DESIGN OF EFFECTIVE DIGITAL RIGHTS MANAGEMENT STRATEGIES: THE ROLE OF ECONOMICS

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Design of Effective Digital Rights Management Strategies: The Role of Economics

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Abstract

Digital rights management (DRM) technologies are the technique utilized by service providers (SPs) to control and manage the use of digital goods, including the provision, safekeeping, offer creation, distribution, booking, payment, authorization, and consumption of these goods. DRM is however not just a technology issue, but rather more significantly an economics issue, as the utility to SPs and to users plays a vital role in its operation. This thesis focuses primarily on the effectiveness, flexibility and serviceability of DRM from an economics perspective, and considers the benefit to SPs and end users where DRM is used with peer-to-peer streaming (P2PS) and mobile cloud computing.

To provide an effective DRM service for the users of P2PS systems, we model the DRM for P2PS systems using various game-theoretic models. We firstly model DRM in terms of SP and user utility, proposing a design for DRM policy based on homogeneous peers and homogeneous digital goods, which gets maximal utility for the SP as well as the criterion that measures whether the DRM is suitable for a P2PS system. Another game model is then used to analyze how a peer deals with digital goods with regard to the various different operating conditions in P2PS systems with DRM, as well as the SP's responses to the peer's actions. Static and dynamic games are constructed to explore three notorious peer misbehaviors: freeriding, jailbreaking and whitewashing. We use examples to demonstrate how these games work in P2PS systems with DRM, and as well as the equilibria that are established in these games. This is then used to derive the

condition required to ensure that misbehaviors do not become the dominant strategies in both static and dynamic games. Numerical experiments are conducted to demonstrate the effectiveness of the strategies devised from these games.

Merely illustrating the effectiveness of a DRM service is not enough, however; flexibility cannot be ignored. We hence take into account the requirements of Bring Your Own Device (BYOD) users, in order to increase the DRM service flexibility. As BYOD users are allowed to leverage their personal mobile devices for work related tasks, and purchase various digital goods (such as mobile cloud services and apps) for both work and personal purposes via the same mobile device, this brings serious security risks to both personal and business uses. BYOD users generally employ DRM to control and manage the execution of the digital goods in both cases. Their security demands of digital goods used for work are however quite different from those used for personal tasks, and the conventional unified cloud-based DRM service model lacks the flexibility to satisfy BYOD users' diversified security demands. In this thesis, we utilize the security of digital goods as a metric for differentiating DRM service into grades. Such differentiated DRM service increases the flexibility of digital goods' security, allowing BYOD users to choose their preferred DRM grades in order to maximize their utility. Differentiated DRM service moreover increases the revenue of the SP, even when multiple SPs are in competition with each other. Quantitative experiments are further conducted to demonstrate and confirm the effectiveness of our scheme.

In this thesis, we also discuss the serviceability of DRM, and apply it as a means to decrease the mobile traffic caused by the explosive growth of mobile applications. Such mobile traffic can easily exceed the capacity of a cloud service due to the bandwidth limits of last mile connections to the cloud, and the legacy backhaul connections to macrocells' base stations. This degrades mobile applications' quality of service as it requires mobile devices to spend more time on data transmission, hence consuming more battery power.

It also requires cloud providers to make huge investments in updating their infrastructure, a cost which is inevitably borne by all mobile users. To resolve this issue, we propose a so-called *community clinic* solution, in which a cloudlet group is embedded between the cloud and mobile users, in order to reduce the potentially massive deployment cost of the cloud's data centers and reduce the battery power consumed by mobile devices. We first show that mobile devices can reduce their energy consumption by choosing the service provided by the cloudlet group. We then model the systems with and without the cloudlet group as two different types of supply chains, and prove that the cloudlet group can increase the cloud's profit without putting any additional cost on mobile users. A real-time group-buying auction is also proposed for the cloudlet group, to promote its service to nearby mobile users at a lower price and maximize its profit. This community clinic arrangement can result in a win-win-win outcome among the cloud, cloudlet group and mobile users. Quantitative experiments are further conducted to demonstrate the effectiveness of this scheme.

Publications

Conference Papers

1. **Jin Zhang**, Tao Xiong and Wei Lou, "Community Clinic: Economizing Mobile Cloud Service Cost via Cloudlet Group", in the *11th IEEE International Conference on Mobile Ad hoc and Sensor Systems (MASS)*, Philadelphia, Pennsylvania, USA, October 2014.

2. **Jin Zhang** and Wei Lou, "The digital rights management game in peer-to-peer streaming systems", in the *30th IEEE International Conference on Computer Communications (INFOCOM)*, Shanghai, China, April 2011.

3. **Jin Zhang**, Tao Xiong and Wei Lou, "What Steward Could BYOD Users Employ? A Differentiated DRM Service between the Cloud and Mobile Devices", in preparation.

4. Tao Xiong, **Jin Zhang** and Wei Lou, "On Eliminating Energy Inefficiency of the Packet Overhearing Problem in High Traffic Wireless LANs", in the *11th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON) poster*, Singapore, June, 2014.

5. Tao Xiong, **Jin Zhang**, Junmei Yao and Wei Lou, "Symbol-Level Detection: A New Approach to Silencing Hidden Terminals", in the *20th IEEE International Conference on Network Protocols (ICNP)*, Austin, Texas, USA, October 2012.

Journal Papers

1. Tao Xiong, Wei Lou, **Jin Zhang** and Hailun Tan, "MIO: Enhancing Wireless Communications Security through Physical Layer Multiple Inter-symbol Obfuscation", IEEE Transactions on Information Forensics and Security, 2015.

2. Junmei Yao, Tao Xiong, **Jin Zhang** and Wei Lou, "On Eliminating the Exposed Terminal Problem Using Signature Detection", IEEE Transactions on Mobile Computing, 2015.

3. **Jin Zhang**, Tao Xiong and Wei Lou, "On Economizing Mobile Cloud Service Cost via Cloudlet Group", in preparation.

4. Tao Xiong, **Jin Zhang** and Wei Lou, "It Can Drain out Your Energy: An Energy Saving Mechanism against Packet Overhearing in High Traffic Wireless LANs", submitted to IEEE Transactions on Mobile Computing.

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List of Abbreviations

AA	Auction assistant
AIP	Auction Information Publisher
AS	Auction Sponsor
BYOD	Bring Your Own Device
DRM	Digital Rights Management
OR	Odds Ratio
P2PS	Peer-to-Peer Streaming
ROI	Return on Investment
SP	Service Provider

Chapter 1

Introduction

The main objective of this research is to investigate effective digital rights management (DRM) strategies for peer-to-peer streaming (P2PS) and mobile cloud computing. In this chapter, we first introduce the background of DRM in Section 1.1. Then we describe the motivation of this thesis in Section 1.2. In Section 1.3, we summarize the main contributions of this research work. Finally, the organization of this thesis is presented in Section 1.4.

1.1 Background

Digital right was first proposed in 1998 [31], which was defined as a broad range of technologies to control and protect the digital medias. It is the prototype of DRM in the early stage. Due to development of the Internet technologies, a variety of digital goods, which not only include digital medias and softwares, but also the service of cloud and so on, are in need of controlling and managing in the process of use. Therefore, DRM service changes into a general means of technologies provided by the service providers (SPs) to control and manage the use of digital goods, which includes the provision, safekeeping, license phrasing and offer creation, distribution, booking, payment, authorization, and consumption of digital goods. It is quite different from copy protection because the copy protection does not need to manage the digital goods and devices. DRM has been well-studied in the last two decades. Many researchers have ever proposed definitions for DRM service [48, 75], however, it has been found that their definitions of DRM service were only constrained within the aspect of technology and too unilateral to describe DRM service as a whole. In fact, DRM service refers to multiple aspects besides technology, such as legality, sociality and economics [10]. Among them, the restrictions from legality and sociality cannot hold back the illegal use of digital goods because the numerous illegal users would cause a tremendous cost. Then it comes very naturally that we should discuss DRM from the aspects of technology and economics. Up to now, many works have proposed diversiform DRM technologies, but they ignore the willingness of the SPs and users to adopt DRM service. The willingness, determined by the revenue of both the SPs and users, is a novel network economics issue which deserves to be deeply studied.

1.2 Motivation

To discuss the willingness of both the SPs and users, we consider three principal concerns about DRM service: effectiveness, flexibility and serviceability, such concerns bring huge challenges to P2PS system and mobile cloud computing.

1.2.1 Effectiveness of DRM

The effectiveness of using DRM has been furiously debated since the DRM technologies came out. Its restrictions to the use of digital goods seem to overprotect the copyright of the content providers, which brings end users much inconvenience. Researchers in the DRM field are apt to a more open architectural framework of DRM which should be vastly different from what they are today and strike a more reasonable balance between SPs and end users. The effectiveness of DRM is very striking in the P2PS system due to the widespread misbehaviors.

1.2.1.1 Misbehaviors in P2PS System

P2PS system is a distributed architecture that partitions tasks or work loads among peers and it needs to manage the digital right of the digital goods. Some misbehaviors induce the crisis about security and trust by the digital goods without DRM which would decrease the utility of the users. The existing DRM technologies could solve these problems by the strict restrictions on the content management and use. Such restrictions result in much inconvenience for the end users and make some of the users give up DRM service owing to the lower utility of the digital goods. Therefore, it is difficult to avoid such misbehaviors through DRM technologies. The main misbehaviors in the P2PS system are as follows:

- Freeriding: The users would not like to share the digital goods with others;
- Jailbreaking: The users may interpolate the digital goods which are created by the SPs;
- Whitewashing: The users renew themselves with new identities to conceal the fact that they have suffered from serious punishments of the SP.

1.2.1.2 Challenges for Effectiveness of DRM

In a P2PS system, a peer of end user can entertain some streaming content offered by the SP. To make the streaming service functioning normally, the SP expects each peer to not only act as a receiver of the streaming content but also share the content with each other. A variety of mechanisms are proposed to motivate the voluntary sharing of peers [33]. However, some selfish users would break the principle of P2P sharing and choose the freeriding in order to save their own costs. Besides that, the jailbreaking users would distribute modified digital goods with security threat to other users and such actions reinforce the distrust among the users. Even though the users suffer a severe punishment owning to freeriding and jailbreaking, they are able to take whitewashing and rejoin the P2PS system with new identities. It turns out that the monitoring and managing the streaming content, as a major part of the DRM in a P2PS system, becomes a challenging issue because the interests of both the SP and peers should be considered. At the same time, the DRM should protect the streaming service from security threats and avoid the misbehaviors of the peers in the system. Moreover, as the user's viewing experience of a streaming content is easily affected by the delay introduced by the execution of a complicated algorithm, the devised DRM strategy should be light-weighted in general. The downgraded service for the user caused by the delay also backfires the revenue for the SP.

1.2.2 Flexibility of DRM

The flexibility of DRM has been widely reviled by the end users as the existing DRM service is so unified that the users cannot choose their preferred DRM service to protect the digital goods. This contradiction seems impossible to be solved for the Bring Your Own Device (BYOD) users because one BYOD user demands varied DRM service for work and personal purposes.

1.2.2.1 Diversified Security Requirements of BYOD Users

A recent survey reveals that the number of mobile devices carried by mobile workers have cut down from 3.47/person in year 2012 to 2.96/person in year 2013 due to the increasing popularity of BYOD [1], which allows employees to use their personal mobile devices to access the corporate networks. Though BYOD greatly increases the flexibility that employees could use their devices at the workplace and makes employees more productive, BYOD users heavily rely on the cloud that rapidly provides a large pool of resources and services with minimal efforts on service interaction and management. This brings many concerns about security risks, such as data leakage or data theft, at both sides of the cloud and mobile devices as the BYOD users leverage the cloud services and mobile software to complete their work. The cloud services and mobile software, collectively called as "digital goods" , are therefore in need of effective controlling and managing to prevent security risks at both sides. These requirements enforce the deployment of a cloud-based DRM service, which provides a general means to keep tracking the execution of the digital goods and prevent them from security risks at both sides of the cloud and mobile devices.

1.2.2.2 Challenges for Diversity of DRM

The typical cloud-based DRM service, associated with a digital good, is provided with three steps (as shown in Figure 1.1): (1) The SP provides the digital goods with a unified DRM service on the cloud. (2) The mobile users can execute the digital goods on

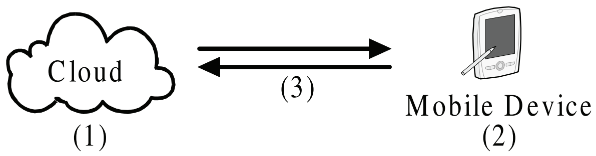


Figure 1.1: The cloud-based DRM service.

their mobile devices, which rely on the installed mobile operation systems to control and manage the digital goods. (3) The purchase and execution of the digital goods involve the interaction between the cloud and mobile devices, which is under the control of the DRM system. Such cloud-based DRM service, unfortunately, does not effectively manage the digital goods for BYOD users and faces several challenges:

- The first challenge is that BYOD users call for the digital goods with security flexibilities to meet their diversified security requirements at the workplace or at home. Generally, BYOD users will use their own mobile devices at both places, and the security requirements of digital goods vary greatly from one user to another or from at home to at work. Though a BYOD user may run the digital goods in an isolated sandbox with high security protection (e.g., BlackBerry Enterprise 10) for work and use the pre-installed platform for the personal use at the mobile device side, SPs usually do not provide the digital goods with diversified securities to satisfy the users' demands at the cloud side nowadays. Due to the popularity of BYOD and its users' diversified demands on the security of the digital goods, it is necessary for SPs to offer the digital goods with diversified security.

- The second challenge for the BYOD users is how to evaluate their security requirements. There is no appropriate metric that allows the BYOD users to measure their security requirements. The lack of the metric lets the BYOD users choose the

DRM service ad hoc.

- The last challenge comes from the impact of cloud and mobile platform on the security of digital goods. At the mobile device side, the security of a mobile operation system will be weakened due to the execution of the digital goods with low security, although the mobile operation system is regarded as an effective shield to prevent the security threats. At the cloud side, the unified DRM service also causes many users to worry about the safety of their digital goods when offloading them to the data center of the cloud, because the users would "have no idea what's in the corporate data center" [57] and some other digital goods stored in the same data center may damage the security of theirs.

1.2.3 Serviceability of DRM

Besides the effectiveness and flexibility of the DRM service, the serviceability of the DRM service is equally important in modern network environment. The responsibility of DRM service, which is to keep track of the digital goods, may increase cost of the digital goods. It would be a nightmare for mobile users to leverage such DRM service.

1.2.3.1 Cost of Mobile Cloud Service

In recent years, mobile devices such as smart phones and tablets have made the information at fingertips whenever and wherever. However, the mobile services provided are greatly degraded by the available resources, including storage and battery power, of the mobile devices. Fortunately, the cloud computing paradigm has fundamentally changed the resource-insufficient situation of mobile devices because the resource-demanding tasks can be offloaded from the mobile devices to the cloud, which provides a tremendous amount of resources and services to the mobile users directly through Internet (Figure 1.2), and thus expedited the explosive growth of mobile data traffic. According to the prediction of Cisco [24], by 2018 the mobile data traffic will surpass 15 exabytes per month, a 11-fold growth from 2013. This will bring a huge burden on the cloud provider since the service demands from mobile users can easily exceed the capacity of current cloud infrastructure due to the following two bottlenecks, last mile connections to the cloud and legacy backhauls to macrocells' base staions [72]. The bandwidth of the last mile connections to the cloud is a major obstacle for providing effective cloud services, which both limits the number of users to access the cloud and increases the access delay. The upgrading of backhauls to cellular networks is lagged far behind the deployment of cellular networks themselves, e.g., 4G networks can achieve maximal data rates at 100$\sim$1000Mbps while their backhuals can support the bandwidth at only 3$\sim$8Mbps (with 2 to 4 T1/E1 lines). However, solutions of either building up massive data centers to increase the bandwidth of the last mile connections to the cloud or enlarging the scale of backhauls to the macrocells will incur a remarkable deployment cost for the cloud provider, which is inevitably borne by all mobile users.

Another critical cost that dominates a mobile user's attitude toward the mobile cloud services is directly related to data rate the mobile user can experience. As the explosive growth of mobile service demands will unfavorably have each mobile user suffer a lower per-service data rate, the mobile user has to spend a longer time in transmitting and receiving the data, consequently causing her mobile device to have a higher battery power consumption. As a consequence, a mobile user will prefer to access the mobile

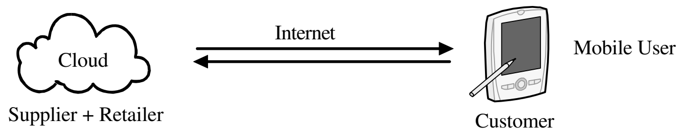


Figure 1.2: The bipartite model with cloud and mobile users.

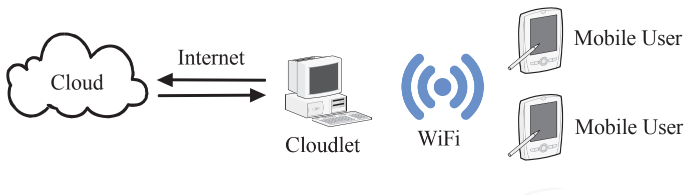


Figure 1.3: The model with cloud, cloudlet and mobile users.

cloud services via a wireless network that provides high per-service data rate connections, which can minimize the energy consumption of her mobile device.

1.2.3.2 Challenges for Serviceability of DRM

Recently, M. Satyanarayanan proposed the cloudlet-based mobile computing model [78] in which the cloudlet is a credible resource-rich computer (or computer cluster) with well-connected Internet, which aims to provide services for proximate mobile users (Figure 1.3). As the cloudlet is close to the mobile devices, which enables a high speed transmission between them, it can serve the mobile users effectively by firstly downloading the contents from the cloud to the cloudlet and then distributing them to the mobile users. Obviously, using the cloudlet is a better solution to overcome the above issues. However, it will raise the following concerns from the viewpoints of the cloud, the cloudlet and the mobile user:

1) *The cloud concerns about the reallocation of the profit*: As a separate entity that serves for the mobile users, the cloudlet should be driven by certain incentives. However,

it should not increase the spending of the mobile users; otherwise, the users would unlikely choose the services provided by the cloudlet. Under this condition, will the cloudlet take away some profit from the cloud when it partakes in serving the mobile users, which sacrifices the cloud's profit if all the services should be originally served by the cloud?

2) *The cloudlet intends to attract more mobile users to use its services*: The cloudlet can get payoff by lessening the burden of the cloud for serving the mobile users. As the mobile users are rational, how can the cloudlet motivate the mobile users to choose its services? Obviously, a most effective way to attract as many mobile users as possible to use the cloudlet's services is to cut down the service price provided by the cloudlet. Then, how can the cloudlet cut down the service price even when the mobile users grow explosively?

3) *The mobile users concern about the energy consumption of the services*: Since leveraging the cloudlet to transmit and receive the data instead of accessing the cloud directly changes the data flow path, will this change introduce more energy consumption to the mobile devices in the process of data transmission and reception? As any change that may cause the mobile devices to consume more energy would likely be abandoned by the mobile users, how can the cloudlet assist the mobile devices to consume less energy?

1.3 Contributions of the Thesis

In this section, we briefly summarize the contributions of this thesis. Our contributions mainly lie in the following three topics: DRM games on P2PS system, differentiated DRM service on mobile cloud service and economized mobile cloud service cost via cloudlet group.

1.3.1 DRM Games on P2PS System

To illustrate the effectiveness of the DRM service, we consider the DRM service as economics models and deploy a preferable DRM service through effective game designs. In our model the users have more initiative to choose whether they are fond of the DRM service or not. If the users consider that they could acquire more utility in the system with DRM service than the system without DRM service, they are willing to choose the system with DRM service. Such DRM service does not need the strict restrictions on the technical aspect, and the users would comply with all the rules in the DRM service to pursue the maximal utility. Here we also design strategies in our DRM service to avoid misbehavioers in the P2PS system, which include freeriding, jailbreaking and whitewashing.

The main contributions of our solution are summarized as follows:

- We establish a bipartite game between the SP and users to compare the payoff in a P2PS system with and without DRM service, and the game assists us to design strategies to make the users, who are in the P2PS system with DRM service, obtain the maximal utility.

- We deploy effective strategies to avoid three misbehaviors of peers in the P2PS system with DRM, such as freeriding, jailbreaking and whitewashing, through the static and dynamic games, and prove that there exists the dominant strategy that could avoid all the users' misbehaviors.

- We conduct numerical experiments to reveal the effectiveness of our strategies.

1.3.2 Differentiated DRM Service on Mobile Cloud Service

To increase the flexibility of the DRM service, we propose a new cloud-based DRM service, called differentiated DRM service, which is flexible enough to meet the diversified security requirements of the BYOD users. To ease our system modeling, we simply treat one BYOD user to be two mobile users: one can execute the digital goods on an isolated virtual platform with high security protection and the other one chooses to use the digital goods with low security protection. Then, the relationship between one BYOD user and the SP now changes to be two independent relationships between each mobile user and the SP, and all the issues are addressed between the SP and mobile users through the differentiated DRM service. The main contributions of this chapter are summarized as follows:

- We improve the existing cloud-based DRM service and divide it into grades based on the security risk, the differentiated DRM service is integrated with the digital goods which is leveraged by the mobile users.
- We introduce a new DRM policy that the mobile user is capable to protect the *primary digital goods set* through employing appropriate mobile platform and associated digital goods.
- We model the utility of a mobile user through drawing supports from some economics concepts, and prove that our differentiated DRM service can bring more utility than any unified DRM service.
- We analyze the benefit of the SP based on linear and nonlinear cost model, and conclude that the SP with the differentiated DRM service gains more than the one

without it.

- We further model the competition between SPs as cooperative games and prove that our differentiated DRM service with multiple grades is the dominant strategy.

1.3.3 Economized Mobile Cloud Service Cost via Cloudlet Group

To address these concerns, we propose a novel solution called as *community clinic*, which embeds a *cloudlet group* component between the cloud and the mobile users. The relationship among the cloud, cloudlet group and the mobile users is analogical to that among the central hospital, community clinic and the patients. The community clinics provide convenient medical treatments for the regional patients at a lower price, which lessens the burden of the central hospitals effectively. To easily describe our scheme, we choose the videos as the examples of digital goods because the mobile videos, which take about 53% of the mobile traffic in 2013, exceeds the total mobile traffic in 2012 [24]. Such mobile videos are paid by the end users directly by purchasing data access services or indirectly by viewing advertisements. We leverage the community clinic scheme to resolve all the above concerns with its unique economics and technic characteristics:

- We evaluate the profit of the cloud by modeling the whole system as a tripartite supply chain where the cloud plays as the supplier, the cloudlet group plays as the retailer, and the mobile users play as the consumer. We prove that, without putting extra cost on the mobile users, the cloudlet group is capable of raising the profit for the cloud through satisfying more demands of mobile users, comparing with the bipartite supply chain model where the cloud plays the dual roles as both supplier and retailer, and the mobile user plays as the consumer. The cloudlet group will make the cloud provider save the cost for deploying massive data centers, which is the premise for lowering the price of any cloud service.

- We introduce the real-time group-buying auction mechanism to greatly reduce the price of the digital goods so as to attract more mobile users to choose the services provided by the cloudlet group instead of the cloud. Based on the group-buying auction, the more users bid for the digital goods, the lower price they get. Interestingly, lowering down the price will not sacrifice the profit of the cloudlet group; on the contrary, it will maximize the expected profit of the cloudlet group. The members of the cloudlet group will cooperate with each other to maximize their benefits. We also analyze the expected profit of the cloudlet group and the rationality of the group-buying auction in our system.

- We build a theoretical model to analyze the energy saving of mobile devices due to the use of the cloudlet group. We demonstrate that the mobile devices can effectively cut down the energy consumption with the service of the cloudlet group.

1.4 Organization of the Thesis

The structure of this thesis is illustrated in Figure 1.4. Chapter 1 is the introduction to this thesis, with a summary of the research background, motivations and the organization of the thesis. Chapter 2 presents the literature review and some background knowledge related to the research issues in this thesis. The main body of this thesis, is from Chapter 3 to Chapter 5. In Chapter 3, We design DRM policies for P2PS system through games, such DRM polices make the peer not taking misbehavious and increase the utility of

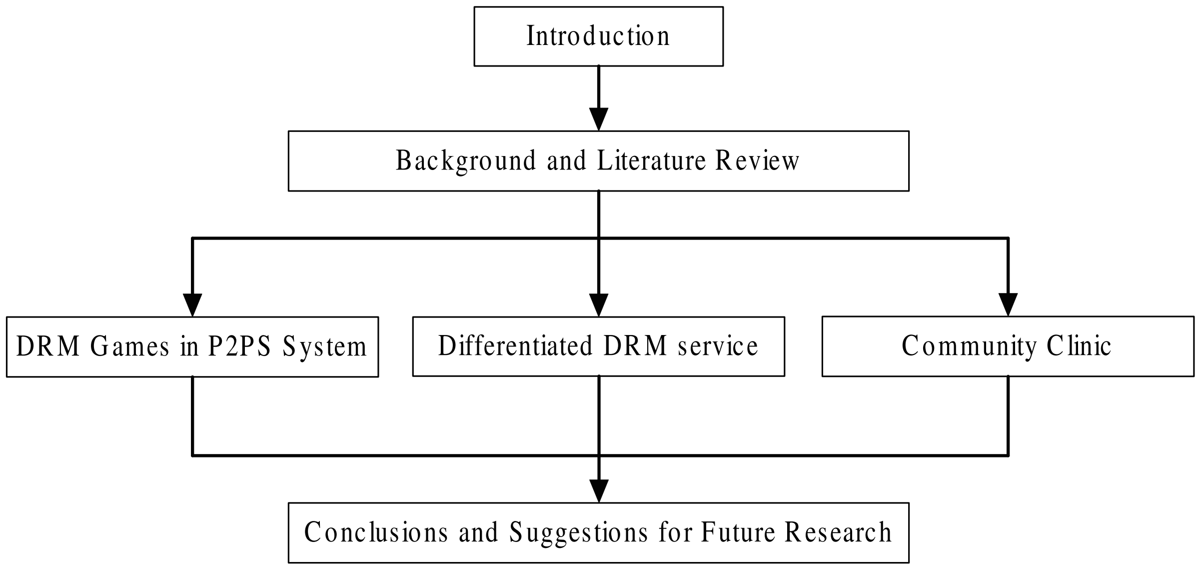


Figure 1.4: The structure of this thesis.

the peers. In Chapter 4, we propose differentiated DRM service through dividing the cloud-based DRM service into multiple grades, such differentiated DRM service increases the payoff of the SPs and mobile users effectively. In Chapter 5, we economize the cost of mobile cloud service via cloudlet group, our model results in a win-win-win outcome among the cloud, cloudlet group and the mobile users. Finally, we conclude this thesis and provide directions for future research in Chapter 6.

Chapter 2

Background and Literature Review

In this chapter, we provide the literature review of the related topics and some necessary background knowledge for the research in this thesis. The organization of this chapter is as follows. We first review the related work about DRM in Section 2.1. Then we review the related work about P2PS system in Section 2.2. The related work about mobile cloud service is presented in Section 2.3. Finally, we review the economics tools in our thesis.

2.1 Background Knowledge about DRM

The conception of digital right was first proposed in 1998 [31], which came the control and management of the digital right. After then, researchers tried to propose precise definitions for the DRM, someone considered that DRM referred to controlling and managing rights to digital intellectual property [74], while others thought that DRM is the description, identification, trading, protection, monitoring and tracking of all forms of rights usages over both tangible and intangible assets including management of rights holders' relationships [48]. However, neither of the definitions could be regarded as a standard since the DRM refers to technology and economics and so on [10].

2.1.1 Technology Aspect of DRM

The principle requirement of DRM service is to allow the fair use of the digital goods. To achieve this goal, there are an amount of DRM technologies developed [7, 36, 49]. The researchers have leveraged a series of methods to assist the SPs in controlling and managing the digital goods, such as authentication [88], watermark [38], encryption [56] and so on. User identification/authentication plays an important role in DRM service as SPs hope the authorized users to be able to access the digital goods. Watermark can be used to detect illegal copies of digital goods that have been modified by the attacks. Encryption is to protect the digital goods from being interception in the process of using. Such methods would make the mechanism of the DRM service more effective. Besides the effectiveness of the DRM, the security of the DRM service has been furiously debated since the DRM technologies came out. Varied mechanisms are deployed to increase the security of DRM service. A security architecture was presented in [69], it made DRM play a role in the authorized domains (where legal digital goods could be used on the devices authorized by the end users). The concern of DRM is far more than the security problem. The security concern is more serious when the digital goods execute in the cloud and mobile devices. The security of the cloud had been considered to overshadow its technology and economics benefits [13].

2.1.2 Economics Aspect of DRM

As the DRM service is the entirety of technology and economics [75], only considering the technology is far from perfect. A great deal of end users who leverage the DRM service consider that the rigid restrictions and enforcement to use the digital goods make the DRM service more like "Digital Restrictions Management" or "Digital Restrictions Malware" [42]. The restrictions of DRM are considered too rigid due to insufficiency of the flexibility [11]. In [11], an optimal economics design improved flexibility in a DRM policy through introducing a secure platform. Besides, Heileman et al. provided a new game-theoretic approach that considered the strategic situations in DRM environments and proposed a different DRM environment along with a new trust authority component that allowed a content provider to effectively influence end users' actions by rewarding good behaviors instead of punishing bad behaviors [42]. [84] also investigated the optimal choice of pricing schedules and technological deterrence levels in a market with digital piracy where sellers can influence the degree of piracy by implementing DRM systems. It seems that researchers are willing to solve the problem of DRM from the economics aspect.

2.2 Existing Work about P2PS System

P2PS system is able to provide the end users on-demand or live video streaming services over the Internet though using P2P technology [40,55]. It is very sensitive to the following delay in the system: SETUP delay (the time from initializing software initialization to playing video normally), END TO END delay (the delay between the SP and users), and PLAYBACK continuity (the rate of received data packets) [81]. In the P2PS system, a peer not only downloads data from the network, but also uploads the downloaded data to other peers in the network. To make the streaming service functioning normally with minimal delay, the SP expects each peer would be a volunteer to share the streaming contents with other peers. A variety of mechanisms were proposed to motivate the voluntary sharing of peers [33]. However, some selfish users would break the principle of P2P sharing and choose the freeriding in order to save their own costs. Many studies showed that the freeriding was a common phenomenon in P2P systems [4, 76] and this freeriding was sustainable in equilibrium and possible to reach a social optimum outcome [53]. Other than freeriding, some peers would leave the system and rejoin with new identities to avoid reputation penalties. Such action is regarded as whitewashing. Whitewashing could conceal the fact that a peer suffers severe punishment [28]. One solution to mitigate the effect of whitewashing was to leverage observation preorder to identify white washers [21], however, such mechanism would cost the SPs a lot.

2.3 Existing Work about Mobile Cloud Service

Recently, mobile cloud computing, as a combination of mobile computing and cloud computing, has been fiercely debated [77]. Several frameworks, including MAUI [25], Cuckoo [51], CloneCloud [23], ThinkAir [52], and WhereStore [83], have offloaded the tasks from mobile devices to the cloud [32]. The cloud leverages effective resource allocation [5] to have the mobile application executed in the geographically distributed data centers [89], for example, CloudFront [6].

2.3.1 Cost of Mobile Cloud Service

Having the mobile applications executed in the geographically distributed data centers enforces the cloud provider to build the massive date centers. As the investment of the massive data center becomes large economies of scale, minimizing the cost of a data center can achieve a high payback. The expenses that data centers cost go mainly to servers (45%), infrastructure (25%), power draw (15%), and networks (15%) [35]. One way to reduce the cost of the data center is to save energy consumption. ElasticTree [43], which has an effective network traffic pattern, can save up to 50% energy cost of the data center. Power saving was also considered in [71, 82] where the proposed models decrease the total electricity cost of the data center with guaranteed quality of service. Decreasing the network traffic is another effective approach to cut down the cost of the data center. Inter-datacenter traffic was studied in [22] which reveals that up to 45% of total traffic goes through data center egress routers. This work motivates the researchers to minimize the cost on inter-datacenter traffic. Jetway [29] is one of the effective algorithms to minimize the expense of inter-datacenter's video traffic through optimal video flows in an online fashion. The GRC-VNE algorithm was proposed in [34] to minimize the cost and maximize the revenue for the infrastructure provider.

2.3.2 Cloud-Based DRM

The DRM service of mobile cloud computing has been paid more attention to because a large amount of digital goods have often been pirated and illegally distributed [27]. [87,94] proposed a cloud-based mobile DRM scheme with a SIM card to improve the flexibility and reduce the vulnerability of its security at a low cost. However, the researcher ignored the phenomenon that most of the mobile devices employed DRM service without a SIM card, e.g, tablets. There were also some cloud-based DRM policies which intended to preserve the privacy of the mobile users, e.g., [68] presented a mechanism which enabled the mobile users to purchase the software anonymously, and the solution in [50] allowed software providers to provide different license models which effectively preserved the user's anonymity. However, such cloud-based DRM ignored both the SPs and users' desire for the payoff.

2.4 Economics Tools

Here we introduce a series of economics tools used in my thesis, including game theory, differentiation, risk aversion, supply chain and group buying auction. These economics tools improve the DRM strategies greatly.

2.4.1 Game Theory

Game theory describes the decision process of multiple players in games where each player takes actions to achieve the best possible rewards for self, while anticipating the rational actions from other players [67]. The game among multiple players can be classified into non-cooperative game and cooperative game. Non-cooperative game is composed of static and dynamic game [61]. Up to now, game theory is more than a tool for the economics. It has been applied in many fields, especially in the network strategy design. For example, it has been applied to network security [59], network routing [61], network traffic control [62] and so on. In my thesis, games are conducted to achieve the equilibrium between the SPs and users.

2.4.2 Differentiation

Differentiation was proposed in 1933, and successful product differentiation led to monopolistic competition [17]. In modern business market, differentiation has been applied into modern fields, e.g., differentiated services have ever been used to classify and manage network traffic and provide varied quality of service (QoS) in the modern networking [60].

There was also another type of differentiation which set the product with varied price based on the products' quality accompanied by varied price, such as [66]. Differentiation increases the flexibility and competitiveness of the product. In this thesis, we deploy a differentiated DRM service, to augment the flexibility and competitiveness in the digital goods market. How to differentiate DRM service is on the basis of diversiform security offered by the SPs, and differentiated security could be evaluated by the cost to break (CTB) into a system [79]. Besides, more and more network pricing strategies are achieved by kinds of game [39, 58].

2.4.3 Risk Aversion

Risk management refers to the practice of identifying potential risks in advance, analyzing them and taking precautionary steps to reduce the risk [90]. As the individuals identify the potential risks, their attitudes to deal with the risk would differ from each other:

- Risk-seeking [47]: It describes the attitude of an investor who is willing to take big risks to increase the potential return on investments;
- Risk-neutral [26]: It reveals a situation in which an investor effectively ignores risk in making investment decisions;
- Risk-averse [45]: It describes the attitude of an investor who is willing to accept a more certain payoff rather than an uncertain one.

For uncertain loss caused by the risk, most of people would attempt to reduce the uncertainty through accepting a more certain, expected payoff [70]. Up to now, the mechanism of risk aversion is employed by many end users to safeguard the security of computers and network information security [12, 46].

2.4.4 Supply Chain

A supply chain is a system, which is composed of organizations, people, activities, information, and resources, to move a product or service from the supplier to the customer [37]. The typical model of the supply chain is the newsvendor problem which deals with the relationship between order quantity of the newspaper and the customer's demand [44]. The supply chain can manage not only the distribution of the physical goods and service, but also digital goods and service [16].

2.4.5 Group-Buying Auction

The earliest auction theory was proposed by Vickrey in 1961 [86], and the auction theory has been applied in many fields [92] since then. Due to the development of e-business, a type of auction, called online auction [15], was studied by lots of experts and scholars. The online auction is different from the traditional auction because the bidders are not limited by the space and time [80]. As a branch of the online auction, group-buying auction [18] is a dynamic pricing mechanism for the homogeneous multi-unit auction [54]. The advantage of group-buying auction is that it aggregates the power of bidders to gain volume discounts, that is, more bidders will lower the price of online goods [20].

Chapter 3

DRM Games on Peer-to-Peer Streaming

In this chapter, we model DRM service in P2PS systems as games from both the SP and users aspects, and propose a series of DRM policies to maximize utility of the SP and avoid the misbehaviors in the P2PS system. Section 3.1 is the overview of this work. Section 3.2 describes the game between the P2PS systems with and without DRM, and acquires the criterion whether the DRM is fit for a P2PS system. Section 3.3 addresses the effectiveness of the DRM service to avoid misbehaviors in the P2PS system through the static and dynamic games. Section 3.4 describes the performance analysis of the proposed DRM policies. Section 3.5 discusses the unique challenges for the P2PS system. Finally, Section 3.6 summarizes this chapter.

3.1 Overview

Recently, DRM has already been a general means of access control technologies to limit the use of digital goods and devices after sale, which is employed by hardware manufacturers, publishers, copyright holders and individual content owners. Consequently, the effectiveness of using DRM has been furiously debated since the DRM technologies came out. Its restrictions to the use of digital goods seem to overprotect the copyright of the content providers, which make the DRM service more like "Digital Restrictions Management" or "Digital Restrictions Malware" [42] and bring end users much inconvenience. Researchers in the DRM field are apt to a more open architectural framework of DRM which should be vastly different from what they are today and strike a more reasonable balance between the SPs and end users. Some desirable properties, such as reusability, portability and flexibility, have been well addressed in numerous previous research studies [41, 69]. In [42], Heileman et al. provided a new game-theoretic approach that considered the strategic situations in DRM environments and proposed a different DRM environment along with a new trust authority component that allowed a content provider to effectively influence end users' actions by rewarding good behaviors instead of punishing bad behaviors. However, this approach is a general one that may not be appropriate for the situations in P2PS systems.

P2PS system distributes digital goods effectively with tracking the use of the digital goods. However, some misbehaviors cause the crisis about security and trust in the P2PS system with DRM which would decrease the utility of users. The main misbehaviors in the P2PS system are as follow:

- Freeriding: The users would not like to share the digital goods with others;
- Jailbreaking: The users may interpolate the digital goods which are created by the SP;
- Whitewashing: The users would renew themselves with new identities to conceal

the fact that they have suffered from severe punishment of the SP.

A peer plays dual roles in the P2PS system: a receiver and a distributor. It causes the distribution of the digital goods seriously influenced by the misbehaviors. In the P2PS system, a peer who takes freeriding will do nothing to distribute the digital goods to other peers, which leads to a long delay for the receivers. The jailbreaking peers would distribute modified digital goods with security threats to other peers. These would reinforce the distrust among the peers. However, a preferable DRM infrastructure is made up of the techniques and management processes that enable all the participants (the SP and the users) trustworthy [3]. In order to enhance the trust among the users, we should avoid all the misbehaviors in the P2PS system with DRM. The existing DRM technologies tried to solve these problems by the strict restrictions on the content management and use, nevertheless, such restrictions backfire for the wish of the SPs, which induce much inconvenience for the end users and have parts of users abandon the DRM service in the P2PS system. Then it is hard for DRM to solve such misbehaviors on the aspect of technology. In fact, DRM service is a collection of technology and economics, and SPs could prevent misbehaviors through a flexible DRM service in the P2PS system from economics aspect. Moreover, as the user's viewing experience of a streaming content is easily affected by the delay introduced by the execution of a complicated algorithm, the devised DRM strategy should be light-weighted in general. The downgraded service for the user caused by the delay also backfires the revenue for the SP.

In this chapter we consider the DRM service as economics models and deploy a preferable DRM service through effective strategy designs. In our model the users have more initiative to choose whether they are fond of the DRM service or not. If the users consider that they could acquire more utility in the system with DRM service than the system without DRM service, they are willing to choose the system with DRM service. Such DRM service does not need the strict restrictions on the technical aspect, and the users would comply with all the rules in the DRM services to pursue the maximal utility. Here we also design strategies in our DRM service to avoid misbehavioers in the P2PS system.

The main contributions of our solution are summarized as follows:

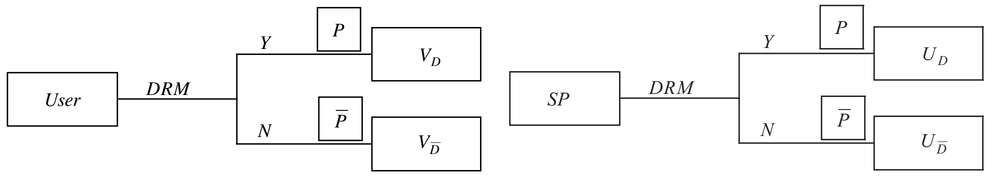
- We first consider a game for both the SP and the users whether or not to choose DRM in a P2PS system and design an optimal strategy for the users to obtain the maximal utility when the users are opt for the P2PS system with DRM service.

- We also discuss the strategies based on the static and dynamic games to discourage three misbehaviors of peers in the P2PS system with DRM: freeriding, jailbreaking and whitewashing, and prove that the dominant strategy could avoid all the three misbehaviors and have the users get the maximal benefit.

- The numerical experiments are conducted to show the effectiveness of our strategies.

3.2 The DRM Game in P2PS System

We start this section with the modeling of the DRM game which considers the P2PS system with and without DRM, then derive the equilibrium price based on this model, and lastly acquire the maximal utility for the SP in the equilibrium as well as the criterion whether the SP should apply the DRM to the P2PS system.



(a) User (b) SP

Figure 3.1: A general model for users and SP to choose the P2PS system with and without DRM. P and $\overline{P}$ represent paying for the digital goods and not paying for the digital goods, respectively.

3.2.1 Model of the DRM Game

We model the P2PS system with the assumption of having homogeneous users and homogeneous digital goods (i.e., a small segment of streaming content) in the system. The utility of a digital good that a user acquires in a P2PS system without DRM consists of two parts, one part is the basic utility of the acquired digital goods, and the other is the losing utility owing to the security threats and misbehaviors of other peers. When a user enters the P2PS system, it will have two choices (Figure 3.1(a)), one choice is that the P2PS system has no DRM and the user does not need to pay for the digital goods, but it may suffer potential security threats and unexpected service downgrading; the other is that the P2PS system has DRM and the user needs to pay for the digital goods, the user can thus encounter considerably less troubles. It is noted that in this work we mainly focus on the difference between the P2PS system without DRM and the one with DRM. Therefore, we make many assumptions to simplify the model of the DRM game.

In the P2PS system without DRM, the gross utility a user could obtain from using a digital good, $V_{\bar{D}}$, is denoted by

$$V_{\bar{D}} = V - L, \tag{3.1}$$

where V represents the basic utility of one digital good and L represents the losing utility owing to the security threats and service downgrading when the user downloads and uploads that digital good. When the P2PS system has DRM, the delay introduced by running the DRM system will have certain impact on the utility of the user, which should also be considered. We denote this influence as $H(t)$ where t is the delay caused by the DRM. Thus, the gross utility a user could obtain from the same digital goods in the P2PS system with DRM, V_D, is denoted as

$$V_D = VH(t) - P - (1-Q)^{\alpha}L + Q^{\beta}C, \tag{3.2}$$

where P is the price of the digital goods. $Q \in [0, 1]$ is the turnover rate of the users when the P2PS system without DRM turns into the system with DRM. If one user adopts the P2PS system with DRM for 5 times among his 10 times' experience on the P2PS system, then the turnover rate is 50%. C is an extra utility obtained by the user due to the workload reduction saved by the turnover of one user, α and β are positive constants. Since the security of the P2PS system is guarded by the DRM, the losing utility turns to be $(1-Q)^{\alpha}L$. In respect that a part of users turnover from the P2PS system with DRM, one user needs to serve for fewer users and its workload reduces, so that the user can get an extra utility $Q^{\beta}C$. Note that functions $(1-Q)^{\alpha}L$ and $Q^{\beta}C$ are just used to indicate the impact of the turnover rate on the utility function of the user and are highly related to a specific system environment.

We characterize the influence function $H(t)$ with respect to the delay in the P2PS system with DRM t as follows:

$$H(t) = \begin{cases} 1 & , \quad t \leq T; \\ -\frac{1}{4T^2}(t-T)^2 + 1 & , \quad T < t \leq 3T; \\ 0 & , \quad t > 3T. \end{cases} \tag{3.3}$$

Here we set $(0, T]$ as the delay range in the P2PS system without DRM. If $t \in (0, T]$, the delay in the system with DRM is the same as that in the system without DRM, and the delay does not affect the utility of digital goods, that is, $H(t) = 1$; we also denote $3T$ as maximal delay which the users can tolerate, and the users will run away from the P2PS system with DRM when $t > 3T$, in other words, the user will give up the digital goods and the digital goods is past its useless to the user, thus $H(t) = 0$. Besides the above two situations, the utility of the digital goods decreases as the delay increase between T and $3T$, in order to illustrate the reduction of the utility, we set the influence function $H(t)$ as

$$H(t) = -\frac{1}{4T^2}(x - T)^2 + 1. \tag{3.4}$$

For the SP, we assume that it could obtain the utility U when one user receives one digital good in the P2PS system without DRM. However, in the P2PS system with DRM, as users need to pay for the goods, some users may leave the system because of the DRM, and the SP gets payment from the remaining users (Figure 3.1(b)). The utility of the SP contributed by one user in the P2PS system without DRM, denoted as $U_{\bar{D}}$, is

$$U_{\bar{D}} = U. \tag{3.5}$$

In the P2PS system with DRM, the utility contributed by one user is

$$UH(t)(1 - Q)^{\gamma}, \tag{3.6}$$

where γ is a positive constant. Moreover, the SP can get a revenue $P(1-Q)$ from the sale of the digital goods. Therefore, the utility of the SP in the P2PS system with DRM is

$$U_D = UH(t)(1-Q)^{\gamma} + P(1-Q). \tag{3.7}$$

3.2.2 Equilibrium Price

In a free competition environment, the P2PS system with DRM may collapse if the SP sells the digital goods at an unreasonable high price. If the SP does not consider the interests of users and just increases the price of digital goods blindly, the users will give up using the digital goods when the price exceeds the utility the users can get from the goods. It is a natural way to get an equilibrium price based on the indifference between the utilities of a user in the P2PS system with and without DRM.

For a rational user, the utilities of the user in the P2PS system with and without DRM will be equal when the equilibrium is reached. That is, $V_D = V_{\bar{D}}$. The indifference between these two utilities can be represented by

$$VH(t) - (1-Q)^{\alpha}L - P + Q^{\beta}C = V - L. \tag{3.8}$$

Therefore, the equilibrium price of the digital goods is

$$P = V(H(t)-1) + [1-(1-Q)^{\alpha}]L + Q^{\beta}C. \tag{3.9}$$

From Eq.(3.9), we can further discuss the relationship between the equilibrium price P and the turnover rate Q under the condition that the utility of a user reaches the balance in the P2PS system with and without DRM. It is easily seen that P is a monotone increasing function of Q when $Q \in [0, 1]$. As its inverse function, Q is also an increasing function of P. Thus, we can get the influence of the equilibrium price P on the turnover rate Q as follows:

Proposition 3.1. The turnover rate Q increases as the equilibrium price P increases when the utility of a user reaches the balance in the P2PS system with and without DRM.

Proof. Let $P = F(Q)$, when $Q \in [0, 1]$, the first-order condition for $F(Q)$

$$\frac{\partial F(Q)}{\partial Q} = L\alpha(1-Q)^{\alpha-1} + c\beta Q^{\beta-1} \geq 0, \tag{3.10}$$

It is easy to get that $F(Q)$ is a monotone increasing function when $Q \in [0, 1]$, as a result, it has its inverse function $Q = F^{-1}(P)$ and its inverse function is also an increasing function according to the properties of the inverse function. □

Considering the function of $H(t)$, we can have the following observation from Eq.(3.9): When $P = 0$, $Q = 0$ only if $t \leq T$. It shows that when the digital good is free in the P2PS system with DRM, there will be no turnover of users if the delay introduced by the DRM does not affect the user's utility. This is the same as the situation in the P2PS system without DRM. However, if the delay affects the user's utility (i.e., $H(t) < 1$ when $T < t \leq 3T$), then $V(1-H(t)) > 0$. Thus, $[1-(1-Q)^{\alpha}]L+Q^{\beta}C = P+V(1-H(t)) > 0$. Even when the digital goods is free in the P2PS system with DRM (i.e., $P = 0$), it holds that $Q > 0$, which means that some users will leave because of the delay introduced by the DRM.

3.2.3 Optimal Strategy for the DRM Game

When the DRM game reaches the equilibrium, the utility of the SP in the P2PS system with DRM depends on the turnover rate Q and price P, with

$$U_D = UH(t)(1-Q)^{\gamma} + P(1-Q). \tag{3.11}$$

Considering the equilibrium price P in Eq.(3.9), we get

$$U_D = UH(t)(1-Q)^{\gamma} + \{V(H(t)-1) + [1-(1-Q)^{\alpha}]L + Q^{\beta}C\}(1-Q). \tag{3.12}$$

To simplify the discussion, we let $\alpha = 1$, $\beta = 1$ and $\gamma = 1$, then we get

$$U_D = UH(t)(1-Q) + [Q(L+C) + V(H(t)-1)](1-Q). \tag{3.13}$$

Maximizing this utility in the P2PS system with DRM leads to the following proposition:

Proposition 3.2. When the DRM game reaches the equilibrium, the maximal utility of the SP is as follows:

$$U_D^* = \begin{cases} \frac{(U+L+C)^2}{4(L+C)} & , \quad U < L+C; \\ U & , \quad U \geq L+C. \end{cases}$$

Moreover, the equilibrium turnover rate Q^*, the equilibrium price P^* and the equilibrium transmission delay t^* are as follows:

1. If $U < L+C$, then $Q^* = \frac{-U+L+C}{2(L+C)}$, $P^* = \frac{-U+L+C}{2}$ and $t^* \leq T$;

2. If $U \geq L+C$, then $Q^* = 0$, $P^* = 0$ and $t^* \leq T$.

Proof. The first-order condition for maximizing the profit function with respect to Q and t

$$\frac{\partial U_D}{\partial Q} = -UH(t) + L + C - 2(L+C)Q = 0 \tag{3.14}$$

and

$$\frac{\partial U_D}{\partial t} = -UH'(t)(1-Q) = 0. \tag{3.15}$$

From Eq.(3.15) we can acquire $H'(t) = 0$. Through Eq.(3.3), it is easy to get

$$H(t) = \begin{cases} 1 & , \quad t \le T; \\ 0 & , \quad t > 3T. \end{cases}$$

Because the users will leave the P2PS system with DRM when $t > 3T$, only $t \le T$ is able to meet our requirement in equilibrium, then $H(t) = 1$ and the equilibrium transmission delay $t^* \le T$.

Inserting $H(t) = 1$ in Eq.(3.14) and Eq.(3.9) with $\alpha = 1$, $\beta = 1$ and $\gamma = 1$, we obtain the equilibrium turnover rate Q^* and the equilibrium price P^*

$$Q^* = \frac{-U + L + C}{2(L+C)} \tag{3.16}$$

and

$$P^* = \frac{-U + L + C}{2}. \tag{3.17}$$

With the limitation to Q that $Q \ge 0$, the maximization is constrained by $Q = 0$ for $U \ge L + C$. Solving this restriction for P, we obtain $P = 0$ as $U \ge L + C$.

In equilibrium, the maximal utility of the SP could be computed based on Eq.(3.13), Eq.(3.16) and Eq.(3.17), then

$$U_D^* = \begin{cases} \frac{(U+L+C)^2}{4(L+C)} & , \quad U < L + C \\ U & , \quad U \ge L + C. \end{cases}$$

□

When $U \geq L + C$, $U_D^* = U = U_{\bar{D}}$. It suggests that the maximal utilities of the SP in the P2PS system with and without DRM are indifferent. The SP could not get any more utility if it uses DRM in the P2PS system. In other words, the SP does not have any motivation to bring DRM into its P2PS system.

Proposition 3.3. The criterion for the SP to apply DRM in the P2PS system is as follows:

1. When $U < L + C$, $U_D^* = \frac{(U+L+C)^2}{4(L+C)} > U = U_{\bar{D}}$, the SP could get more utility in the P2PS system with DRM than without DRM;

2. When $U \geq L + C$, $U_D^* = U = U_{\bar{D}}$, the SP would not choose the P2PS system with DRM.

3.3 DRM Games for Misbehaviors

In this section, we use game theory and currency mechanism to combat three misbehaviors of peers: freeriding, jailbreaking and whitewashing, in P2PS systems with DRM. We design effective strategies for the SP to discourage such misbehaviors in the case of hidden actions, then we illustrate such strategies through static and dynamic games.

3.3.1 Static DRM Games for Misbehaviors

In this part, we consider the actions of the peer in per-stage game, and the actions of the peers in every stage are independent of that in other stages. Our strategies in this part could avoid these misbehaviors in per-stage game effectively.

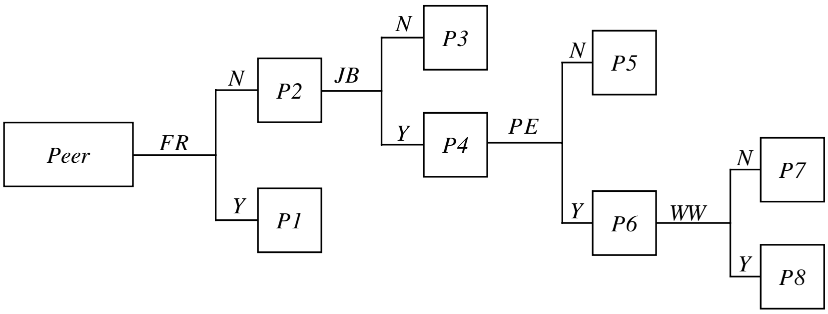


Figure 3.2: A general model that illustrates a peer's actions in the P2PS system with DRM, where FR represents the freeriding, JB represents the jailbreaking, PE represents receiving penalty from the SP, WW represents the whitewashing.

3.3.1.1 Hidden Actions in P2PS Systems

In a P2PS system with DRM, peers may make strategic actions on the time when they join and leave the system. Since their actions are hidden from the rest peers of the system, many of them may take misbehaviors. Consider a peer and its actions in the P2PS system with DRM. Figure 3.2 shows different situations after the peer chooses different strategic actions. We denote these situations as $P1 \sim P8$. When a peer receives the streaming content, it should share it with other peers according to the mechanism of the P2PS system. Some peer would break the rule of sharing and take the action of "freeriding" ($P1$). The peer can also choose to take the "not-freeriding" action that shares the streaming content with other peers ($P2$). Among the peers that share the streaming content with others, some peer may try to acquire extra interests by cracking the encryption of the digital goods, modifying the content and distributing the modified one to other peers. We call this action as "jailbreaking" ($P4$). For example, a peer may insert some advertisements in the digital goods and forward the modified digital goods along with advertisements to its neighbors to obtain the extra interests from the advertisements. The peer can also take the "not-jailbreaking" action ($P3$). If the peer takes the jailbreaking action, it may escape the penalty from the SP ($P5$) or suffer the penalty from the SP ($P6$). When the peer's expected interests, after getting the penalty from the SP, drop below a new comer's interests in the P2PS system, the peer may choose to leave the P2PS system and rejoin the system with a new identity. Such action is called "whitewashing" ($P8$). The peer may also take the "not-whitewashing" action that keeps its identity unchanged during the whole process ($P7$). How can effective strategies be devised to combat these misbehaviors in the P2PS system with DRM?

3.3.1.2 Game for the Freeriding

In a P2PS system, peers are expected to share the streaming content with other peers to make the streaming service work normally. Clearly, such service would cease the function if all peers decide not to forward any streaming content. However, a peer could strategically choose the freeriding probabilistically so as to save its forwarding costs without destroying the service. Such a hidden action is not easily observable nor readily identified since the data packets are distributed on a best-effort approach and the network topology keeps changing as peers join and leave the network. How can the SP provide incentives for the peers to perform the forwarding task?

We model this situation as a principle-agent game in [9]: the SP, as a principle, employs a set of n peers of agents, N, to forward a digital good to a receiver of the goods. The possible actions of peer i ($i \in N$) form a set A_i, $A_i = \{0, 1\}$, and the effort exerted by peer i is $C(a_i)$ where $C(a_i) \geq 0$ for $a_i \in A_i$. Here $a_i = 0$ indicates the "freeriding" and $a_i = 1$ indicates the "not-freeriding". We assume that the cost of taking the freeriding is 0 while the cost of taking the not-freeriding is $c > 0$, i.e., $C(0) = 0$ and $C(1) = c$.

The outcome is determined according to a success function $G : A_1 \times \cdots \times A_n \longrightarrow [0,1]$, where $G(a_1, \ldots, a_n)$ denotes the success probability when peers adopt the action profile $a = (a_1, \ldots, a_n) \in A_1 \times \cdots \times A_n = A$.

If the SP pays peer i an amount $p_i \geq 0$, then the utility of peer i under the action profile $a = (a_1, \ldots, a_n)$ is given by $u_i(a) = p_i G(a) - C(a_i)$. The action profile of all peers excluding peer i is denoted as $a_{-i} \in A_{-i}$, i.e., $a_{-i} = (a_1, \cdots, a_{i-1}, a_{i+1}, \cdots, a_n)$. For simplicity, we assign the payment p_i for each peer i as p. Thus, peer i's own utility is $u(a_i) = pG(a_i, a_{-i}) - C(a_i)$.

In a P2PS system, more efforts contributed by peers will lead to a high probability of success. Formally, $\forall i \in N, \forall a_{-i} \in A_{-i}, G(1, a_{-i}) > G(0, a_{-i})$. In addition, we assume that $G(a) > 0$ for any $a \in A$. The marginal contribution of peer i, $\triangle_i(a_{-i}) = G(1, a_{-i}) - G(0, a_{-i})$, is the increase in the success probability due to peer i moving from taking the freeriding to not taking the freeriding, given the actions of the others are fixed. The best strategy of peer i can be determined as following: *If* $p > \frac{c}{\triangle_i(a_{-i})}$*, peer* i *does not take the freeriding; if* $p < \frac{c}{\triangle_i(a_{-i})}$*, peer* i *takes the freeriding; in case* $p = \frac{c}{\triangle_i(a_{-i})}$*, peer* i *is freely choosing either of these two alternatives.*

The reason behind this strategy is that, $p > \frac{c}{\triangle_i(a_{-i})}$ if and only if $u(1, a_{-i}) = pG(1, a_{-i}) - c > pG(0, a_{-i}) = u(0, a_{-i})$. In this case, peer i's best strategy is to choose $a_i = 1$, i.e., peer i will not take the freeriding in order to obtain a higher utility, given other peers keep their actions unchanged.

Assume that the success probability when one peer takes the freeriding among the n peers is θ ($\theta < 0.5$). The success probability when m peers take the freeriding among the n peers is $1 - \theta^{n-m}(1-\theta)^m$. Consider that each peer may take the freeriding with probability x and not take the freeriding with probability $1-x$, given other peers' actions are fixed, the expected success probability when peer i takes the freeriding is

$$E[G(0,a_{-i})] = \sum_{m=0}^{n-1} C_{n-1}^{m} x^m (1-x)^{n-m-1}[1-\theta^{n-m-1}(1-\theta)^{m+1}];$$

and the expected success probability when peer i takes the not-freeriding is

$$E[G(1,a_{-i})] = \sum_{m=0}^{n-1} C_{n-1}^{m} x^m (1-x)^{n-m-1}[1-\theta^{n-m}(1-\theta)^{m}].$$

Therefore, the expected utility when peer i takes the freeriding with probability x is

$$\begin{aligned} E[\pi_p] &= (pE[G(1,a_{-i})]-c)(1-x) + pE[G(0,a_{-i})]x \\ &= p\sum_{m=0}^{n} C_{n}^{m} x^m (1-x)^{n-m}[1-\theta^{n-m}(1-\theta)^{m}] - (1-x)c. \end{aligned} \tag{3.18}$$

We wish that the expected utility of peer i decreases as the probability that peer i chooses the freeriding increases. In other words, a peer which always takes the freeriding will receive the lowest payoff, and the strategy for the peer to acquire the highest payoff is to take the not-freeriding all the time. It shows that peers are willing to share the digital goods with each other in order to get a higher utility.

Proposition 3.4. *If we would like the peer who is to take not-freeriding all the time to obtain the highest payoff, the payment (P) should satisfy the following relationship:*

$$p \geq \frac{c}{n\theta^{n-1}(1-2\theta)} \tag{3.19}$$

Proof. Let $f(x) = E[\pi_p]$, then

$$\begin{aligned} f(x) &= p\sum_{m=0}^{n} C_{n}^{m} x^m (1-x)^{(n-m)} - (1-x)c - p\sum_{m=0}^{n} C_{n}^{m}[x(1-\theta)]^m[(1-x)\theta]^{(n-m)} \\ &= p - p[(1-2\theta)x+\theta]^n - (1-x)c \end{aligned} \tag{3.20}$$

then the first-order of $f(x)$ should be as follows:

$$f'(x) = -np[(1-2\theta)x + \theta]^{n-1}(1-2\theta) + c \tag{3.21}$$

and the model we want to prove is equal to $f'(x) \leq 0$ when $x \in [0,1]$. The second-order of $f(x)$ is

$$f''(x) = -np[(1-2\theta)x + \theta]^{n-2}(1-2\theta)^2. \tag{3.22}$$

$f''(x) < 0$ as $P, C > 0$, $(1-2\theta) > 0$ and $[(1-2\theta)x+\theta]^{n-2} > 0$. It means that $f'(x)$ decreases in $[0,1]$. As a result, $f'(x) \leq f'(0) \leq 0$, that is

$$p \geq \frac{c}{n\theta^{n-1}(1-2\theta)} \tag{3.23}$$

□

In the discussion above, we have considered the scenario that multiple peers forward one digital good to one peer. However, the representative scenario in the P2PS network is the case that multiple peers are serving the digital goods to multiple receivers, such case can be regarded as several simultaneous scenarios in which multiple peers forward one digital good to one peer. For example, Figure 3.3 is a schematic drawing for the P2PS system. In this figure, peers *A*-*G* forward digital goods to peers *O* and *P*. We can regard this scenario as two simultaneous scenarios. One scenario is that *A*, *B*, *C* and *D* forward one digital good to *O*, and the other scenario is that *C*, *D*, *E*, *F* and *G* forward one digital good to *P*. As a result, our propositions, which come from the scenario that multiple peers forward one digital good to one peer, are also fit for the scenario that multiple peers are serving the digital goods to multiple receivers.

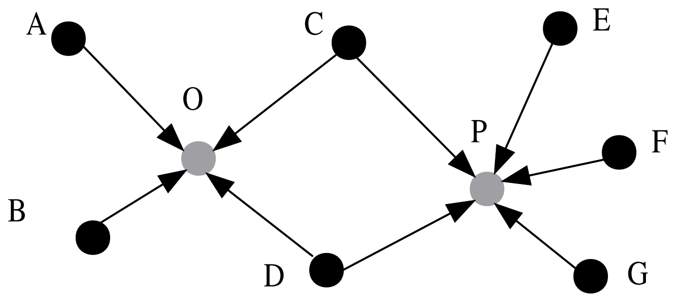


Figure 3.3: The Schematic Drawing for P2PS System

3.3.1.3 Game for the Jailbreaking

Even when DRM is implemented in a P2PS system, a peer could strategically choose the jailbreaking probabilistically to acquire some extra interests in addition to the reward from the SP for forwarding the digital goods successfully. This jailbreaking action certainly infringes the right of the SP and at the same time pollutes the digital goods in the P2PS system. How can the SP provide DRM strategies to suppress such actions?

We consider a mixed game for this situation: the peer can either choose the jailbreaking with probability r or choose the not-jailbreaking with probability $1-r$. The SP will play a strategy either punishing the jailbreaking action severely with probability s or not punishing it with probability $1-s$. Under this mixed game, the peer will get a reward R for forwarding the streaming goods if the peer does not take the jailbreaking. The peer will get an extra reward E if it takes the jailbreaking without being caught by the SP. As a result, the interests a peer gets for taking the jailbreaking without penalty is $R+E$. If the peer's jailbreaking action is caught by the SP, the peer will suffer a penalty W. In this game, the expected payoff for the peer is

$$E[\pi_p] = r[(R+E)(1-s) - Ws] + R(1-r). \tag{3.24}$$

If the expected payoff is no larger than zero, that is,

$$E[\pi_p] = r[(R+E)(1-s) - Ws] + R(1-r) \leq 0, \tag{3.25}$$

the peer will not choose the jailbreaking action. Let $W = \lambda R$ and $E = \mu R$, where $\lambda > 0$ and $\mu > 0$. With $R > 0$, then Eq. (3.25) is equivalent to

$$E[\pi_p] = r[-\lambda s + (\mu+1)(1-s)] + (1-r) < 0. \tag{3.26}$$

Suppose that r and s are uniform distribution in [0,1], we can obtain the following corollary:

Proposition 3.5. *The probability for $E[\pi_p] < 0$ is*

$$Prob(E[\pi_p] < 0) = \frac{\lambda - \ln(\lambda+1)}{\lambda+\mu+1} \tag{3.27}$$

when r and s are uniform distribution in [0,1].

Proof. Let $r[-\lambda s + (\mu+1)(1-s)] + (1-r) = 0$, then $r = f(s) = \frac{1}{(\lambda+\mu+1)s-\mu}$. The conclusion equals to the calculation of the area which is enclosed by $r = f(s)$ and $r = 1$. As a result, the probability for $E[\pi_p] < 0$ is

$$\begin{aligned} Prob(E[\pi_p] < 0) &= \int_0^1 (1 - f(s))ds \\ &= \int_{\frac{\mu+1}{\lambda+\mu+1}}^1 (1 - \frac{1}{(\lambda+\mu+1)s-\mu})ds \\ &= \frac{\lambda - \ln(\lambda+1)}{\lambda+\mu+1}. \end{aligned} \tag{3.28}$$

□

State	Expected payoff
$P1$	$pG(0, a_{-i})x$
$P2$	$(pG(1, a_{-i}) - c)(1 - x)$
$P3$	$(pG(1, a_{-i}) - c)(1 - x)(1 - r)$
$P4$	$[(pG(1, a_{-i}) - c)(1 - x) + E]r$
$P5$	$[(pG(1, a_{-i}) - c)(1 - x) + E](1 - s)r$
$P6$	$-Wsr(1 - x)$

Table 3.1: The expected payoff for peer's strategy

3.3.1.4 Game for Whitewashing

Let us consider the game that the peer plays a mixed strategy involving the freeriding and jailbreaking with probabilities x and r, and the SP makes the punishment with probability s, as shown in Figure 3.2. The outcomes are situations $P1 \sim P6$. Since the probability for the peer to forward the digital goods successfully is $G(1, a_{-i})$, the reward R is $pG(1, a_{-i}) - c$. We summarize the payoff of every situation in Table 3.1. Then, the expected payoff of peer i is

$$\begin{aligned} E[\pi_p] &= [(pG(1, a_{-i}) - c)(1 - x) + E](1 - s)r + (pG(1, a_{-i}) - c)(1 - x)(1 - r) \\ &\quad -Wsr(1 - x) + pG(0, a_{-i})x. \end{aligned} \tag{3.29}$$

When the expected payoff of peer i is not positive ($E[\pi_p] \leq 0$), the peer will not choose the freeriding and jailbreaking. However, our strategy can be skewed by the feasibility of cheap pseudonyms [30]. For example, a peer that takes the jailbreaking may choose the whitewashing after suffering a severe punishment. It will leave the P2PS system and rejoin the system again with a new identity. The record of its deviltry before the whitewashing would be vanished. How can we reduce the effect of cheap pseudonyms?

There are two types of cheap pseudonyms, permanent identity (PI), whose cost is infinite, and free identity (FI), whose cost is free. The identity cost of each peer is a positive finite value between the cost of FI and that of PI. That user may decide to take the whitewashing if its identity cost is less than the expected payoff after the penalty imposed on the jailbreaking. Let the identity cost be Y, if we want to discourage the peer's whitewashing behavior on a repeated basis, we should let $E[\pi_p] \geq -Y$.

Proposition 3.6. *The peer will not take the whitewashing even after suffering a severe penalty for the jailbreaking as* $-Y \leq E[\pi_p] \leq 0$.

3.3.1.5 Dominant Strategy in the Static Game

From the discussion above, it is obvious that the peer could acquire different utilities from different strategy profiles (S1-S4). Here we still denote FR and $\overline{FR}$ as freeriding and not-freeriding, JB and $\overline{JB}$ are jailbreaking and not-jailbreaking, WW and $\overline{WW}$ are whitewashing and not-whitewashing.

S1 The peers are subject to all the rules in the P2PS system without any misbehaviors and the strategy profile $S1$ is $(\overline{FR}, \overline{JB}, \overline{WW})$. Then the payoff of the peer is just the reward from the SP for not-freeriding, that is, $E[\pi_p^{S1}] = pG(1, a_{-i}) - c$;

S2 The peers break the rule of freeriding with the strategy profile $(FR, \overline{JB}, \overline{WW})$ and only win a low reward from the SP according to our game for the freeriding, the payoff is $E[\pi_p^{S2}] = pG(0, a_{-i})$;

S3 The strategy of $S3$ is mixed with two strategy profiles $(\overline{FR}, JB, \overline{WW})$ and $(\overline{FR}, \overline{JB}, \overline{WW})$, the probability of the two profiles are r and $1-r$. According to the Eq. (3.24), the payoff of the peers is $E[\pi_p^{S3}] = (pG(1, a_{-i}) - c + E)(1-s)r - Wsr + (pG(1, a_{-i}) - c)(1-r)$;

S4 The peers run away from the P2PS system as soon as they suffer penalty and the strategy profile is $(\overline{FR}, JB, WW)$, under that condition, the payoff of the peers is $E[\pi_p^{S4}] = -Y$.

Proposition 3.7. *If* $p > \frac{c}{\triangle_i(a_{-i})}$ *and* $s > \frac{E}{pG(1,a_{-i})-c+E+W}$*, the strategy profile* $S1$ *is a strictly dominant strategy.*

Proof. In the P2PS system with DRM, we compare the payoff of the peers under the strategies $S1 - S4$, it is obvious that $E[\pi_p^{S1}] > 0$ and $E[\pi_p^{S4}] < 0$, then $E[\pi_p^{S1}] > E[\pi_p^{S4}]$, we can also acquire the result $E[\pi_p^{S1}] > E[\pi_p^{S2}]$ through $p > \frac{c}{\triangle_i(a_{-i})}$. At last, we will prove $E[\pi_p^{S1}] > E[\pi_p^{S3}]$.

$$E[\pi_p^{S1}] - E[\pi_p^{S3}] = Er - (pG(1, a_{-i}) - c + E + W)rs \geq 0. \tag{3.30}$$

Here $E[\pi_p^{S1}] - E[\pi_p^{S3}] \geq 0$ because $s > \frac{E}{pG(1,a_{-i})-c+E+W}$. Then we can see that the peers will acquire maximal utility under the strategies $S1$. The peers who choose $S1$ are surely legal peers and the strategy $S1$ is the strictly dominate strategy. □

From Proposition 3.7, it is obvious that the probability for the peers to take jailbreaking (r) couldn't affect the strategy $S1$ to be the dominant strategy if the probability for the SP to punish the jailbreaking (s) satisfies the condition that

$$s > \frac{E}{pG(1, a_{-i}) - c + E + W}.$$

3.3.2 Dynamic DRM Games for Misbehaviors

In the previous part, we build three static games to avoid the misbehaviors, but the performance of the peer in the previous stage has nothing to do with the payoff in the current stage, and the SP would use the same strategy to avoid the misbehaviors for every peer. In the P2PS system, some peers never take misbehaviors while some peers often take misbehaviors, but the SP applies the same strategy for these peers. Although such strategy of the SP is effective, it may not be efficient enough. In order to make the strategy more efficient, we would like to find a new strategy which could dynamically adjust the rewarding mechanism according to the peers' action in the previous stages. Here we introduce a mechanism of reputation into the dynamic game, the reputation could record the peer's history actions in the previous stages, and the SP would reward the peers dynamically according to their reputation. Such dynamic game is an incomplete information game, in which one peer does not know what the other peers do in the game, that is, this peer's action will not be influenced by other peers' actions in the game. Therefore, what we need to consider is the game between one peer and the SP. We also compare the dynamic game with the static game and find that the dynamic game is more efficient.

3.3.2.1 Game for Misbehaviors

In this part, what we consider is very different from that in the static game. The actions of the peers in the current stage are no longer independent of the previous stage, on the contrary, they have been affected by the actions in previous stages. Then a dynamic Bayesian equilibrium could be built in this model. Consider the dynamic game with complete but imperfect information (Figure 3.4). Peers could choose between FR and $\overline{FR}$, if the peer chooses $\overline{FR}$, it shows that the peer doesn't take free-riding. Then the peer will select between two actions, JB and $\overline{JB}$. According to the action of the peer, the SP would make its decision. The SP would hunt the peers' illegal actions with a

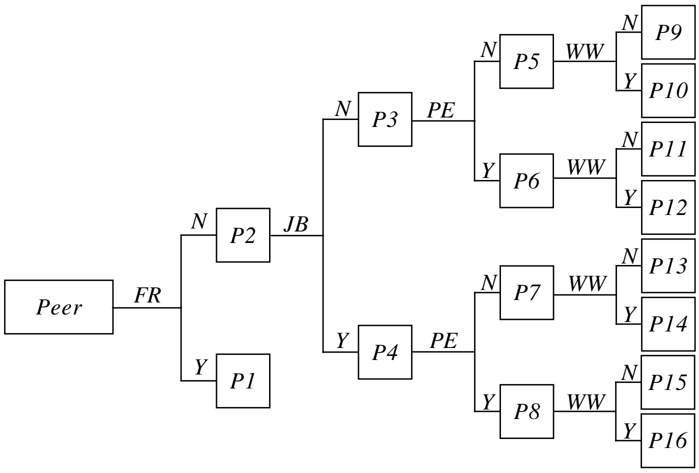


Figure 3.4: The process of dynamic game, FR represents freeriding, JB represents jailbreaking, PE represents receiving penalty from the SP, WW represents whitewashing.

reasonable probability and punish the illegal peers if the SP hunts their illegal actions.

In Figure 3.4, it can be seen that a subgame exists, this subgame is defined to begin at the decision node $P2$ that is a singleton information set. If we want to acquire the equilibrium of the whole game, we only need to achieve the equilibrium of this subgame.

This dynamic subgame involves two players: a peer and a SP. We transform this subgame as hybrid strategies in Figure 3.5. The timing of this subgame is as follows:

1. A peer would first design its strategy, it will decide to take jailbreaking or not. The prior probability for the SP to assess peer's taking jailbreaking and not-jailbreaking are q ($P3$) and $1 - q$ ($P4$).

2. If the peer takes jailbreaking, it will run the risk of being hunted by the SP ($P6$), and the probability for the peer to be hunted is p, and this peer may not be hunted by the probability $1 - p$ ($P5$). Otherwise, if the peer takes not-jailbreaking, the SP will consider this peer as a legal peer all the time ($P7$), and never hunt the peer's

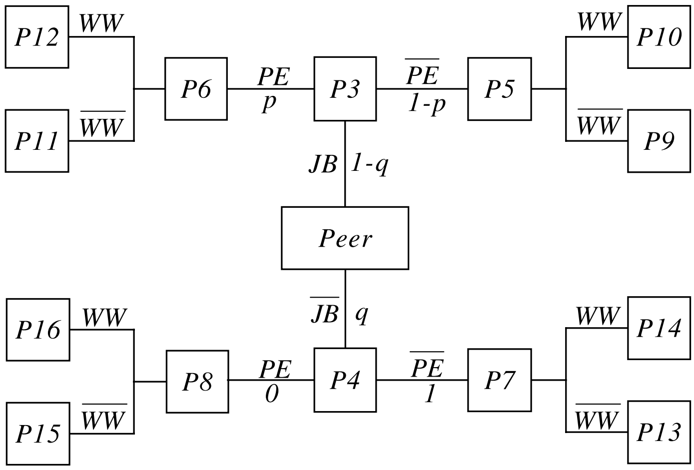


Figure 3.5: The hybrid strategies for the subgame.

misbehavior ($P8$). Then the SP will calculate the reputation of the peer ($P5 - P8$) and give the reward (involving the punishment) according to the actions of the peer.

3. The peer will accept the SP's decision and stay in the system if it doesn't take whitewashing ($P9, P11, P13, P15$), or else, the peer does not satisfy the SP's decision and takes whitewashing ($P10, P12, P14, P16$).

As we assume, a peer will pay a price for the misbehaviors, then we should set a flexible mechanism to record the peer's actions in all the previous stages and generate the peer's reputation. First, we define a function δ_k to illustrate whether the peer suffers punishment in the kth stage, if the peer takes jailbreaking and is punished by the SP, then δ_k=-1, otherwise, δ_k=1. According to the function δ_k we defined above, the reputation of the peer in the ith stage (r_i) is:

$$\begin{cases} r_1 = \delta_1, & i = 1; \\ r_i = \frac{1}{i-1}\sum_{k=1}^{k=i-1}\delta_k, & i \leq l; \\ r_i = \frac{1}{2}(\frac{1}{i-1}\sum_{k=1}^{k=i-1}\delta_k + \frac{1}{l}\sum_{k=i-l}^{k=i-1}\delta_k), & i > l. \end{cases}$$

Where l is the last l stages in the dynamic game. In order to avoid the marginal utility diminishing, we define the reputation as a composition of two parts, the cumulation of previous stages ($\frac{1}{i-1}\sum_{k=1}^{k=i-1}\delta_k$) and the last l stages ($\frac{1}{l}\sum_{k=i-l}^{k=i-1}\delta_k$). From the equation above, we can see that the peer's reputation has some connection with the peer's action in the previous stages of the dynamic games. It is obvious that the peer who never takes jailbreaking (δ_k=1 for any k) will acquire a reputation 1 ($r_i = 1$), otherwise the reputation r_i will be less than 1 if the peer takes jailbreaking and is hunted by the SP for one or more times in the previous i stages.

We define taking not-jailbreaking as a good action (G), while taking jailbreaking as a bad action (B), a peer's bad action could be hunted by the SP randomly (with probability p). If the SP does not hunt the bad action (with probability $1-p$), the SP will consider that the peer chooses a good action. The SP's assessment for the peer to choose a good action is denoted as AG. According to Bayes' rule, we could acquire the probability of the peer choosing a good action under AG,

$$P(G|AG) = \frac{q}{q + (1-q)(1-p)}. \tag{3.31}$$

Three observations could contribute to illustrate the equation above:

1. The peers who always choose good actions would not be recognized as illegal peers, while the ones taking bad actions will be hunted by the SP with probability p ($0 < p \leq 1$), as a result $P(G|AG) > q$ through Eq. (3.31);

2. When p approaches 1, that is, $1-p$ approaches 0, the peer's bad action almost never pools with its good action, so $P(G|AG)$ approaches 1;

3. When p approaches 0, that is $1-p$ approaches 1, the peer's bad action almost pools with its good action, so $P(G|AG)$ approaches the prior belief q.

As we discuss in the last section, the SP would punish the peer if the peer is hunted by the SP as an illegal peer, and the SP is not willing to pay the illegal peers the same reward as the one who never takes misbehaviors. Therefore, the SP will offer the reward to the peer according to the peer's reputation. If the peer's reputation r_i is high enough ($r_i = 1$), the SP will offer the peer high reward R_H. If the peer's reputation is less than a threshold (r_L), the reward is R_L, here $R_L < R_H$. Otherwise the peer will receive a hybrid result which is combined with R_H and R_L linearly, then the reward is

$$R = \begin{cases} R_H, & r_i = 1; \\ P(G|AG)R_H + (1 - P(G|AG))R_L, & r_L \leq r_i < 1; \\ R_L, & r_i < r_L. \end{cases}$$

In this dynamic game, the peer would still acquire an extra payoff ER if it takes jailbreaking without being hunted. Here we suppose that $R_L + ER \geq R_H$, it means the peer who takes jailbreaking without being hunted by the SP could acquire more interest than the one who takes not-jailbreaking. However, if the illegal peers hunted by the SP, they will receive a punishment W ($W > 0$ and $W > R_L+ER$). Then the expected payoff for the peer is as follows:

$$E[\pi_p] = \begin{cases} E[\pi_p^H], & r_i = 1; \\ E[\pi_p^M], & r_L \leq r_i < 1; \\ E[\pi_p^L], & r_i < r_L. \end{cases}$$

where $E[\pi_p^H]$, $E[\pi_p^M]$ and $E[\pi_p^L]$ represent the peer's payoff under different reputation. $E[\pi_p^H]$ is the expected payoff when $r_i = 1$, it shows that the peer has never been hunted as an illegal peer, as a result, the reward for the peer is

$$E[\pi_p^H] = R_H.$$

$E[\pi_p^M]$ is a hybrid result when $r_L \leq r_i < 1$, the peer has been hunted by the SP with probability p, and suffers a severe punishment W, then the expected reward for the peer with the reputation $r_L \leq r_i < 1$ is

$$E[\pi_p^M] = [P(G|AG)R_H + (1 - P(G|AG))(R_L + ER)](1 - p) - Wp. \quad (3.32)$$

$E[\pi_p^L]$ is the expected payoff for the peer with low reputation $r_i < r_L$, the peer has also been hunted by the SP with probability p, so the reward for the peer is

$$E[\pi_p^L] = [R_L + (1 - P(G|AG))ER](1 - p) - Wp.$$

It is obvious that $E[\pi_p^M] > E[\pi_p^L]$ under the condition that $R_H > R_L$. As the aim of this dynamic game is to have the peer not take jailbreaking, the peer should acquire more interests when $r_i = 1$, that is, $E[\pi_p^H] \geq E[\pi_p^M]$. When the dynamic game reaches the equilibrium, $E[\pi_p^H] = E[\pi_p^M]$. It concludes that

$$R_H = [P(G|AG)R_H + (1 - P(G|AG))(R_L + ER)](1 - p) - Wp. \quad (3.33)$$

Inserting the Eq.(3.31) in Eq.(3.33), the result is

$$R_H = \frac{qR_H + (1 - q)(1 - p)(R_L + ER)}{q + (1 - q)(1 - p)}(1 - p) - Wp. \quad (3.34)$$

then,

$$p = \frac{-n_2 + \sqrt{{n_2}^2 - 4n_1n_3}}{2n_1}, \quad (3.35)$$

where

$$\begin{cases} n_1 = (1-q)(R_L + ER + W); \\ n_2 = (1-2q)R_H - 2(1-q)(R_L + ER) - W; \\ n_3 = (1-q)(R_L + ER - R_H). \end{cases}$$

After the peer acquires the reward from the SP, the peer will evaluate his gain from the SP, and determine either to take whitewashing or not. We still introduce the definition of the identity cost into our dynamic game, and assume that the identity cost is Y ($Y > 0$). If we do not want the peer to leave and rejoin the network with a new identity on a repeated basis, we should design effective game to avoid whitewashing.

As we discuss in the dynamic game, $E[\pi_p^H] \geq E[\pi_p^M] > E[\pi_p^L]$, if the lowest expected payoff is more that $-Y$, that is, $E[\pi_p^L] \geq -Y$, the rational peer will not take whitewashing even after the punishment. The strategy could be expressed as

$$E[\pi_p^L] = [R_L + (1 - P(G|AG))ER](1-p) - Wp \geq -Y. \tag{3.36}$$

Here, we also find that the punishment should not be so severe that the expected payoff of the peer is less than $-Y$, as a result, the punishment in the dynamic game should satisfy the condition below,

$$-Y \leq E[\pi_p^L] < E[\pi_p^M] \leq E[\pi_p^H]. \tag{3.37}$$

3.3.2.2 Dominant Strategy in the Dynamic Game

In the reward mechanism, the peer will receive more benefit if it takes not-freeriding, in other words, not-freeriding is the dominant strategy relative to freeriding. As a result, the dominant strategy of the subgame is that of the dynamic game. All the strategies taken by the peers are as follows:

D1 The peers would never take any misbehaviors with the strategy profile $(\overline{JB}, \overline{WW})$ in this subgame. Then it will be paid by the SP according to its good reputation, and the reward is $E[\pi_p^{D1}] = E[\pi_p^H]$;

D2 The peers rarely choose the strategy profile $(JB, \overline{WW})$ (with the reputation r_i, $r_L \leq r_i < 1$), and the payoff for the peer is $E[\pi_p^{D2}] = E[\pi_p^M]$;

D3 The peers often choose the strategy profile $(JB, \overline{WW})$ (with the reputation r_i, $r_i < r_L$), the payoff of the peer is $E[\pi_p^{D3}] = E[\pi_p^L]$;

D4 The peers leave and rejoin the system with a new identity after punishment and the profile is (JB, WW), under that condition, the payoff of the peers is $E[\pi_p^{D4}] = -Y$.

Proposition 3.8. *If the subgame satisfies the follow conditions:*

$$p \geq \frac{-n_2 + \sqrt{{n_2}^2 - 4n_1n_3}}{2n_1}, \tag{3.38}$$

the strategy $D1$ would be the dominant strategy of the subgame, where n_1, n_2, n_3 is the same in Eq. (3.35).

Proof. It is obvious $E[\pi_p^{D2}] \geq E[\pi_p^{D3}]$. When $p \geq \frac{-n_2 - \sqrt{{n_2}^2 - 4n_1n_3}}{2n_1}$, according to Eq. (3.34), $E[\pi_p^H] \geq E[\pi_p^M]$, that is $E[\pi_p^{D1}] \geq E[\pi_p^{D2}]$. What's more, R_H is positive, $R_H > -Y$, then $E[\pi_p^{D1}] \geq E[\pi_p^{D4}]$. In general, the strategy $D1$ is the dominant strategy of the subgame. □

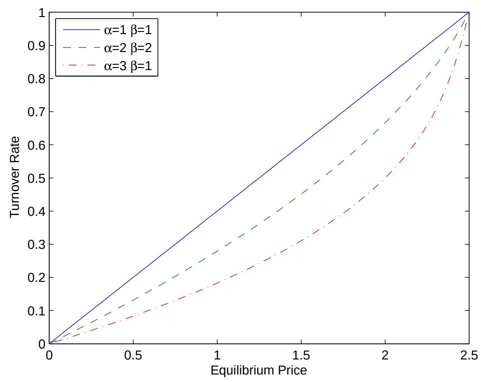
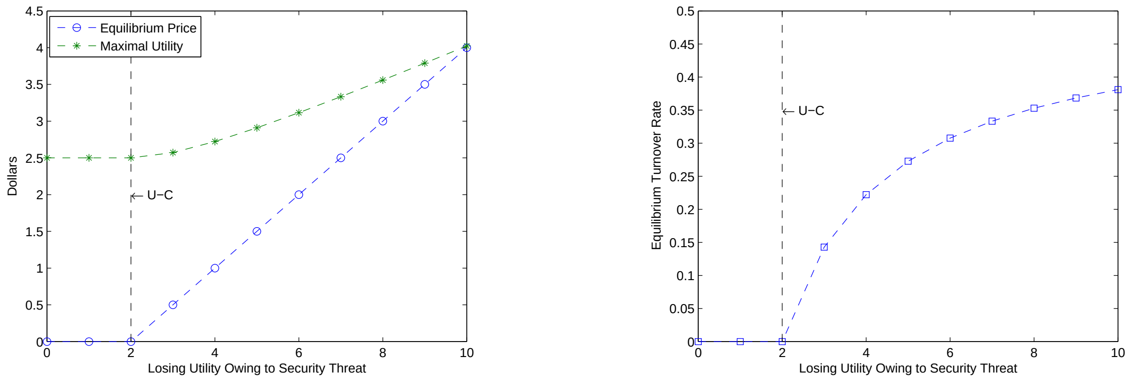


Figure 3.6: The relationship between the equilibrium price and turnover rate with $L = 2$ and $C = 0.5$.

3.4 Performance Analysis

3.4.1 The DRM Game in P2PS System

The influence of the equilibrium price for turnover rate is shown in the Figure 3.6, here we let $L = 2$ and $C = 0.5$, measured in dollar. When $P = L + C$, the turnover rate is equal to 1. It means the equilibrium price reaches the threshold that the peers in the P2PS system with DRM would run off and the system would collapse. When $\alpha = 1$ and $\beta = 1$, the turnover rate increases linearly as the equilibrium price increases with no change in the slope of the curve. However, the relationship is nonlinear under the condition that $\alpha = 2$, $\beta = 2$ and $\alpha = 3$, $\beta = 1$ in Figure 3.6, the slope of the curve increases gradually, which shows that the changing rate of the curve is small when the equilibrium price is close to 0, while the changing rate is large as the equilibrium price is close to $L + C$. It illustrates that the turnover rate of the users increases by a wide margin as the equilibrium price grows gradually. On one hand, lower equilibrium price causes lower turnover rate, which implies that more users would like to stay in the P2PS system with DRM, but the lower price makes the SP receive more profits from the system



(a) (b)

Figure 3.7: The influence of losing utility owing to security threats with $C = 0.5$ and $U = 2.5$.

with DRM; on the other hand, higher equilibrium price forces more users to run away from the system with DRM, which also leads to a low income for the SP. Therefore, we need an optimal strategy to look for the appropriate equilibrium price and turnover rate in order to maximize the utility of the SP.

Figure 3.7 shows the influence of losing utility owing to security threats when $U = 2.5$ and $C = 0.5$. We would discuss the results in two cases: (1) When $U \geq L + C$, i.e., $L < U - C$, the SP would not deploy the P2PS system with DRM. In that case, all the peers stay in the P2PS system without DRM, then the price and the turnover rate are 0 (on the left of line $U - C$ in Figure 3.7(a) and Figure 3.7(b)); (2) While $U < L + C$, i.e., $L > U - C$ (on the left of line $U - C$ in Figure 3.7(a) and Figure 3.7(b)) the SP will deploy the P2PS system with DRM, the maximal utility of SP and equilibrium price, which increase with losing utility owing to security threats L (Figure 3.7(a)), are larger than that in the system without DRM. The SP is able to set a higher price if the losing utility L is larger, which leads to higher maximal utility of the SP (U_D^*). However, higher price brings a high turnover rate of the user (Figure 3.7(b)). Besides, according to Proposition 4.5, when $Q^* = \frac{-U+L+C}{2(L+C)} < 0.5$, the upper bound of the turnover rate is 0.5, that is, the turnover rate should be less than 0.5 in order to get the maximal utility.

3.4.2 DRM Games for Misbehaviors

We first illustrate the effectiveness of the strategy based on the static games.

Freeriding: In Figure 3.8, $p = 200$ and $c = 3$, which satisfy Eq. (3.19). We can see that the expected payoff for the peer decreases as the probability to adopt free-riding increases. A peer who always takes free-riding will acquire the lowest payoff, and the strategy for the peer to acquire highest payoff is never taking free-riding. It shows that the currency mechanism is very effective in this game, the peers are willing to share the digital goods between each other in order to get the maximal payoff. We also leverage normal distribution perturbation (NDP), where the normal distribution is $N(x, \sigma)$ and $\sigma = 0.1$, to simulate the differences between the actual condition and the probability for the peer to take free-riding. The perturbation changes the utility for the peer slightly, it further shows that the currency mechanism is very effective in the static game.

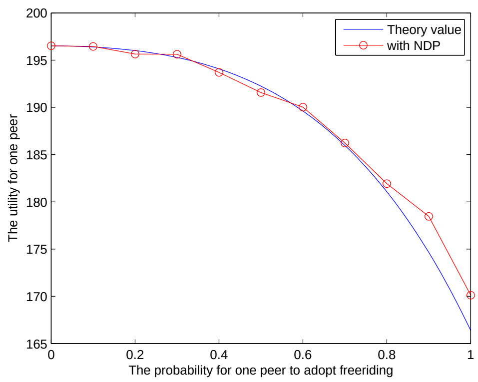


Figure 3.8: The expected utility for peer i. Here, $n = 5$, $p = 200$, $c = 3$ and $\theta = 0.3$.

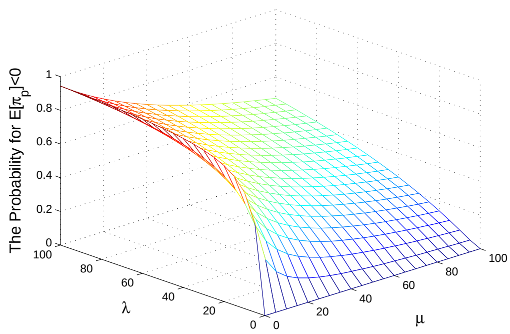


Figure 3.9: The probability for $E[\pi_p] \leq 0$.

Jailbreaking: The probability of $E[\pi_p] \leq 0$, $P\{E[\pi_p] \leq 0\}$ (in Eq. (3.27)), is shown in Figure 3.9. We can see that if the SP puts no penalty on peers' jailbreaking (i.e., $\lambda = 0$), then $P\{E[\pi_p] \leq 0\} = 0$. It means that the peer has a strong motivation to take the jailbreaking. However, if the penalty W is much larger than the extra reward E (i.e., $\lambda \gg \mu$), $P\{E[\pi_p] \leq 0\}$ is close to 1. That is, the peer has almost no motivation to take the jailbreaking. Figure 3.10 further shows that when the penalty W is much larger than the extra reward E, a small probability for the SP to catch the jailbreaking (i.e., s is small) could have the peer's expected payoff be not positive (i.e., $E[\pi_p] \leq 0$), even if the peer takes the jailbreaking with a high probability (i.e., r is large). We can also see that the peer could acquire a maximal utility if it does not take the jailbreaking (i.e., $r = 0$).

Whitewashing: Let $pG(1, a_{-i}) - c = 1$. According to Proposition 3.6, we can see from Figure 3.11 that the decision domain of W is the marked region guarded by line $-Y \leq E[\pi_p]$ and line $E[\pi_p] \leq 0$, which becomes wider as Y increases. As a result, the SP could have more choices of the punishment W if the identity cost Y is large. When the identity cost approaches zero, the decision domain of W nearly reaches to a fixed point. This suggests that the punishment W should not be too severe, otherwise the peer will

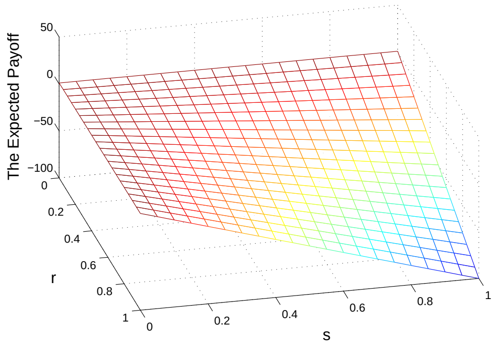


Figure 3.10: The expected payoff for the peers, here $W = -100$, $E = 2$, $R = 1$.

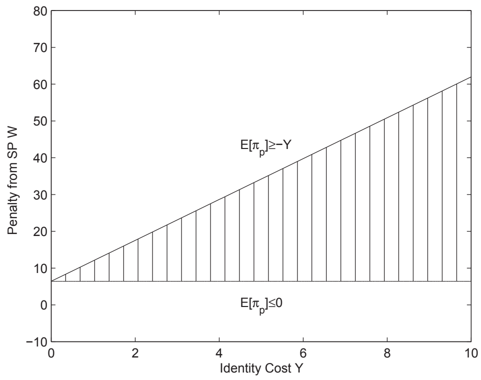


Figure 3.11: The decision domain of the punishment, where $E = 6$, $x = 0$, $r = 0.6$ and $s = 0.3$.

take the whitewashing when $E[\pi_p] < -Y$.

Then we analyze the effectiveness of the dynamic games to avoid misbehaviors.

Jailbreaking: The hunting probability could be acquired by Eq. (3.35). Let $q = 0.6$, $R_L = \frac{1}{2}R_H$, $ER = \phi R_H$ and $W = \theta R_H$ ($\phi, \theta > 1$), the change of hunting probability shows in Figure 3.12. From this figure, we could draw a conclusion that if the punishment is large enough (θ is large), the SP could set the hunting probability small in equilibrium; if the extra interest is large (ϕ is large), a severe punishment would be effective for the SP to keep a low hunting probability. It means that our strategy is effective to avoid

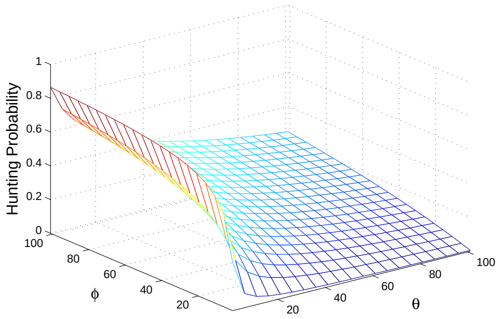


Figure 3.12: The hunting probability in the dynamic game.

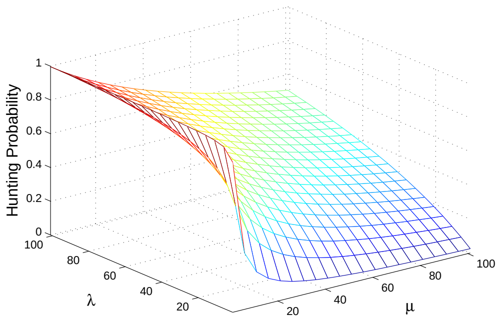


Figure 3.13: The hunting probability in the static game.

jailbreaking.

We could also acquire the hunting probability in the static equilibrium according to Eq. (3.25). Let $W = \lambda R$ and $ER = \mu R$. When the game is in equilibrium ($E[\pi_p] = 0$), the hunting probability s in Eq. (3.25) should be:

$$s = \frac{R + rER}{r(R + ER + W)} = \frac{1 + rk}{r(1 + k + j)}. \tag{3.39}$$

If we use the same condition in the static game as that in the dynamic game, we could get the result in Figure 3.13, we can compare the result between the dynamic game and static game. It is obvious that the hunting probability in the dynamic game is smaller

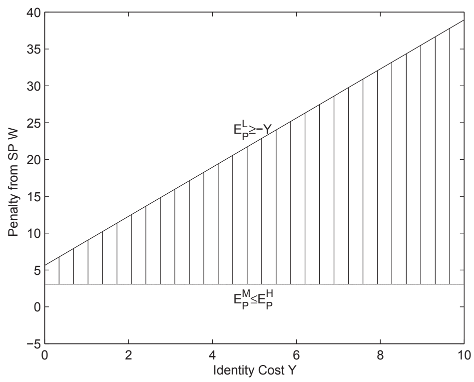


Figure 3.14: The decision domain of the punishment in the dynamic game, where $R_H = 1$, $R_L = \frac{1}{2}R_H$ $ER = 6$, $q = 0.6$ and $p = 0.3$.

than that in the static game under the same conditions. In the P2PS system, the cost for the SP to hunt the illegal peer is extremely high, in other words, the smaller the hunting probability is, the less the SP costs. Comparing the result in Figure 3.12 with that in Figure 3.13, the SP would apply smaller hunting probability in the dynamic game in order to cut down the cost.

Whitewashing: We still assume that no peer takes free-riding. The decision domain of W is the marked region guarded by line $E[\pi_p^M] \leq E[\pi_p^H]$ and line $E[\pi_p^L] \geq -Y$, then we could acquire the decision domain of W as Figure 3.14 shows.

In contrast with the case in the static game (Figure 3.11), the range of W's decision domain in the dynamic game becomes wider than that in the static game as Y increases. The superiority of the dynamic game stands out when the identity cost approaches 0, because the range of W nearly reaches to a fixed point in the static game (Figure 3.11) while there is more choices for the punishment W in the dynamic game.

3.5 Discussion

DRM service is certainly important for P2PS and we try our best to address the issue from different aspects, mostly related to peer-to-peer. However, the very unique challenge, that is available to streaming only, is how to guarantee the QoS of the streaming. For the P2PS system, the key points to guarantee the QoS of the streaming are the low delay and integrate streaming flow. Such key points need the SPs to control and manage all the digital goods in the system. The only tool for the SPs is the DRM service which can accomplish the SPs' requirements. To guarantee the streaming with lower delay, the SPs should motivate all the peers to share their digital goods (taking not-freeriding) since the more peers are willing to share the digital goods, the lower delay will be. To have the streaming flow integrate, the peers should not break the digital goods in the system (taking not-jailbreaking) because the modified digital goods would pollute the source of the digital goods and even bring some security problems. In the implementation of the P2PS system with DRM, there are also many practical issues related to the DRM strategy. Such issues will be presented in the future work of this thesis.

3.6 Summary

In this chapter, we model the DRM for P2PS systems as a game for the SP and users, derive the equilibrium price of the digital goods, and maximize the utility of the SP in the P2PS system with DRM based on that equilibrium price. This game model is effective in deciding whether DRM should apply in the P2PS system. We also present effective strategies through static and dynamic games to avoid three misbehaviors of peers: freeriding, jailbreaking and whitewashing. These strategies have the peers acquire the maximal utility if the peers do not take these actions. Experiments are conducted to demonstrate the effectiveness of our strategies, and we find that dynamic game is more effective than the static game.

Chapter 4

Differentiated DRM Service on Mobile Cloud Computing

In this chapter, we present differentiated DRM service to increase the utility of the mobile users and the benefit of the SPs. The organization of this chapter is as follows. Firstly, a brief overview is given in Section 4.1. Section 4.2 describes the system model. Section 4.3 and Section 4.4 analyze the the utility of the mobile users and the benefit of the SPs. Performance analysis is discussed in Section 4.5. Section 4.6 discusses the practicality of our model. Finally, Section 4.7 summarizes this chapter.

4.1 Introduction

A recent survey reveals that the number of mobile devices carried by employees have cut down from 3.47 per person in year 2012 to 2.96 per person in year 2013 due to the increasing popularity of Bring Your Own Device (BYOD) [1]. BYOD, is a new style of IT, which encourages employees to use their personal mobile devices to access corporate networks. Though BYOD greatly increases the flexibility that employees could use their devices at the workplace and be more productive, BYOD users heavily rely on the cloud that rapidly provides a large pool of resources and services with minimal effort for service interaction and management. This brings many concerns about security risks, such as data leakage or data theft, at both sides of the cloud and mobile devices as the BYOD users leverage the cloud services and mobile softwares to complete their work. The cloud services and mobile apps, collectively referred to as "digital goods" in this chapter, are therefore in need of effective control and management to prevent security risks on both sides. These requirements enforce the deployment of a cloud-based DRM service, which provides a general means including the provision, safekeeping, license phrasing and offer creation, distribution, booking, payment, authorization, and consumption [36], to keep track of the execution of the digital goods, preventing them from security risks on both sides of the cloud and mobile devices.

There are three steps associated with digital goods in a typical cloud-based DRM service as shown in Fig. 4.1:

1. The SP provides the digital goods with a unified DRM service on the cloud.
2. The mobile users can execute the digital goods on their mobile devices, which rely on the installed mobile operating systems to control and manage the digital goods.
3. The purchase and execution of the digital goods involve interactions between the cloud and mobile devices, which are under the control of the DRM system.

Such cloud-based DRM services, unfortunately, do not effectively manage the digital goods for BYOD users and face several challenges:

One challenge is that BYOD users call for the digital goods with security flexibilities to meet their diversified security requirements at the workplace or at home. Generally,

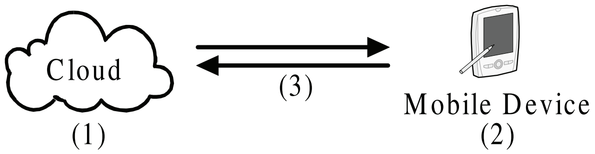


Figure 4.1: The cloud-based DRM service.

BYOD users will use their own mobile devices at both places, and the security requirements of digital goods vary greatly from one user to another or from at home to at work. Though a BYOD user may run the digital goods in an isolated sandbox with high security protection (e.g., BlackBerry Enterprise 10) for work and use the pre-installed platform for the personal use at the mobile device side, current SPs usually do not provide the digital goods with diversified security levels to satisfy the users' demands at the cloud side. Due to the popularity of BYOD and its users' diversified demands on the security of the digital goods, it is necessary for SPs to offer the digital goods with diversified security.

Another challenge for BYOD users is how to evaluate their security requirements on the digital goods. There is no appropriate metric that allows the BYOD users to measure their security requirements. The lack of the metric lets the BYOD users choose their DRM services in an ad hoc fashion.

The last challenge comes from the impact of cloud and mobile platform on the security of digital goods. At the mobile device side, the security of a mobile operation system will be weakened due to the execution of the digital goods with low security, although the mobile operation system is regarded as an effective shield to prevent security threats. At the cloud side, the unified DRM service also has the disadvantage that there is no transparency of the state of digital goods in commercial servers, which causes many users to worry about the safety of their digital goods when offloading them to the data center of the cloud, because the users would "have no idea what's in the corporate data center" [57] and some other digital goods stored in the same data center may damage the security of theirs.

It is obvious that the current unified security offered by the cloud-based DRM service is out of date and not flexible enough to satisfy the diversified security requirements of BYOD users, which calls for an effective mechanism to increase the security flexibility of the DRM services. Generally, a SP could deploy diversiform DRM services as "flexible DRM services" to provide the security flexibility of the DRM service for BYOD users. As both the BYOD users and SPs are rational entities, would the service become preferable for both the BYOD users and SPs? The most direct mechanism to motivate them to adopt the flexible DRM service is to increase the utility of BYOD users and the benefit of the SP at the same time when they choose the new service, compared with the previous cloud-based DRM service. The BYOD user, after adopting the new flexible DRM service, should realize more utility from the new service than the previous cloud-based one. For the SP, it would make a decision to deploy the flexible DRM service under the condition that it can gain more net benefit, even though the new DRM service will introduce extra cost. Moreover, the SP with a flexible DRM service has to compete with other SPs in the market. If the flexible DRM service cannot develop a competitive edge over the other SPs, then the SP in question will definitely not change its DRM services. Therefore, another challenge here is how to design an effective DRM system to make both entities profitable at the same time.

In this chapter, we propose a new cloud-based DRM service, called differentiated DRM service, which is flexible enough to meet the diversified security requirements of BYOD users. To ease our system modeling, we treat one BYOD user to be two mobile users who executes the digital goods in two different security models: (1) on an isolated virtual platform with high security protection; (2) on an mobile platform in a lower security mode. With this treatment, the relationship between one BYOD user and the SP now changes to be two independent relationships between each mobile user and the SP, and all the corresponding issues are addressed between the SP and mobile users through the differentiated DRM service. The main contributions of this chapter are summarized as follows:

- The existing cloud-based DRM service is improved and differentiated it into multiple grades based on the security risk. The differentiated DRM service is integrated with the digital goods, and is leveraged by the mobile users.
- We introduce a new DRM policy,in which the mobile user is capable of protecting the *primary digital goods set* through employing appropriate mobile platform software and associating digital goods.
- We model the utility of a mobile user using some economics concepts, and prove that our differentiated DRM service can bring more utility than any unified DRM service.
- We analyze the benefit of SPs based on linear and nonlinear cost models, and conclude that the SP with the differentiated DRM service gains more than the one without it.
- We further model the competition between SPs as a cooperative game, and prove

that our differentiated DRM service with multiple grades is the dominant strategy.

4.2 System Model

We propose a differentiated DRM service, which can provide mobile users flexible security options for the digital goods. We also establish a mechanism for the mobile users to adopt for the mobile platform and associated digital goods. To ease our discussion, we first give the definition of differentiation used in our system model.

Definition 4.1. *Differentiation* is an approach that develops and markets a product or service from others, to make it more attractive to a particular customer segment. In our model, differentiation is to provide one type of digital goods with varied DRM services for different mobile users. Here, DRM services are divided into multiple grades, and different prices are set for the digital goods with different DRM service grades. Such DRM services are called *differentiated DRM services.*

In our system model, there are two platforms, the cloud platform and mobile platform, which are defined as follows:

The cloud platform: The cloud is an entity where abundant digital goods with differentiated DRM services are provisioned. However, the digital goods will often have security risks when executed on the cloud and thus bear a utility loss, even though it is protected by the DRM system. In our model, the loss is varied for the digital goods with different DRM grades. A lower grade DRM service will cause a digital good to lose its utility more, while a higher grade DRM service is able to resist the utility loss more effectively. Here we differentiate the DRM service for each digital good into 5 grades

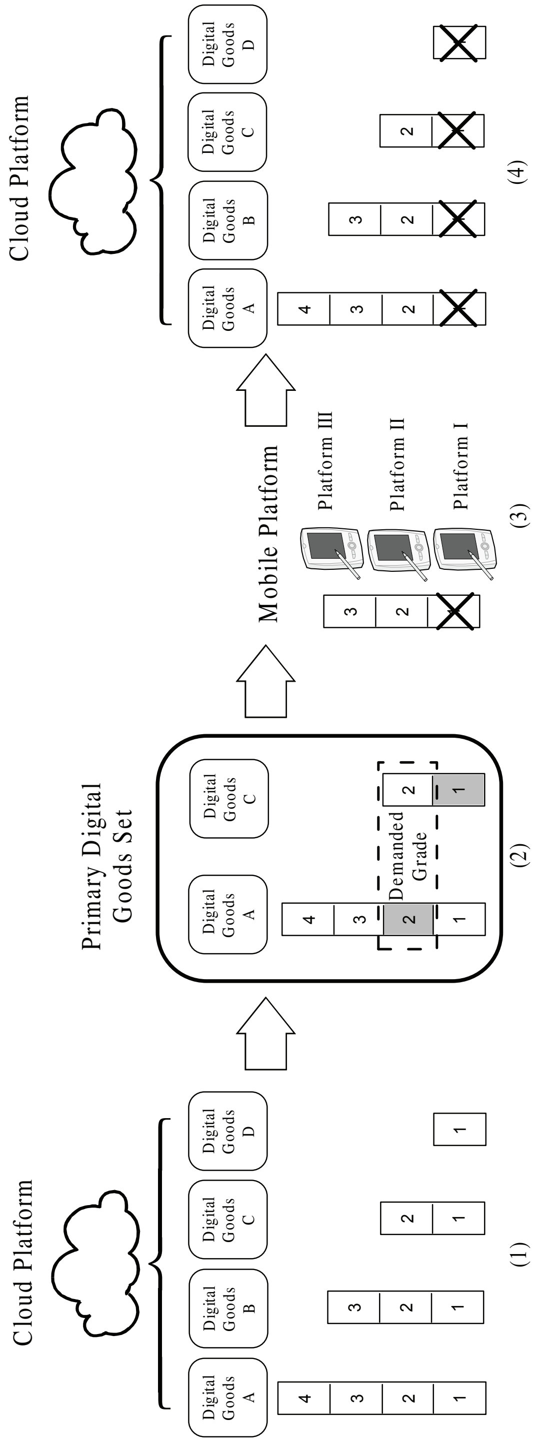


Figure 4.2: The guidelines for the mobile users to protect the security of primary digital goods.

based on its utility loss ratio caused by the security risks, according to the security service differentiation scale introduced in [73]. Generally, with the support of the cloud platform, the DRM grade of each digital good on the cloud can be maintained and will not be affected by others.

The mobile platform: The mobile platform represents the mobile operating system installed on the mobile device which is the main platform for the mobile users to control and manage their digital goods. It provides both the mobile operating system and corresponding DRM security protection. In our model, a mobile platform also has its own DRM grade and it will affect the DRM grade of a digital good when the digital good is being executed on the platform. The actual DRM grade of the digital good will be downgraded to the DRM grade of the mobile platform if the original DRM grade of the digital good is higher than the DRM grade of the platform; otherwise, its DRM grade will keep the same. If the mobile platform has several digital goods with different DRM grades running simultaneously, as their DRM grades will be mutually affected, the actual DRM grades of the goods will be determined by their lowest DRM grade.

As a mobile user may have several digital goods with different DRM grades running on the mobile device simultaneously, and their DRM grades may be mutually affected with one another, the mobile user has to make sure that those critical digital goods executed are well protected by the DRM service. Here, we propose a new policy that gives a list of guidelines to protect the execution of those digital goods on the mobile device. To ease the description, we further give some definitions used in our system model.

Definition 4.2. *A primary digital good* is a digital good which is mostly used by a mobile user. The security of the primary digital good is protected by the DRM service. *The* *primary digital goods set* is the set that consists of all the primary digital goods. The security of the primary digital goods set is protected by the differentiated DRM services.

Definition 4.3. *The demanded grade* of a primary digital good is the lowest DRM grade that meets the mobile user's security demand of the digital good. *The demanded grade of the primary digital goods set* is the highest demanded grade of all the goods in the primary digital goods set. The DRM service that provides the demanded grade of the primary digital goods set is called a *demanded DRM service.*

Definition 4.4. *An associated digital good* is a digital good, other than any primary digital goods, that can be simultaneously executed on the mobile platform with any goods in the primary digital goods set, while putting no harm to the DRM grade of the primary digital goods. *The associated digital goods set* is the set that consists of the associated digital goods.

The guidelines for the mobile users to protect the primary digital goods set on both the cloud and mobile platforms are described as follows.

1. The SP provides the digital goods with differentiated DRM services on the cloud platform, where a higher grade DRM service leads to stronger security protection;

2. A mobile user determines the demanded grade according to the primary digital goods set. For instance, if Email is the primary concern of the mobile user, then all the digital goods related to the Email compose the primary digital goods set. The demanded grade of the primary digital goods set is determined as the highest demanded grade of the primary digital goods in the set.

3. For the security of the primary digital goods set, the mobile user needs to choose a mobile platform with the DRM grade not below the demanded DRM grade. Otherwise, the security of the primary digital goods set will be breached due to the lower security of the mobile platform.

4. Besides the primary digital goods set, the user can also use associated digital goods whose DRM grade is not below the demanded grade.

Example 4.1. We illustrate these guidelines using the example shown in Fig. 4.2.

1. Suppose the SP provides four digital goods (A, B, C and D) with differentiated DRM services on the cloud platform. The DRM grades for these digital goods are 4, 3, 2 and 1 (Step (1) of Fig. 4.2).

2. The primary digital goods set consists of two digital goods: A and C. The demanded grade of A is 2 while that of C is 1. The demanded grade of the primary digital goods set is grade 2, which is marked with the dashed box (Step (2) of Fig. 4.2).

3. There are three optional platforms (I, II and III) from which the mobile user can select in order to meet the demanded DRM service, and the DRM grades of these three mobile platforms are the 1st, 2nd, and 3rd grade, respectively. As the DRM grade of platform I cannot meet the demanded grade of the primary digital goods set, the eligible platforms are platforms II and III (Step (3) of Fig. 4.2);

4. Besides the two primary digital goods (A and C), there are two more digital goods provided by the cloud (B and D). The mobile user will not purchase D because its highest DRM grade is 1, which is lower than the demanded grade of the primary

digital goods set. As a result, the available associated digital good is B (Step (4) of Fig. 4.2).

4.3 The Utility of Mobile Users

In this section, we first valuate the utility of the mobile users as they choose their demanded grade DRM service, and then prove that the utility brought by differentiated DRM service is higher than any single grade DRM service.

4.3.1 Risk Aversion of the User

As we know, a rational consumer who is risk averse will accept a bargain with a higher degree of certainty in the payoff rather than on another bargain with an uncertain payoff [8]. This also applies to rational mobile users. The digital goods without DRM service may result in a considerable loss to the mobile users' utility due to the security risks, and as such, these digital goods are less likely to be accepted by the mobile users. The situation is very different for the digital goods with DRM service. Under the protection of the DRM service, the mobile users suffer the security risk with a lower probability and lose a portion of utility, and we denote the ratio of loss to the mobile users' utility as the **loss ratio**. The rational mobile users who make use of DRM services have a tendency toward risk aversion . We suppose that the **risk aversion tendency** of the mobile user is $\theta \in [0, 1]$, and the loss ratio of the mobile users is $e^{-\theta D}$, in accordance with an exponential utility function [63]. With the basic utility D and price P of one digital good, the utility of mobile users who purchase the digital good with DRM service is:

$$U = D(1 - e^{-\theta D}) - P. \tag{4.1}$$

Eq. (4.1) can also calculate the utility of a mobile user who adopts the digital goods without any DRM service as well. The digital goods without any DRM services are free (i.e., $P = 0$), and the mobile users have no risk aversion tendency to prevent any security threats (i.e., $\theta = 0$). In that case, the utility of these mobile users is $U = 0$ according to Eq. (4.1). The prerequisite for a mobile user to choose the digital goods with the DRM service is that the digital goods with the DRM service are able to bring more utility to the mobile users than the digital goods without DRM service, $U = D(1 - e^{-\theta D}) - P > 0$. That is, $\theta > -\frac{1}{D}\ln(1 - \frac{P}{D})$, which results in:

Proposition 4.1. *If the user's risk aversion tendency $\theta > -\frac{1}{D}\ln(1 - \frac{P}{D})$, the user would prefer the digital goods with the DRM service.*

Proof. When $\theta > -\frac{1}{D}\ln(1 - \frac{P}{D})$, we can get $U = D(1 - e^{-\theta D}) - P > 0$, which indicates the user would prefer the digital goods with DRM service to gain more utility. □

The mobile user's utility is closely related to both the risk aversion tendency and the basic utility of the digital goods. As shown in Eq. (4.1), the basic utility of the digital goods plays a critical role in valuating the utility of the digital goods to the mobile user. This gives the reason why Apple gave up its online music DRM service in 2009. The basic utility of music is very low (i.e., D is very small), and the price of the music P could not be too small because the price should cover the cost to deploy the DRM service. These conditions induce the mobile users' risk aversion tendency θ to be close to or greater than unity, according to Proposition 4.1, and the utility of the mobile users U decreases to or below zero, according to Eq. 4.1. This result reveals that only the users with large risk aversion tendency (θ approaching to 1) are willing to purchase the music in the Apple Store even though $\theta < 1$, nevertheless, the quantity of such users is so small that Apple gave up its music DRM service.

4.3.2 Odds Ratio for DRM Service

In this chapter, we introduce another concept, the **odds ratio** (OR) [93], which measures the effect on the utility that is caused by the demanded grade. OR is denoted as a metric of relation between an exposure and an outcome, which expresses the odds that an outcome will occur given a particular exposure, compared to the odds of the outcome occurring in the absence of that exposure. The odds ratio can be used to determine whether an exposure is a risk factor or a protection factor for the outcome:

- $OR = 1$ corresponds to an exposure that is not associated with the outcome,
- $OR > 1$ corresponds to an exposure that is a risk factor for the outcome,
- $OR < 1$, corresponds to an exposure that is a protection factor for the outcome.

OR could clearly illustrate the relative risk between the exposure and outcome. In our system model, we evaluate the relative risk between the adopted DRM service and the demanded DRM service in order to understand if an associated digital good is a risk factor or a protection factor for the primary digital goods. Let $R \in [0, 1]$ be the loss ratio of the demanded DRM service (**demanded loss ratio**), and $L \in [0, 1]$ be the loss ratio of the DRM service adopted by the mobile users. Then the relative risk in our model could be calculated as

$$OR = \frac{\frac{L}{1-L}}{\frac{R}{1-R}} = \frac{L(1-R)}{R(1-L)}, \tag{4.2}$$

which is in accordance with the definition of OR in [93]. Then we give a more detailed description of OR in our system model:

1) If $OR > 1$, the associated digital goods will be a risk factor and threaten the security of the primary digital goods;

2) If $OR \leq 1$, the associated digital goods will be a protection factor for the primary digital goods and are able to be used by the users.

In our system model, the mobile user will pick a mobile platform to execute the digital goods once he or she determines the demanded DRM service. The platform should bring a positive effect to the primary digital goods. If L_M is the loss ratio of the mobile platform, then the odds ratio of the DRM service on the mobile platform must satisfy

$$\frac{L_M(1-R)}{R(1-L_M)} \geq 1. \tag{4.3}$$

In the rest of this chapter, we assume that the digital goods are executed on the mobile platform whose loss ratio (L_M) meets the above equation.

4.3.3 Utility of the Users with DRM Service

Although Eq. (4.1) is the utility function of mobile users, it only reveals the utility of mobile users that is interrelated with the users' risk aversion tendency, the basic utility and price of the digital goods. This loses insight of the effect from the demanded DRM service. To explain how the demanded DRM service plays a key role in the mobile users' utility, we rewrite the utility function with regards to the odds ratio in Eq. (4.2) as an influential factor,

$$U = [1 - \frac{L(1-R)}{R(1-L)}][D(1 - e^{-\theta D}) - P]. \tag{4.4}$$

Eq. (4.4) expresses the utility of the mobile users based on the effect of the demanded DRM service. It is obvious that the mobile users gain a negative utility while $OR > 1$. Eq. (4.4) also well explains the reason why most of iTunes users are not willing to break the law and use the free digital goods without DRM service. The DRM-free digital goods lead to a large loss ratio ($L = 1$), and has the feature that most mobile users' utility is subtractive due to $OR > 1$ (i.e., their demanded loss ratio R is less than 1).

4.3.4 Utility of the Users with Differentiated DRM Service

For the mobile users, the price is critical point to determine the quantity of the users and the SPs are able to attract more users through decreasing the price of the digital goods. Although a lower price could attract more users to purchase the digital goods with the DRM service, it may reduce the payoff of the SPs. In contrast, high price directly causes the vast majority of mobile users to give up the use of the DRM service. For the sake of persuading as many users as possible to adopt the DRM service, a better way is to provide a tiered price to the digital goods with differentiated DRM service. In our model, the SPs offer the digital goods with five-grade DRM service integrated into the digital goods. The higher grade DRM services lead to higher prices and lower loss ratios. Here we define the loss ratio and the price at the gth grade DRM service as L_g and P_g. With a demanded grade Λ, the demanded loss ratio caused by demanded DRM service R_Λ is

$$R_\Lambda = \beta L_\Lambda + (1-\beta)L_{\Lambda-1} \quad \Lambda \in N, 0 < \beta < 1.$$

Here we treat service without DRM as the 0th grade DRM service. Since the digital goods without DRM service accompany no protection from security threats, the loss ratio for the 0th grade is $L_0 = 1$. For the mobile users with demanded grade $\Lambda > 0$, we set their demanded loss ratio to be the linear combination of the loss ratios at the Λth and $\Lambda - 1$th grades as given by Eq. (4.3.4), where the coefficient of that combination is $\beta \in (0, 1)$. Then the utility of the digital goods with the gth grade DRM service is

$$U_g = [1 - \frac{L_g(1-R_\Lambda)}{R_\Lambda(1-L_g)}][D(1-e^{-\theta D}) - P_g]. \tag{4.5}$$

Then we obtain the following proposition about the equilibrium risk aversion tendency:

Proposition 4.2. *The equilibrium risk aversion tendency is*

$$\theta_g^* = \begin{cases} -\frac{1}{D}\ln(1-\frac{P_1}{D}) & \text{if } g = 1 \\ -\frac{1}{D}\ln[1-\frac{P_g}{D} - \frac{\Delta P_g(1-L_g)}{D(1-R_\Lambda)} + \frac{\Delta P_g L_g(1-L_g)}{D\Delta L_g}], & \text{if } g > 1. \end{cases} \tag{4.6}$$

Here, $\Delta P_g = P_g - P_{g-1}$ *and* $\Delta L_g = L_g - L_{g-1}$*. As the risk aversion tendency* $\theta \geq \theta_g^*$*,* $U_g \geq U_{g-1}$ *and vice versa.*

Proof. We compare the utility of the mobile user between the adjacent DRM grade g and $g-1$, it achieve the equilibrium when $U_g = U_{g-1}$. If $g = 1$, the equilibrium is between the 0th and first grade, that is

$$[1-\frac{L_1(1-R_\Lambda)}{R_\Lambda(1-L_1)}][D(1-e^{-\theta D})-P_1]=0, \tag{4.7}$$

then the equilibrium risk aversion tendency is

$$\theta_1^* = -\frac{1}{D}\ln(1-\frac{P_1}{D}). \tag{4.8}$$

If $g > 1$, $U_g = U_{g-1}$, that is,

$$[1-\frac{L_g(1-R_\Lambda)}{R_\Lambda(1-L_g)}][D(1-e^{-\theta D})-P_g]=[1-\frac{L_{g-1}(1-R_\Lambda)}{R_\Lambda(1-L_{g-1})}][D(1-e^{-\theta D})-P_{g-1}].$$

Then we could acquire the equilibrium risk aversion tendency:

$$\theta_g^* = -\frac{1}{D}\ln[1-\frac{P_g}{D}-\frac{\Delta P_g(1-L_g)}{D(1-R_\Lambda)}+\frac{\Delta P_g L_g(1-L_g)}{D\Delta L_g}]. \tag{4.9}$$

□

The notable superiority of the differentiated DRM service is that the mobile users' utility is higher than the utility of those adopting single grade DRM service. The following proposition will illustrate this advantage.

Proposition 4.3. *For the typical cloud-based DRM service with a single grade, there exists a strategy that satisfies the following requirement: The utility of all the mobile users in the differentiated DRM system is higher than the utility of the users in the DRM system with a single grade.*

Proof. Suppose the demanded loss ratio, the basic utility of the digital goods and the risk aversion tendency are the same for the single and differentiated DRM system, e.g., R, D and θ. Let the price and loss ratio in the DRM system with single grade be P^S and L^S. Then the utility of the mobile users in single grade DRM system U^S is

$$U^S = [1 - \frac{L^S(1-R)}{R(1-L^S)}][D(1-e^{-\theta D}) - P^S]. \tag{4.10}$$

For the differentiated DRM system, the price and loss ratio for the gth grade are P_g^D and L_g^D, and the utility of the mobile users is

$$U_g^D = [1 - \frac{L_g^D(1-R)}{R(1-L_g^D)}][D(1-e^{-\theta D}) - P_g^D]. \tag{4.11}$$

1) If single grade DRM service is equivalent to the first grade in the differentiated DRM service ($P^S = P_1^D$ and $L^S = L_1^D$, $U^S = U_1^D$), then $U_2^D > U_1^D = U^S$ when $\theta > \theta_2^*$ by Proposition 4.2, and the utility of all the mobile users in differentiated DRM system is higher than that in the single grade DRM system;

2) If single grade DRM service is the same as the DRM service at gth ($g > 1$) grade ($P^S = P_g^D$ and $L^S = L_g^D$), we consider the result in two cases: I) when $\theta \geq \theta_g^*$, $U_{g+1}^D > U_g^D = U^S$ based on step (1); II) when $\theta < \theta_g^*$, $U_{g-1} > U_g$ by Proposition 4.2, and all the mobile users' utility in the differentiated DRM system is higher than that in the DRM system with single grade;

3) If P^S and L^S are not in accordance with the case of any grade in the differentiated DRM system, we insert P^S and L^S as the price and loss ratio of a new grade in the differentiated DRM system, the proof is similar to the two steps above. □

4.4 The Benefit of SPs

In this section, we calculate the benefit of the SPs based on linear and nonlinear cost models, and illustrate that differentiated DRM services provide a higher gain to the SPs than single grade DRM services. We also prove the DRM service with five grades is a dominant strategy through cooperative games.

4.4.1 Cost Model for SP

Due to unavailability of the detailed costs for SPs on the DRM service, it is impossiple to model the cost of DRM services accurately since the SPs would not publish its detailed cost for the DRM service and the cost could not form a unified model for different SPs. Due to such uncertainties, we deploy the cost for the differentiated DRM services as linear and non-linear functions with the assumption that deploying higher grade DRM service will cost more. In other words, the cost of the differentiated DRM service is a step function of the DRM grade g. We denoted C_1 as the cost of the first grade DRM service in both linear and nonlinear cost models.

Linear cost of DRM service: The most straightforward way to evaluate the cost of the differentiated DRM service is to assume that the cost scales linearly with the grade. To simplify the model, we set the cost of the DRM service at the gth grade as $C_g = gC_1$.

Non-linear cost of DRM service: However, the linear cost model for DRM service does not work in some cases. For example, if the mobile user's digital good is of large basic utility and he or she will have high security requirements, then a linear function is not fit for the cost of the DRM service. The DRM service of such digital good will be differentiated as too many grades if we use the linear cost of DRM service, and the differences between adjacent grades are inconspicuous as the DRM grade is higher. In order to illustrate the cost of such cases, we set the cost of the gth grade DRM service to be an exponential function of g, that is $C_g = e^{g-1}C_1$.

4.4.2 Return on Investment for Differentiated DRM

The DRM service is divided into five grades in our system. How to price the digital goods with varied DRM service would be a critical issue that directly impacts the SPs' payoff, which is a decisive factor in deploying the differentiated DRM service or not. Here we borrow the economics concept called "return on investment" (ROI), which is a popular performance and evaluation metric used for business investments, as the relevant measure for the SPs. ROI simply defines the relationship between financial returns and costs, which is expressed as a percentage of the returned investment over a specific amount of time. ROI equals the accumulated net benefits over a certain time period, divided by the initial costs of investment.

For our differentiated DRM service, we can evaluate the ROI at each DRM grade. The gain from one digital good at the gth grade is the price of the digital goods P_g and the corresponding cost is C_g. Then we define the ROI at gth grade as:

$$ROI_g = \frac{P_g - C_g}{C_g}, \tag{4.12}$$

where $1 \leq g \leq 5$.

To motivate the SPs to develop higher grades of DRM service, the ROI at higher grades should not be less than lower grades, otherwise, the SPs will give up the investment for the higher grades of DRM because it will be more cost effective to use a lower grade. we define this conclusion as the ROI requirement of the differentiated DRM service.

Definition 4.5. The **ROI requirement** of the differentiated DRM service is $ROI_{g-1} \leq ROI_g (1 < g \leq 5)$, and the **minimum ROI requirement** is $ROI_{g-1} = ROI_g$.

Next, we discuss the price based on the linear and non-linear cost models for the SPs when the ROI reaches the minimum ROI requirement. Suppose that $ROI_g = ROI_{g-1} = r$, then $P_g = (1 + r)C_g$ by Eq. (4.12).

Linear cost model: In this model, $C_g = gC_1$. Then

$$P_g = (1 + r)C_g = (1 + r)gC_1 = gP_1. \tag{4.13}$$

Therefore, the linear cost model leads to a linear pricing for the digital goods with differentiated DRM service.

Non-linear cost model: With $C_g = e^{g-1}C_1$, the pricing function is calculated as

$$P_g = (1 + r)C_g = (1 + r)e^{g-1}C_1 = e^{g-1}P_1. \tag{4.14}$$

Hence non-linear pricing the digital goods with differentiated DRM service is applicable to the nonlinear cost model.

4.4.3 Maximizing the Payoff of the SPs

To simplify the calculation, we suppose that the loss ratio L_g at gth grade is monotonically decreasing. This means that the users would lose less when there is a higher grade DRM service. Here we leverage the exponential utility function to express the loss ratio at gth grade [63], that is $L_g = e^{-g}$. By Eq. (4.5), the users' utility at gth grade becomes:

$$U_g = [1 - \frac{e^{-g}(1 - R_\Lambda)}{R_\Lambda(1 - e^{-g})}][D(1 - e^{-\theta D}) - P_g]. \tag{4.15}$$

Then the equilibrium risk aversion tendency is derived using Proposition 4.2:

$$\theta_g^* = \begin{cases} -\frac{1}{D}\ln(1 - \frac{P_1}{D}) & \text{if } g = 1 \\ -\frac{1}{D}\ln[1 - \frac{P_g}{D} - \frac{\Delta P_g(1-e^{-g})}{D(1-R_\Lambda)} - \frac{\Delta P_g(1-e^{-g})}{D(e-1)}] & \text{if } g > 1. \end{cases} \tag{4.16}$$

Proposition 4.4. *θ_g^* is a monotonically increasing function with DRM grade g no matter whether $P_g = gP_1$ or $P_g = e^{g-1}P_1$.*

Proof. We consider the case under linear pricing first, that is $P_g = gP_1$. According to Eq. (4.16), it is obvious that $\frac{\theta_{g+1}^*}{\theta_g^*} \geq 1$.

The proof is similar when $P_g = e^{g-1}P_1$. □

Then the SPs' benefit brought by the digital goods with the gth grade DRM service is

$$B_g = (P_g - C_g)(F(\theta_{g+1}^*) - F(\theta_g^*)). \tag{4.17}$$

Here $F(\theta)$ is the cumulative distribution function (CDF) of the users' risk aversion tendency, $1 - F(\theta_g^*)$ is the quantity of the users whose risk aversion tendency is more than θ_g^*, and the quantity of the mobile users at gth grade is $1 - F(\theta_g^*) - (1 - F(\theta_{g+1}^*)) = F(\theta_{g+1}^*) - F(\theta_g^*)$. The total benefit $B(G)$ for the SPs to initiate the differentiated DRM service with the maximal grade G is

$$B(G) = \sum_{g=1}^{G}(P_g - C_g)(F(\theta_{g+1}^*) - F(\theta_g^*)), \tag{4.18}$$

where $F(\theta_{G+1}^*) = 1$.

Proposition 4.5. *If $P_1 - C_1 > 0$, the SP will acquire its maximal benefit $B(G)$ when the pricing function is either $P_g = gP_1$ or $P_g = e^{g-1}P_1$.*

Proof. With $P_g = gP_1$ and $C_g = gC_1$, the benefit of the SP will be:

$$B_g = g(P_1 - C_1) - \sum_{i=1}^{g}(P_1 - C_1)F(\theta_i^*). \tag{4.19}$$

According to Eq. (4.19),

$$B_g - B_{g-1} = (P_1 - C_1)(1 - F(\theta_g^*)) > 0. \tag{4.20}$$

Therefore, B_g increases with g, and $B_{max} = B(G)$. Similar result could be proved when $P_g = e^{g-1}P_1$. □

Proposition 4.6. *For any single grade DRM service, there exists a differentiated DRM service that has the SP gain more than the single grade DRM service.*

Proof. We construct a new differentiated DRM service whose first grade equates with the grade in the single grade DRM service, its maximal grade is G and the benefit is denoted as $B^D(G)$. Let the benefit of the SP with single grade DRM service be B^S. With Proposition 4.5, it is obvious that $B^D(G) \geq B^S$. □

4.4.4 Cooperative Game between SPs

The above discussions can only reveal the SP's benefit in a monopoly market. We now discuss the case in the free competition market. We firstly model the competition between two SPs as a cooperative game and the sequence of events are listed as follows. (1) Both of the SPs develop their own DRM service. (2) The mobile users would choose the SP who brings them more utility (and if the mobile user could gain equal utility for the same price from both SPs, the mobile users are set to select the SPs randomly). We denote the SP with a single grade DRM service as "SSP" and the SP with differentiated DRM service as "DSP". Then we consider three types of competition between two SPs: (1) SSP *vs* SSP; (2) SSP *vs* DSP; (3) DSP *vs* DSP.

(1) **SSP *vs* SSP**: Both SPs (SP I and II) deploy their own DRM service with only one grade, grades g_I and g_{II}. Without loss of generality, we suppose $g_I \leq g_{II}$ and compare the benefit of the two SPs when they compete with each other.

The utility of the mobile users purchasing the digital goods with g_Ith and g_{II}th grade DRM service are U_{g_I} and $U_{g_{II}}$, and the equilibrium risk aversion tendency $\theta^*_{g_I}$ and $\theta^*_{g_{II}}$ could be calculated through $U_{g_I} = 0$ and $U_{g_{II}} = U_{g_I}$. Then the benefit of the two SPs are as follows.

1) When $g_I = g_{II}$, $U_{g_{II}} = U_{g_I}$, then SP I and II are leveraged by the mobile users with equal opportunity, the quantity of the mobile users for each SP is $\frac{1}{2}(1 - F(\theta^*_{g_I}))$, and the benefit for either SP is obtained by Eq. (4.18), that is

$$B_I = B_{II} = \frac{1}{2}(P_{g_I} - C_{g_I})(1 - F(\theta^*_{g_I})). \tag{4.21}$$

2) When $g_I < g_{II}$, $\theta^*_{g_I} < \theta^*_{g_{II}}$, then the quantity of the mobile users using the DRM service of SP I and II are $F(\theta^*_{g_{II}}) - F(\theta^*_{g_I})$ and $1 - F(\theta^*_{g_{II}})$ respectively, the benefit for

SP I and II are

$$B_I = (P_{g_I} - C_{g_I})(F(\theta^*_{g_{II}}) - F(\theta^*_{g_I})), \tag{4.22}$$

$$B_{II} = (P_{g_{II}} - C_{g_{II}})(1 - F(\theta^*_{g_I})). \tag{4.23}$$

(2) **SSP *vs* DSP**: SP I develops its own DRM service with only one grade g_I, and SP II adopts a differentiated DRM service with five grades g_1, g_2, $\cdots$, g_5. To simplify the model, we suppose that g_I is one element among g_1, g_2, $\cdots$, g_5. We assume SP I is able to attract half of the mobile users who are willing to purchase the digital goods with the g_Ith grade DRM service, while the other mobile users would purchase the digital goods from SP II. The benefit for both SPs are

$$B_I = \frac{1}{2}(P_{g_I} - C_{g_I})(F(\theta^*_{g_I+1}) - F(\theta^*_{g_I})), \tag{4.24}$$

$$B_{II} = \Sigma^5_{g=1}(P_g - C_g)(F(\theta^*_{g+1}) - F(\theta^*_g)) - B_I. \tag{4.25}$$

(3) **DSP *vs* DSP**: Both SP I and II adopt differentiated DRM services with multiple grades. The DRM service of SP I is differentiated by grade g_{I1}, $\cdots$, g_{In} ($n \leq 5$), while SP II adopts differentiated DRM service with five grades g_1, g_2, $\cdots$, g_5. Here it is assumed that g_{I1}, $\cdots$, g_{In} are n elements among g_1, g_2, $\cdots$, g_5. The mobile users who are willing to use g_{I1}th, $\cdots$, g_{In}th grade DRM service are shared by both SPs, while the other DRM service users would purchase the digital goods from SP II. The payoff of both SPs are

$$B_I = \frac{1}{2}\sum_{i=1}^{n}(P_{g_{Ii}} - C_{g_{Ii}})(F(\theta^*_{g_{Ii}+1}) - F(\theta^*_{g_{Ii}})), \tag{4.26}$$

$$B_{II} = \Sigma^5_{g=1}(P_g - C_g)(F(\theta^*_{g+1}) - F(\theta^*_g)) - B_I. \tag{4.27}$$

Then the following proposition can be achieved:

Proposition 4.7. *The differentiated DRM service with five grades is a dominant strategy when two SPs compete with each other through cooperative games.*

Proof. Comparing the Eq. (4.24) and Eq. (4.25), we can verify that $B_I < B_{II}$, it show that differentiated DRM service has an advantage over the single grade DRM service. Through Eq. (4.26) and Eq. (4.27), it is obvious that $B_I \leq \frac{1}{2}\Sigma_{g=1}^{5}(P_g - C_g)(F(\theta_{g+1}^*) - F(\theta_g^*)) \leq B_{II}$, then we conclude that differentiated DRM service with less grades will makes the SP earn less. $\square$

The above case only models and analyzes the competition between two SPs, next we will discuss the competition among multiple SPs. As the extension of the case with two SPs, we can achieve the following proposition:

Proposition 4.8. *The differentiated DRM service with five grades is a dominant strategy when multiple SPs compete with each other through cooperative games.*

Proof. Supposing that there are N SPs compete with each other. The first $N-1$ SPs adopt the DRM service with either single grade or multiple grades, and the DRM service adopted by the kth SP is the service with n_k grades $g_1^k, \cdots, g_{n_k}^k$, and the Nth SP adopts the differentiated DRM service with five grades $g_1, g_2, \cdots, g_5$. Here it is assumed that $g_1^k, \cdots, g_{n_k}^k$ are n_k elements among $g_1, g_2, \cdots, g_5$, that is, $\{g_1^k, \cdots, g_{n_k}^k\} \subseteq \{g_1, g_2, \cdots, g_5\}$. Before we discuss the competition among multiple SPs, we first define a flag matrix to tag those DRM grades adopted by the SPs. The flag matrix of the kth SP is defined as follows:

$$FLAG(k) = \begin{pmatrix} f(g_1) \\ f(g_2) \\ f(g_3) \\ f(g_4) \\ f(g_5) \end{pmatrix}. \tag{4.28}$$

Here $f(g_i)$ (i=1, 2, 3, 4, 5) is

$$f(g_i) = \begin{cases} 1, & g_i \in \{g_1^k, \cdots, g_{n_k}^k\}; \\ 0, & \text{otherwise.} \end{cases} \tag{4.29}$$

Through the flag matrix, we can calculate the quantity of the SPs adopting a certain grade as follows:

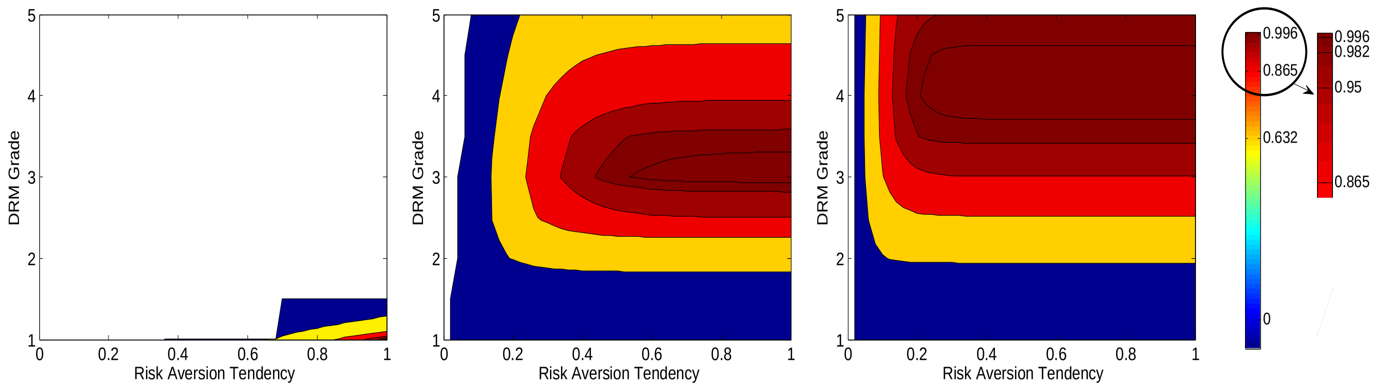
$$\begin{pmatrix} Q_1 \\ Q_2 \\ Q_3 \\ Q_4 \\ Q_5 \end{pmatrix} = \sum_{k=1}^{N} FLAG(k), \tag{4.30}$$

where Q_i (i=1, 2, 3, 4, 5) is the quantity of the SPs who adopt the DRM service with the ith grade. With Eq. (4.17), the payoff of the kth SP can be calculated as:

$$B_k = FLAG(k)^T \begin{pmatrix} (P_1 - C_1)(F(\theta_2^*) - F(\theta_1^*))/Q_1 \\ (P_2 - C_2)(F(\theta_3^*) - F(\theta_2^*))/Q_2 \\ (P_3 - C_3)(F(\theta_4^*) - F(\theta_3^*))/Q_3 \\ (P_4 - C_4)(F(\theta_5^*) - F(\theta_4^*))/Q_4 \\ (P_5 - C_5)(1 - F(\theta_5^*))/Q_5 \end{pmatrix}. \tag{4.31}$$

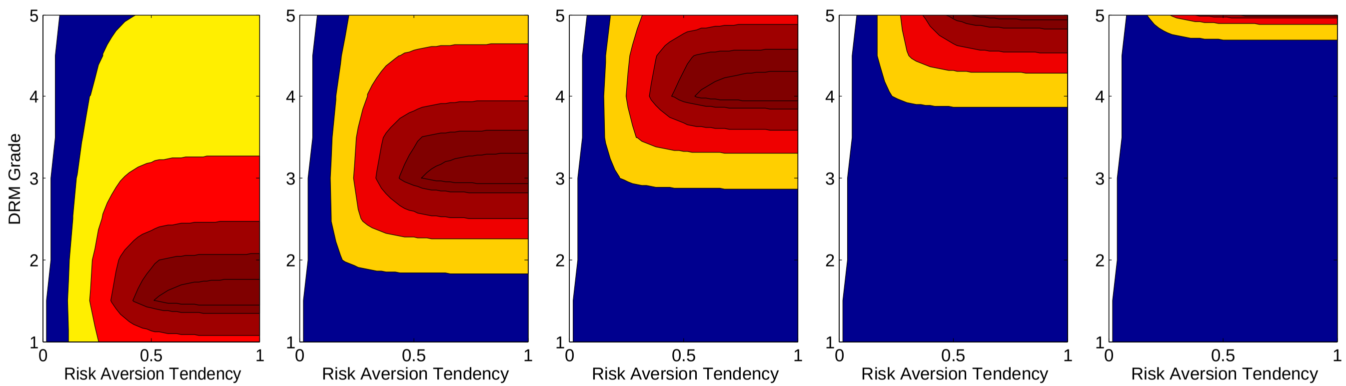
It is obvious that $B_N \geq B_k$ $(1 \leq k \leq N-1)$ since $FLAG(N)^T = (1 \quad 1 \quad 1 \quad 1 \quad 1)$. □

4.5 Performance Analysis



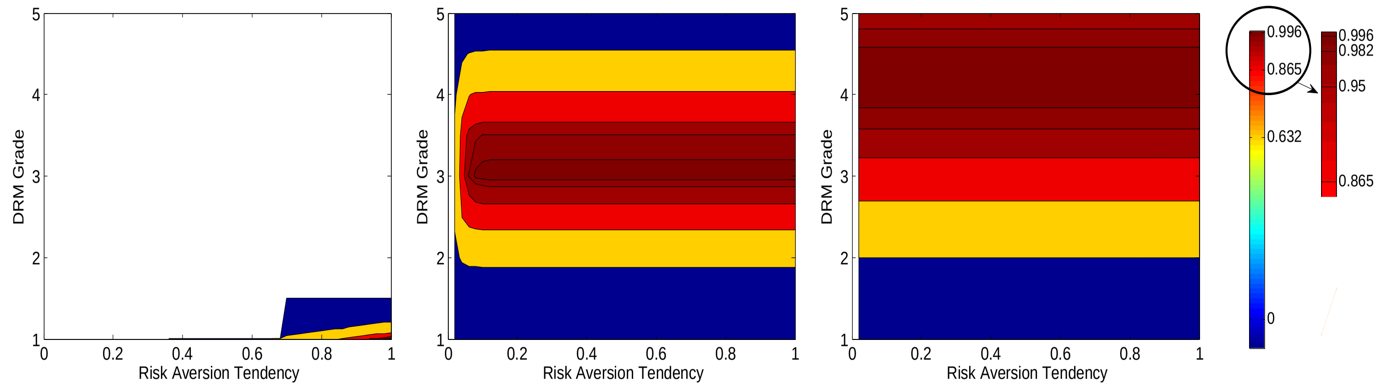
(a) Low Basic Utility (b) Medium Basic Utility (c) High Basic Utility (d) Colorbar

Figure 4.3: The utility of mobile users with $P_1 = 1$, $\beta = 0.4$, the basic utility of the digital goods D are 2, 10 and 25 for these three case, while the demanded grade d are 1, 2 and 2.



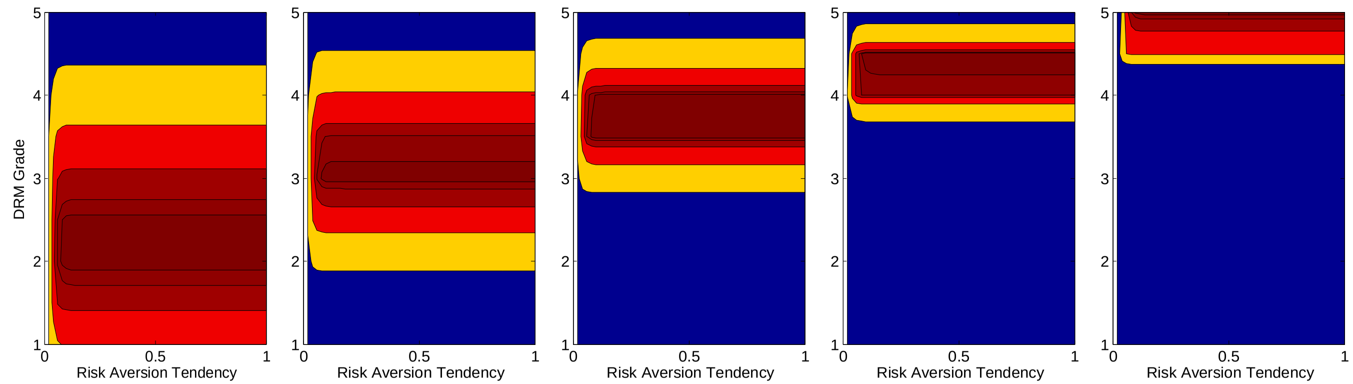
(a) Grade 1 (b) Grade 2 (c) Grade 3 (d) Grade 4 (e) Grade 5

Figure 4.4: The utility of mobile users with $P_1 = 1$, $\beta = 0.4$, the basic utility of the digital goods D is 10, while the demanded grade are 1, 2, 3, 4 and 5 respectively.



(a) Low Basic Utility (b) Medium Basic Utility (c) High Basic Utility (d) Colorbar

Figure 4.5: The utility of mobile users with $P_1 = 1$, $\beta = 0.4$, the basic utility of the digital goods D are 2, 70 and 600 for these three case, while the demanded grade d are 1, 2 and 2.



(a) Grade 1 (b) Grade 2 (c) Grade 3 (d) Grade 4 (e) Grade 5

Figure 4.6: The utility of mobile users with $P_1 = 1$, $\beta = 0.4$, the basic utility of the digital goods D is 70, while the demanded grade are 1, 2, 3, 4 and 5 respectively.

In this section, we will analyze the performance of the differentiated DRM service, which is mainly a question about the payoff of the mobile users and the SPs.

4.5.1 The Utility of Mobile Users

We first consider the utility of mobile users under linear pricing $P_g = gP_1$. We assume the price at the first grade is $P_1 = 1$, in dollars, since the price of most mobile software application are 0.99\$. Let the coefficient of the linear combination be $\beta = 0.4$. Then we calculate the utility of the mobile users based on three types of basic utility D: low, medium and high (Fig. 4.3). To illustrate the change of the utility clearly, we normalize the utility and leverage the colorbar in Fig.4.3(d) to express the users' utility. The blue regions show the user's utility is negative. Otherwise, the utility is positive and the maximum is in the red regions.

1) Fig. 4.3(a) is a contour graph to illustrate the utility of mobile users when they purchase the digital goods with low basic utility ($D = 2$). We also assume that the demanded grade of these mobile users is grade 1. The figure shows the utility of mobile users whose risk aversion tendency is more than $\theta_1^* = 0.37$. For these mobile users, their utility is positive, since they purchased the digital goods with the first grade DRM service. The utility is negative at higher grades ($g \geq 2$) and they would not adopt the digital goods with higher grade DRM service. Therefore, the digital goods with low basic utility can only attract small amounts of mobile users whose risk aversion tendency is $\theta \geq \theta_1^*$, and such kinds of digital goods are not suitable to be integrated with DRM service.

2) For the mobile user who purchases the digital goods with medium basic utility (i.e. the demanded grade is 2), the utility of the digital goods is shown in Fig. 4.3(b)

which is also a contour graph. While purchasing the digital goods with grade 1 DRM service, grade 1 is predicted to be unable to satisfy the user's demanded DRM service since the mobile user's utility is less than 0. There will be a surplus when mobile users buy the digital goods at the second grade and above. The figure also reveals that the mobile user whose risk aversion tendency is more than 0.2 ($\theta > 0.2$) will get maximum utility through purchasing the digital goods with the third grade DRM service, and the mobile users whose risk aversion tendency is less than 0.2 gain the negative utility at all five DRM grades. Such results mean that the users whose risk aversion tendency is more than 0.2 will not adopt the forth and fifth grade DRM services, and dividing the DRM service into three grades will be enough for the digital goods with medium basic utility.

3) In Fig. 4.3(c), the digital goods have high basic utility ($D = 25$) and the demanded grade is 2. Similar to the case with medium utility, the digital good with first grade DRM service brings the mobile user a subtractive utility because of the demanded grade. When the mobile user opts for the digital goods with the DRM service at grade 2 or above, the users will obtain positive benefit. For the users whose risk aversion tendency is more than 0.02, they are able to maximize the utility using the digital goods with the forth grade DRM services. Therefore, the DRM service with four grades may be enough for such digital goods.

4) Fig. 4.4(a)-Fig. 4.4(e) show the users' utility based on the medium basic utility ($D = 10$) as the demanded grade changes. It can be found that the DRM grade which offers the user maximal utility is higher as the demanded grade increases. For example, the peak value is at the second DRM grade when the demanded grade is 1, while the maximum is at the third grade when the demanded grade is 2. Otherwise, the range of

available DRM grade is smaller as the demanded grade increases.

We also consider the utility of the mobile users under nonlinear pricing $P_g = e^{g-1}P_1$ (Fig. 4.5). Similar to linear pricing, we still assume that the price at the 1st grade is $P_1 = 1$, and consider the utility of users with low, medium and high basic utility with the coefficient of the linear combination $\beta = 0.2$. We leverage the same colorbar to illustrate the change of the users' utility (Fig. 4.5(d)).

1) The results shown in Fig. 4.5(a) are similar to those in Fig. 4.3(a), only the users with large risk aversion tendency (more than 0.37) would use the DRM service. However, they have only one option, the first grade DRM service.

2) Fig. 4.5(b) illustrates the utility of the users when they purchase the digital goods with basic utility $D = 70$ and the demanded grade is 2. From the figure, it is easy to see that the digital goods at the 1st DRM grade cannot meet mobile users' requirements since the utility is negative. Mobile users acquire positive utility as they purchase the digital goods at DRM grades above 1, and most of the users will maximize their utility using the digital goods at the 3rd grade. It seems that three DRM grades are enough for this digital good and the SP need not develop 4th and 5th grade DRM services.

3) In Fig. 4.5(c), the contour graph expresses the utility of the mobile users with the basic utility $D = 800$ and demanded grade $\Lambda = 2$. It reveals the users will obtain more as they choose the forth grade DRM service.

4) Fig. 4.6(a)-Fig. 4.6(e) illustrate the DRM grade which offers the user maximal utility becomes higher as the demanded grade increases. What's more, the available DRM grade is less as the demanded grade increases, that is, the available DRM grades are the first to the forth DRM grade as the demanded grade is 1, while the available

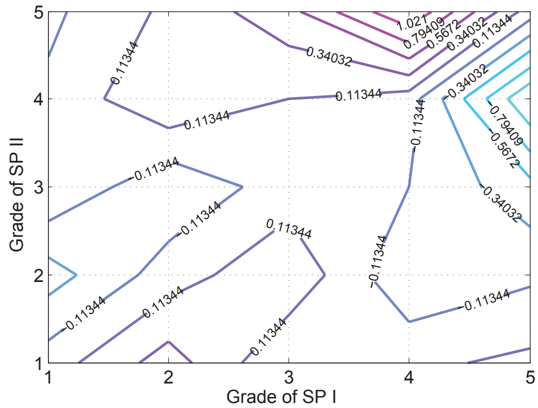


Figure 4.7: The Benefit of both SSPs under $P_1 = 1$, $C_1 = 0.5$, $\beta = 0.25$ and $\Lambda = 2$.

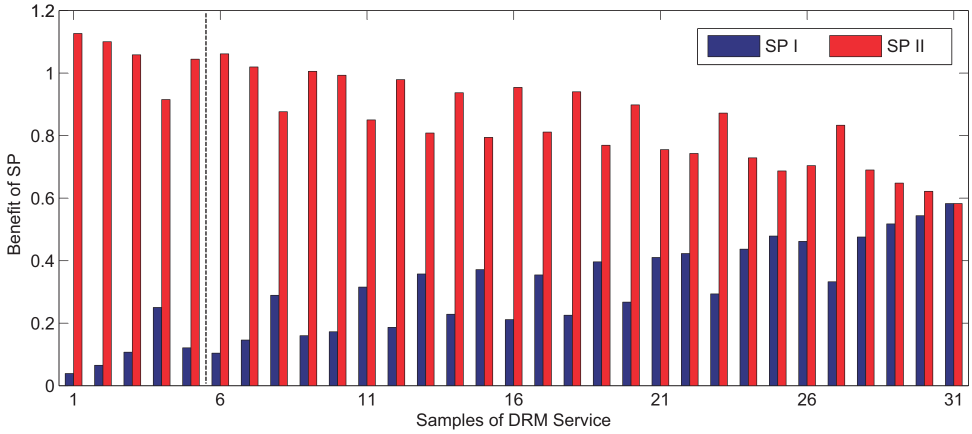


Figure 4.8: The Benefit of both SSPs with $P_1 = 1$, $C_1 = 0.5$, $\beta = 0.25$ and $\Lambda = 2$ as SP *II* is the DSP with five grades DRM service.

grades become the fifth grade with the demanded grade being the fifth DRM grade.

4.5.2 The Benefit of SPs

Next we analyze the payoff of the SPs when two SPs compete with each other through cooperate games. As mentioned, there are three types of competition: (1) SSP *vs* SSP; (2) SSP *vs* DSP; (3) DSP *vs* DSP.

For the model with linear pricing, let the price and cost at the first grade be $P_1 = 1$ and $C_1 = 0.5$, in dollars. The coefficient of the linear combination and demanded grade

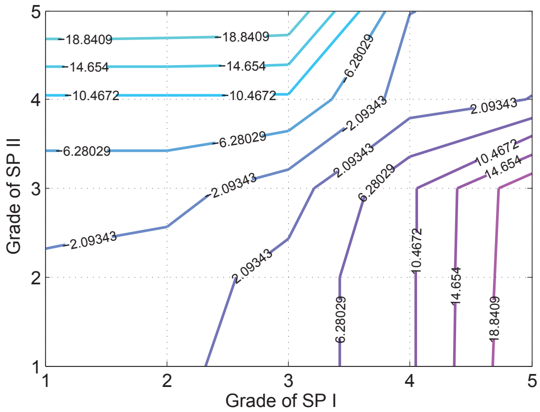


Figure 4.9: The Benefit of both SSPs under $P_1 = 1$, $C_1 = 0.5$, $\beta = 0.2$ and $\Lambda = 2$.

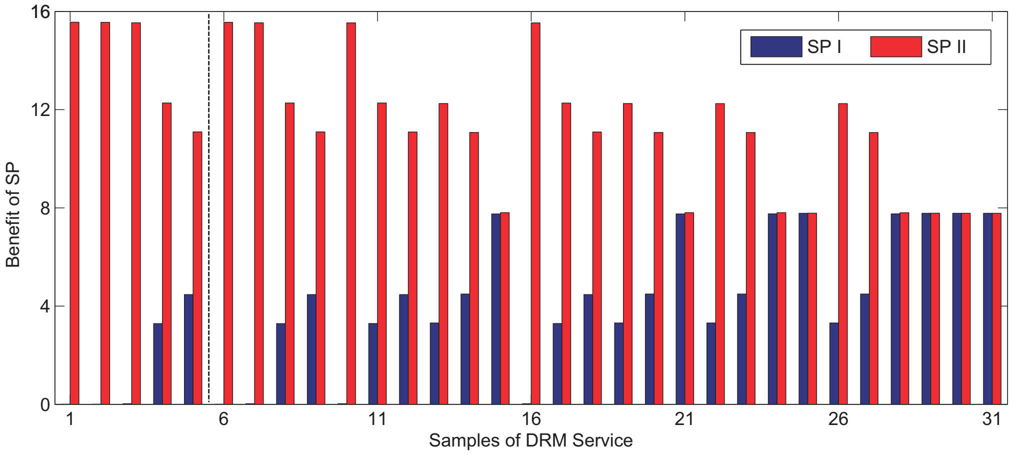


Figure 4.10: The Benefit of both SSPs with $P_1 = 1$, $C_1 = 0.5$, $\beta = 0.25$ and $\Lambda = 2$ as SP II is the DSP with five grades DRM service.

are $\beta = 0.25$ and $\Lambda = 2$. We also assume that the risk aversion tendency of mobile users satisfies the β-distribution $F(x, 1, 5)$. Based on such conditions, we calculate the benefit of both SPs (B_I and B_{II}) through Eq. (4.22) and Eq. (4.23). For the sake of describing the differences between these two SPs, we take the divergence between the benefit of both SPs ($B_I - B_{II}$), to generate a contour graph as shown in Fig. 4.7. From that figure, it is clear that no single grade DRM strategy has an absolute advantage to make one SP maximize its benefit no matter which grade the other chooses. If one of the SPs (say, SP II) changes its strategy to adopt a differentiated DRM service with five grades, and the other SP (SP I) remains the single grade DRM service, the benefit of both SPs will change greatly. Through the equilibrium risk aversion tendency and corresponding CDF (Table 4.1), the benefit of both SPs could be calculated by Eq. (4.24) and Eq. (4.25). The results are shown on the left side of the dotted line (No.1-No.5 samples in Fig. 4.8). It is obvious that the benefit of SP II (DSP) outweighs that of SP I (SSP) greatly. In order to pursue a high profit, SP I with single grade DRM service will introduce more DRM grades in its own DRM service system, and become a DSP. All the possible differentiated DRM services (No.6-No.31 samples in Fig. 4.8) developed by SP I are listed, and compete with SP II through a cooperative game. The benefit of both SPs is shown on the right side of the dotted line in Fig. 4.8, it is obvious that the benefit of SP II is larger than that of SP I, and both SPs gain the same benefit when the five grades of DRM service are selected. Therefore, adopting the differentiated DRM service with five grades is a dominant strategy for the competition between both SPs through a cooperative game.

g	1	2	3	4	5
θ_g^*	0.0494	0.0910	0.1329	0.1907	0.3729
$F(\theta_g^*)$	0.2238	0.3794	0.5098	0.6528	0.9030

Table 4.1: The equilibrium risk aversion tendency and corresponding CDF.

Then we consider the case under nonlinear pricing. We still assume that $P_1 = 1$, $C_1 = 0.5$, and coefficient of the linear combination and demanded grade are $\beta = 0.2$ and $\lambda = 2$. The CDF of the risk aversion tendency is still $F(x, 1, 5)$. Similar to the linear

g	1	2	3	4	5
θ_g^*	0.0001	0.0004	0.0011	0.0036	0.2002
$F(\theta_g^*)$	0.0005	0.0020	0.0055	0.0179	0.6727

Table 4.2: The equilibrium risk aversion tendency and corresponding CDF.

pricing model, we show the difference of the payoff between SP I and II in Fig. 4.9. The figure reveals that if SP I adopts the 5th grade DRM service, it earns more than SP II no matter how SP II deploys any single grade DRM service. As a result, grade 5 DRM service is superior to the other single grade DRM services. If SP II become a DSP with five grades of DRM service (No.1-No.5 samples in Fig. 4.10), the superiority of the SP I disappears. We calculate the payoff of SP I and II based on the equilibrium risk aversion tendency θ_g^* and CDF $F(\theta_g^*)$ in Table 4.2, and conclude that SP II (DSP) gains more than SP I (SSP). If SP I also develops differentiated DRM services (No.6-No.31 samples in Fig. 4.10), SP II gains more than SP I for most cases except No.15, No.21, No.24, No.25, No.28, No.29, No.30 and No.31. This is because these samples include the 4th and 5th grade DRM services. These two grades of DRM services have covered nearly all the mobile users ($1 - F(\theta_4^*) = 98.21\%$). When the SP I develops DRM service with the forth and fifth grade, both SPs have nearly equal benefit.

4.6 Discussion

In this paper, we divide our DRM service into five grades on the cloud platform. A direct question could be raised accordingly: "Are five grades enough to satisfy the mobile users' requirements?" Our strategy is made due to the following reason. As stated above, we leverage the exponential utility function, using a classical risk aversion model, to express the loss ratio in the differentiated DRM service, that is, $L_g = e^{-g}$. Thus, the loss ratio of each grade in the differentiated DRM system with five grades can be easily calculated, which is given in Table 4.3.

We further validate our model through the real world data about mobile security.

Grade	1	2	3	4	5
Loss Ratio	36.79%	13.53%	4.98%	1.83%	0.67%

Table 4.3: The loss ratio of each grade in the differentiated DRM system with 5 grades.

In [64], the detection rates of ten popular antivirus products are evaluated. It shows that the minimum detection rate of these ten popular antivirus products is around 65%, which means the probability for the users to lose the utility due to security risks is $1 - 65\% = 35\%$. It approaches to the loss ratio of the first grade in our differentiated DRM service in Table 4.3 (36.79%). Moreover, according to the real-world test from the AV-Comparatives [2], the highest detection rate of the current antivirus products in the fixed platforms (e.g., desktop PCs) could reach over 99.5%, i.e., their security loss ratio is $1 - 99.5\% = 0.5\%$. Due to the limited capacity of hardware and software, mobile devices (e.g., smartphones and tablets) can hardly have their mobile security as safe as that of the fixed platforms [65]. Interestingly, the loss ratio of the fifth grade (0.67%) in our model is still consistent with the real world data. Though our differentiated DRM model only shows an approximate estimation of the security loss when the mobile users access the digital goods from the cloud and mobile platforms, it can shed some light on designing and implementing practical differentiated DRM services in the real world.

4.7 Summary

In this chapter, a differentiated DRM service is proposed to satisfy mobile users' diversified requirements. This service can control and manage the digital goods between the cloud and mobile devices with varied security requirements for different purposes. Differentiated DRM services not only guarantee the security of the digital goods, but also the mobile platform. The proposed differentiated DRM services can provide choices to the users who can decide on their preferred grades for a given digital good to increase their utility more than the DRM service with a single grade. We also consider the benefit of SPs, and find that the differentiated DRM service with five grades can bring more payoff to the SPs. It is also a dominant strategy when the SPs compete with others through a cooperative game. Numerical experiments are conducted to demonstrate the effectiveness of our differentiated DRM service. In general, the differentiated DRM service achieves a win-win outcome between the cloud and mobile users.

Chapter 5

Economizing Mobile Cloud Service Cost via Cloudlet Group

In this chapter, we propose *community clinic*, which embeds the cloudlet group between the cloud and mobile users, as a better solution to cut down the cost introduced by the massive deployment of cloud's data centers and save the battery power consumed by the mobile devices. The organization of this chapter is as follows. Section 5.1 is the overview of this work. Section 5.2 describes the system model of *community clinic*. Section 5.3 presents two types of supply model. Section 5.4 proposes the real-time group-buying auction. Section 5.5 shows the performance analysis, and finally Section 5.6 summarizes this chapter.

5.1 Overview

In recent years, mobile devices such as smart phones and tablets have made the information at fingertips whenever and wherever. However, the mobile services provided are greatly degraded by the available resources, including storage and battery power, of the mobile devices. Fortunately, the cloud computing paradigm has fundamentally changed the resource-insufficient situation of mobile devices because the resource-demanding tasks can be offloaded from the mobile devices to the cloud, which provides a tremendous amount of resources and services to the mobile users directly through Internet (Figure 5.1), and thus expedited the explosive growth of mobile data traffic. According to the prediction of Cisco [24], by 2018 the mobile data traffic will surpass 15 exabytes per month, a 11-fold growth from 2013. This will bring a huge burden on the cloud provider since the service demands from mobile users can easily exceed the capacity of current cloud infrastructure due to the following two bottlenecks, last mile connections to the cloud and legacy backhauls to macrocells' base staions [72]. The bandwidth of the last mile connections to the cloud is a major obstacle for providing effective cloud services, which both limits the number of users to access the cloud and increases the access delay. The upgrading of backhauls to cellular networks is lagged far behind the deployment of cellular networks themselves, e.g., 4G networks can achieve maximal data rates at 100∼1000Mbps while their backhuals can support the bandwidth at only 3∼8Mbps (with 2 to 4 T1/E1 lines). However, solutions of either building up massive data centers to increase the bandwidth of the last mile connections to the cloud or enlarging the scale of backhauls to the macrocells will incur a remarkable deployment cost for the cloud provider, which is inevitably borne by all mobile users.

Another critical cost that dominates a mobile user's attitude toward the mobile cloud services is directly related to data rate the mobile user can experience. As the explosive growth of mobile service demands will unfavorably have each mobile user suffer a lower per-service data rate, the mobile user has to spend a longer time in transmitting and receiving the data, consequently causing her mobile device to have a higher battery

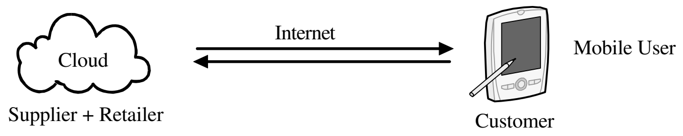


Figure 5.1: The bipartite model with cloud and mobile users.

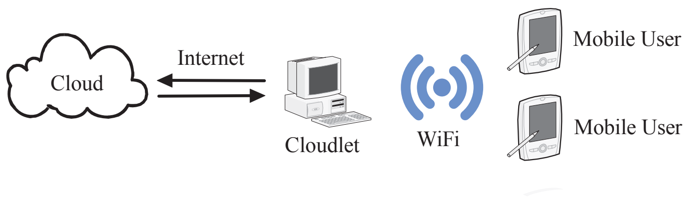


Figure 5.2: The model with cloud, cloudlet and mobile users.

power consumption. As a consequence, a mobile user will prefer to access the mobile cloud services via a wireless network that provides high per-service data rate connections, which can minimize the energy consumption of her mobile device.

Recently, M. Satyanarayanan proposed the cloudlet-based mobile computing model [78] in which the cloudlet is a credible resource-rich computer (or computer cluster) with well-connected Internet, which aims to provide services for proximate mobile users (Figure 5.2). As the cloudlet is close to the mobile devices, which enables a high speed transmission between them, it can serve the mobile users effectively by firstly downloading the contents from the cloud to the cloudlet and then distributing them to the mobile users. Obviously, using the cloudlet is a better solution to overcome the above issues. However, it will raise the following concerns from the viewpoints of the cloud, the cloudlet and the mobile user:

1) *The cloud concerns about the reallocation of the profit*: As a separate entity that serves for the mobile users, the cloudlet should be driven by certain incentives. However, it should not increase the spending of the mobile users; otherwise, the users would unlikely

choose the services provided by the cloudlet. Under this condition, will the cloudlet take away some profit from the cloud when it partakes in serving the mobile users, which sacrifices the cloud's profit if all the services should be originally served by the cloud?

2) *The cloudlet intends to attract more mobile users to use its services*: The cloudlet can get payoff by lessening the burden of the cloud for serving the mobile users. As the mobile users are rational, how can the cloudlet motivate the mobile users to choose its services? Obviously, a most effective way to attract as many mobile users as possible to use the cloudlet's services is to cut down the service price provided by the cloudlet. Then, how can the cloudlet cut down the service price even when the mobile users grow explosively?

3) *The mobile users concern about the energy consumption of the services*: Since leveraging the cloudlet to transmit and receive the data instead of accessing the cloud directly changes the data flow path, will this change introduce more energy consumption to the mobile devices in the process of data transmission and reception? As any change that may cause the mobile devices to consume more energy would likely be abandoned by the mobile users, how can the cloudlet assist the mobile devices to consume less energy?

To address these concerns, we propose a novel solution called as *community clinic* in this chapter, which embeds a *cloudlet group* component between the cloud and the mobile users. The relationship among the cloud, cloudlet group and the mobile users is analogical to that among the central hospital, community clinic and the patients. The community clinics provide convenient medical treatments for the regional patients at a lower price, which lessens the burden of the central hospitals effectively. To easily describe our scheme, we choose the videos as the examples of digital goods because the mobile videos, which take about 53% of the mobile traffic in 2013, exceeds the total mobile traffic in 2012 [24]. Such mobile videos are paid by the end users directly by purchasing data access services or indirectly by viewing advertisements. We leverage the community clinic scheme to resolve all the above concerns with its unique economics and technic characteristics:

1) We evaluate the profit of the cloud by modeling the whole system as a tripartite supply chain where the cloud plays as the supplier, the cloudlet group plays as the retailer, and the mobile users play as the consumer. We prove that, without putting extra cost on the mobile users, the cloudlet group is capable of raising the profit for the cloud through satisfying more demands of mobile users, comparing with the bipartite supply chain model where the cloud plays the dual roles as both supplier and retailer, and the mobile user plays as the consumer. The cloudlet group will make the cloud provider save the cost for deploying massive data centers, which is the premise for lowering the price of any cloud service.

2) We introduce the real-time group-buying auction mechanism to greatly reduce the price of the digital goods so as to attract more mobile users to choose the services provided by the cloudlet group instead of the cloud. Based on the group-buying auction, the more users bid for the digital goods, the lower price they get. Interestingly, lowering down the price will not sacrifice the profit of the cloudlet group; on the contrary, it will maximize the expected profit of the cloudlet group. The members of the cloudlet group will cooperate with each other to maximize their benefits. We also analyze the expected profit of the cloudlet group and the rationality of the group-buying auction in our system.

3) We build a theoretical model to analyze the energy saving of mobile devices due

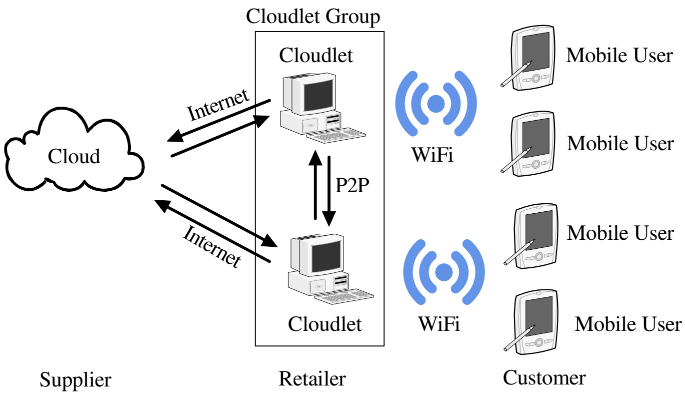


Figure 5.3: The tripartite model with cloud, cloudlet group and mobile users.

to the use of the cloudlet group. We demonstrate that the mobile devices can effectively cut down the energy consumption with the service of the cloudlet group.

5.2 System Model

For the sake of lessening the burden of the cloud to distribute digital goods, we propose a new system model that introduces the cloudlet group component between the cloud and mobile users (Figure 5.3). To compare the difference between the system with and without the cloudlet group, we denote the system model with the cloud and mobile users as the bipartite model (Figure 5.1), and that with the cloud, the cloudlet group and mobile users as the tripartite model (Figure 5.3). We describe the system components of the two models and analyze their energy consumptions.

5.2.1 Bipartite Model

The bipartite model is composed of the cloud and mobile users which are described as following:

- *Cloud*: The cloud is an entity with abundant digital goods. The access to a digital good is controlled by its digital right license. When a mobile user wants to view a digital good, she has to purchase the corresponding digital right license before she can access the digital goods;

- *Mobile users*: Mobile users are the consumers of digital goods. They must own the digital right licenses before they can access the digital goods; otherwise, they could not view the corresponding digital goods.

The procedure that a mobile user purchases a digital good from the cloud directly is composed of two rounds, one is the purchasing round in which the mobile user searches the resources on the cloud, chooses the interested digital goods, and pays the cloud for the digital goods; the other is the downloading round, in which the mobile user downloads the digital goods and corresponding digital right license from the cloud at the same time.

We further analyze the energy consumption of the mobile device in the process of acquiring the digital goods under the bipartite model. In this model, we assume that purchasing the digital goods requires I_C instructions from the cloud, and the mobile device can process M instructions per second. Then it will take $\frac{I_C}{M}$ seconds for the purchasing round. We further assume that the available bandwidth of the mobile device when it connects to the cloud is B_C[1] bytes per second. It takes $\frac{D}{B_C}$ seconds to download D bytes of digital goods from the cloud. The total amount of the energy to acquire the digital goods from the cloud, E_C, is:

[1] All the variables about bandwidth and cost in this chapter are the average since they are capable to simplify the model and do nothing for the conclusion fundamentally.

$$E_C = P_I \frac{I_C}{M} + P_D \frac{D}{B_C}. \tag{5.1}$$

Here P_I and P_D are the power consumptions of the mobile device for processing instructions and downloading the digital goods, respectively.

5.2.2 Tripartite Model

The tripartite model introduces a new entity, cloudlet group, between the cloud and mobile users. The cloudlet group is defined as follows:

- *Cloudlet group*: A cloudlet group is comprised of a number of cloudlets which are geographically close to each other and well inter-connected in a peer-to-peer way. Each cloudlet is able to provide services to proximate mobile devices efficiently. The digital goods can be firstly pre-downloaded from the cloud to the cloudlet, and then distributed to the mobile users. The cloudlet group can further meet the diversified demands of mobile users by providing enough resources to accommodate various digital goods.

This model describes an alternative scenario that the mobile users can purchase the digital goods via the cloudlet group. The cloudlet group firstly pre-downloads the digital goods and corresponding digital right licenses from the cloud. When a mobile user wants to purchase a digital good, she can acquire the digital good and corresponding digital right license from the cloudlet group if the digital goods can be found from the cloudlet group. Otherwise, she will purchase the digital goods from the cloud directly.

Since mobile users are rational, they prefer to purchase the QoS-guaranteed digital goods with low price from the cloud or cloudlet. To motivate the mobile users to use the cloudlet group to acquire digital goods, in the tripartite model the cloudlet group offers a low price service through a group-buying auction mechanism. Within the cloudlet group, there is a cloudlet leader that manages all the members' information. This cloudlet leader is called as *auction information publisher* (AIP) as it collects all the auction information in this cloudlet group and publicizes such information to the mobile users when they want to purchase the digital goods. For a valid group-buying auction, it is initiated by a cloudlet and lasts for a given period of time, and it can be accessed by mobile users via the nearest cloudlet within the same cloudlet group. We call the cloudlet that initiates the group-buying auction as *auction sponsor* (AS) and the cloudlet that assists the mobile user to link up to the auction sponsor as *auction assistant* (AA). The process that a mobile user purchases a digital good from the cloudlet group is as follows: The mobile user first connects to the cloudlet group via the nearest available cloudlet and then visits the AIP and reviews the information about the digital goods in this cloudlet group. After the mobile user selects an interested digital goods, she will link up to the AS that owns the digital goods. After that, the mobile user can make a bid for the digital goods. If the mobile user bids the digital goods successfully, the AS will deliver the digital goods to her device. If the mobile user directly connects to the AS, she will obtain the digital goods and its digital right license directly; otherwise, if the mobile user connects to an AA, she will obtain the digital goods together with its digital right license from the AS via the AA.

Similar to the bipartite model, we could analyze the energy consumption of the mobile device in the process of group-buying auction under the tripartite model. We still use M as the mobile device's instruction processing rate. Assume that purchasing the digital goods requires I_{CG} instructions from the AS, the available bandwidth between the mobile device and AS is B_{CG} bytes per second. In order to download D bytes of digital goods from the AS, the energy consumption of the mobile device could be calculated as:

$$E_{CG} = P_I \frac{I_{CG}}{M} + P_D \frac{D}{B_{CG}}. \tag{5.2}$$

P_I and P_D are the same as those in the bipartite model.

We compare the energy consumption of the mobile device for viewing the video programs under these two models. As the energy consumed by the mobile device to process the instructions of purchasing the videos from either the cloud or AS is negligible in contrast to the energy consumed by downloading the videos, the difference of the energy consumption in the purchasing process is close to zero, that is, $P_I \frac{I_{CG}}{M} - P_I \frac{I_C}{M} \approx 0$. The ratio of the energy saving could be

$$\frac{E_C - E_{CG}}{E_C} \approx 1 - \frac{B_C}{B_{CG}}. \tag{5.3}$$

As the cloudlet group supports the mobile device with a high data rate connection, we denote g to be the bandwidth gain ratio between B_{CG} and B_C, i.e., $g = \frac{B_{CG}}{B_C}$. Then, Eq. (5.3) will be

$$\frac{E_C - E_{CG}}{E_C} \approx 1 - \frac{1}{g}. \tag{5.4}$$

Considering that the videos pre-downloaded to the cloudlet group may not always meet the mobile user's request, the ratio of energy saving should be adjusted by a hit ratio α, which denotes the probability that the videos on the cloudlet group could meet the mobile users' requests, that is, the ratio of energy saving of the cloudlet group, η_T, should be:

$$\eta_T = \alpha(1 - \frac{1}{g}). \tag{5.5}$$

From Eq. (5.5), we can see that the cloudlet group can assist the mobile device to save its energy consumption by providing high hit ratio α and bandwidth gain ratio g. In Section 5.5 we further conduct numerical experiments to demonstrate its performance improvement on energy saving.

5.3 The Supply Chain Model

In this section, we formulate the bipartite model and tripartite model as the bipartite supply chain and tripartite supply chain, respectively and analyze the profit of the cloud on these two supply chains based on the classic *Newsvendor problem model* [44]. For the bipartite supply chain, the cloud plays dual roles as both the supplier and retailer, the mobile user who purchases the digital goods plays as the customer. Different from the bipartite supply chain, in the tripartite supply chain, the cloud only plays a sole role as the supplier to provide the digital goods to the cloudlet group, and the cloudlet group acts as the retailer to sell the digital goods to the mobile users who act as the customers. We compare the profit of the cloud before and after the cloudlet group participates in the supply chain and draw the conclusion that the cloudlet group can enlarge the profit of the cloud. To simplify our supply chain model, we analyze the profit of the cloud based on the process of selling one video programm through these two supply chains.

5.3.1 Bipartite Supply Chain

Before discussing the bipartite supply chain, we briefly describe the Newsvendor problem. The Newsvendor problem is to find the optimal order quantity of newspapers for the newsvendor to maximize the expected average profit in the condition that the demand distribution and cost parameters are known. Mathematically, assuming that the order quantity of the newspapers is Q, and the uncertain demand of the newspaper is a random variable D defined by the demand distribution density function $f(D)$. If the newspapers are over-ordered, the unsold newspapers will have to be thrown away or sold as scrap papers at a very low price at the end of the day, that is, $min(Q, D)$ units are sold and $(Q-D)^+$ units are residual (Here, a^+ is defined as $max(a, 0)$). With the per-unit salvage value of residual newspapers S where the salvage value defines the residual value of unsold newspapers, the value of the salvaged newspapers is $S \cdot (Q-D)^+$. If the newspapers are not enough ordered, some customers will be disappointed at the unmet demands for the newspaper, that is, $min(Q, D)$ units are sold and $(D-Q)^+$ units are unmet. We denote G as the per-unit goodwill cost of newspapers, then the goodwill cost for all unmet newspapers is $G \cdot (D-Q)^+$. Let P and C denote the per-unit price and cost of newspapers respectively, then the profit of the newsvendor is calculated as follows:

$$\Pi(Q) = P \cdot min(Q, D) + S \cdot (Q-D)^+ - G \cdot (D-Q)^+ - CQ. \tag{5.6}$$

Generally speaking, most video programs are seasonal goods and their popularity (click-through rate) declines dramatically after the season is passed. With the reason that the sale of video programs can be controlled by selling their digital right licenses and each digital right license cannot be duplicated, the retailer must predict the demands of the video programs and order a proper quantity of digital right licenses to maximize its profit. For the bipartite supply chain model, the cloud plays as the supplier and retailer to provide the mobile video service and the mobile users play as the consumers. Based on the Newsvendor problem model, we can get the profit of the cloud. Let P denote the per-unit price of videos, S is the per-unit salvage value of residual digital right license, G is the per-unit goodwill cost for the unmet digital right license, Q_B is the quantity of the videos ordered by the cloud and D is a random variable that represents the mobile users' demand distribution for the videos. The cost for the cloud to provide the mobile video service includes two parts: one part is the expense on purchasing the digital right licenses of the video, denoted as C_L; the other part is the system cost for distributing the videos from the cloud to the mobile devices, denoted as $C_C(\mu)$ where μ is the mean of mobile users' demand. Note that the system cost is mainly spent on the deployment of system infrastructure and its operation cost such as power draw. This cost is closely related to the mobile users' demand. When the users' demand exceeds the capacity of the cloud provider, this cost will become higher as the mobile users have to spend more time on downloading the videos. Moreover, though the cloud, playing as the supplier and retailer at the same time, has unlimited quantity of digital right licenses and will leave no residual digital right licenses at the end, its service capacity is capped by its network bottleneck between the cloud and mobile users. As a result, the cloud will also suffer a goodwill loss G for per-unit unmet video and the profit of the cloud in the bipartite supply chain, $\Pi^B(Q_B)$, is

$$\Pi^B(Q_B) = P \cdot min(Q_B, D) - G \cdot (D - Q_B)^+ - (C_C(\mu) + C_L)Q_B. \tag{5.7}$$

We assume that the service capacity of the cloud is to satisfy the service orders up to $\widetilde{Q}$. If the orders are more than $\widetilde{Q}$, that is, the users' demand exceeds the capacity of the cloud, the system cost will be much higher. Thus, $C_C(\mu)$ can be denoted as a segment function with the mean of demand μ and the capacity of the cloud $\widetilde{Q}$, that is,

$$C_C(\mu) = \begin{cases} C_C & , \quad \mu \leq \widetilde{Q}; \\ C_C \cdot H(\mu/\widetilde{Q}) & , \quad \mu > \widetilde{Q}. \end{cases} \tag{5.8}$$

Here $H(\mu/\widetilde{Q})$ is the cost gain factor when the mean of mobile users' demand exceeds the capacity of the cloud. In Eq. (5.7), the profit of the cloud in the bipartite supply chain, $\Pi^B(Q_B)$, is relative to order quantity Q_B. To guarantee the QoS of the mobile users, the cloud would not accept more demand when the demand exceeds the upper bound of service capacity $\lambda_C\widetilde{Q}$. Here λ_C ($\lambda_C \geq 1$) is the tolerance factor for the service capacity of the cloud. Then we could acquire the optimal order quantity to maximize the profit of the cloud by the following proposition:

Proposition 5.1. The optimal order quantity Q_B^* and the maximum expected profit of the cloud $E\Pi^B(Q_B^*)$ should be

$$Q_B^* = min\left(F^{-1}\left(\frac{P + G - C_C(\mu) - C_L}{P + G}\right), \lambda_C\widetilde{Q}\right), \tag{5.9}$$

$$E\Pi^B(Q_B^*) = (P + G)\int_{D=0}^{Q_B^*} Df(D)dD - \mu G. \tag{5.10}$$

Here $f(D)$ and $F(D)$ are the density function and cumulative distribution function of demand D, $F^{-1}(b) = inf\{a : F(a) = b\}$, and the means of demand $\mu = \int_{D=0}^{\infty} Df(D)dD$.

Proof. We assume that

$$C_B(Q_B) = (P + G - C_C(\mu) - C_L)(D - Q_B)^+ - (C_C(\mu) + C_L)(Q_B - D)^+,$$

then,

$$\Pi^B(Q_B) = (P - C_C(\mu) - C_L)D - C_B(Q_B).$$

The first derivative of $\Pi^B(Q_B)$ is

$$\frac{d\Pi^B(Q_B)}{dQ_B} = -\frac{dC_B(Q_B)}{dQ_B}.$$

According to the properties of the cumulative distribution, the expected function of $C_B(Q_B)$, denoted as $EC_B(Q_B)$, is

$$\begin{aligned} EC_B(Q_B) &= \int_{D=0}^{\infty} C_B(Q_B)f(D)dD \\ &= (P + G - C_C(\mu) - C_L) \int_{D=Q_B}^{\infty} (D - Q_B)f(D)dD \\ &\quad +(C_C(\mu) + C_L) \int_{D=0}^{Q_B} (Q_B - D)f(D)dD. \end{aligned}$$

In order to obtain the optimal order quantity Q_B^*, we calculate the first derivative of $EC_B(Q_B)$ and set it to zero:

$$\frac{dC_B(Q_B)}{dQ_B} = (P+G)F(Q_B) - (P+G-C_C(\mu)-C_L) = 0.$$

Then, we can get:

$$Q_B^* \quad = \quad F^{-1}\left(\frac{P+G-C_C(\mu)-C_L}{P+G}\right).$$

With the upper bound of the service capacity, $\lambda_C\widetilde{Q}$,

$$Q_B^* = min\left(F^{-1}\left(\frac{P+G-C_C(\mu)-C_L}{P+G}\right), \lambda_C\widetilde{Q}\right).$$

As the second derivative of $EC_B(Q_B)$ is

$$\frac{d^2EC_B(Q_B^*)}{d(Q_B^*)^2} = (P+G)f(Q_B^*) \geq 0,$$

and the optimal order quantity Q_B^* is

$$Q_B^* = min\left(F^{-1}\left(\frac{P+G-C_C(\mu)-C_L}{P+G}\right), \lambda_C\widetilde{Q}\right),$$

then,

$$\begin{aligned} E\Pi^B(Q_B^*) \quad &= \quad EC_B(Q_B) + (P - C_C(\mu) - C_L)\int_{D=0}^{\infty} Df(D)dD \\ &= \quad (P+G)\int_{D=0}^{Q_B^*} Df(D)dD - \mu G. \end{aligned}$$

□

5.3.2 Tripartite Supply Chain

In what follows, we consider the profit of the cloud in the tripartite supply chain. As we have mentioned in Section 5.2.B, in the tripartite model, both the cloud and cloudlet group can sell the videos to the mobile users. We consider the scenario that the users' demand on a video exceeds the capacity of the cloud in which the service of the cloudlet group is critical. Let Q_T ($Q_T > \widetilde{Q}$) be the quantity units of the videos consumed by the mobile users in the tripartite supply chain model, among which the quantity units $\widetilde{Q}$, where $\widetilde{Q} < Q_T$, are directly provided by the cloud and the remaining quantity units $Q_T - \widetilde{Q}$ are provided by the cloudlet group. For the videos directly provided by the cloud, the total cost can be calculated as $(C_C + C_L)\widetilde{Q}$ since $C_C(\mu)$ equals to C_C when $Q_T < \widetilde{Q}$. For the remaining videos that are provided by the cloudlet group, they are first purchased by the cloudlet group and then sold to the mobile users. Thus, the cloudlet group needs to pre-download one unit of the video and $Q_T - \widetilde{Q}$ units of the digital right licenses from the cloud, which induce the total cost of $C_C + (Q_T - \widetilde{Q})C_L$. Besides, the cost for the cloudlet group to distribute the video from AS to each end user, $C_{CG}(\mu)$, should also be considered. By introducing the cloudlet group, the capacity to serve the mobile users in the tripartite model will be enlarged by the bandwidth gain ratio h compared to that in the bipartite model, that is, the service capacity of the tripartite model is $h\widetilde{Q}$. Then the cost for the cloudlet group to distribute a per-unit video could be expressed as:

$$C_{CG}(\mu) = \begin{cases} C_{CG} & , \quad \mu \leq h\widetilde{Q}; \\ C_{CG} \cdot H(\mu/h\widetilde{Q}) & , \quad \mu > h\widetilde{Q}. \end{cases} \tag{5.11}$$

In this chapter we only consider the scenario that the mobile users' demand does not exceed the service capacity of the cloud with the cloudlet group, that is, $C_{CG}(\mu) = C_{CG}$.

The cost for the cloudlet group to distribute the videos to all mobile users is $(Q_T - \widetilde{Q}) \cdot C_{CG}$. As we have mentioned, the cloudlet group should order a proper quantity of digital right licenses of the video from the cloud in advance so that it can sell the video to the end users. There are several reasons why the cloudlet group should do this: (1) The digital right license has its value and will not be ordered freely; (2) The cloud will offer the video to the cloudlet group with a lower wholesale price if more quantity units are ordered; (3) The residual digital right licenses could not be returned to the cloud with its original price because it will reduce the profit of the cloud. Thus, the cloudlet group must order a proper quantity of digital right licenses to maximize its profit. The unsold digital right licenses are of salvage value S which is much less than the lowest wholesale price. The cloudlet group also suffers the goodwill cost G when the order quantity cannot totally meet the mobile users' demand. With the same variables P defined in the bipartite supply chain, the profit of both the cloud and cloudlet group in the tripartite supply chain is:

$$\begin{aligned} \Pi^T(Q_T) &= P \cdot min(Q_T, D) + S \cdot (Q_T - D)^+ - G \cdot (D - Q_T)^+ \\ &\quad -(C_C + C_L)\widetilde{Q} - (C_{CG} + C_L)(Q_T - \widetilde{Q}) - C_C. \end{aligned} \tag{5.12}$$

For the tripartite supply chain model, there is also an upper bound of the service capacity $\lambda_{CG} h \widetilde{Q}$ to limit the quantity of the demand served by the cloudlet group, where λ_{CG} is the tolerance factor for the service capacity of the cloudlet group. Then we have the following proposition:

Proposition 5.2. The optimal order quantity Q_T^* and the maximum profit of both the cloud and cloudlet group, $E\Pi^T(Q_T^*)$, should be

$$Q_T^* = min\left(F^{-1}\left(\frac{P+G-C_{CG}-C_L}{P+G-S}\right), \lambda_{CG}h\widetilde{Q}\right), \tag{5.13}$$

$$E\Pi^T(Q_T^*) = (P+G-S)\int_{D=0}^{Q_T^*} Df(D)dD - \mu G + \widetilde{Q}C_{CG} - (\widetilde{Q}+1)C_C. \tag{5.14}$$

Proof. We assume that $C_T(Q_T) = (P+G-C_{CG}-C_L)(D-Q_T)^+ - (C_{CG}+C_L-S)(Q_T-D)^+$, then

$$\Pi^T(Q_T) = (P-C_{CG}-C_L)D - C_T(Q_T) - C_C,$$

The first derivative of $\Pi^T(Q_T)$ is

$$\frac{d\Pi^T(Q_T)}{dQ_T} = -\frac{dC_T(Q_T)}{dQ_T}.$$

According to the properties of the cumulative distribution, the expected function of $C_T(Q_T)$ ($EC_T(Q_T)$) is

$$\begin{aligned} EC_T(Q_T) &= \int_{D=0}^{\infty} C(Q_T)f(D)dD \\ &= (P+G-C_{CG}-C_L)\int_{D=Q_T}^{\infty}(D-Q_T)f(D)dD \\ &\quad +(C_{CG}+C_L-S)\int_{D=0}^{Q_T}(Q_T-D)f(D)dD. \end{aligned} \tag{5.15}$$

In order to obtain the optimal order quantity Q_T^*, we calculate the derivative of Eq. (5.15) and set it to zero:

$$\frac{dC_T(Q_T)}{dQ_T} = (C_{CG}+C_L-S)F(Q_T) - (P+G-C_C-C_L)(1-F(Q_T)) = 0.$$

Then, we can get:

$$Q_T^* \quad = \quad F^{-1}(\frac{P+G-C_{CG}-C_L}{P+G-S}).$$

With the upper bound of service capacity $\lambda_{CG}h\widetilde{Q}$,

$$Q_T^* = min\left(F^{-1}\left(\frac{P+G-C_{CG}-C_L}{P+G-S}\right), \lambda_{CG}h\widetilde{Q}\right).$$

As the second derivative of Eq. (5.15) is

$$\frac{d^2EC_T(Q_T^*)}{d(Q_T^*)^2} = (P+G-S)f(Q_T^*) \geq 0,$$

and the optimal order quantity Q_T^* is

$$Q_T^* = min\left(F^{-1}\left(\frac{P+G-C_{CG}-C_L}{P+G-S}\right), \lambda_{CG}h\widetilde{Q}\right),$$

Then,

$$\begin{aligned} E\Pi^T(Q_T^*) &= EC_T(Q_T) + (P - C_{CG} - C_L)\int_{D=0}^{\infty} Df(D)dD + C_C \\ &= (P+G-S)\int_{D=0}^{Q_T^*} Df(D)dD - \mu G + \widetilde{Q}C_{CG} - (\widetilde{Q}+1)C_C. \end{aligned}$$

□

Comparing the expected profit of the bipartite supply chain (Eq. (5.10)) with that of tripartite supply chain (Eq. (5.14)), we can obtain the difference between the two supply chains: $\Delta_{E\Pi} = E\Pi^T(Q_T^*) - E\Pi^B(Q_B^*) = (P+G)\int_{D=Q_B^*}^{Q_T^*} Df(D)dD - S\int_{D=0}^{Q_T^*} Df(D)dD + \widetilde{Q}C_{CG} - (\widetilde{Q}+1)C_C$. As $\Delta_{E\Pi}$ is the surplus profit of the tripartite supply chain in contrast to the bipartite supply chain, it can be shared between the cloud and cloudlet group. If the cloudlet group only takes partial surplus profit [2], i.e., $\delta\Delta_{E\Pi}$ where $0 < \delta < 1$, the cloud will also benefit from the tripartite supply chain because the expected profit of the cloud will be $E\Pi^B(Q_B^*) + (1-\delta)\Delta_{E\Pi}$, which shows that the cloud obtains more profit in the tripartite supply chain. From the discussion above, we can see that the cloudlet group could earn extra income in the tripartite supply chain, which can motivate multiple parties, e.g., home gateway providers and cloud providers, to deploy cloudlet groups.

5.4 Real-time Group-Buying Auction Model

The previous section sums up that both the cloud and cloudlet group would get more profits in the tripartite supply chain when the order quantity increases. In this section, we propose a real-time group-buying auction for the cloudlet group to promote its service to the mobile users. Based on this strategy, the more videos are sold, the lower price it is. The lower price would consequently attract more and more users to choose the service provided by the cloudlet group.

[2] Although the cloud and the cloudlet group can achieve their own benefit, they should cooperate with each other. If the cloud does not consider the benefit of the cloudlet group, it may make the cloudlet group have a negative benefit. Otherwise, if the cloudlet group only considers its own benefit, it will make the cloud's benefit in the tripartite supply chain less than that in the bipartite supply chain and the cloud would not offer the digital goods to cloudlet group. In this thesis, we calculate the profit of the cloud and the cloudlet together by Eq.(5.12), because we hope to reach a reasonable benefit distribution between the cloud and the cloudlet group.

5.4.1 Real-time Group-buying Auction

In our model, the users' demand for the digital goods is changing constantly, therefore a dynamic mechanism is needed to price the digital goods and has the cloud and cloudlet maximize their own profit. The group-buying auction [18,19] is a dynamic pricing mechanism which outperforms the fixed price mechanism in the scenario with economies of scale, because the group-buying auction can automatically set up a higher price for a product when its unit cost increases and a lower price for the same product when its unit cost decreases. It is a variant of the double auction in which the trading price is affected by both the seller's offer and the buyer's bid. The group-buying auction process has two rounds, offer round and bidding round. In the offer round, the vendor sets up a group-buying auction for a product with quantity N, price curve Q and auction period T which are open to all bidders. In the bidding round, the bidders bid the goods orderly based on their arrival times, and the auction price will change in accordance with the price curve as the number of the successful bidders increases. The auction ends when the amount of successful bidders reaches N or the auction time T expires. The successful bidders will acquire the products and the final auction price becomes the final deal price for all the bidders. However, this group-buying auction should not be directly adopted by the cloudlet group to promote its service to the mobile users due to the reason that it does not make the product available in real-time, that is, the mobile user has to wait for the end of the group-buying auction to acquire the product. Otherwise, different bidders may obtain the product with different deal prices since their bids success at different auction prices.

To deal with this issue, we design the *real-time group-buying auction* which allows

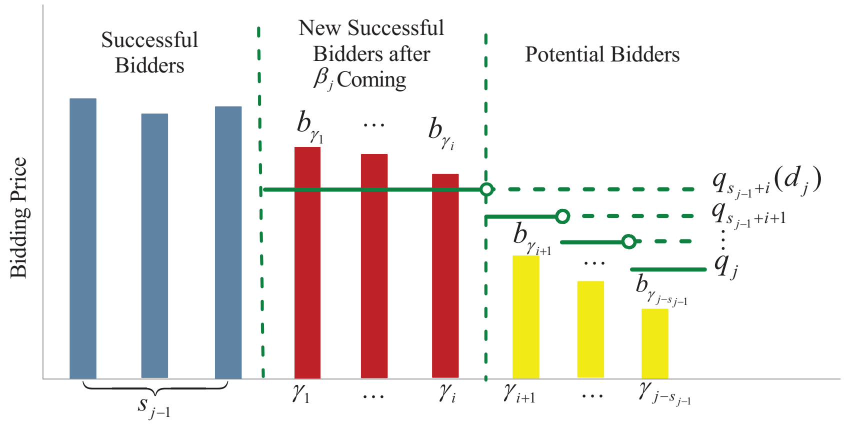


Figure 5.4: The process of real-time group-buying auction.

each successful bidder to obtain the video in real-time with identical deal price. We define the mobile users in the real-time group-buying auction as two types of bidders: *successful bidder* and *potential bidder*. If a mobile user bids a video successfully, she becomes a successful bidder. She can download the video together with its digital right license and view the video immediately. If the mobile user's bidding is unsuccessful, she has two choices: one choice is to quit the auction, another is to stay in the auction until the auction price of the video turns to be no higher than the bidding price. When the mobile user chooses to stay in the group-buying auction and waits for a lower auction price, she becomes a potential bidder. She can download the video first and acquire the corresponding digital license later when she becomes a successful bidder, for the sake that she can view the video as soon as possible. We denote that the price curve Q is $Q = (q_1, q_2, \cdots, q_N)$, where q_i $(1 \leq i \leq N)$ is the auction price for the ith copy of the video and $q_1 \geq q_2 \geq \cdots \geq q_N$. Let the jth $(j \leq N)$ mobile user be β_j, her bidding price and deal price are b_j and d_j. We denote the number of the successful bidders are s_{j-1} before the jth mobile user arrives (assuming that $s_0 = 0$). The lists of the successful bidders and the potential bidders are defined as Λ and Γ, the orders of the bidders in successful bidders list and potential bidders list are determined by the deal price and the bidding price, respectively. Then the real-time group-buying auction process can be described as follows (Figure 5.4):

1: The AS starts a group-buying auction with initial auction price q_1, quantity N and auction time T, and waits for mobile users to bid the video during the active auction time.

2: Suppose there are already s_{j-1} successful bidders in Λ and $j-1-s_{j-1}$ potential bidders in Γ. When a new mobile user β_j comes to bid the video with the bidding price b_j, the mobile user β_j will be inserted in Γ in descending order according to the bidding price b_j.

3: The AS continues comparing each potential bidder's bidding price with each auction price in the price curve starting from the last bidder $\gamma_{j-s_{j-1}}$ in Γ until it finds the first bidder γ_i whose bidding price b_{γ_i} is not less than the auction price $q_{s_{j-1}+i}$ in the price curve.

4: If such bidder γ_i exits, all the potential bidders $(\gamma_1, \gamma_2, \cdots, \gamma_i)$ become the successful bidders and are inserted into Λ according to the auction price $q_{s_{j-1}+i}$. The potential bidders list turns to be $\Gamma = (\gamma_{i+1}, \cdots, \gamma_{j-s_{j-1}})$.

5: When the auction ends, the AS refunds $d_j - d$ (d is the final deal price) to the jth successful bidder for the fair treatment.

We can see that the bidder (either a new comer or a potential bidder) will become a successful bidder once her bidding price reaches the auction price. A successful bidder can obtain the product immediately, that is, she can watch the video in real-time. Besides, the AS will refund the extra payment to all the successful bidders when the final deal price is determined, which makes all the successful bidders purchase the video at the same price. Based on the price curve Q, the more the successful bidders are, the lower the final deal price is. This strategy can effectively motivate more and more mobile users to choose the service provided by the cloudlet group.

The process of real-time group-buying auction can be illustrated more clearly by the following examples:

Example 5.1. Assume that the price curve is $Q = (9.8, 8.5, 8.1, 7.9, 7.9)$, and the AS has five pieces of license. The AS can attract five bidders to purchase the digital goods, and the bidders bid the digital goods one by one with the prices (8, 10, 9, 9, 8). All the prices here are in dollars. The detailed process of the bidding (Table 5.1) is as follows:

Table 5.1: The Process of group-buying Demo

Auction price	Bidder	Bidding price	Successful bidder list	Deal price	Potential bidder list
9.8	$\beta1$	8	$\emptyset$	-	$\beta1$
9.8	$\beta2$	10	$\beta2$	9.8	$\beta1$
8.5	$\beta3$	9	$\beta2$, $\beta3$	8.5	$\beta1$
8.1	$\beta4$	9	$\beta2$, $\beta3$, $\beta1$, $\beta4$	7.9	$\emptyset$
7.9	$\beta5$	8	$\beta2$, $\beta3$, $\beta1$, $\beta4$, $\beta5$	7.9	$\emptyset$

1. The AS starts the group-buying auction and sets the initial auction price as 9.8 based on the price curve;

2. The first bidder $\beta1$ arrives and his bidding price is $b_1 = 8$, and he becomes a potential bidder because his bidding price is less than the current auction price ($b_1 < q_1$). Then, there are no successful bidders ($s_1 = 0$ and $\Lambda = \emptyset$) but one potential bidder $\beta1$ ($\Gamma = \{\beta1\}$);

3. The second bidder $\beta 2$ comes with the bidding price $b_2 = 10$, and β_2 is inserted in Γ based on the bidding price and $\Gamma = \{\beta_2, \beta_1\}$. The second bidder is a successful bidder and the deal price of $\beta 2$ is $d_2 = 9.8$. There are one successful bidder ($s_2 = 1$, $\Lambda = \{\beta 2\}$) and one potential bidder $\beta 1$ ($\Gamma = \{\beta 1\}$);

4. The third bidder $\beta 3$ joins the auction with bidding price $b_3 = 9$. β_3 is inserted to the potential bidder list ($\Gamma = \{\beta_3, \beta_1\}$). $\beta 3$ is a successful bidder through the above algorithm, and the deal price is $d_3 = 8.5$. $\beta 2$ and $\beta 3$ are successful bidders ($\Lambda = \{\beta 2, \beta 3\}$) while $\beta 1$ is still a potential bidder ($\Gamma = \{\beta 1\}$);

5. The forth one $\beta 4$ bids with the price $b_4 = 9$, then the potential bidder list turns to be $\Gamma = \{\beta_4, \beta_1\}$. Due to the auction price $q_4 = 7.9$, both $\beta 4$ and $\beta 1$ join the group of the successful bidders, and their deal price is $d_1 = d_4 = 7.9$. The first four bidders are successful bidders ($s_4 = 4$, $\Lambda = \{\beta 2, \beta 3, \beta 1, \beta 4\}$) and there is no potential bidder ($\Gamma = \emptyset$);

6. The fifth bidder $\beta 5$ bids the digital goods with the price $b_5 = 8$, and he becomes a successful bidder and his deal price is $d_5 = 7.9$;

7. The auction closes, the AS determines the final deal price as $q_5 = 7.9$. As the deal price for $\{\beta 2, \beta 3, \beta 1, \beta 4, \beta 5\}$ are (9.8, 8.5, 7.9, 7.9, 7.9), the AS will refund the overpaid amount (1.9, 0.6, 0, 0, 0) to these five bidders respectively;

8. The group-buying auction ends.

5.4.2 The Price Curve of the Auction Sponsor

The group-buying auction can lower the price of the video and attract more mobile users to choose the cloudlet group to purchase the video. However, lowering the price of the video may reduce the profit for the AS, even though much more copies of the video may be sold in the group-buying auction. Therefore, we need to determine a proper price curve to ensure that the AS can maintain a maximum expected profit even when the price of the video is lowered in the group-buying auction.

We model the determination of the price curve as a multi-stage game between the AS and the bidders. The sequence of events is listed as follows: 1) The AS determines the video's quantity and picks a price curve; 2) The bidders offer their bidding prices for the video and become successful bidders or potential bidders; 3) The AS can achieve the optimal price curve and maximum profit when the multi-stage game reaches the equilibrium.

Now we discuss how the price curve is designed in detail. As mentioned, the price curve is denoted as a vector $Q = (q_1, q_2, \cdots, q_N)$ with $q_1 \geq q_2 \geq \cdots \geq q_N$, which is mainly determined by the cost of this video. The cost includes two parts: one part is the expense for the AS to distribute the video from the cloud, i.e., C_C; the other is the cost to sell the video from the cloudlet group to each mobile user, i.e., $C_{CG} + C_L$. The AS would evaluate the cost to distribute the video before bidding because such factors will affect the AS's profit significantly. Suppose that the cost to serve v successful bidders is c_v, that is, $c_v = (C_{CG} + C_L)v + C_C$. Then we can get $\frac{c_v}{v} - \frac{c_{v+1}}{v+1} \leq \frac{c_{v-1}}{v-1} - \frac{c_v}{v}$. This suggests that the marginal cost for each bidder is decreasing. We also assume that each bidder's bidding price is independent and drawn from a uniform distribution with the unit interval [0,1]. The AS needs to consider the scenario that, when the auction ends, there is a total of m mobile users who bid the video, among which v mobile users bid the video successfully and these v successful bidders' bidding prices are not less than the auction price q_v. When $m \geq N$, the probability of this scenario is $C_m^v q_N^{m-N} q_N!(1-q_v)^v/q_v!$, where $q_v! = q_v q_{v-1} \cdots q_1$; when $m < N$, the probability of the scenario is $C_m^v q_m!(1-q_v)^v/q_v!$. Then the expected profit for the AS is

$$E\Pi^{AS}(Q) = \begin{cases} \sum_{v=1}^{N} C_m^v q_N^{m-N} q_N!(1-q_v)^v(vq_v - c_v)/q_v! & , \quad m \geq N; \\ \sum_{v=1}^{m} C_m^v q_m!(1-q_v)^v(vq_v - c_v)/q_v! & , \quad m < N. \end{cases}$$

We maximize the expected profit for the AS $E\Pi^{AS}$, which is a nonlinear programming problem:

$$\begin{aligned} max \quad & E\Pi^{AS}(Q), \\ s.t. \quad & q_1 \geq q_2 \geq \cdots \geq q_N. \end{aligned} \tag{5.16}$$

We solve this programming problem using the Karush Kuhn Tucker (KKT) condition and get a price curve as the optimal solution [14]. The optimal solution is able to impel the multi-stage game to reach the equilibrium. Thus, we can obtain the following proposition:

Proposition 5.3. The optimal solution of the nonlinear programming problem in Eq. (5.16) reaches the unique subgame-perfect equilibrium for the real-time group-buying auction.

From the above discussion, we achieve a price curve composed of a non-increasing sequence of auction prices, which is the optimal solution for Eq. (5.16). Based on such price curve, the AS can maximize its expected payoff from the real-time group-buying auction.

Proof. The nonlinear programming problem in Eq. (5.16) is equivalent to the following nonlinear programming problem:

$$\begin{aligned} min \quad & -E\Pi^{AS}(Q), \\ s.t. \quad & q_1 \geq q_2 \geq \cdots \geq q_N. \end{aligned} \tag{5.17}$$

To illustrate above nonlinear programming meeting the KKT condition, we need to prove that $-E\Pi^{AS}(Q)$ is a convex function.

When $m < N$, we assume that

$$E\Pi_v^{AS} = -q_m!(1-q_v)^v(vq_v - c_v)/q_v!. \tag{5.18}$$

The Hessian Matrix of $E\Pi_v^{AS}$ is

$$H(E\Pi_v^{AS}) = \begin{pmatrix} \frac{\partial^2 E\Pi_v^{AS}}{\partial q_1^2} & \cdots & \frac{\partial^2 E\Pi_v^{AS}}{\partial q_1 \partial q_m} \\ \vdots & \ddots & \vdots \\ \frac{\partial^2 E\Pi_v^{AS}}{\partial q_m \partial q_1} & \cdots & \frac{\partial^2 E\Pi_v^{AS}}{\partial q_m^2} \end{pmatrix}. \tag{5.19}$$

We can verify that the leading principle minor of $H(E\Pi_v^{AS})$ is not less than 0. Therefore, $H(E\Pi_v^{AS})$ is a positive-semidefinite matrix and $E\Pi_v^{AS}$ is a convex function [14], which causes $-E\Pi^{AS}(Q)$ to be a convex function. Therefore, the nonlinear programming problem in Eq. (5.16) satisfies the KKT condition and the solution of this nonlinear programming problem reaches the unique subgame-perfect equilibrium for the real-time group-buying auction.

Similar result could be proved when $m \geq N$. □

5.4.3 Cooperation or not in the Cloudlet Group

In the group-buying auction, AS needs to distribute the video and its digital right license to the mobile users, and the AA is assumed to help the AS complete this process. If the AA is willing to assist the AS to complete the auction, such auction is called "cooperation". However, an AA may also start a new auction for the same video, causing both cloudlets (AS and AA) to have the auctions for the same video at the same time. The two cloudlets will compete with each other and none of them is willing to be the AA of its competitor, which causes both of them not to cooperate with each other. Fortunately, our group-buying auction mechanism can avoid such competition and prompt the AA to cooperate with the AS, because the cooperation can raise the expected profit for every cloudlet and mobile user.

Assume that the cloudlet group has M homogeneous cloudlets and the expected profit of this cloudlet group is $E\Pi_{CG}$, then the expected profit of every cloudlet in this cloudlet group is $\frac{E\Pi_{CG}}{M}$, which implies that each cloudlet's expected profit is only related to the expected profit of its cloudlet group. We then estimate the expected profit of the cloudlet group under the condition whether the two cloudlets cooperate or compete with each other, respectively. We denote the two cloudlets as A and B, and the quantities of videos to be sold by A and B are G_A and G_B. Without loss of generality, we assume $G_A \geq G_B$. For the cloudlet A, the price curve is $Q^A = (q_1, q_2, \cdots, q_{G_A})$, where $q_1 \geq q_2 \geq \cdots \geq q_{G_A}$; the cost for cloudlet A to sell i units is c_i $(i = 1, 2, \cdots, G_A)$. In the same way, the price curve and the cost for cloudlet B are $Q^B = (q_1, q_2, \cdots, q_{G_B})$ where $q_1 \geq q_2 \geq \cdots \geq q_{G_B}$, and c_i $(i = 1, 2, \cdots, G_B)$. Then, the following proposition can be derived:

Proposition 5.4. Given that the expected profit of the cloudlet group, under the condition whether the two cloudlets cooperate or compete with each other, are $E\Pi_{CG}^{coop}$ and $E\Pi_{CG}^{comp}$ respectively, $E\Pi_{CG}^{coop} > E\Pi_{CG}^{comp}$.

Proof. Both cloudlets A and B are homogenous, and they adopt the same price curve to maximize their own profits as they compete with each other. We combine the price curve of cloudlets A and B together to be a new vector Q' and arrange the elements of Q' in the descending order, $Q' = (q'_1, q'_2, \cdots, q'_{G_A+G_B})$. For the case that the two cloudlets cooperate with each other, we achieve the price curve $Q^* = (q^*_1, q^*_2, \cdots, q^*_{G_A+G_B})$ through solving Eq. (5.16).

When $m \geq G_A + G_B$ (m is the number of the mobile users bidding for the video), Q^* reaches the unique subgame-perfect equilibrium, then $E\Pi_{AS}(Q^*) > E\Pi_{AS}(Q')$ according to Proposition 5.3. Cloudlets A and B purchase the video from the cloud twice and the cost is more than purchasing the video once, which leads to $E\Pi_{AS}(Q') > E\Pi_{CG}^{comp}$. Therefore, $E\Pi_{CG}^{coop} = E\Pi_{AS}(Q^*) \geq E\Pi_{AS}(Q') > E\Pi_{CG}^{comp}$.

Similar result could be proved when $m < G_A + G_B$.

□

From Proposition 5.4, we can see that cooperation is the better choice for the cloudlets, and it makes the cloudlet group get more profit, which also brings more expected profit for every cloudlet. It is also noted that the price curves of cloudlets A and B are $Q^A = (q_1, q_2, \cdots, q_{G_A})$ and $Q^B = (q_1, q_2, \cdots, q_{G_B})$ when they compete with each other. With $G_A \geq G_B$, we can get $q_{G_A} \leq q_{G_B}$, that is, the final deal price of cloudlet A is less than that of cloudlet B. For the cloudlet group with the two cloudlets cooperating with each other, the price curve is $Q^* = (q^*_1, q^*_2, \cdots, q^*_{G_A+G_B})$, and the final deal price is $q^*_{G_A+G_B}$.

It is obvious that $q^*_{G_A+G_B} \leq q_{G_A} \leq q_{G_B}$, then the mobile users under the scenario that the two cloudlets cooperate with each other will get more surplus in the group-buying auction.

To be an extension of Proposition 5.4, we also consider the case that multiple cloudlets should cooperate or compete with each other. Then we acquire the following proposition:

Proposition 5.5. Given that the expected profits of the cloudlet group, under the condition whether the multiple cloudlets cooperate or compete with each other, are $E\Pi_{CG}^{Mcoop}$ and $E\Pi_{CG}^{Mcomp}$ respectively, $E\Pi_{CG}^{Mcoop} \geq E\Pi_{CG}^{Mcomp}$.

Proof. We divide all the cloudlet into m $(m \geq 2)$ sub-groups, the cloudlets in the same sub-group will cooperate with each other, and sub-groups will compete with each other. The price curves for each sub-group are $Q_1, \cdots, Q_m$. Here we also introduce a new function $Rank(x)$, which can rank all the elements of the vector x in the descending order. Based on these conditions, we are able to achieve the new price curve for the cloudlet group Q', that is, $Q' = Rank(Q_1, \cdots, Q_m)$. When all the cloudlets cooperate with each other, the price curve Q^* reaches the unique subgame-perfect equilibrium, then $E\Pi_{AS}(Q^*) \geq E\Pi_{AS}(Q')$ according to Proposition 5.3. Therefore, $E\Pi_{CG}^{Mcoop} \geq E\Pi_{CG}^{Mcomp}$. □

Therefore, all AAs are willing to cooperate with the AS and the same type of group-buying auctions should not be initiated by multiple cloudlets at the same time.

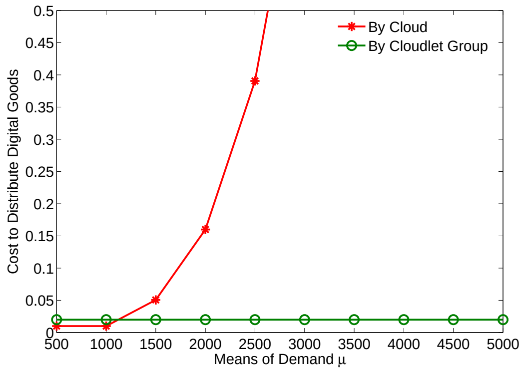


Figure 5.5: Distribution cost

5.5 Performance Analysis

In this section, we will analyze the performance of *community clinic*, which includes economics analysis and energy analysis.

5.5.1 Economics Analysis

5.5.1.1 Supply Chain

We take the cumulative distribution function of demand D to be the normal distribution [3] as an example to compare the profit of the cloud in the bipartite supply chain model and tripartite supply chain model. With $H(Q) = \int_{D=0}^{Q} Df(D)dD = \mu\Phi(x) - \sigma\phi(x)$ [91], we can evaluate the profit of the cloud easily. Here μ and σ are the mean and standard deviation of demand D, $\phi(x)$ and $\Phi(x)$ are the density function and cumulative distribution function of the standard normal distribution, and $x = \frac{Q-\mu}{\sigma}$.

[3] The cloud or the cloudlet group would serve for a certain amount of users per unit time, so the cumulative distribution function of demand D should follow the Poisson distribution. As we know, the demand is of large scale, then the normal distribution would be an excellent approximation to the Poisson distribution. Therefore, we regard the normal distribution as the cumulative distribution function of demand D here.

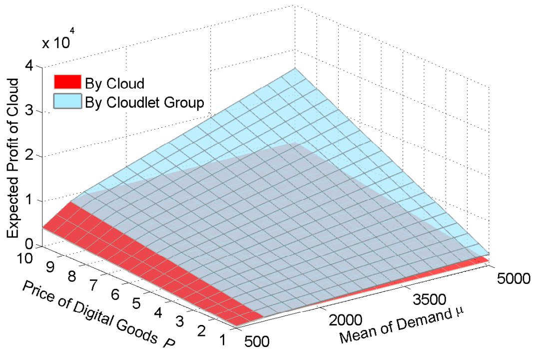
We consider an application scenario that a mobile cloud service is deployed in an airport lounge for a total coverage of $200,000m^2$ where the bandwidth of Internet access is 1Gbps. The users would obtain videos from the cloud directly. For simplicity, we assume each video file lasts for one hour with the size of about 450MB, so the data rate to the video is around $450MB/h = 128KB/s$. With 1Gbps bandwidth in the airport lounge, the cloud can support nearly 1000 (1Gbps/128KBps=1024) users simultaneously, that is, the capacity of the cloud is 1000 (i.e., $\widetilde{Q} = 1000$). In other words, the airport lounge would employ the cloud to distribute the videos up to about 1000 users (under the bipartite supply chain model). When the users' demand is more than 1000, the users would prefer purchasing the videos from the cloudlet group. Assume that the cloudlet group is comprised of 1000 cloudlets, and one cloudlet is assumed to support at most 5 users simultaneously, the capacity of this cloudlet group is 5000 mobile users ($1000 \times 5 = 5000$), that is, the cloudlet group could support the users' demand 5 times bigger than the original one. The cost to deploy and operate the cloudlet group can be estimated with the following example: The cost of the cloudlet group C_{CG} includes the CAPEX (capital expenditure) and OPEX (operational expenditure). Each cloudlet unit is implemented by a WiFi-enabled PC "Lenovo ThinkCentre M78" (retail price: 499\$; power consumption: $300W$), which connects to 10 powerful switches "Cisco WS-C4506-E" (retail price: 3000\$; power consumption: $3000W$). With 3 years' service lifetime, the CAPEX for one cloudlet per day can be estimated as $(3000 \times 10/1000 + 499)/(3 \times 365) = 0.48\$$. The OPEX for one cloudlet is mainly the power consumption (average retail price: $< 0.1\$/kWh$ [85]), considering that the cloudlets are connected with each other through the switch. Then the OPEX for one cloudlet per day is around $(300W + 3000W \times 10/1000) \times 24h \times 0.1\$/kWh = 0.72\$$ (as the work period for a cloudlet is 24 hours per day). For the cloudlet group system, each cloudlet can support n users to play videos simultaneously, where $n \in [0, 5]$. That is, each cloudlet can sell at most 5 videos per hour. If there are more than 5 users who would like to purchase the videos from the cloudlet at the same time, the cloudlet would only serve for the first five users. Suppose that the users' request X follows the Poisson distribution with mean μ, and the cloudlet can satisfy the users' request with a probability of 95%, that is,

$$\sum_{n=0}^{5} P(X=n) = \sum_{n=0}^{5} \frac{\mu^n}{n!} e^{-\mu} = 0.95. \tag{5.20}$$

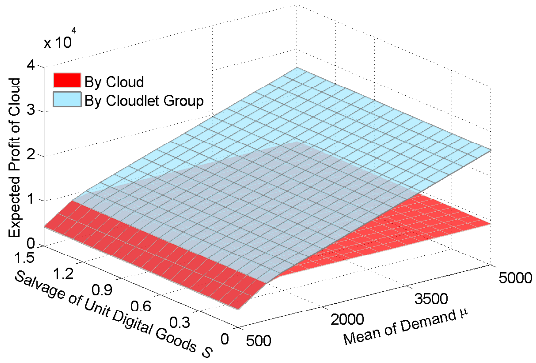
Solving Eq. (5.20), we get $\mu = 2.61$. When $n \geq 6$, the cloudlet only serves the first five requests. The average number of video copies served is $\sum_{n=0}^{5} n \frac{\lambda^n}{n!} e^{-\lambda} + \sum_{n=6}^{\infty} 5 \frac{\lambda^n}{n!} e^{-\lambda} = 2.54$. Therefore, one cloudlet can sell 2.54 videos per hour on average. The cost of the cloudlet group C_{CG} for one video is around $(0.48\$ + 0.72\$)/(2.54/h \times 24h) \approx 0.02\$$.

We conduct numerical experiments to compare the cost to distribute digital goods by the cloud directly and with the help of the cloudlet group (Fig. 5.5). According to the above cost estimation, the cost to distribute videos by the cloudlet group is $C_{CG} = 0.02$.[4] We assume $C_C = 0.01$ since the cost to distribute videos by the cloud C_C is, due to the economies of scale, lower than that by cloudlet group C_{CG}. We assume the cost gain factor follows the function $H(t) = t^4$ when the mean of demand exceeds the capacity of the cloud ($\widetilde{Q} = 1000$) and cloudlet group ($h\widetilde{Q} = 5000$). According to Eq. (5.8) and Eq. (5.11), we obtain the change of the cost to distribute unit digital goods by the cloud and cloudlet group in Fig. 5.5. The distribution cost of the cloud increases rapidly right after the users' demand exceeds the cloud's capacity (when $\mu = 1000$) and surpasses the

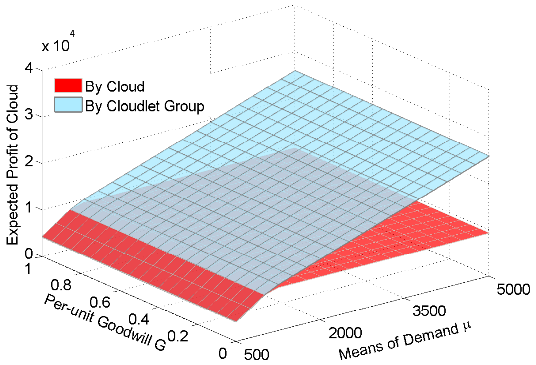
[4] All the values are represented in dollars.



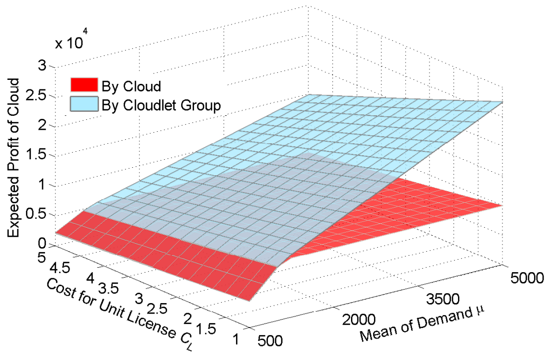
(a) Price of digital goods P



(b) Salvage S



(c) Goodwill G



(d) Expense on digital right license C_L

Figure 5.6: The Effect of parameters on the expected profit of the cloud.

cost to distribute videos via the cloudlet group (when $\mu = 1100$). The distribution cost by the cloud continuously increases when the mean of demand increases, and it is nearly 10 times larger than that with the help of the cloudlet group when $\mu = 5000$ as the distribution cost via the cloudlet group does not increase when the mean of demand is below the cloudlet group's capacity (when $\mu = 5000$).

With $C_{CG} = 0.02$ and $C_C = 0.01$, the expected profits of cloud for the two models are evaluated in Fig. 5.6 under the effects of the following parameters: price of digital goods P, salvage of unit digital goods S, per-unit goodwill G and cost for unit license C_L, respectively. The mean of demand μ ranges from 500 to 5000 and the standard deviation of demand is $\sigma = 100$. With a tolerance factor of the cloud $\eta_C = 1.1$, the cloud will stop serving more user demands when $\eta_C \widetilde{Q} = 1100$.

We firstly consider the expected profit of cloud for the two models in Fig. 5.6(a) with the change of price P from 1 to 10. Here, we set $S = 0.1P$, $G = 0.05P$ and $C_L = 0.15P$. Fig. 5.6(a) shows that the expected profits of the cloud for the two models are nearly the same when the mobile users' demand is not more than the cloud's capacity (when $\mu = 1000$). However, the cloud will earn more via the cloudlet group than by the cloud directly when the users' demand exceeds the cloud's capacity. This experiment reveals that the cloud will earn more with the help of the cloudlet group. It also shows that, when $\mu > 1100$, the expected profit of the cloud reaches the maximum value and does not increase any more via the cloud directly, because the cloud would not accept more users' requests. The profit of the cloud via the cloudlet group continuously increases when the demand does not exceed the capacity of the cloudlet group ($\mu > g\tilde{Q} = 5000$). Fig. 5.6(a) also reveals that the profit difference between the two models becomes much larger with the increase of the digital goods' price P.

Next, we illustrate the expected profit of cloud with the change of salvage S. According to Eq. (5.13), to ensure the existence of the optimal order quantity Q_T^* for the cumulative distribution of the normal distribution $F(Q_T)$, $C_{CG}+C_L$ should be larger than S. Here, we set $P = 10$, $G = 0.05P$ and $C_L = 0.15P$, and change the value of S from 0 to 1.5 to evaluate its effect on the expected profit of cloud, which is shown in Fig. 5.6(b). The maximal expected profit of the cloud is achieved when $\mu = 1100$ by the direct cloud model as the cloud would stop serving the users even though the demand is still growing.

On the other hand, the expected profit of the cloud obtained by the cloudlet group can be higher than that by the cloud directly when the users' demand exceeds the capacity of the cloud and this profit obtained via the cloudlet group continuously increases as μ increases. However, for both models, the expected profit of the cloud is insensitive to the salvage S as long as the constraint $C_{CG} + C_L > S$ is met.

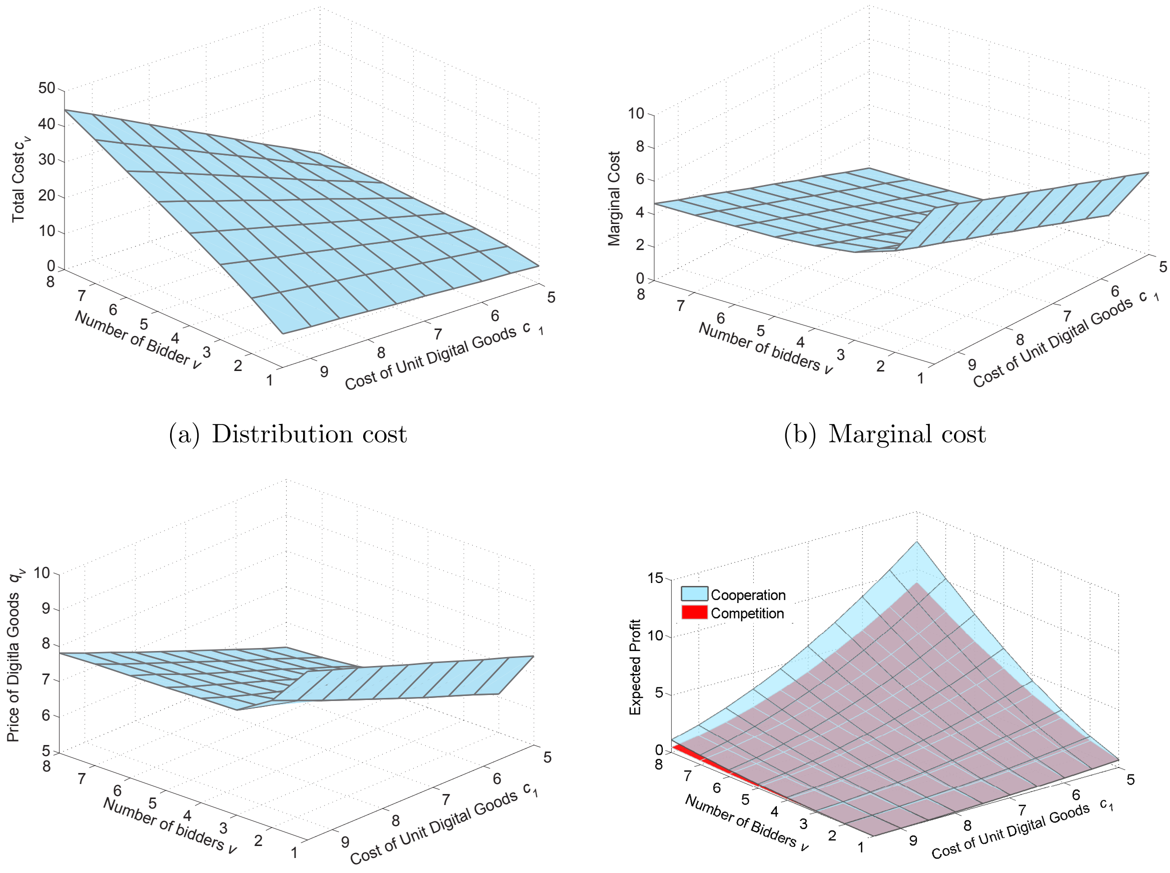
The result derived for the per-unit goodwill G is quite similar to that for the salvage S when $G \in [0.1]$, $P = 10$, $S = 0.1P$ and $C_L = 0.15P$, which is shown in Fig. 5.6(c). The increase of G slightly increases the expected profit. The cloud would achieve more profit by the cloud directly when the demand is below the capacity of the cloud. Otherwise, the cloud would achieve more profit by the cloudlet group.

At last, we show the effect of the expense on the digital right license C_L in Fig. 5.6(d) with the condition $C_L \in [1, 5]$, $P = 10$, $S = 0.1P$ and $G = 0.05P$. The expected profit of cloud by the cloudlet group is more than that by the cloud directly when the demand exceeds the capacity of the cloud. The cost for the digital right license also has an impact on the expected profit. With the increase of C_L, the expected profit decreases gradually in both the two models.

As a summary of the above experiments, we find that the cloud can achieve more profit via the cloudlet group when the users' demand surpasses the cloud's capacity.

5.5.1.2 Real-time Group-Buying Auction

From the nonlinear programming problem described in Eq. (5.16), we can see that the price curve and expected profit of AS are totally determined by the cost to serve the successful bidder. In order to satisfy the condition that the marginal cost to serve the



(a) Distribution cost

(b) Marginal cost

(c) Price curve

(d) Expected profit of AS

Figure 5.7: The effect of number of bidders and cost of unit digital goods on the real-time group-buying auction model.

successful bidder is diminishing, $\frac{c_v}{v} - \frac{c_{v+1}}{v+1} \leq \frac{c_v}{v} - \frac{c_{v-1}}{v-1}$, where $v = 1, 2, \cdots$, we set the marginal cost as $\frac{c_v}{v} - \frac{c_{v+1}}{v+1} = \frac{1}{(v+1)(v+2)}$. Here we assume $P \in (0, 10]$ and $c_1 \in [5, 9.5]$. Then, we can normalize P and c_1 with the following formulas:

$$P' = \frac{P - P_{min}}{P_{max} - P_{min}} = \frac{P}{10}, \tag{5.21}$$

$$c_1{}' = \frac{c_1 - P_{min}}{P_{max} - P_{min}} = \frac{c_1}{10}. \tag{5.22}$$

Here P_{max} and P_{min} is the maximum and minimum of the price P, respectively. P' and

${c_1}'$ satisfy Eq. (5.16) and we are able to achieve P through Eq. (5.21), that is, $P = 10P'$. Fig. 5.7(a) illustrates that the total cost grows with the increase of mobile users and the cost grows fast when c_1 is large (e.g., $c_1 = 9.5$). We also consider the marginal cost in Fig. 5.7(b). The marginal cost decreases as the number of the bidders increases, and it becomes higher when c_1 is larger. By solving the nonlinear programming problem, the price curve and expected profit of AS are shown in Fig. 5.7(c) and Fig. 5.7(d). In Fig. 5.7(c), the price curve decreases as the number of the mobile users increases. This clearly shows that the price of the video becomes lower when more mobile users bid successfully. The lower price will reduce the mobile users' cost on acquiring the digital goods, which motivates more mobile users to use the service of the cloudlet group. The value of c_1 plays a critical role in determining the price curve. The price for the first bidder is low when c_1 is small ($c_1 = 5$). Larger costs of the digital goods c_1 lead to larger prices. As c_1 approaches to 9.5, the price is nearly 10. From the AS's expected profit curve shown in Fig. 5.7(d), we can see that, the AS's expected profit grows as it serves more mobile users no matter the members of the cloudlet group cooperate or compete with each other, and therefore the cloudlet group has incentives to sell more videos to the mobile users with lower prices. However, the cooperation can bring more profit to the AS than the competition. The gap in the expected profit between the cooperation and competition becomes larger with the increase of the mobile users. For a fixed number of mobile users, the gap between the cooperation and competition becomes smaller as c_1 increases. In summary, the real-time group-buying auction could lower the price of the digital goods and increase the benefit of the AS. Such strategy can have the mobile users regard the cloudlet group as their first choice if the requested video can be found in the cloudlet group. For an AS of the cloudlet group, if it would like to maximize its profit, it

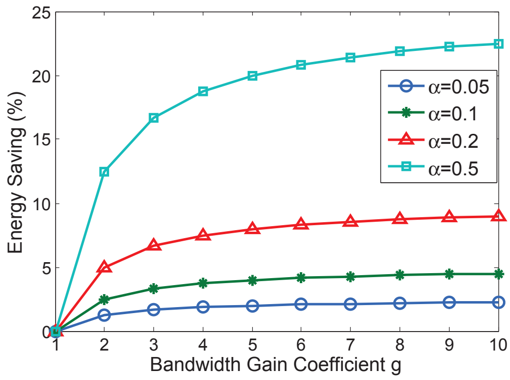


Figure 5.8: Energy Saving (%) with $g \in [1, 10]$ and $\alpha = 0.05, 0.1, 0.2, 0.5$.

should cooperate with other members of the group.

5.5.2 Energy Analysis

According to Eq. (5.5), the cloudlet group can assist the mobile device to save its energy consumption by providing high hit ratio α and bandwidth gain ratio g. We conduct numerical experiments with $g \in [1, 10]$ and $\alpha = 0.05, 0.1, 0.2, 0.5$, and acquire the ratio of energy saving η_T in Fig. 5.8. The bandwidth gain between the cloudlet group and mobile device makes η_T grow fast at the beginning ($g = 2, 3$), then the change rate of η_T is slower gradually as the bandwidth gain increases. That means only increasing the bandwidth between the cloudlet group and mobile device would not help much in saving the energy consumption. At that time, we have to raise the hit ratio to meet the mobile users' requests on energy saving. Fig. 5.8 shows that the larger hit ratio it is, the more energy it will be saved. That is why we bring the cloudlet group model into our system design. If the cloudlet group can satisfy half of mobile users' requests (i.e., $\alpha = 0.5$), the mobile device could save considerable energy even if the bandwidth gain ratio g is small ($\eta_T = 25\%$ and 35% when $g = 2$ and 3). From the discussion above, we could see that distributing video programmes through the cloudlet group will consume less energy than directly transmitting the videos from the cloud through wireless connections.

5.6 Summary

In this chapter, we have proposed the community clinic scheme to economize the mobile cloud service cost under the condition that the service demands exceed the capacity of the cloud. The unique economics and technic characteristics of the scheme bring benefit to the cloud, the cloudlet and mobile users. We have firstly analyzed the energy consumption of the mobile device and found that the mobile devices can save more energy with the service of the cloudlet group. Then we have proven that the cloudlet group can assist to increase the profit of the cloud through modeling the system with and without the cloudlet group as two types of supply chains. Moreover, we present the real-time group-buying auction to attract more mobile users to be served by the cloudlet group with a lower price, and design the effective price curve for the unique subgame-perfect. The real-time group-buying auction also promotes the cooperation among the members of the cloudlet group and maximizes the expected profit for the cloudlet group. Numerical experiments are conducted to demonstrate the effectiveness of our tripartite model compared with the bipartite model. In general, the community clinic achieves a win-win-win outcome among the cloud, cloudlet group and mobile users.

Chapter 6

Conclusions and Suggestions for Future Research

In this chapter, we conclude this thesis by summarizing our original contributions in Section 6.1, and outline the directions for future research in Section 6.2.

6.1 Conclusions

In this dissertation, we investigate the DRM games for the P2PS system, differentiated DRM service and *community clinic* to discuss the effectiveness, flexibility and the serviceability of the DRM service.

To illustrate the effectiveness of DRM service , we model the DRM for P2PS systems as a game for the SP and users, derive the equilibrium price of the digital goods, and maximize the utility of the SP in the P2PS system with DRM based on that equilibrium price. This game model is effective in deciding whether DRM should apply in the P2PS system. We also present effective strategies through static and dynamic games to avoid three misbehaviors of peers: freeriding, jailbreaking and whitewashing. These strategies have the peers acquire the maximal utility if the peers do not take these actions. Experiments are conducted to demonstrate the effectiveness of our strategies, and we find that the dynamic game is more effective than the static game.

To increase the flexibility of DRM service, we propose a new mechanism, differentiated DRM service, to satisfy the mobile users' requirement about how to control and manage the digital goods between the cloud and mobile devices. The differentiated DRM service guarantees not only the security of the digital goods, but also the mobile platform. With the differentiated DRM service between the cloud and mobile devices, the mobile users can select their preferred grades to increase their utilities and acquire more than that with the DRM service using single grade. We also consider the benefit of the SPs, and find that the differentiated DRM service with five grades can bring more payoff and is a dominant strategy when the SPs compete with others through a cooperative game. Numerical experiments are conducted to demonstrate the effectiveness of our differentiated DRM service between the cloud and mobile devices. All in all, the differentiated DRM service is a win-win strategy between the SPs and mobile users.

Finally, the serviceability of DRM service is considered. We propose the community clinic scheme to economize the mobile cloud service cost under the condition that the service demands exceed the capacity of the cloud. The unique economics and technic characteristics of the scheme bring benefits to the cloud, the cloudlet and mobile users. We firstly analyze the energy consumption of the mobile device and find that the mobile devices can save more energy with the service of the cloudlet group. Then we prove that the cloudlet group can assist to increase the profit of the cloud through modeling the system with and without the cloudlet group as two types of supply chains. Moreover, we present the real-time group-buying auction to attract more mobile users to be served by the cloudlet group with a lower price, and design the effective price curve for the unique subgame-perfect. The real-time group-buying auction also promotes the cooperation among the members of the cloudlet group and maximizes the expected profit for the cloudlet group. Numerical experiments are conducted to demonstrate the effectiveness of our tripartite model compared with the bipartite model. In general, the community clinic achieves a win-win-win outcome among the cloud, cloudlet group and mobile users.

6.2 Suggestions for Future Research

In this section, we provide some suggestions for future research. The research work that has been completed so far can be extended in the following three directions:

1. The effectiveness of the DRM service:

    - We consider the effectiveness of the DRM service in a P2PS system, and all the DRM games are constructed in respect to one SP. The case would be different with the competition among multiple SPs. We should consider whether the proposed DRM strategies are still effective based on such competition. The competition among the SPs can be modeled as cooperative and non-cooperative games, and malicious competition taken by the SPs may decrease the effectiveness of the DRM service.
    - We only investigate the control and management of digital goods in the P2PS system. The DRM strategies should be extended to other network environments, such as cloud. The DRM strategies for the cloud service would be more complicated because the digital goods on the cloud are no longer video

steaming but many types of services, e.g., platform as a service, software as a service and so on.

- We only present a theoretical model to illustrate the effectiveness of the DRM service in the P2PS system. As a matter of fact, a prototype of P2PS system with DRM service is on demand. To implement this prototype, there are many practical issues related to the DRM strategy. We list several of them here: (1) How much should the SP reward the peers as they distribute the digital goods successfully? The digital goods are of various utility, and the same digital good is likely to be distributed by different numbers of peers. It needs an effective mechanism to reward peers; (2) What method should the SP leverage to check the integrity of the digital goods? In the process of distributing the digital goods, keeping the integrity of the digital goods is very important, the SP should find a way to monitor the digital goods in the distribution; (3) How does the SP make the peer's identity cost to be high? To avoid the peer to rejoin the P2PS system with a new identity after the punishment, the identity of the peers must be related to something that the peers really care about. All in all, there is a long way to implement a practical P2PS system with DRM service, and we wish such issues can shed some light on designing and implementing effective DRM service for the P2PS system.

2. The flexibility of the DRM service:

   - To increase the flexibility of the DRM service, we import the security of the DRM service as the metric to differentiate the DRM service. In fact, there are many other features of the DRM service that can be regarded as the metrics of differentiation. Some other features or the combination of multiple features may be more suitable metrics to differentiate the DRM service.

- To improve the flexibility of the DRM service, SP has to spend more money on deploying higher grade DRM service. The SP expects that the investment on the DRM service should lead to a high ROI. Then we should design an optimal investment strategy for the SP under the condition that the new DRM strategy would not decrease the utility of mobile users.
- The differentiated DRM service can increase the payoff of the SPs and users. A realizable prototype is needed to examine the benefit of the SP and users through the use of differentiated DRM service. Besides that, the cost of differentiated DRM service should be estimated in order to evaluate its effect on the differentiation of DRM service.

3. The serviceability of the DRM service:

- We consider the serviceability of the DRM service through the supply chain model and real-time group-buying auction, and price the digital goods in the two economics models without any interrelations. However, the price of the digital goods, purchased by the cloudlet, would be the cost of digital goods in the process of group-buying auction. We should develop a dynamic mechanism to price the digital goods in the supply chain model. It greatly helps the AS determine an optimal price curve for the group-buying auction.
- The theoretical analysis in *community clinic* model sheds a light on the serviceability of the DRM service. To reveal practicability of *community clinic*, a prototype should be built to reveal the process of distributing the digital

goods by the tripartite supply chain and bidding the digital goods through real-time group-buying auction. We should also measure the service capability of cloudlet group and the energy saving of the mobile devices through the testbed.

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