $K = 100$. It is obvious to observe that there is a performance degradation when $\widetilde{K} \neq K$. The degradation caused by $\widetilde{K} > K$ is steeper due to the poor SINRs with more interfering packets. One can see that the maximum sum rate is achieved by a slightly larger $\widetilde{K}$ (rather than K). This is because multiple packets of the same power level have a chance to be decoded successfully, while the algorithm is designed for decoding one packet per level.

4.5 Chapter Summary

In this chapter, a decentralized multilevel power allocation for a general random access with the SIC receiver is proposed. With the obtained transmit power levels and probabilities, a simple random access of slotted ALOHA type can achieve the superior sum rate performance by efficiently exploiting the benefit of resolving multiple packets in one collision. Further research in this area includes evaluating the scenario where there exists a random SIC error due to the inaccurate channel estimation. It would be challenging to take into account a critical factor of the cancellation error in the design of decentralized power allocation algorithm.

5

Proposal of DPA for Secondary Random Access in CR Networks with SIC

This chapter studies a decentralized power allocation for uplink random access of secondary users in cognitive network using successive interference cancellation receiver. First, for the additive white Gaussian noise channel, a novel algorithm is proposed, which enables to obtain discrete power levels and optimize the corresponding probabilities, iterating per-level from the lowest power level to the highest one. Under a fading environment, an opportunistic transmission protocol is further proposed to reduce the interference temperature at the primary base station, by allocating power levels only to the secondary users who will result in small interference.

This chapter is organized as the follows. Section 5.1 provides an introduction for the proposed scheme. Section 5.2 shows the system model. Sections 5.3 and 5.4 shows the proposed DPA and OTP. Section 5.5 presents the numerical results obtained via computer simulations. Section 5.6 summarizes this chapter.

5.1 Introduction

Cognitive radio has been extensively studied as a promising technology to solve the growing problem of wireless spectrum scarcity [66, 67, 68]. In spectrum sharing CR networks, SUs are allowed to transmit simultaneously using the same frequency band assigned to PUs, provided that the requirement of an interference temperature constraint at the PBS is fulfilled [67]. The interference temperature is defined as the tolerable interference level at the primary receiver such as the PBS for uplink [69]. Hence, it is critical to protect the transmission of PUs by restricting the resulting interference temperature at the PBS through transmit power allocation at the SUs (see [52, 53, 70] for the seminal works on the optimal power allocation).

5.1.1 Related Works

The transmit power allocation algorithms have been extensively studied in various multiple access scenarios and can be classified into two types, depending on whether the power allocation process is controlled and assigned by the BS. In the *centralized power allocation* algorithms, the BS allocates the transmit power levels to the users through the downlink channels. The optimal CPA algorithm has been proposed for the CDMA with the assumption of the imperfect SIC receiver in [42]. The optimal power allocation algorithms have also been proposed for the multiple access of SUs in the fading CR environment [52, 53], turned out to be a form of water-filling allocation policy.

In the DPA algorithms used in the random access, the transmit power levels are not assigned by the BS but are selected by the users in a decentralized manner. As originally pointed out in [30], the DPA enhances the resulting throughput of the random access system with the MPR capability. In [37], a random transmit power allocation was proposed to achieve higher throughput assuming that the receiver can decode one packet from the collision. Xu *et al.* proposed a DPA algorithm for the random access with the SIC receiver [56], using the MPR model of the SINR. For the secondary random access without the SIC receiver in the CR network, Nekouei *et al.* proposed an optimal threshold-based water-filling DPA policy [58]. Chapters 3 and 4 show the proposed DPA algorithms for the common random access without constraint of interference temperature, which were designed for maximizing the throughput of the MAC layer or the system sum rate. The motivation of proposing a DPA algorithm for the cognitive radio network is that the DPA scheme is suitable for the secondary multiple access of cognitive radio. Since the secondary users have to access the channel quickly after the idle channel is detected, the time and resource to perform protocol set up such as the handshake process in CSMA/CA is limited. The primary user may use the channel again before finishing the set up. Hence, the slotted ALOHA and the proposed DPA scheme are more suitable, where no such protocol set up is required.

5.1.2 Novelty and Contributions

In the aforementioned related works, the CPA algorithm for the multiple access of SUs in the CR networks and the DPA algorithm for the random access with the SIC receiver have been investigated separately. While in this chapter, a novel DPA algorithm for the secondary random access in the CR networks is proposed firstly, which enables to obtain discrete power levels and optimize the corresponding probabilities for the AWGN channel, taking into account the imperfect SIC assumption. Under a fading environment, an *opportunistic transmission protocol* that allocates power levels only to the users who will cause small interference is further proposed. Compared to the conventional DPA schemes, the proposed DPA can improve the performance on the sum rate of the secondary system, while fulfills the constraint of interference temperature at the PBS. In practical CR fading environments, the proposed OTP can further reduce the interference temperature at the PBS, in a decentralized manner. Other major contributions are summarized as the following.

- The issue of imperfect cancellation via the numerical results is addressed and evaluated.
- The mismatch between the estimated number of users and the practical number of users in the network are considered and evaluated.
- The tradeoff between the system sum rate and the interference temperature over the OTP parameter is discovered. A method is also provided to choose the proper parameter value for different QoS requirements.

5.2 System Model

5.2.1 Channel Model

As shown in Fig. 5.1, consider a slotted ALOHA based random access in the CR network, where K SUs contend the transmission to one common SBS with the SIC capability, sharing the same uplink spectrum with the PBS. Let $\mathbf{K} = \{1, 2, \cdots, K\}$ denote the set of users. Channels are assumed to be quasi-static, i.e., the channels are constant during each time slot, but independently change from one slot to another. For the current time slot, let h_i and g_i denote the fading channel coefficients from the i-th user to the SBS and PBS, respectively, where $i \in \mathbf{K}$. In this chapter, these fading coefficients are modeled as independent and identically distributed (i.i.d.) circularly symmetric complex Gaussian random variables, following the PDF of $\mathcal{CN}(0, 1)$. The AWGN channel corresponds to $h_i = 1, g_i = 1$ for $\forall i$. Assume that the CSI is available at the SBS and each user has the local knowledge of its own transmit CSI.

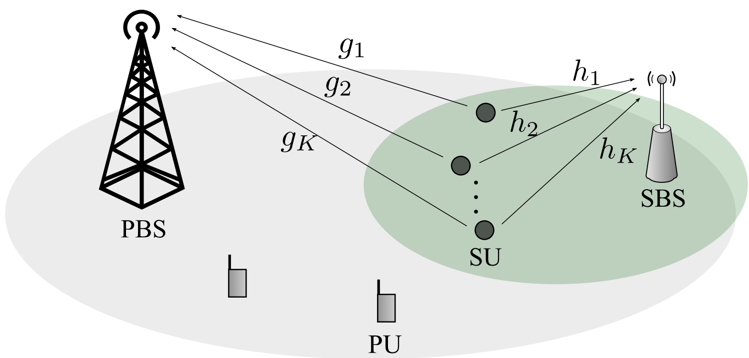

Figure 5.1: The random access system model of the CR network - with K SUs, one SBS, and one PBS.

5.2.2 Transceiver Structure

At the transmitter side, the information blocks are first encoded by sufficiently powerful channel codes, such as turbo codes, and then the coded packets are modulated to complex signals. The channel coding and the modulation together constitute the *base code* with the data rate R_o. For each time slot, each user randomly selects a transmit power from a set of discrete power levels $\mathbf{E} = \{E_0, E_1, \cdots, E_L\}$ according to the PMF $\mathbf{p} = [p_0, p_1, \cdots, p_L]$. Here $l \in \{1, 2, \cdots, L\}$ and L are the index and the number of power levels, respectively. Specifically, a user keeps idle during the time slot if $E_0 = 0$ is selected, and the corresponding probability is $1 - \sum_{i=1}^{L} p_i \geq 0$. Here $0 < E_1 < \cdots < E_L \leq 1$ due to the transmit power constraint such that the maximum transmit power of each user is 1. Let e_k denote the transmit power of user k. Then the probability that user k transmits with E_l is $p_l = \Pr(e_k = E_l)$. Each user selects the transmit power independently in a decentralized manner, and none has any knowledge of the transmit power of the other users. The network is assumed to be fully loaded. That is, each user always has a packet to transmit and the buffer is assumed to be sufficient.

The received signal y at the SBS is given by

$$y = \sum_{i=1}^{K} h_i \sqrt{e_i} x_i + w + z, \tag{5.1}$$

where x_i is the transmitted signal from the i-th SU with unit amplitude, w is the received signal from the PU, and z is the AWGN. Since the SU packets are assumed to be protected from the PU interference using the BICM [64], $z' = w + z$ can be modeled as a circularly symmetric complex Gaussian random variable following $\mathcal{CN}(0, N_0)$. Then, the signal-to-interference-and-noise ratio (SINR) corresponding to the user k can be calculated by

$$\mathrm{SINR}_k = \frac{|h_k|^2 e_k}{\Theta_k + \epsilon\Phi_k + N_0}, \tag{5.2}$$

where Θ_k is the sum interference power from the received packets before past processing, Φ_k is the sum power of the decoded signals, and ϵ is the residual power ratio due to the imperfect SIC subtraction. Hence, $\epsilon\Phi_k$ is the sum of the residual power from the decoded packets. Note that the value of ϵ may change with the received SNR in the practical systems but it is assumed to be constant in this proposal for simplicity. The proposed algorithm can be easily modified if the correspondence to the SNR is known. The SBS can decode the packet of user k if and only if SINR_k exceeds the *decoding threshold* ρ defined as R_o. The threshold of the ideal channel coding is given by $\tilde{\rho} = 2^{R_o} - 1$. However, owing to a performance gap between the data rate achieved by the practical codes and the channel capacity, a higher SINR is required to correctly decode the information. Hence, when a small $\Delta > 0$ is used to capture this gap, the practical decoding threshold is given by

$$\rho = \left(2^{R_o} - 1\right)(1 + \Delta). \tag{5.3}$$

Upon successfully decoding the information packet, the SIC process begins to subtract the decoded packet from the received signal but still leaves the residual of power $e_k \epsilon$ as interference due to the imperfect cancellation. The SIC process is repeated in the order of descending SINR until all packets are decoded except that none's SINR exceeds the decoding threshold.

5.2.3 Constraint of Interference Temperature

In the CR network, the SUs share the same uplink spectral with the PBS when transmitting to the SBS. To guarantee the reception at the PBS, use the constraint of interference temperature E_{IT} in the proposed decentralized power allocation algorithm, which is given by

$$\sum_{i=1}^{K} |g_i|^2 e_i \leq E_{IT}. \tag{5.4}$$

In addition, since each user selects the transmit power independently and the channel gain is random, the actual interference temperature for an individual time slot may exceed the constraint, which corresponds to an outage. Define the outage probability as

$$P_{out} = \Pr\left(\sum_{i=1}^{K} |g_i|^2 e_i > E_{IT}\right). \tag{5.5}$$

5.3 DPA for AWGN Channel

Let T_l denote the MAC throughput contributed by the l-th power level assuming that the packets at higher power levels are subtracted. Let ζ_i denote the probability that the SIC process successfully continues to a lower power level from the current i-th level (i.e., at the i-th level, the received packet is decoded successfully or no packet is received). The throughput optimization problem is then formulated as

$$\max_{\mathbf{p},\mathbf{E}} \quad T_L + \sum_{j=1}^{L-1}\left(T_j \prod_{i=j+1}^{L} \zeta_i\right) \tag{5.6a}$$

$$\text{s.t.} \quad 0 < E_i \leq 1, E_{i-1} - E_i < 0, \quad i = 1, \dots, L \tag{5.6b}$$

$$\sum_{i=1}^{K} e_i \leq E_{IT} \tag{5.6c}$$

$$0 < p_i < 1, \sum_{i=1}^{L} p_i \leq 1, \quad i = 1, \dots, L. \tag{5.6d}$$

Compared to our previous works in Chapters 3 and 4, there is a new additional constraint of the interference temperature (5.6c) in the problem formulation.

Since this optimization is intractable, a bottom-up per-level algorithm is proposed to obtain $\mathbf{E}$ and $\mathbf{p}$. For the lowest power level ($l = 1$), the SBS decodes the corresponding packet treating the SIC residual of the higher power levels as noise. This power E_1 should fulfill

$$\frac{E_1}{(E_{IT} - E_1)\epsilon + N_0} \geq \rho, \tag{5.7}$$

where $(E_{IT} - E_1)\epsilon$ is the estimated SIC residual for power level 1 according to the constraint of interference temperature. As in the slotted ALOHA, the optimal transmit probability is given by $p_1^* = 1/K$, resulting in the MAC throughput $T_1 = e^{-1}$. For higher power levels ($l \geq 2$), use Algorithm 3 to calculate the power and the corresponding probability.

5.3.1 Power Estimation

For the l-th power level ($l \geq 2$), to successfully decode the corresponding packet from the noise N_0, the sum interference from the lower power levels Θ_l, and the

Algorithm 3 Optimize $\mathbf{E}$ and $\mathbf{p}$

Initialization: $l = 2, E_0 = 0$, estimate E_1 by (5.7), $p_1^* = 1/K$, save E_0, E_1 to $\mathbf{E}$, save p_1^* to $\mathbf{p}$.
while 1 **do**
  Estimate E_l by (5.12), estimate γ_l by (5.9), obtain p_l^* by (5.16).
  if $E_l \leq 1$ & $\sum_i^l p_i^* \leq 1$ **then**
    Save E_l to $\mathbf{E}$, save p_l^* to $\mathbf{p}$, calculate T_l by (5.13), $l = l + 1$, continue.
  else
    Discard E_l and p_l^*, break.
  end if
end while
$L = l, p_0^* = 1 - \sum_{i=1}^{L} p_i^*$, save p_0^* to $\mathbf{p}$.

sum SIC residual from the higher power levels $\epsilon\Phi_l$, the power E_l should satisfy:

$$\frac{E_l}{\Theta_l + \epsilon\Phi_l + N_0} \geq \rho \tag{5.8}$$

following with high probability (whp), where K_l denotes the number of transmitting users with power E_l, $\Theta_l = \sum_{i=1}^{l-1} K_i E_i$, and $\Phi_l = \sum_{i=l+1}^{L} K_i E_i$.

Let γ_l denote the probability of successful decoding when a single packet at the l-th level is received, which is given by

$$\gamma_l = \Pr\left(\frac{E_l}{\Theta_l + \Phi_l + N_0} > \rho\right), \tag{5.9}$$

where $\zeta_l = \Pr(K_l = 1)\gamma_l + \Pr(K_l = 0)$. With probability of $1 - \gamma_l$, the SBS fails to decode the packet and the decoding is terminated at the l-th level. Hence, E_l should lead to sufficient large γ_l. Since each of Θ_l and Φ_l is the sum of random variables, to guarantee the successful decoding, an estimated Θ_l, $\hat{\Theta}_l$, is given by

$$\begin{aligned}\hat{\Theta}_l &= \sum_{i=1}^{l-2} K p_i E_i + \beta E_{l-1} \\ &= \sum_{i=1}^{l-1} K p_i E_i + (\beta - K p_{l-1}) E_{l-1},\end{aligned} \tag{5.10}$$

where β is an adjustable parameter in the DPA algorithm to satisfy $\hat{\Theta}_l \geq \Theta_l$ whp. An estimated Φ_l, $\hat{\Phi}_l$, is given by

$$\hat{\Phi}_l = E_{IT} - \sum_{i=1}^{l-1} K p_i E_i - \alpha E_{l-1}, \tag{5.11}$$

where α is an adjustable parameter in the DPA algorithm to satisfy $\hat{\Phi}_l \geq \Phi_l$ whp. From these estimated values, it follows that

$$E_l = \left(\hat{\Theta}_l + \epsilon \hat{\Phi}_l + N_0\right) \rho. \tag{5.12}$$

5.3.2 Probability Optimization

Regarding the throughput T_{l-1} as a constant, the optimal probability p_l^* can be obtained by maximizing the following target function of the MAC throughput

$$\begin{aligned} f_l(\lambda_l) &= \Pr(K_l = 0) T_{l-1} + \gamma_l \Pr(K_l = 1)(1 + T_{l-1}) \\ &= e^{-\lambda_l} T_{l-1} + \gamma_l \lambda_l e^{-\lambda_l}(1 + T_{l-1}). \end{aligned} \tag{5.13}$$

For given K, deriving the optimal probability p_l^* is equivalent to deriving the optimal λ_l^*. The optimization problem is thus formulated as

$$\lambda_l^* = \arg \max_{0 \leq \lambda_l \leq K} \{f_l(\lambda_l)\}. \tag{5.14}$$

To obtain λ_l^*, the first order derivative of $f_l(\lambda_l)$ with respect to λ_l is calculated as follows:

$$f_l'(\lambda_l) = e^{-\lambda_l}(T_{l-1}\gamma_l + \gamma_l - T_{l-1} - \gamma_l(1 + T_{l-1})\lambda_l). \tag{5.15}$$

Proposition 2. *For fixed T_{l-1}, there is one and only one λ_l^* that maximizes $f_l(\lambda_l)$.*

If $\gamma_l < T_{l-1}/(1 + T_{l-1})$, then λ_l^* becomes negative, which is not allowed since the probability $p_l^* = \lambda_l^*/K$ must be nonnegative. In consequence,

$$\begin{cases} \lambda_l^* = 0, & \gamma_l < \frac{T_{l-1}}{1+T_{l-1}} \\ \lambda_l^* = \frac{1+T_{l-1}(1-1/\gamma_l)}{1+T_{l-1}}, & \frac{T_{l-1}}{1+T_{l-1}} \leq \gamma_l \leq 1. \end{cases} \tag{5.16}$$

By substituting the optimal λ_l^* into (5.13), T_l is given by

$$T_l = f_l(\lambda_l^*) = e^{-\lambda_l^*} T_{l-1} + \gamma_l \lambda_l^* e^{-\lambda_l^*}(1 + T_{l-1}). \tag{5.17}$$

5.4 OTP for CR Fading Environment

According to the random nature of fading channels and the decentralized random access, the OTP is proposed to reduce the interference temperature at the PBS along with a smaller sum transmit power of the SUs, which is based on **E** and **p** obtained by the DPA algorithm for the AWGN channel. In each time slot, choose such SUs that yield small $|g_i|$ and large $|h_i|$, which result in less interference temperature and less sum transmit power, respectively. Specially, the OTP divides all the SUs into the following two groups: candidate group and idle group. The SUs satisfying $|g_i|/|h_i| < \eta$ belong to the candidate group to randomly allocate power levels while the other users belong to the idle group in this time slot, where $\eta > 0$ is an adjustable coefficient. The probability of $|g_i|/|h_i| < \eta$ is given by [71]

$$\delta(\eta) = \Pr\left(\frac{|g_i|}{|h_i|} < \eta\right) = \frac{2}{\pi}\arctan\left(\frac{\sigma_g}{\sigma_h}\eta\right), \tag{5.18}$$

where σ_h and σ_g are the standard deviations of $|h_i|$ and $|g_i|$, respectively. In this chapter, $\sigma_h = \sigma_g$, thereby leading to $\delta(\eta) = 2/\pi \arctan(\eta)$. The number of SUs in the candidate group is given by $K_{CG} = \lfloor \delta(\eta) K \rfloor$. Among these K_{CG} SUs, the transmit power levels are allocated from **E** according to the probabilities of the adjusted **p** for the reduced number of available SUs. For instance, if the i-th user belongs to the candidate group and its allocated power level is E_l, then this user transmits with the power of $E_l/|h_i|^2$. To give an intuition, plot this function in Fig. 5.2. For the sake of simplicity, $\delta(\eta)$ and δ is used interchangeably.

The power allocation for the fading environment is based on the DPA for the AWGN channel. The obtained power levels **E** can be used without modification, but have to adjust the TX probabilities, since there are only δK users will be involved in the power allocation and the other $(1-\delta)K$ users just keeps idle during that time slot. According to the obtained probabilities **p**, for the AWGN channel, the probability of keeping idle is p_0 and the probability of transmitting is $1 - p_0$. Let p'_0 and p'_j $(j \in \{1, 2, \cdots, L\})$ denote the probabilities of keeping idle and transmitting using E_j for the fading environment, respectively. For the case of $\delta \geq 1 - p_0$ (there are enough candidates for the power allocation), the

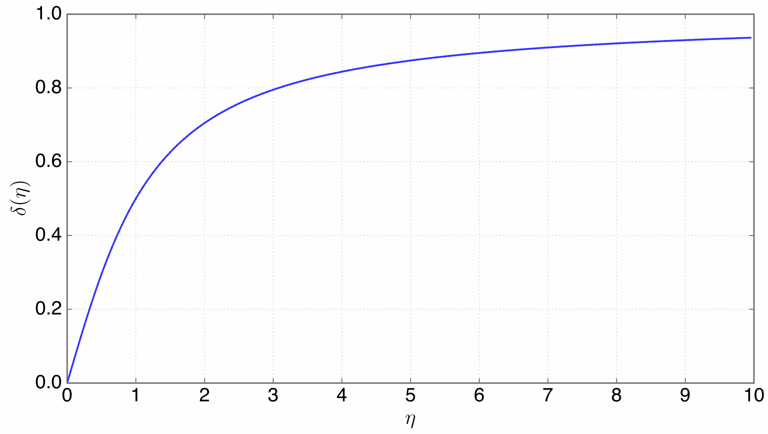

Figure 5.2: Illustration of function $\delta(\eta)$ - intuitive illustration.

following equations should be fulfilled.

$$\begin{cases} p_0 = (1-\delta) + p_0'\delta \\ p_j = p_j'\delta, \quad \forall j \in \{1, 2, \cdots, L\}. \end{cases} \tag{5.19}$$

From these equations,

$$\begin{cases} p_0' = \frac{p_0-(1-\delta)}{\delta} \\ p_j' = p_j/\delta, \quad \forall j \in \{1, 2, \cdots, L\}. \end{cases} \tag{5.20}$$

For the case of $\delta < 1 - p_0$, there are not enough candidates for the power allocation. Hence all the candidates should transmit and $p_0' = 0$. From the following equations

$$\begin{cases} p_j' = \sigma p_j \quad \forall j \in \{1, 2, \cdots, L\} \\ \sum_{i=1}^{L} p_i' = \sigma \sum_{i=1}^{L} p_i = 1, \end{cases} \tag{5.21}$$

where σ is a scaling factor, it follows that

$$\begin{cases} p_0' = 0 \\ p_j' = \frac{p_j}{1-p_0}, \quad \forall j \in \{1, 2, \cdots, L\}. \end{cases} \tag{5.22}$$

In this case, since there are too many idle SUs and the DPA is not fully exploited, the resulted sum rate will be affected.

5.5 Numerical Results

To validate the proposed algorithms, numerical evaluation is performed via computer simulations. Consider a simple slotted ALOHA type random access with K

full-loaded SUs contending the transmission to the SBS, without using the carrier sensing and the backoff mechanism. Both the AWGN and flat Rayleigh fading channels are assumed. All the transmitted packets are encoded using a powerful channel code with data rate $R_o = 2/25$ and $\Delta = 0.1$. For the estimation of power levels, set $\alpha = 1, \beta = 6$ to make the probability of successful decoding γ_l high enough but without overestimate. In every time slot, each user randomly selects the transmit power from the power level set $\mathbf{E}$ according to the corresponding probabilities $\mathbf{p}$, independent of the choices of the other users.

5.5.1 Performance for AWGN Channels

Figure 5.3 shows the sum rate performance of a practical scenario where K varies from slot to slot. Model K as a normal random variable with mean $\mu_K = 100$ and variance σ_K^2 that captures the rapidity of variation. As σ_K^2 increases from 10 to 50, the sum rate performance degrades more severely. However, with low or moderate σ_K^2, the performance close to that of the ideal scenario can still be achieved, e.g., the scenario with $\sigma_K^2 = 10$ achieves 95.10% of the ideal case for SNR = 30 [dB].

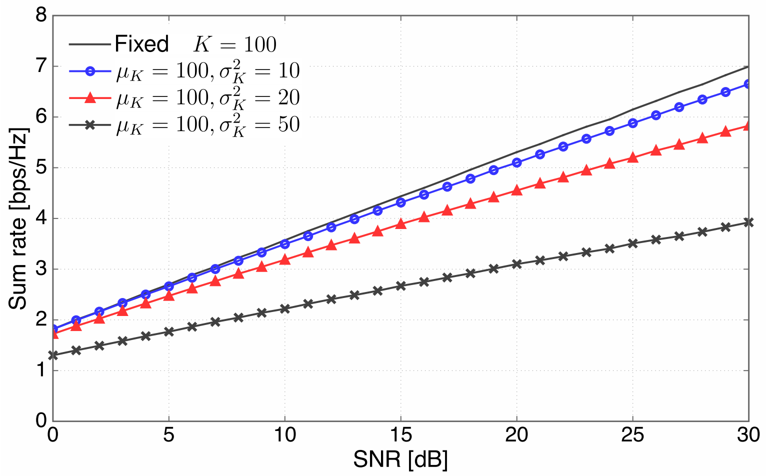

Figure 5.3: Sum rate performance of the cases with random number of users - $\mathbf{E}$ and $\mathbf{p}$ are obtained for $K = 100$.

Figure 5.4 shows the performance improvement by the countermeasure DPA algorithm for the imperfect SIC process. In the previously proposed scheme, termed original DPA, the algorithm is designed for the perfect cancellation that $\epsilon = 0$. While the DPA algorithm in this chapter, termed improved DPA, is designed for the imperfect cancellation that $\epsilon \in (0, 1)$. For the perfect cancellation $\epsilon = 0$, these two algorithms becomes the same. Obviously, this scheme achieves the superior performance. For the original DPA, the cancellation residual causes severe sum rate performance degradation and as the value of ϵ increases, the degradation becomes more severe. For the improved DPA, although there are still degradations comparing with the perfect cancellation scheme, the improvements are obvious when the cancellation is imperfect. The sum rate performance of the improved DPA is quite close to that of the perfect cancellation scheme for the low cancellation residual ratio case of $\epsilon = 10^{-4}$.

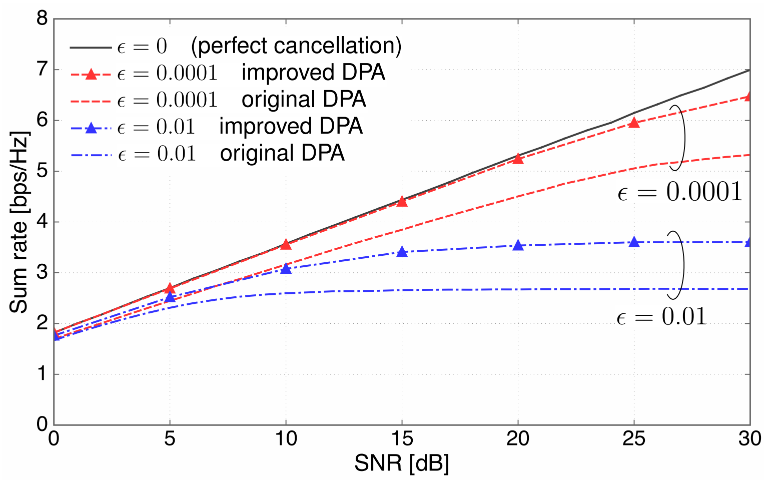

Figure 5.4: Comparison between the original DPA and the improved DPA - for various values of the cancellation residual ratio ϵ.

5.5.2 Performance for CR Fading Environment

In practical CR fading environments, take into account $\epsilon > 0$ to capture the effect of the imperfect SIC caused by the inaccurate channel estimation and set the constraint of interference temperature to $E_{IT} = 10$. In this chapter, set $\epsilon = 10^{-4}$ (which may be adjusted according to the accuracy of the channel estimation). The performance of the system sum rate R_{sum} is presented in Fig. 5.5 according

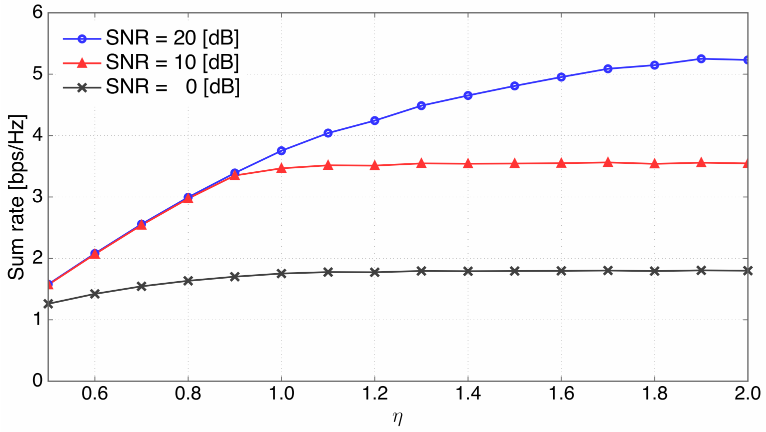

Figure 5.5: System sum rate according to η using the proposed DPA and OTP - for various values of SNR.

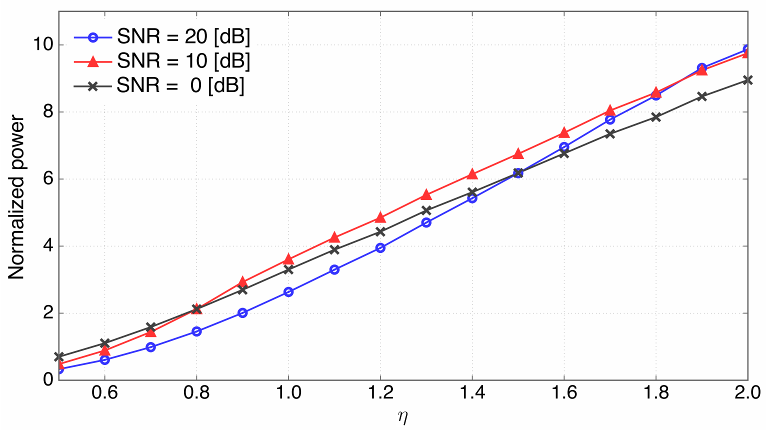

Figure 5.6: Average interference temperature at the PBS according to η - for various values of SNR.

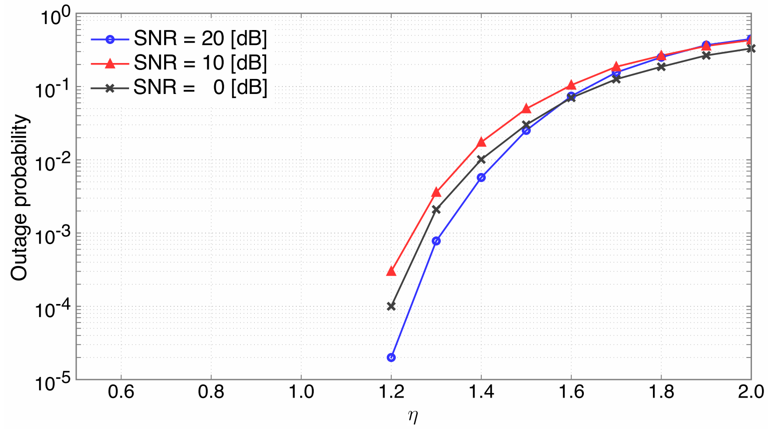

Figure 5.7: Outage probability of the interference temperature at the PBS according to η - for various values of SNR.

to the parameter η that is used to control the ratio of candidate SUs $\delta(\eta)$. If $\delta(\eta) < 1 - p_0$, there are not enough candidate SUs for allocating the non-zero power levels and the resulted performance of R_{sum} degrades. For instance, if SNR $= 10$[dB], $1 - p_0 = 0.469$ is obtained from the proposed DPA algorithm. The minimum $\eta = \tan(\pi/2(1 - p_0)) = 0.907$ that generates enough candidate SUs can be calculated. If using larger η, the system achieves close sum rate performance to that of the AWGN channel, which is verified by the numerical results shown in Fig. 5.5 and Fig. 5.4. Hence, it can be used as a rule to determine the value of η.

Figures 5.6 and 5.7 show the average $\bar{E}_{IT}$ and the outage probability P_{out} of the interference temperature according to η, respectively. Although these three curves for various values of SNR are not fitting perfectly, the common trend with respect to the parameter η can be observed. Both $\bar{E}_{IT}$ and P_{out} increase with η since more SUs that generate more interference are involved. Hence the value of η can be used to control the interference temperature in the fading CR environment. For the case of SNR $= 10$[dB], by setting $\eta = 1.0$, reduced $\bar{E}_{IT} = 3.606$ that is much less than that of AWGN channel ($\bar{E}_{IT} = 10$) is obtained, with very low P_{out} that is close to 0.

The case of SNR $= 20$[dB] is more complicated due to the trade off between increasing the sum rate and reducing the interference temperature. Determine the

Table 5.1: Performance of the system sum rate, the average interference temperature, and the outage probability for the selection of η.

η	R_{sum}	$\bar{E}_{IT}$	P_{out}
1.0	3.75	2.63	0
1.2	4.24	3.95	2.00×10^{-5}
1.4	4.65	5.43	5.73×10^{-3}
1.6	4.95	6.96	7.40×10^{-2}

value of η in an integrated manner, taking account of both the sum rate and the interference temperature. Table 5.1 provides the numerical results of some values of η and can be used to determine η for different requirements. For example, if the requirement of controlling interference is strict, set $\eta = 1.0$ to reduce the interference, with the cost of relative low system sum rate. Otherwise, if the PBS is tolerant with a modest interference temperature outage (e.g., less than 1%), set $\eta = 1.4$ to achieve relative high system sum rate and also the reduced average interference temperature.

5.6 Chapter Summary

In this chapter, a decentralized power allocation algorithm for the secondary random access with the SIC receiver in the CR networks is proposed, to increase the system sum rate at the SBS. The DPA algorithm is designed taking into account the practical assumption of imperfect SIC. Based on this algorithm, an opportunistic transmission protocol for the fading CR networks is also proposed, to reduce the interference temperature at the PBS. By selecting proper parameter, this protocol achieves close system sum rate performance to that of the AWGN channel and also the reduced interference temperature.

6

Conclusions and Future Work

This chapter concludes the dissertation, organized as the following. Section 6.1 summarizes the contributions of the research work. Section 6.2 provides discussions on the other novel ideas on MAC and the related work. Section 6.3 shows the possible future directions of the research.

6.1 Contributions

Multiple access communication systems require the techniques that achieve higher spectrum efficiency, due to the consistent growth of the amount of usage and the number of users. For the channelized access protocols that the BS assign channel resource to the users, the conventional orthogonal multiple access protocols (FDMA, TDMA, OFDMA) are suboptimal according to the information theory. To achieve the capacity of the multiple access channel, the non-orthogonal multiple access protocols (CDMA, IDMA) and the MUD techniques are necessary. As one of the MUD techniques, the SIC has been extensively studied due to its low complexity and near-optimal performance.

This dissertation focuses on improving the spectrum efficiency of the random access scheme with the SIC receiver. The conventional random access protocols (ALOHA, slotted ALOHA, CSMA) try to improve the MAC layer efficiency (MAC throughput) according to the simplified collision model, assuming the PHY layer as a blackbox (the receiver cannot decode any packet whenever the collision happens). However, in the practical wireless networks, it has been observed that the BS can decode the packet whose received power is much higher when a collision happens, which is termed as the capture effect. Furthermore, by using the spectrum spreading or the powerful channel coding, the SIC technique can be used to decode multiple packets from one collision, if the corresponding SINRs of the received packets fulfill the decoding requirement. The MPR and the SIC techniques can be used to further improve the spectrum efficiency of the random access system, with the well-designed DPA algorithms.

However, there are not many literatures on the DPA algorithm for the random access with the SIC receiver [32, 37, 56]. An optimal DPA that maximizes the MAC throughput has been proposed in [56] for the case that the SIC receiver can decode two packets from a collision at most. This research is inspired by this work, but consider s the more general and practical scenarios. First, this work deals with the general SIC receiver that can decode multiple packets (could be more than two), and hence the more complicated optimization problem. Second, this work takes into account both the MAC and PHY layers, and try to maximize the system sum rate. Third, this work considers more practical assumptions, such as the imperfect cancellation, the mismatch of number of users, the random varying number of users. Finally, this work applies the DPA to the CR networks and makes corresponding improvements. In the following, the contributions are summarized according to the publications.

- A DPA algorithm for the case of general SIC receiver is proposed to improve the MAC throughput performance. The throughput analysis and the computer simulations are performed to verify the effectiveness of the proposal in Chapter 3.

- An improved DPA algorithm is proposed, taking account of both the MAC and PHY layers to improve the system sum rate performance. The sensitivity of mismatch of number of users for the practical scenarios are also investigated in Chapter 4.

- The DPA is applied to the CR secondary random access, by modifying the DPA algorithm that controls the interference temperature at the PBS. An opportunistic transmission protocol for the fading environment is also proposed to reduce the interference temperature, at the same time of achieving close system sum rate at the SBS. In addition, the effect of the imperfect cancellation and the random varying number of users are also investigated in Chapter 5.

6.2 Discussions on Other Related Novel MAC Schemes

From the viewpoint of user behavior in the multiple access system, with the channelized access protocols, the users are scheduled passively by the BS in a centralized way. Although each user can use the assigned sub-channel by itself without collision, the efficiency may be low and the delay may be large for some traffic patterns, due to the idle sub-channel assigned to the users without traffic. With the random access protocols, the users are contending the channel actively, regardless of the other users (ALOHA) or more politely (CSMA). One metaphor for the aforementioned user behaviors is the human behavior in different economic forms. The centrally planned economy can be consider as the channelized access, where the resources are assigned by the central organization to the individuals and the system efficiency is low due to the inevitable waste. While the liberal economy can be considered as the random access protocols, where the interest of individuals may conflict but the overall efficiency can be improved by advanced rules.

Beyond the centralized scheduling and the decentralized contention, various novel ideas are also brought to improve the multiple access systems. For instance, in the network the users can cooperate to forward the packets of the other users. In the adaptive network coded cooperation (ANCC) for the multiple access system with massive users [72, 73], the users transmit to the BS with the assigned sub-channel (either TDMA or FDMA) in the first phase. Each user also listens to the transmissions of other users when it is not transmitting. Then in the second phase, users randomly select some received and decoded packets, XORs them, and help to forward the XORed packets to the BS. At the receiver end, after listening to both two phases, the BS maps the received information packets and the XORed packets on a bipartite graph, forming a low-density generator matrix (LDGM) code that can improve the BER of the overall system [74, 75, 76]. However, the LDGM code has the problem of high decoding error floor due to the weight-1 columns in the parity check matrix. To overcome this problem, a serially-concatenated layering network coded cooperation is proposed to generate the serially-concatenated LDGM code that effectively reduces the decoding error floor.

Besides, the distributed version of some rateless coding schemes can also be considered as a type of non-orthogonal multiple access protocol [77, 78, 79, 80]. A distributed layering rateless code as a multiple access protocol and an adaptive power control algorithm for the fading environment are proposed. Inspired by the idea of codes-on-graph, the random access among multiple time slots can be mapped to bipartite graph and decode more packets on the graph using the SIC [44, 45]. The collision resolution process is similar to the belief propagation decoding process of the LDPC codes and rateless LT codes [81, 82].

6.3 Future Directions

Due to the rapid growth of mobile internet and the application of Internet of Things, more and more devices will be connected by the wireless communication networks. The requirements for higher connectivity density and higher spectrum efficiency always exist. In addition, application scenarios with bursty traffic prefer the uncoordinated random access protocols. It can be predicted that such applications will increase explosively in the future, along with the implementations of Internet of Things, Machine to Machine communications, Intelligent Transportation Systems, WSN, CR networks, and so on. This work has investigated the DPA algorithm for random access with SIC. Based on the widely used slotted ALOHA protocol, the spectrum efficiency can be significantly improved with the proposed DPA. This research is one of few works known on this area and has extended the previous works. However, there are still many open issues to be addressed, such as the optimal decentralized resource allocation strategy. In the following subsections, first one future direction that is closely related to this work on the power allocation for random access with the SIC receiver is discussed. Then the long-range target of implementing the coded MAC that should achieve the multiple access capacity with low processing complexity by effectively using the ideas of channel coding and rateless coding is discussed.

6.3.1 Optimal DPA for Random Access with SIC Receiver

Since the proposed DPA algorithm for the random access with the SIC receiver are suboptimal, one of the future directions is to find the optimal DPA strategy that maximize the system sum rate. Specifically, for the slotted ALOHA type random access, users randomly select transmit power levels from a discrete power levels or a continuous power range, denoted by $\mathbf{E}$, according to the PDF or the PMF $\mathbf{p}$. The target is to find the optimal $\mathbf{E}$ and $\mathbf{p}$ that maximize the system sum rate.

6.3.2 Coded MAC

It is already known that the channelized access protocols and the random access protocols have their own advantages and disadvantages. It is also known that the orthogonal multiple access protocols are suboptimal from the information-theoretic perspective [2, 26]. Hence, the future multiple access protocol should be non-orthogonal to achieve the multiple access capacity with the low-complexity SIC receiver and have the benefits of both the channelized access protocols and the random access protocols. Besides, inspired by the repetition slotted ALOHA schemes, in the multiple access process, the discarded received packets caused by the collision or the severe channel impairment in the previous time slot should be used efficiently. The multiple access process should be mapped to graph, to exploit the gain of codes-on-graph using the belief propagation decoding. This future multiple access protocol is termed as coded MAC. The target of the coded MAC is to achieve or approach the multiple access capacity in a decentralized manner with acceptable complexity.

6.3.3 Power Efficiency Aspect

All the proposed DPA optimization algorithms focus on how to maximize the spectrum efficiency of the random access system. However, due to the increasing demands on green communication, power efficiency issue has been receiving more and more attention from both the academia and the industry. Hence, another interesting future direction of this research is the DPA optimization algorithm that maximize the power efficiency of the random access system with SIC, at the same time of fulfilling certain QoS requirements.

Appendices

Appendix A

Proof. For large $K \gg 1$ and small $p_l \ll 1$, the function $D_l(\nu)$ can be approximated by

$$\begin{aligned} D_l(\nu) &= \sum_{i=0}^{\nu-1} \left(\binom{K}{i} p_l^i \left(1 - p_l\right)^{K-i} (i+d) \right) \\ &\approx \sum_{i=0}^{\nu-1} \frac{i+d}{i!} \lambda^i e^{-\lambda}, \end{aligned} \tag{1}$$

where d is a positive real number and $\lambda = Kp_l$. The first-order and second-order derivatives of $D_l(\nu)$ are given by

$$D_l' = \frac{\Gamma(\nu, \lambda) - e^{-\lambda}\lambda^{\nu-1}(d+\nu)}{\Gamma(\nu)}, \tag{2}$$

$$D_l'' = \frac{e^{-\lambda}\lambda^{\nu-2}(\lambda(-1+d+\nu) - (d+\nu)(\nu-1))}{\Gamma(\nu)}. \tag{3}$$

We can derive the unique root for $D_l'' = 0$:

$$\lambda^{**} = \frac{(d+\nu)(\nu-1)}{-1+d+\nu}. \tag{4}$$

Since $(d+\nu)(\nu-1)$ and $(-1+d+\nu)$ are both positive, we have $D_l'' < 0, \lambda \in [0, \lambda^{**})$ and $D_l'' > 0, \lambda \in (\lambda^{**}, \infty)$. Hence D_l' is monotonically decreasing for $\lambda \in [0, \lambda^{**})$ and reaches the minimal negative value at $\lambda = \lambda^{**}$. It is also obvious that $D_l'(0) > 0$. It can be proved that there is one and only one $\lambda^\star$ that makes $D_l'(\lambda = \lambda^\star) = 0$ and $D_l'(\lambda < \lambda^\star) > 0, D_l'(\lambda > \lambda^\star) < 0$. This proves the quasi-concavity of D_l. □

Appendix B

Proof. We prove that there is one and only one solution for $f_l'(\lambda_l) = 0$, which maximizes $f_l(\lambda_l)$. The second order derivative with λ_l is derived as

$$f_l''(\lambda_l) = e^{-\lambda_l}\left(T_{l-1} + \gamma_l(1 + T_{l-1})(\lambda_l - 2)\right). \tag{5}$$

Since $f_l''(\lambda_l) < 0$ for $\lambda_l \in [0, 2 - \frac{T_{l-1}}{\gamma_l(1+T_{l-1})})$, $f_l(\lambda_l)$ is concave in this interval with the maximal point $\lambda_a \triangleq \frac{1+T_{l-1}(1-1/\gamma_l)}{1+T_{l-1}}$. The function $f_l(\lambda_l)$ is convex for $\lambda_l \in [2 - \frac{T_{l-1}}{\gamma_l(1+T_{l-1})}, \infty)$ since $f_l''(\lambda_l) \geq 0$, and the maximal point is to be found on boundary. Hence the the maximal point could be either $\lambda_l = 2 - \frac{T_{l-1}}{\gamma_l(1+T_{l-1})}$ or $\lambda_l \to \infty$. Obviously, $\lim_{\lambda_l \to \infty} f_l(\lambda_l) = 0$ and the maximal point of this interval is $\lambda_b \triangleq 2 - \frac{T_{l-1}}{\gamma_l(1+T_{l-1})}$. We know that $f_l(\lambda_a)$ is always greater than $f_l(\lambda_b)$ since

$$\begin{aligned} f_l(\lambda_a) - f_l(\lambda_b) &= \gamma_l(1 + T_{l-1})\left(e^{-\lambda_a} - 2e^{-\lambda_b}\right) \\ &= \gamma_l(1 + T_{l-1})e^{\frac{T_{l-1}}{\gamma_l(1+T_{l-1})}}\left(e^{-1} - e^{\ln 2 - 2}\right) > 0. \end{aligned} \tag{6}$$

Hence $\lambda_l^* = \lambda_a = \frac{1+T_{l-1}(1-1/\gamma_l)}{1+T_{l-1}}$. □

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Publications

List of Publications Directly Related to The Dissertation

Journal Papers

1. Huifa Lin*, Koji Ishibashi, Won-Yong Shin, Takeo Fujii, **"Decentralized Multilevel Power Allocation for Random Access"**, IEICE Trans. Commun., vol. E98-B, no. 10, Oct. 2015. **(Related to Chapter 3, published)**

2. Huifa Lin*, Koji Ishibashi, Won-Yong Shin, Takeo Fujii, **"A Simple Random Access Scheme with Multilevel Power Allocation"**, IEEE Commun. Lett., vol. 19, no. 12, pp. 2118 – 2121, 2015 **(Related to Chapter 4, published)**

Conference Proceedings

3. Huifa Lin*, Koji Ishibashi, Takeo Fujii, **"Adaptive Network Coded Cooperation with One-bit Feedback,"** in Proceedings of the 2013 IEICE General Conference, B-5-98, (Gifu, Japan), Mar. 2013. **(Related to Chapter 6, Japan domestic)**

4. Huifa Lin*, Koji Ishibashi, Takeo Fujii, **"Design of Layered Adaptive Network Coded Cooperation for Wireless Sensor Networks,"** IE-

ICE Technical Report Vol.113 No.130, RCS2013-120, (Hamamatsu, Japan), July 2013. **(Related to Chapter 6, Japan domestic)**

5. Huifa Lin*, Koji Ishibashi, Takeo Fujii, **"Distributed Layering Rateless Code with Adaptive Power Control,"** in Proceedings of APWCS'14, (Ping Tung, Taiwan), Aug. 2014. **(Related to Chapter 6)**

6. Huifa Lin*, Koji Ishibashi, Takeo Fujii, **"Serially-Concatenated Layered Network Coded Cooperation for Wireless Sensor Networks,"** in Proceedings of WPMC'14, pp.419–423, (Sydney, Australia), Sept. 2014. **(Related to Chapter 6)**

7. Huifa Lin*, Koji Ishibashi, Won-Yong Shin, Takeo Fujii, **"Decentralized Power Allocation for Secondary Random Access in Cognitive Radio Networks with Successive Interference Cancellation" (Related to Chapter 5, accepted by IEEE ICC'16)**