國 立 臺 灣 科 技 大 學
電 機 工 程 系
碩 士 學 位 論 文

具有時變通道的URLLC系統排程

Scheduling of the URLLC System with Time-varying Channel

研究生：周沂潔

學號：M11007601

指導教授： 鍾順平 博士

中華民國 一百一十三 年 七 月 十五 日

M11007601

碩士學位論文指導教授推薦書

Master's Thesis Recommendation Form

系所：
Department/Graduate Institute
電機工程系
Department of Electrical Engineering

姓名：
Name
周沂潔
CHOW, YI-JIE

論文題目：
(Thesis Title)
具有時變通道的URLLC系統排程
Scheduling of the URLLC system with time-varying channel

係由本人指導撰述，同意提付審查。

This is to certify that the thesis submitted by the student named above, has been written under my supervision. I hereby approve this thesis to be applied for examination.

指導教授簽章：
Advisor's Signature
鍾順平

共同指導教授簽章（如有）：
Co-advisor's Signature (if any)

日期：
Date(yyyy/mm/dd)
113 / 8 / 5

M11007601

碩士學位考試委員審定書

Qualification Form by Master's Degree Examination Committee

系所：
Department/Graduate Institute

電機工程系
Department of Electrical Engineering

姓名：
Name

周沂潔
CHOW, YI-JIE

論文題目：
(Thesis Title)

具有時變通道的URLLC系統排程
Scheduling of the URLLC system with time-varying channel

經本委員會審定通過，特此證明。

This is to certify that the thesis submitted by the student named above, is qualified and approved by the Examination Committee.

學位考試委員會

Degree Examination Committee

委員簽章：
Member's Signatures

鍾順平　林永松

王乃堅

指導教授簽章：
Advisor's Signature

鍾順平

共同指導教授簽章（如有）：
Co-advisor's Signature (if any)

系所（學程）主任（所長）簽章：
Department/Study Program/Graduate Institute Chair's Signature

郭政謙

日期：
Date(yyyy/mm/dd)

113 / 7 / 15

誌謝

本論文得以順利的完成，首先要感謝指導教授-鍾順平博士，在課業上耐心地給予我們方向及建議，同時間也分享在電機領域的經驗，是我們學習的典範。感謝口試委員-林永松博士和王乃堅博士能撥冗參與口試，並給予此論文寶貴建議和指導，讓本論文完整性及正確性更加完善。

在研究生活中，謝謝實驗室學長、同屆同學以及學弟妹的陪伴，互相幫助和鼓勵，都讓研究生活更有動力，和你們一起的生活平凡簡單卻快樂。謝謝在瑞典交換時期的一切，是我最勇於面對自己的時候。

能夠順利完成此篇論文，必須感謝我的家人，感謝您們的悉心栽培，讓我的研究生活更加豐富。謝謝我的吉娃娃貝嚕，小嚕的存在給我更多力量。謝謝阿柏當初陪我來面試，永遠聆聽我的煩惱。謝謝台中人陪伴我的低潮，帶著我出去玩散散心。

最後對於所有關心我和幫助我的大家獻上最誠摯的感謝，願您們和我一起分享這份喜悅和榮耀。

周 沂 潔 謹致於

國 立 台 灣 科 技 大 學

一百一十三 年 七 月 十五 日

摘要

超可靠低延遲通訊（URLLC）是工業 4.0、5G 和物聯網服務中不可或缺的通訊技術。物聯網設備在工廠自動化、醫療保健和農業等各個領域的快速發展，突顯了 URLLC 的重要性。然而，URLLC 在確保服務品質（QoS）方面面臨著重大挑戰。URLLC 系統中的一個關鍵問題是優化封包傳輸排程，不僅要在各種服務之間提供服務區分，還要平衡功耗和延遲。本文考慮了先進先出（FIFO）和非佔先優先權 (Non-preemptive priority) 佇列兩種方式。假設存在兩種類型的服務，一種具有較嚴謹誤碼率（LBER）要求，例如與安全相關的封包，另一種具有較寬鬆誤碼率（HBER）要求，例如智慧電表讀數。為了更加符合現實，我們假設通道在好和壞狀態之間交替變化。具體而言，我們研究了三種情況下的排程策略：（1）封包傳輸延遲至通道切換到好狀態，（2）封包傳輸在壞狀態下對 LBER 和 HBER 封包使用不同的傳輸機率，以及（3）封包傳輸根據佇列長度相對於傳輸閾值來調整傳輸機率。通過將系統建模為四維離散時間馬可夫鏈，我們分析了不同排程策略對效能的影響，特別是功耗與延遲之間的權衡。結果表示，數學分析結果與模擬結果一致，驗證了我們方法的準確性和可靠性。

關鍵詞：超可靠低延遲通訊、物聯網、服務品質、排程策略、先進先出、非佔先優先權系統、馬可夫鏈

Abstract

Ultra-Reliable Low Latency Communications (URLLC) is a cutting-edge communication technology integral to Industry 4.0, 5G, and IoT services. The rapid expansion of IoT devices across various fields, including factory automation, healthcare, and farming, underscores the significance of URLLC, which faces substantial challenges in ensuring quality of service (QoS). A key issue in URLLC systems is optimizing data transmission scheduling to provide not only service differentiation among various services but also balance power consumption and delay. This thesis considers both the First-In-First-Out (FIFO) and non-preemptive priority queueing disciplines. It is assumed that there are two types of services, one with Lower Bit-Error-Rate (LBER) requirement, e.g., safety-related packets, and the other with Higher Bit-Error-Rate (HBER) requirement, e.g., smart-meter readings. To be more realistic, we assume that the channel alternates between the good and bad states. Specifically, we study the scheduling policies in three scenarios: (1) The packet transmissions are delayed until the channel switches to the good state, (2) The packet transmissions use different delivery probabilities for LBER and HBER packets in the bad state, and (3) The packet transmissions adjust delivery probabilities based on the queue length relative to the threshold. By modeling the systems as four-dimensional discrete-time Markov chains, we analyze the impact of different scheduling policies on performance, particularly the trade-off between energy consumption and delay. It is shown that the analytical results align well with the simulation results, validating the accuracy and reliability of our approach.

Keywords: Ultra-Reliable Low Latency Communications (URLLC), IoT, quality of service (QoS), scheduling policies, First-In-First-Out (FIFO), non-preemptive priority system, Markov chain

Contents

List of Figures

List of Tables

1. Introduction

Nowadays, Ultra-Reliable Low Latency Communications (URLLC) has emerged as an innovative type of communication, which has been used for application in Industry 4.0, fifth-generation technology (5G), and Internet of Things (IoT) services. According to the rapid growth of IoT devices, there are many types of IoT devices utilized in different fields such as factory automation, healthcare surgery, and farming automation. URLLC has become significant but also started to face great challenges [1]. The quality of service (QoS) between different IoTs needs to be concerned. Consequently, how to optimize the scheduling of data transmission between different types of packets to trade off average power consumption against average delay has evolved into an important issue in queuing systems.

To maintain quality of service, a performance analysis of the LTE-WLAN (LWA) under saturated and unsaturated Wi-Fi to maintain QoS of LTE has been proposed [2], and it assumes that the time axis is divided into slots with the same size. To consider the congestion control in networks, a cross-layer approach has been presented to prolong the system lifetime [3], where it measures the ratio of packet inter-arrival time along service time as congestion degree and utilizes the congestion degree to determine the action in each slot. To our best knowledge, a good scheduling policy should consider the current queue state as well as the current channel state to decide the action in each time slot [4]. Furthermore, the optimal scheduling scheme for a single user under Rayleigh fading channel with a constraint of power consumption has been designed [5]. According to the above assumptions, a cross-layer design for quality of service guaranteed traffic would be derived to satisfy the packet loss rate constraint and average delay constraint, in order to maximize the throughput [6]. On top of that, there may be different power consumption requirements for packets with different QoS requirements [7]. Thus, it would be critical to know of which type the packet being transmitted is in each time slot. Finally, to bargain with average power consumption and average delay, we must design a scheduling for packets with different QoS requirements.

In this thesis, we will put the focus on differential scheduling for supporting service differentiation among different services. We first consider a First-In-First-Out (FIFO) system with two types of packets which have Lower Bit-Error-Rate (LBER) and Higher Bit-Error-Rate (HBER) requirements, respectively [8] [9]. Next, we also consider a non-preemptive priority system with the same setting as the FIFO system. Specifically, the channel state alternates between two states, the good channel state and the bad channel state. If the power requirement of a packet transmitted at the good channel state is smaller than that of the same packet transmitted at the bad channel state. At the beginning of each slot, our model will decide whether to transmit the packet in the server taking account of the channel state. After that, the packet will arrive and backlog in queue. Since the LBER packets only allow low error rate, they require higher power to transmit; on the other hand, the HBER packets could be transmitted with lower power since they could tolerate more errors. Moreover, the current channel state will change at the beginning of each time slot; therefore, we must consider the power consumption between good channel state and bad channel state. Thus, a Markov chain is deduced to represent the number of LBER in queue, the number of HBER in queue, the channel state, and the server state. In [10], the scheduling scheme considers the similar packets and sampling before transmission, but it only considers the first few packets in the queue. In our research, when the channel is in the bad condition, we will set a transmission probability for each type of packet and the scheduler will decide if the server transmits the packet according to its transmission probability. Additionally, we will consider another scenario where the total number in queue at the beginning of each slot is detected and if the total number in queue has already exceeded the transmission threshold, we will switch the transmission probability to a better one and the system will decide whether to transmit the packet in server or not accordingly. From our research, we could observe the different scheduling policies will impact the performance measures and trade-off between energy consumption and average delay. The above two system studied are modeled as four-dimensional discrete time Markov chains with FIFO and non-preemptive priority queueing disciplines, respectively.

The remainder of this thesis will be in the following. In Chapter 2, we will introduce our system models in detail. In Chapter 3, the analytical models will be deduced, and the associated feasible states will be described. In Chapter 4, we will describe our simulation models and explain the pseudo code. In Chapter 5, we will demonstrate our result charts with analytical and simulation results, and we will also compare the performances of different models. Ultimately, in Chapter 6, we will draw a conclusion and present our thoughts for further research.

2. System model

We focus on the packet scheduling policy of a URLLC system that can achieve differential QoS and acceptable power consumption with time-varying channel. We assume that the considered system has only one server and a finite buffer or queue. It is assumed there are two types of packets; one with the Lower Bit-Error-Rate (LBER), and another one with Higher Bit-Error-Rate (HBER). Since the QoS requirements of these two types of packets are different, the power they consume will be different as well. We assume that the time axis is divided into periodic time slots. In each time slot, each type of packets arrives based on its associated packet arrival probability. It is noted that the system has at most one packet arrival in each time slot and thus the sum of both packet arrival probabilities must be less than unity. When a packet arrives in the system and the server has already been occupied, then the packet will backlog in the queue. Besides, if there is no anyone in the server while the packet arrives, it can enter the server directly; however, the packet in the server could only be transmitted until next time slot. Furthermore, we study two queueing disciplines: First-In-First-Out (FIFO) and Non-Preemption. Under FIFO, the packets are queued in the buffer according to the time of arrival. On the other hand, under non-preemption, the packets with LBER are queued before those with HBER in the buffer.

At the beginning of each time slot, the time-varying channel will alternate between two states, state 0 (good state) or state 1 (bad state), based on the channel transition probability. After determining the channel state, if the channel state is in state 0, the scheduler will transmit the packet in the server to Access Point (AP) without hesitation. Otherwise, if the channel is in state 1, the scheduler will determine whether to transmit the packet based on its scheduling policy. In this work, we consider three scheduling policies as follows.

(1) Policy 1

When the channel is in the state 0 in any slot and there is a packet in the server, the scheduler will not transmit the packet in the server, and will rather wait until the channel state transits to the state 1.

(2) Policy 2

There are two kinds of delivery probabilities for LBER and HBER packets, respectively. When the channel is in the state 0 in any slot and there is a packet in the server, the scheduler detects the type of the packet in the server, and decide if it could be transmitted in this time slot according to its own delivery probability.

(3) Policy 3

There is a transmission threshold for the number of packets waiting in the queue which represents the switching point of the delivery probability. Specifically, for each type of packets, there are two delivery probabilities, where a delivery probability is used if the transmission threshold is not exceeded and another delivery probability is adopted once the transmission threshold is exceeded. While the channel is in state 0 in any slot and there is a packet in the server, the scheduler will calculate the total number of packets in the queue. If the total number in queue is no greater than the transmission threshold, the scheduler will decide if the packet could be transmitted in this time slot according to a smaller delivery probability. If the total number in queue is greater than the transmission threshold, the scheduler will decide if the packet could be transmitted in this time slot according to another higher delivery probability.

When a packet is transmitted in the system, the power consumed should be adjusted to fulfill the QoS requirements. As an example, 64-QAM and 256-QAM are supported in 5G network. More power would be consumed to achieve a lower BER under the same channel state. As is well known, the power consumed by a packet will be different according to its Bit-Error-Rate requirement. For example, each LBER packet needs more power to maintain a lower Bit-Error-Rate; on the other hand, HBER packets can tolerate more errors and do not need that much power consumption. Moreover, the channel state will also affect the power consumption. The packet transmitted in state 0 is more likely to succeed because the detrimental effect, e.g., noise and interference, is weaker. On the other hand, in state 1, the detrimental effect is stronger and more power is needed to transmit a packet in order to maintain a low BER.

To summarize up, to avoid higher power consumption resulting from transmission in the bad channel state, if we postpone the transmission and wait until the channel becomes better, time delay will be increased for the whole system. Therefore, there exists a tradeoff between the average power consumption and average delay in our system.

3. Analytical model

In this chapter, we are going to present three different kinds of models for the packet scheduling policies which are (1) Power Consumption Control Policy (PCCP) (2) Adaptive Delivery Policy (ADP) (3) Threshold-based Transmission Policy (TTP). Besides, each of the models has two types of disciplines which are (a) First-In-First-Out and (b) Non-preemption priority. Assume we have two types of packets $\{p_L, p_H\}$, which are LBER and HBER, respectively. In the FIFO discipline, the packet which arrives first will enter the server without considering priority; on the other hand, the LBER packet will have higher priority over the HBER packet in the queue but it will not disturb the packet which already enters the server in non-preemption priority discipline. The arrival probability of the LBER (HBER) packet at each time slot is λ_L (λ_H); thus, the total arrival rate of the system will be $\lambda_{Total} = \lambda_L + \lambda_H$. For simplicity there is only one server with one channel in this system and the arrivals of packets at each time slot are independently and identically distributed.

(a) First-In-First-Out (FIFO) system

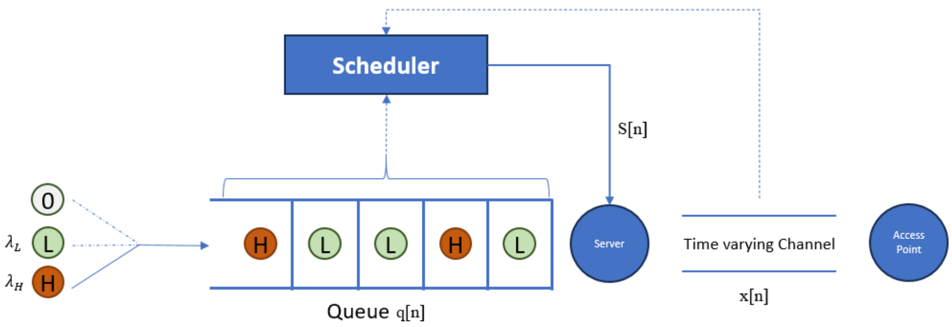


Fig 3. 1: The system model with FIFO discipline

(b) Non-Preemption Priority system

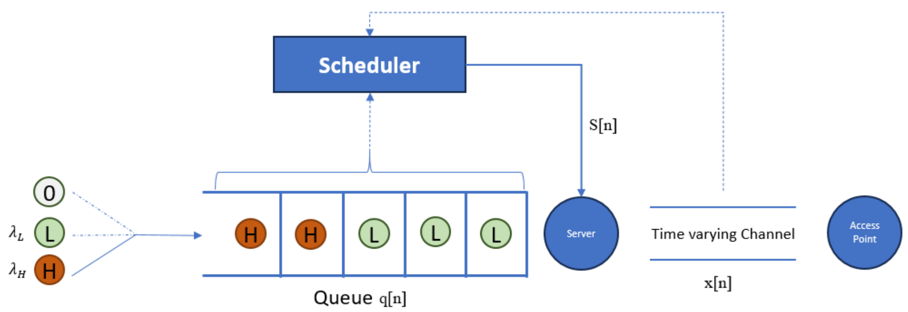


Fig 3. 2: The system model with priority discipline

At the beginning of each time slot, the time-varying channel will alternate between state 0 (bad state) and state 1 (good state), which are denoted as $x[n] = 0$ and $x[n] = 1$ based on the channel transition probability. Naturally, a packet is transmitted if the channel is in state 1. To discuss the trade-off between power consumption and time delay, while the channel is in state 0, three types of scheduling policies are proposed and studied as follows.

3.1.Power Consumption Control Policy (PCCP)

3.1.1 Model diagram

In order to control the power consumption of the system, when it is in state 0, i.e., $x[n] = 0$ in slot n, the scheduler will not transmit any packet; thus, $S[n] = 0$, and it will wait until the channel is good, i.e., x[n]=1. Assume the system size is K, and the queue size is $K-1$, and the arrival rates of LBER and HBER are λ_L and λ_H, respectively. Naturally, $0 < \lambda_L + \lambda_H < 1$. At the beginning of each slot, the channel will alter between state 0 and state 1 according to channel transition rate γ. In FIFO discipline, the probability that the HoL (head of line) packet is LBER can be obtained as follows:

$$\beta = nq_L / (nq_L + nq_H) \qquad (3-1)$$

(a) FIFO discipline

Table 3. 1: System parameter list of PCCP with FIFO discipline

Parameters	Description
$\boldsymbol{\lambda_L}$	Arrival rate of LBER packets at the queue
$\boldsymbol{\lambda_H}$	Arrival rate of HBER packets at the queue
$\boldsymbol{\gamma}$	The probability of good channel in each time slot
$\boldsymbol{\beta}$	The probability of the HoL packet is LBER
$\boldsymbol{nq_L}$	The number of LBER packets in queue
$\boldsymbol{nq_H}$	The number of HBER packets in queue

(b) Priority discipline

Table 3. 2: System parameter list of PCCP with priority discipline

Parameters	**Description**
$\boldsymbol{\lambda_L}$	Arrival rate of LBER packets at the queue
$\boldsymbol{\lambda_H}$	Arrival rate of HBER packets at the queue
$\boldsymbol{\gamma}$	The probability of good channel in each time slot

3.1.2 State balance equations

The system is modeled as a four-dimensional discrete time Markov chain with state (i, j, x, y), for both FIFO and priority disciplines, where i presents the number of LBER packets in queue, j presents the number of HBER packets in queue, x presents the channel state, and y presents the server state. While $x = 0$ means the channel state is bad (state 0), and $x = 1$ means the channel state is good (state 1). And $y = 0$ means there is no one in server, $y = 1$ means the LBER packet in server, and $y = 2$ means the HBER packet in server. The steady sate probability of the model is described as $\pi(i, j, x, y)$; thus, the state space can be denoted as follows:

$$S = \{(i, j, x, y) |\ 0 \le i \le Q, 0 \le j \le Q - i, 0 \le x \le 1, 0 \le y \le 2\} \qquad (3-2)$$

Hence, the number of feasible states is as follows:

$$|S| = 3(Q + 1)(Q + 2) \qquad (3-3)$$

As an example, if Q is equal to 20, we can see the total number of feasible states is 1386. For both FIFO and priority disciplines, the feasible states can be classified into 32 cases as below.

(a) First-In-First-Out

Case 1： $i = 0, j = 0, x = 0, y = 0$

$$\pi_{0,0,0,0} = (1 - \lambda_L - \lambda_H)(1 - \gamma)\,\pi_{0,0,0,0} + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,0,1,0} + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,0,1,1} + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,0,1,2}$$

Case 2 : $0 \leq i \leq K-2, 0 \leq j \leq K-i-2, x=0, y=1$

$$
\begin{aligned}
\pi_{i,j,0,1} = {} & \lambda_L(1-\gamma)\pi_{0,0,0,0} + (1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{i,j,0,1} + \lambda_L(1-\gamma)\pi_{i-1,j,0,1} \\
& + \lambda_H(1-\gamma)\pi_{i,j-1,0,1} + \lambda_L(1-\gamma)\pi_{0,0,1,0} + \lambda_L(1-\gamma)\pi_{0,0,1,1} \\
& + \lambda_L(1-\gamma)\pi_{0,0,1,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{i+1,0,1,1} \\
& + \lambda_L(1-\gamma)\pi_{i,0,1,1} + \lambda_H(1-\gamma)\pi_{i+1,0,1,1} \\
& + (1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{i+1,0,1,2} + \lambda_L(1-\gamma)\pi_{i,0,1,2} \\
& + \lambda_H(1-\gamma)\pi_{i+1,0,1,2} + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{i+1,j,1,1} \\
& + \beta\lambda_L(1-\gamma)\pi_{i,j,1,1} + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,1} \\
& + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{i+1,j,1,2} + \beta\lambda_L(1-\gamma)\pi_{i,j,1,2} \\
& + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,2}
\end{aligned}
$$

Case 3 : $0 \leq i \leq K-2, 0 \leq j \leq K-i-2, x=0, y=2$

$$
\begin{aligned}
\pi_{i,j,0,1} = {} & \lambda_H(1-\gamma)\pi_{0,0,0,0} + (1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{i,j,0,2} + \lambda_L(1-\gamma)\pi_{i-1,j,0,2} \\
& + \lambda_H(1-\gamma)\pi_{i,j-1,0,2} + \lambda_H(1-\gamma)\pi_{0,0,1,0} + \lambda_H(1-\gamma)\pi_{0,0,1,1} \\
& + \lambda_H(1-\gamma)\pi_{0,0,1,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,j+1,1,1} \\
& + \lambda_L(1-\gamma)\pi_{0,j+1,1,1} + \lambda_H(1-\gamma)\pi_{0,j,1,1} \\
& + (1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,j+1,1,2} + \lambda_L(1-\gamma)\pi_{0,j+1,1,2} \\
& + \lambda_H(1-\gamma)\pi_{0,j,1,2} + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{i,j+1,1,1} + (1 \\
& - \beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,1,1} + (1-\beta)\lambda_H(1-\gamma)\pi_{i,j,1,1} + (1 \\
& - \beta)(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{i,j+1,1,2} + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,1,2} \\
& + (1-\beta)\lambda_H(1-\gamma)\pi_{i,j,1,2}
\end{aligned}
$$

Case 4 : $0 \leq i \leq K-1, j = K-i-1, x=0, y=1$

$$
\begin{aligned}
\pi_{i,j,0,1} = {} & (1-\gamma)\,\pi_{i,j,0,1} + \lambda_L(1-\gamma)\pi_{i-1,j,0,1} + \lambda_H(1-\gamma)\pi_{i,j-1,0,1} \\
& + \beta\lambda_L(1-\gamma)\pi_{i,j,1,1} + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,1} + \beta\lambda_L(1-\gamma)\pi_{i,j,1,2} \\
& + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,2}
\end{aligned}
$$

Case 5 : $0 \le i \le K-1, j = K-i-1, x = 0, y = 2$

$$\pi_{i,j,0,2} = (1-\gamma)\,\pi_{i,j,0,2} + \lambda_L(1-\gamma)\pi_{i-1,j,0,2} + \lambda_H(1-\gamma)\pi_{i,j-1,0,2}$$
$$+(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,1,1} + (1-\beta)\lambda_H(1-\gamma)\pi_{i,j,1,1}$$
$$+(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,1,2} + (1-\beta)\lambda_H(1-\gamma)\pi_{i,j,1,2}$$

Case 6 : $i = 0, j = 0, x = 1, y = 0$

$$\pi_{0,0,1,0} = (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,0} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,0} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,1}$$
$$+ (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,2}$$

Case 7 : $i = 0, j = 0, x = 1, y = 1$

$$\pi_{0,0,1,1} = \lambda_L\gamma\pi_{0,0,0,0} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,1} + \lambda_L\gamma\pi_{0,0,1,0} + \lambda_L\gamma\pi_{0,0,1,1}$$
$$+ \lambda_L\gamma\pi_{0,0,1,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,0,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,0,1,2}$$

Case 8 : $i = 0, j = 0, x = 1, y = 2$

$$\pi_{0,0,1,2} = \lambda_H\gamma\pi_{0,0,0,0} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,2} + \lambda_H\gamma\pi_{0,0,1,0} + \lambda_H\gamma\pi_{0,0,1,1}$$
$$+ \lambda_H\gamma\pi_{0,0,1,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,1,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,1,1,2}$$

Case 9 : $i = 0, 1 \le j \le K-1, x = 1, y = 1$

$$\pi_{0,j,1,1} = (1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,1} + \lambda_H\gamma\pi_{0,j-1,0,1} + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{1,j-1,1,1}$$
$$+ \beta\lambda_H\gamma\pi_{1,j-1,1,1} + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{1,j-1,1,2} + \beta\lambda_H\gamma\pi_{1,j-1,1,2}$$

Case 10 : $i = 0, 1 \le j \le K-1, x = 1, y = 2$

$$\pi_{0,j,1,2} = (1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,2} + \lambda_H\gamma\pi_{0,j-1,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,1,1}$$
$$+ \lambda_H\gamma\pi_{0,j,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,1,2} + \lambda_H\gamma\pi_{0,j,1,2}$$

Case 11 : $1 \leq i \leq K-1, j=0, x=1, y=1$

$$\pi_{i,0,1,1} = (1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,1} + \lambda_L\gamma\pi_{i-1,0,0,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,1,1} + \lambda_L\gamma\pi_{i,0,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,1,2} + \lambda_L\gamma\pi_{i,0,1,2}$$

Case 12 : $1 \leq i \leq K-1, j=0, x=1, y=2$

$$\pi_{i,0,1,2} = (1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,2} + \lambda_L\gamma\pi_{i-1,0,0,2} + \gamma\pi_{K-1,0,0,2} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i-1,1,1,1} + (1-\beta)\lambda_L\gamma\pi_{i-1,1,1,1} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i-1,1,1,2} + (1-\beta)\lambda_L\gamma\pi_{i-1,1,1,2}$$

Case 13 : $1 \leq i \leq K-2, 1 \leq j \leq K-i-1, x=1, y=1$

$$\pi_{i,j,1,1} = (1-\lambda_L-\lambda_H)\gamma\pi_{i,j,0,1} + \lambda_L\gamma\pi_{i-1,j,0,1} + \lambda_H\gamma\pi_{i,j-1,0,1} + \lambda_H\gamma\pi_{i+1,0,1,1} + \lambda_H\gamma\pi_{i+1,0,1,2} + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,1} + \beta\lambda_L\gamma\pi_{i,j,1,1} + \beta\lambda_H\gamma\pi_{i+1,j-1,1,1} + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,2} + \beta\lambda_L\gamma\pi_{i,j,1,2} + \beta\lambda_H\gamma\pi_{i+1,j-1,1,2}$$

Case 14 : $1 \leq i \leq K-2, 1 \leq j \leq K-i-1, x=1, y=2$

$$\pi_{i,j,1,2} = (1-\lambda_L-\lambda_H)\gamma\pi_{i,j,0,2} + \lambda_L\gamma\pi_{i-1,j,0,2} + \lambda_H\gamma\pi_{i,j-1,0,2} + \lambda_L\gamma\pi_{0,j+1,1,1} + \lambda_L\gamma\pi_{0,j+1,1,2} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,1,1} + (1-\beta)\lambda_L\gamma\pi_{i-1,j+1,1,1} + (1-\beta)\lambda_H\gamma\pi_{i,j,1,1} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,1,2} + (1-\beta)\lambda_L\gamma\pi_{i-1,j+1,1,2} + (1-\beta)\lambda_H\gamma\pi_{i,j,1,2}$$

(b) Priority discipline

Case 1 : $i = 0, j = 0, x = 0, y = 0$

$$\pi_{0,0,0,0} = (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,0,0,0} + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,0,1,0} + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,0,1,1} + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,0,1,2}$$

Case 2 : $0 \le i \le K - 2, 0 \le j \le K - i - 2, x = 0, y = 1$

$$\begin{aligned}\pi_{i,j,0,1} = {} & \lambda_L(1 - \gamma)\pi_{0,0,0,0} + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{i,j,0,1} + \lambda_L(1 - \gamma)\pi_{i-1,j,0,1} \\ & + \lambda_H(1 - \gamma)\pi_{i,j-1,0,1} + \lambda_L(1 - \gamma)\pi_{0,0,1,0} + \lambda_L(1 - \gamma)\pi_{0,0,1,1} \\ & + \lambda_L(1 - \gamma)\pi_{0,0,1,2} + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{i+1,j,1,1} \\ & + \lambda_L(1 - \gamma)\pi_{i,j,1,1} + \lambda_H(1 - \gamma)\pi_{i+1,j-1,1,1} \\ & + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{i+1,j,1,2} + \lambda_L(1 - \gamma)\pi_{i,j,1,2} \\ & + \lambda_H(1 - \gamma)\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 3 : $0 \le i \le K - 2, 0 \le j \le K - i - 2, x = 0, y = 2$

$$\begin{aligned}\pi_{i,j,0,2} = {} & \lambda_H(1 - \gamma)\pi_{0,0,0,0} + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{i,j,0,2} + \lambda_L(1 - \gamma)\pi_{i-1,j,0,2} \\ & + \lambda_H(1 - \gamma)\pi_{i,j-1,0,2} + \lambda_H(1 - \gamma)\pi_{0,0,1,0} + \lambda_H(1 - \gamma)\pi_{0,0,1,1} \\ & + \lambda_H(1 - \gamma)\pi_{0,0,1,2} + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,j+1,1,1} \\ & + \lambda_L(1 - \gamma)\pi_{0,j+1,1,1} + \lambda_H(1 - \gamma)\pi_{0,j,1,1} \\ & + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,j+1,1,2} + \lambda_L(1 - \gamma)\pi_{0,j+1,1,2} \\ & + \lambda_H(1 - \gamma)\pi_{0,j,1,2}\end{aligned}$$

Case 4 : $0 \le i \le K - 1, j = K - i - 1, x = 0, y = 1$

$$\begin{aligned}\pi_{i,j,0,1} = {} & (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{i,j,0,1} + \lambda_L(1 - \gamma)\pi_{i-1,j,0,1} + \lambda_H(1 - \gamma)\pi_{i,j-1,0,1} \\ & + (1 - \gamma)\pi_{i,j,0,1} + \lambda_L(1 - \gamma)\pi_{i,j,1,1} + \lambda_H(1 - \gamma)\pi_{i+1,j-1,1,1} \\ & + \lambda_L(1 - \gamma)\pi_{i,j,1,2} + \lambda_H(1 - \gamma)\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 5 : $0 \leq i \leq K-1, j = K-i-1, x = 0, y = 2$

$$\pi_{i,j,0,2} = (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,2} + \lambda_L(1-\gamma)\pi_{i-1,j,0,2} + \lambda_H(1-\gamma)\pi_{i,j-1,0,2} + (1-\gamma)\pi_{i,j,0,2} + \lambda_L(1-\gamma)\pi_{0,j+1,1,1} + \lambda_H(1-\gamma)\pi_{0,j,1,1} + \lambda_L(1-\gamma)\pi_{0,j+1,1,2} + \lambda_H(1-\gamma)\pi_{0,j,1,2}$$

Case 6 : $i = 0, j = 0, x = 1, y = 0$

$$\pi_{0,0,1,0} = (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,0} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,0} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,2}$$

Case 7 : $i = 0, j = 0, x = 1, y = 1$

$$\pi_{0,0,1,1} = \lambda_L\gamma\pi_{0,0,0,0} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,1} + \lambda_L\gamma\pi_{0,0,1,0} + \lambda_L\gamma\pi_{0,0,1,1} + \lambda_L\gamma\pi_{0,0,1,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,0,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,0,1,2}$$

Case 8 : $i = 0, j = 0, x = 1, y = 2$

$$\pi_{0,0,1,2} = \lambda_H\gamma\pi_{0,0,0,0} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,2} + \lambda_H\gamma\pi_{0,0,1,0} + \lambda_H\gamma\pi_{0,0,1,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,1,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,1,1,2}$$

Case 9 : $i = 0, 1 \leq j \leq K-1, x = 1, y = 1$

$$\pi_{0,j,1,1} = (1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,1} + \lambda_H\gamma\pi_{0,j-1,0,1} + \gamma\pi_{0,K-1,0,1} + \lambda_H\gamma\pi_{1,0,1,1} + \lambda_H\gamma\pi_{1,0,1,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,j,1,1} + \lambda_H\gamma\pi_{1,j-1,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,j,1,2} + \lambda_H\gamma\pi_{1,j-1,1,2}$$

Case 10 : $i = 0, 1 \leq j \leq K-1, x = 1, y = 2$

$$\pi_{0,j,1,2} = (1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,2} + \lambda_H\gamma\pi_{0,j-1,0,2} + \gamma\pi_{0,K-1,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,1,1} + \lambda_H\gamma\pi_{0,j,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,1,2} + \lambda_H\gamma\pi_{0,j,1,2}$$

Case 11 : $1 \leq i \leq K-1, j = 0, x = 1, y = 1$

$$\pi_{i,0,1,1} = \lambda_L\gamma\pi_{i-1,0,0,1} + \gamma\pi_{K-1,0,0,1} + \lambda_L\gamma\pi_{i,0,1,1} + \lambda_L\gamma\pi_{i,0,1,2}$$

Case 12 : $1 \leq i \leq K-1, j=0, x=1, y=2$

$$\pi_{i,0,1,2} = (1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,2} + \lambda_L\gamma\pi_{i-1,0,0,2} + \gamma\pi_{K-1,0,0,2} + \lambda_L\gamma\pi_{0,1,1,1} + \lambda_L\gamma\pi_{0,1,1,2}$$

Case 13 : $1 \leq i \leq K-2, 1 \leq j \leq K-i-1, x=1, y=1$

$$\pi_{i,j,1,1} = (1-\lambda_L-\lambda_H)\gamma\pi_{i,j,0,1} + \lambda_L\gamma\pi_{i-1,j,0,1} + \lambda_H\gamma\pi_{i,j-1,0,1} + \gamma\pi_{i,K-i-1,0,1} + \lambda_H\gamma\pi_{i+1,0,1,1} + \lambda_H\gamma\pi_{i+1,0,1,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,1} + \lambda_L\gamma\pi_{i,j,1,1} + \lambda_L\gamma\pi_{i+1,j-1,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,2} + \lambda_L\gamma\pi_{i,j,1,2} + \lambda_H\gamma\pi_{i+1,j-1,1,2}$$

Case 14 : $1 \leq i \leq K-2, 1 \leq j \leq K-i-1, x=1, y=2$

$$\pi_{i,j,1,2} = (1-\lambda_L-\lambda_H)\gamma\pi_{i,j,0,2} + \lambda_L\gamma\pi_{i-1,j,0,2} + \lambda_H\gamma\pi_{i,j-1,0,2} + \gamma\pi_{i,K-i-1,0,2} + \lambda_L\gamma\pi_{0,j+1,1,1} + \lambda_L\gamma\pi_{0,j+1,1,2}$$

3.1.3 State diagram

(a) First-In-First-Out

(1) $i=0, j=0, x=0, y=0$

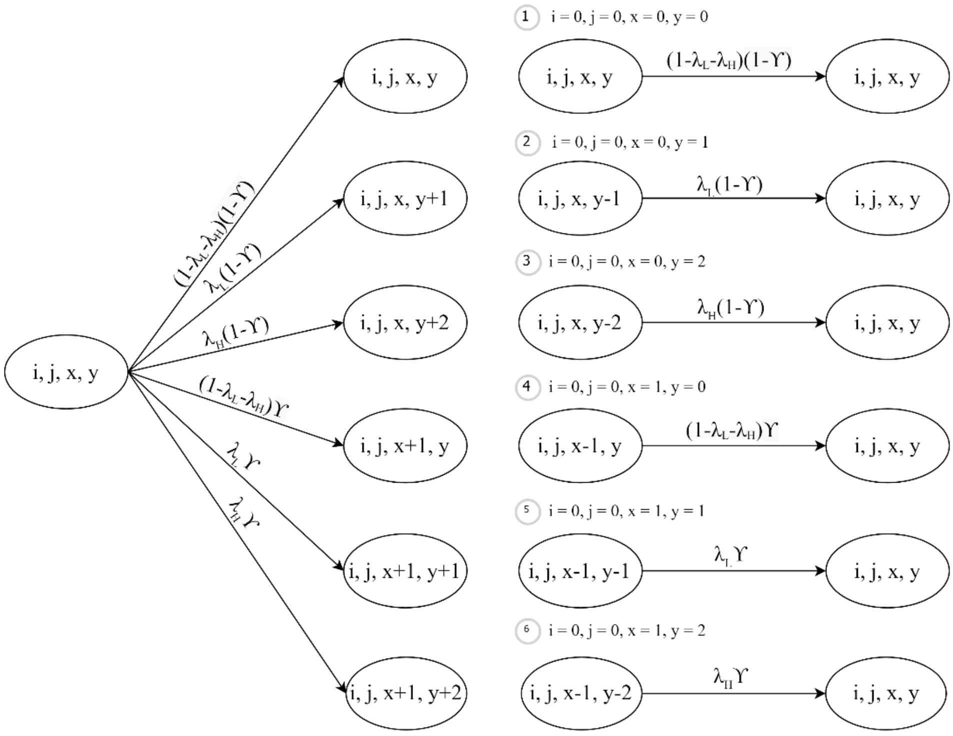


Fig 3. 3: The state diagram for $i=0, j=0, x=0, y=0$

(2) $0 < i < K-2, 0 \leq j \leq K-i-2, x = 0, y = 1$ 、2

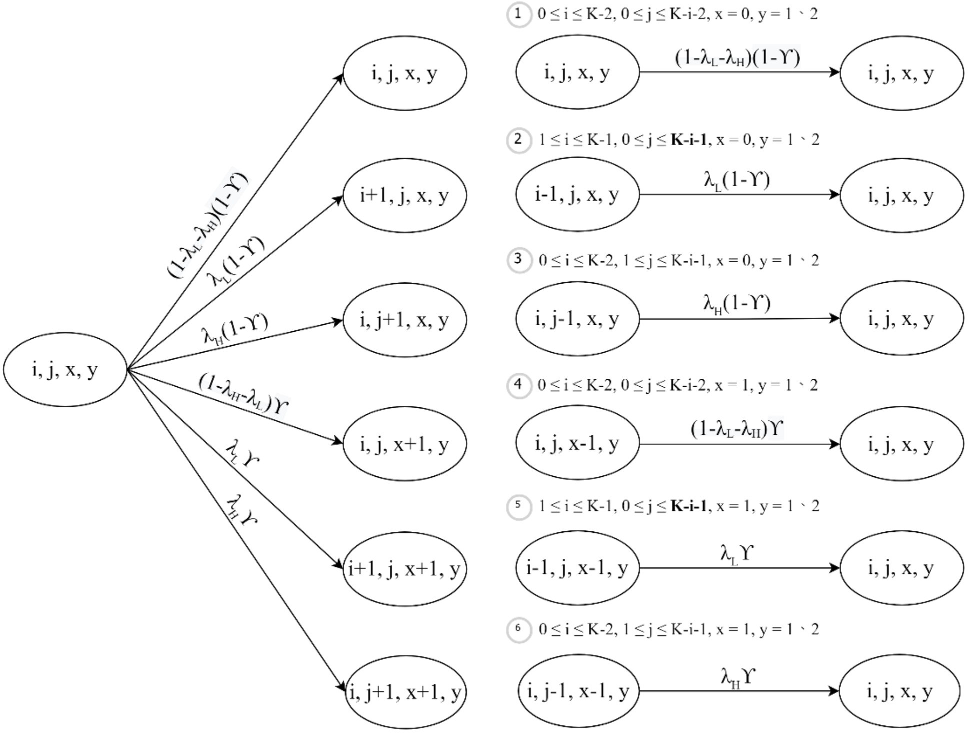


Fig 3. 4: The state diagram for $0 < i < K-2, 0 \leq j \leq K-i-2, x = 0, y = 1$ 、2

(3) $0 \leq i \leq K-1, j = K-i-1, x = 0, y = 1$ 、2

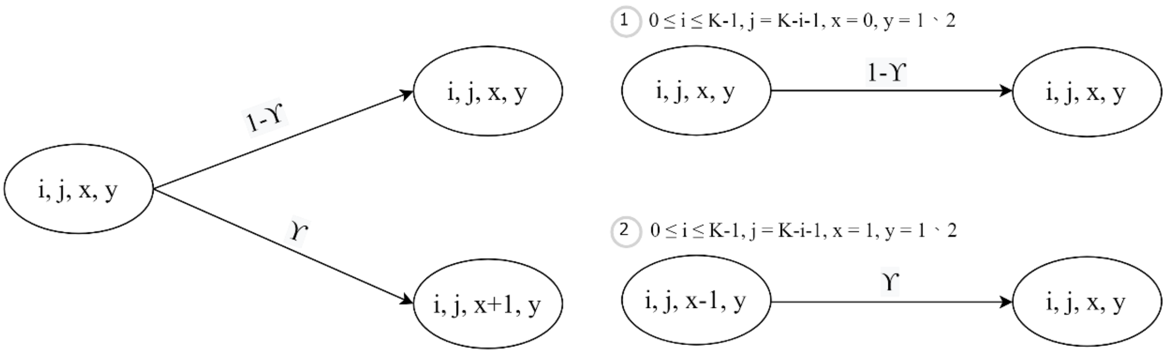


Fig 3. 5: The state diagram for $0 \leq i \leq K-1, j = K-i-1, x = 0, y = 1$ 、2

(4) $i = 0, j = 0, x = 1, y = 0$

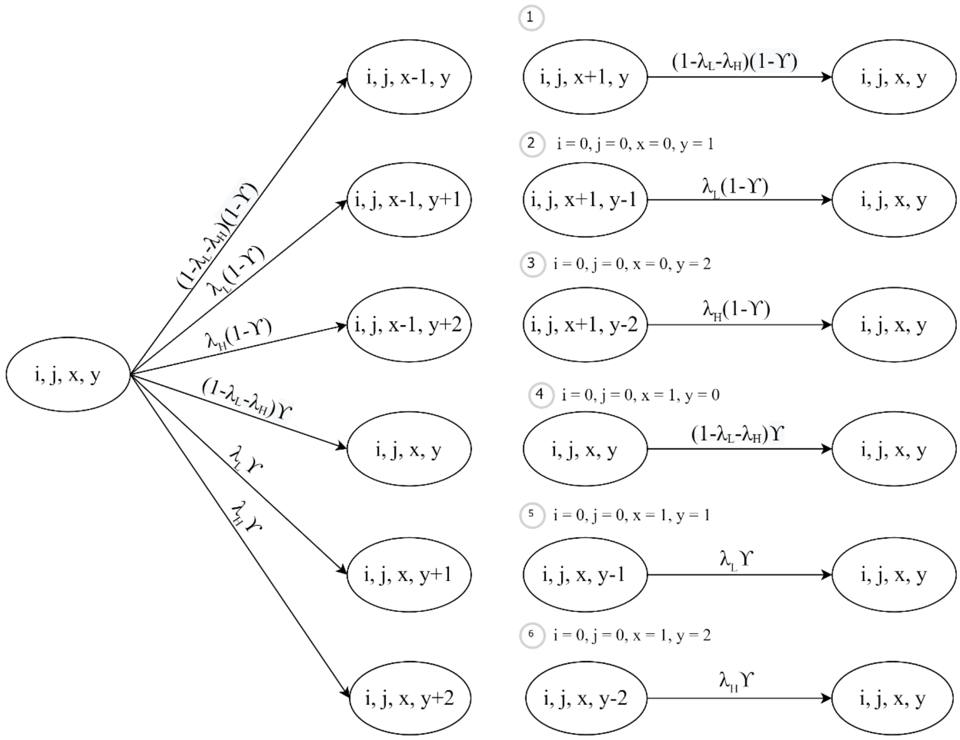


Fig 3. 6: The state diagram for $i = 0, j = 0, x = 1, y = 0$

(5) $i = 0, j = 0, x = 1, y = 1$

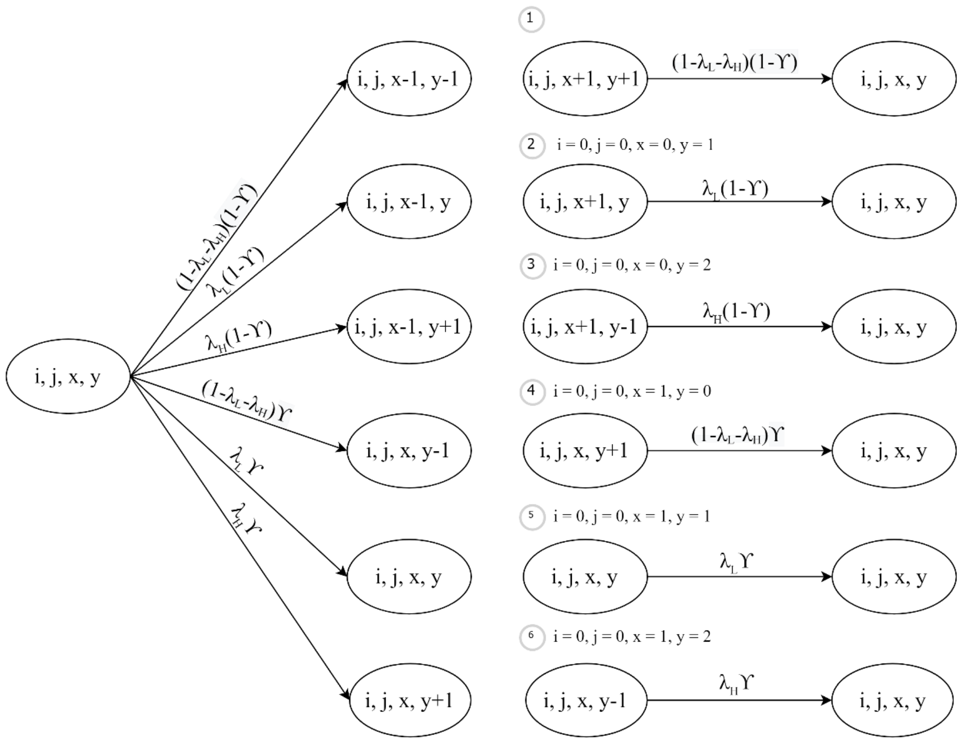


Fig 3. 7: The state diagram for $i = 0, j = 0, x = 1, y = 1$

(6) $i = 0, j = 0, x = 1, y = 2$

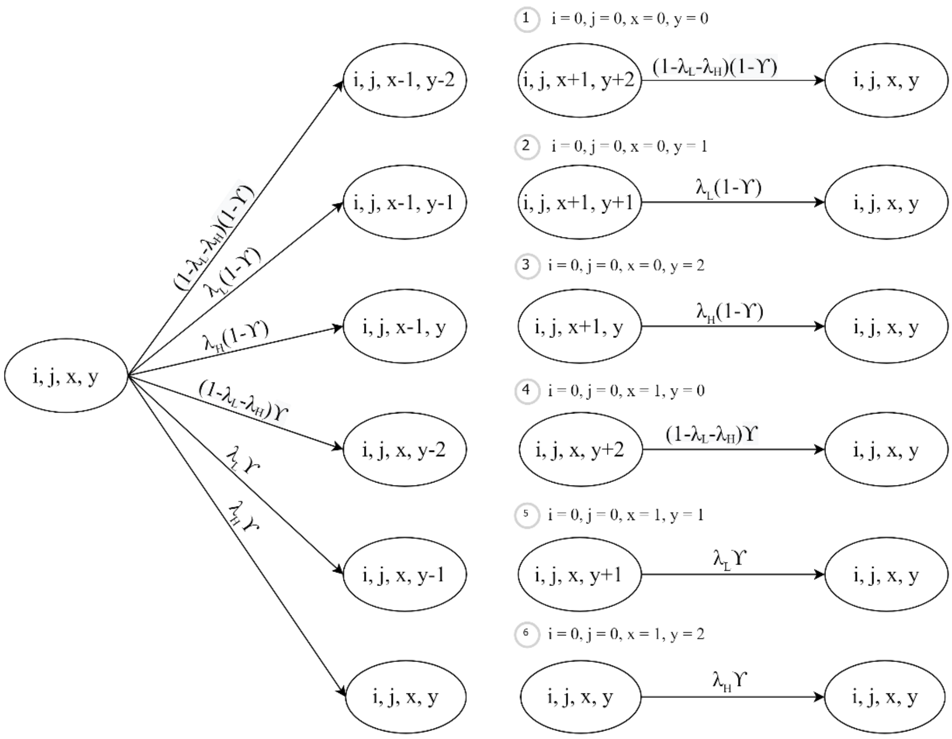


Fig 3. 8: The state diagram for $i = 0, j = 0, x = 1, y = 2$

(7) $i = 0, 1 \leq j \leq K - 1, x = 1, y = 1$

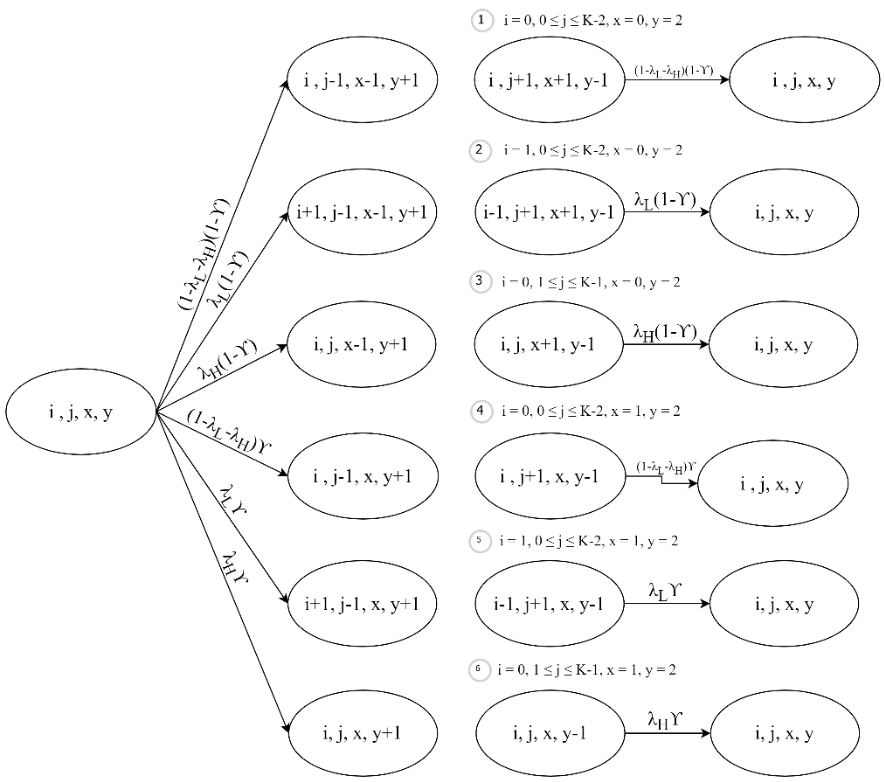


Fig 3. 9: The state diagram for $i = 0, 1 \leq j \leq K - 1, x = 1, y = 1$

(8) $i = 0, 1 \le j \le K-1, x = 1, y = 2$

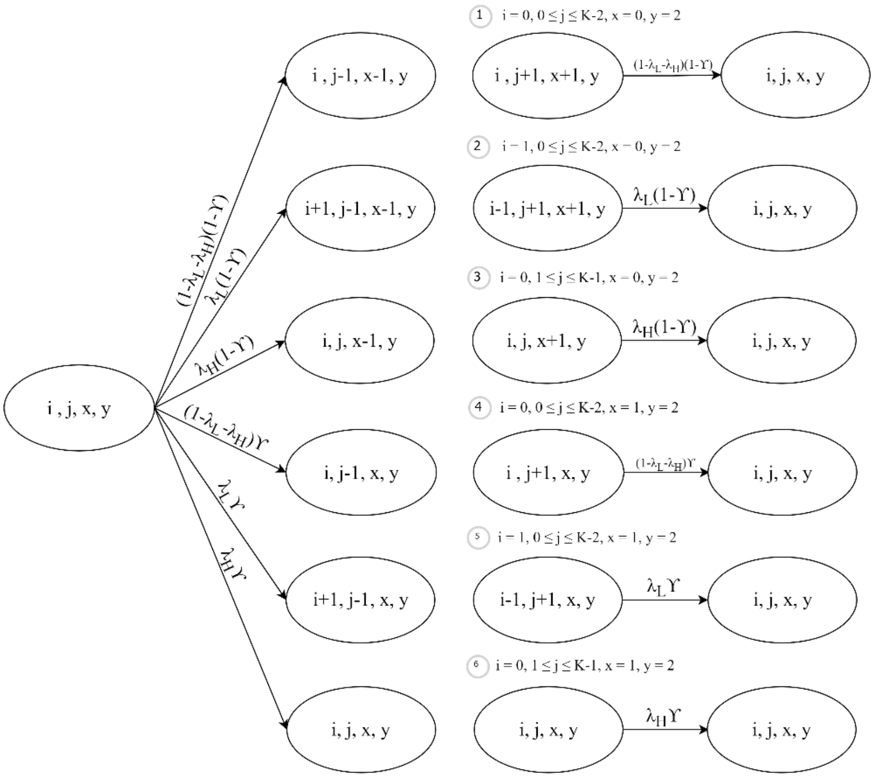


Fig 3. 10: The state diagram for $i = 0, 1 \le j \le K-1, x = 1, y = 2$

(9) $1 \le i \le K-1, j = 0, x = 1, y = 1$

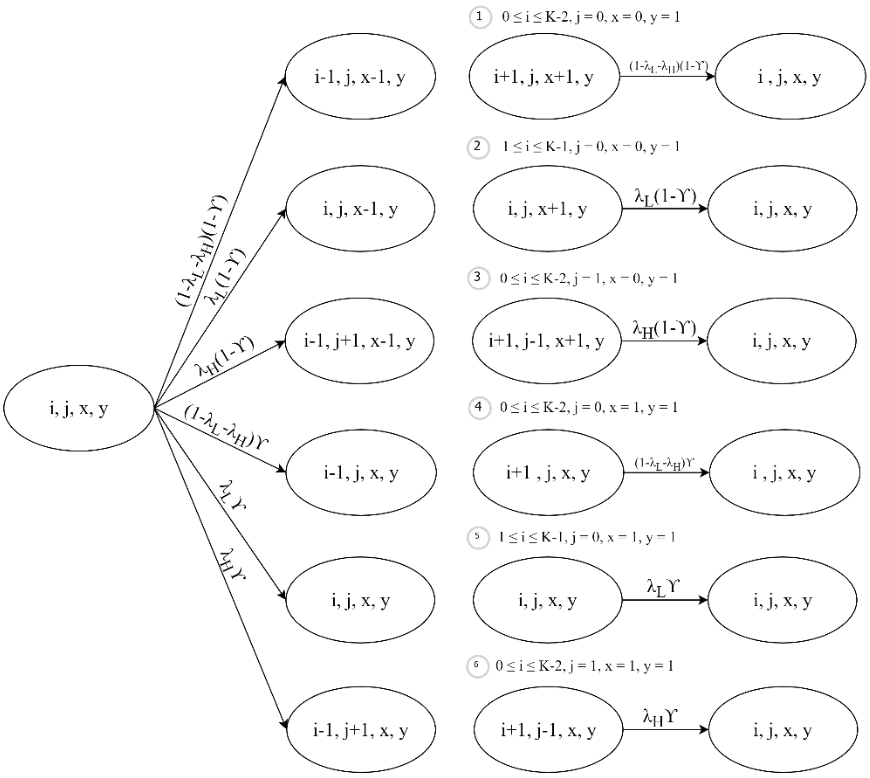


Fig 3. 11: The state diagram for $1 \le i \le K-1, j = 0, x = 1, y = 1$

(10) $1 \leq i \leq K-1, j=0, x=1, y=2$

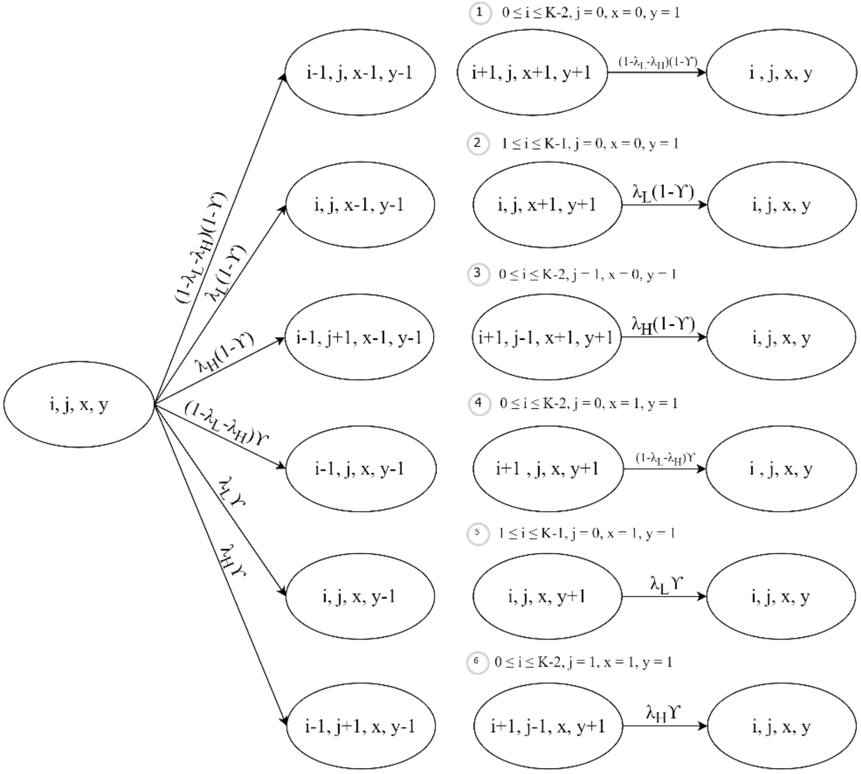
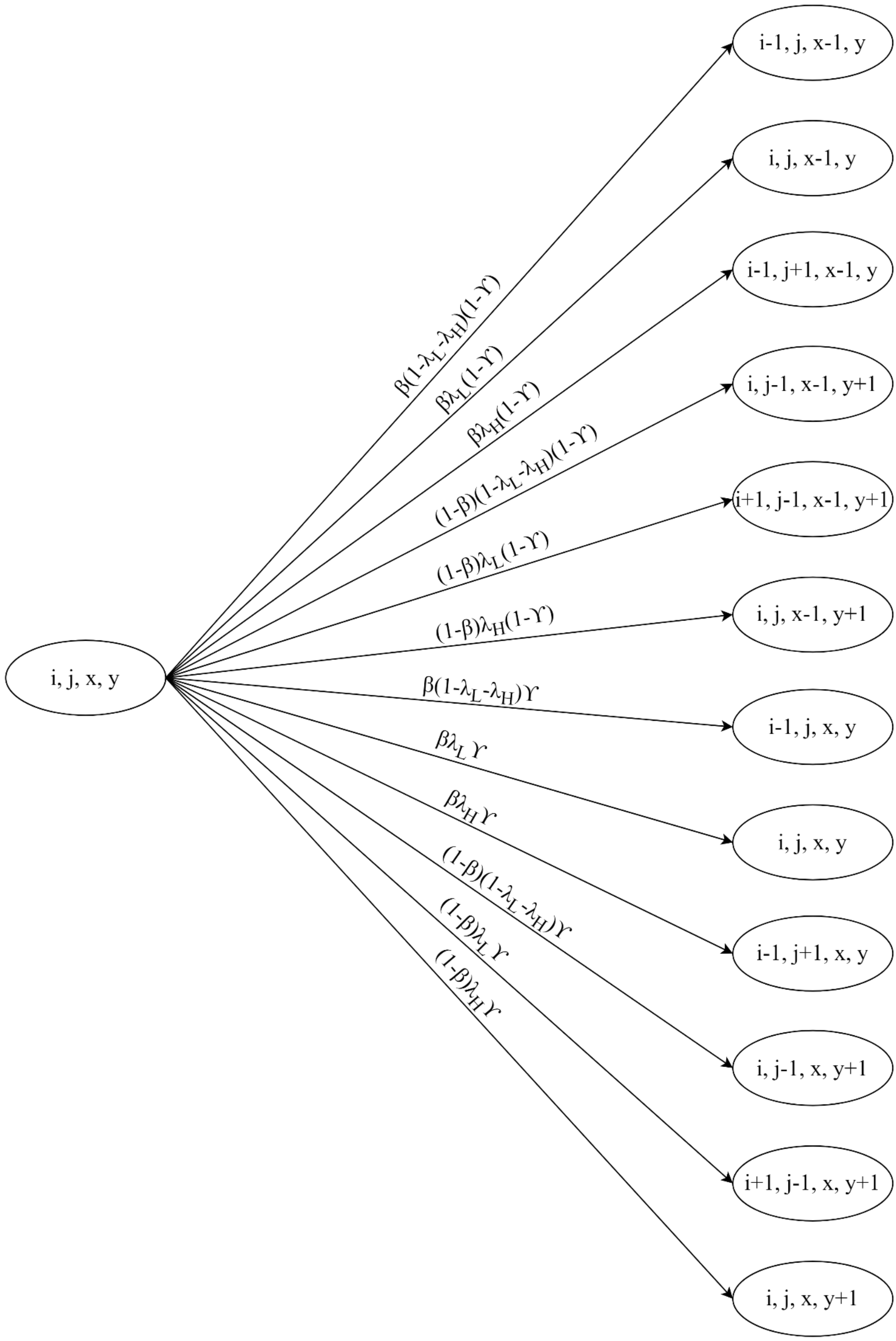


Fig 3. 12: The state diagram for $1 \leq i \leq K-1, j=0, x=1, y=2$

(11) $1 \le i \le K-2, ,1 \le j \le K-i-1, x=1, y=1$



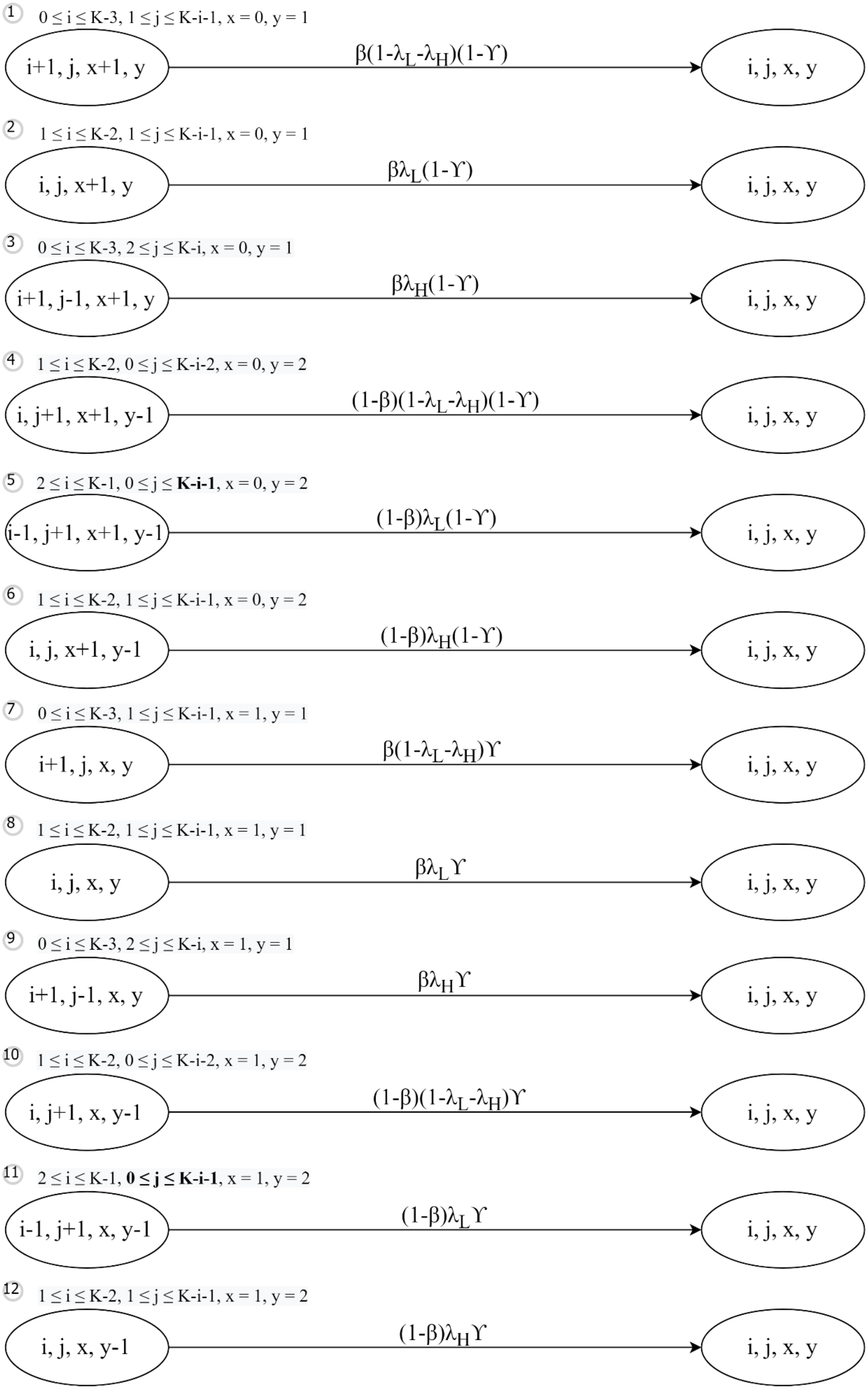
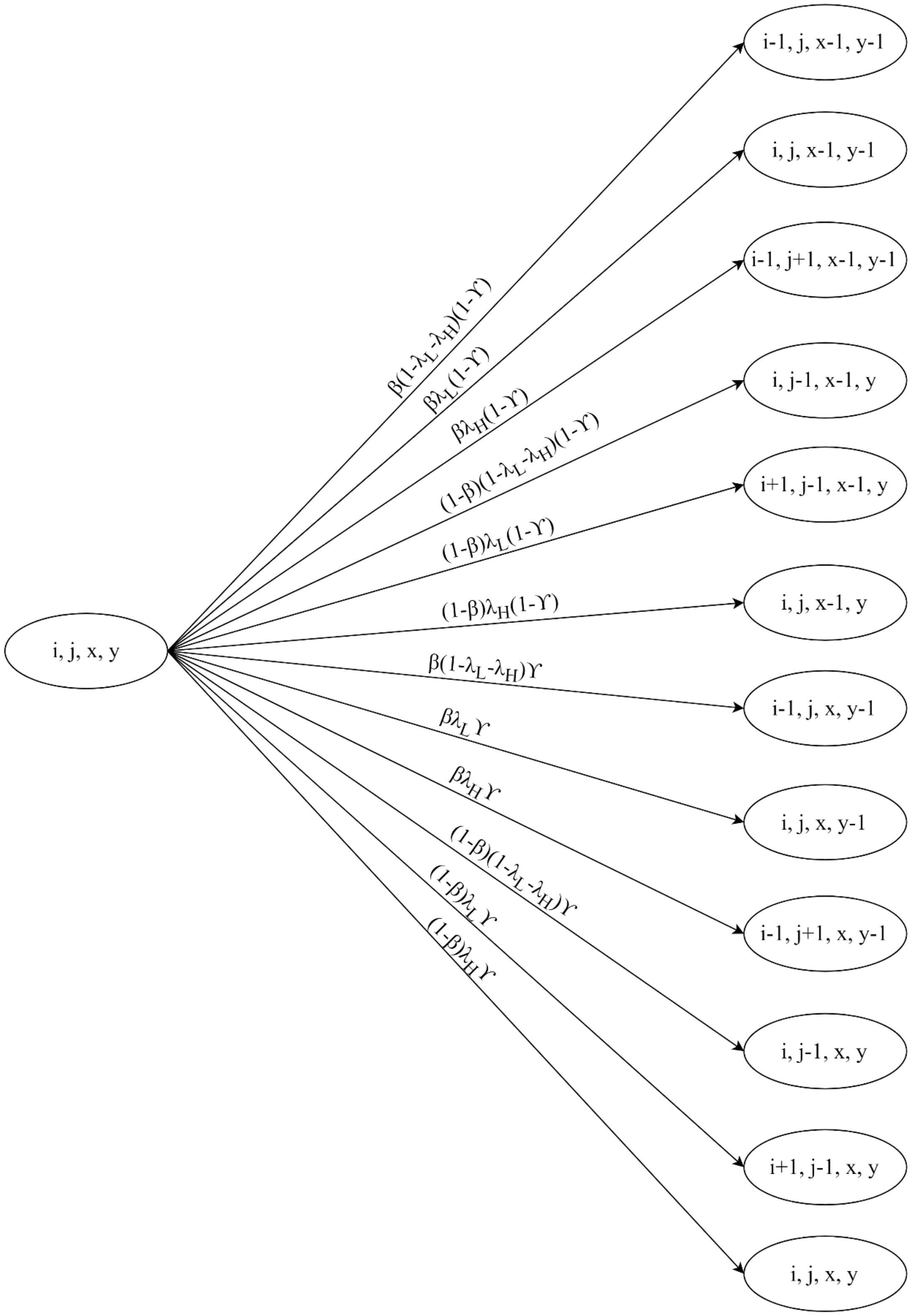


Fig 3. 13: The state diagram for $1 \leq i \leq K-2, ,1 \leq j \leq K-i-1, x=1, y=1$

$(12)\ 1 \leq i \leq K-2, ,1 \leq j \leq K-i-1, x=1, y=2$



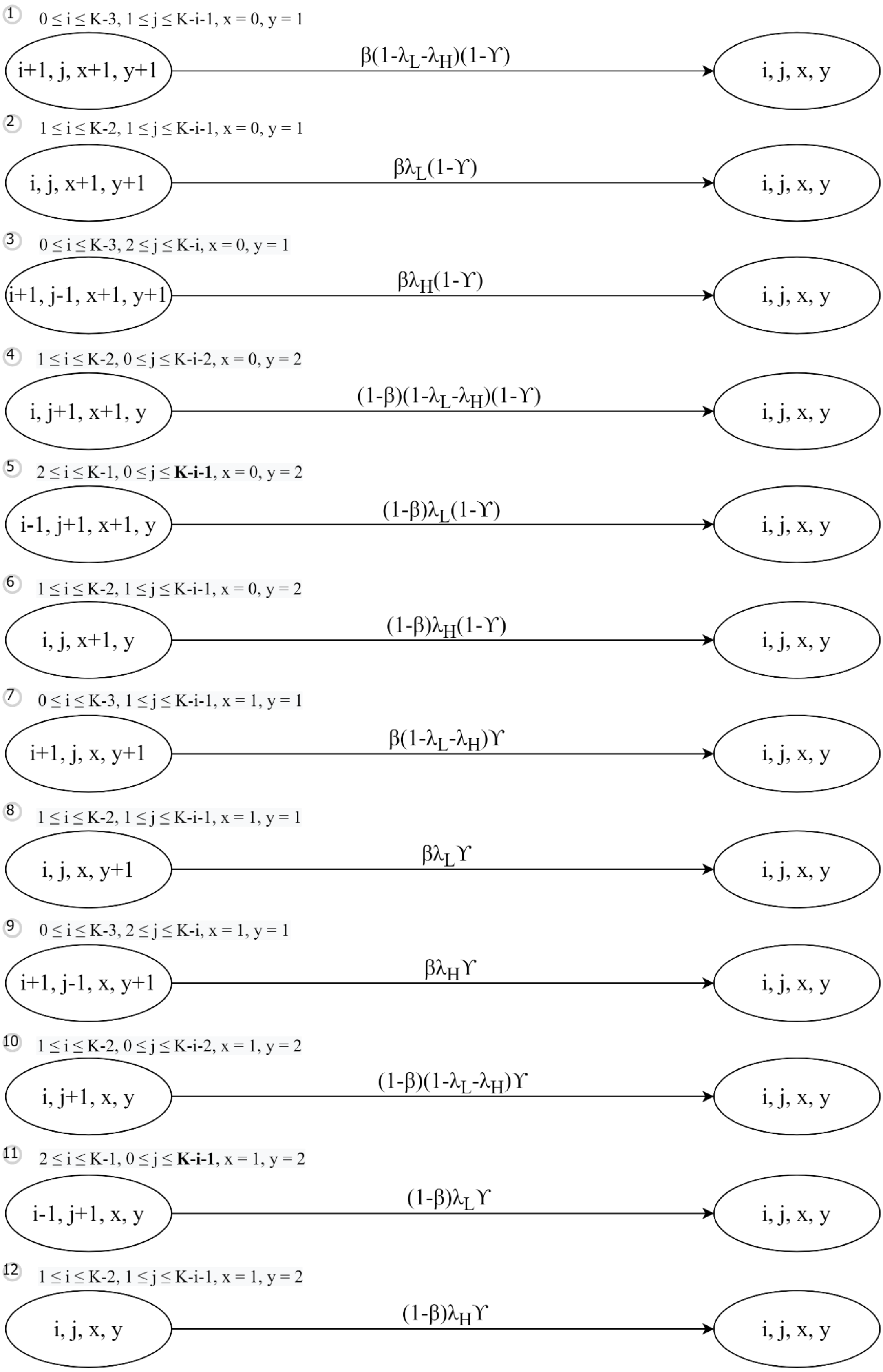


Fig 3. 14: The state diagram for $1 \leq i \leq K-2, , 1 \leq j \leq K-i-1, x=1, y=2$

(b) Priority discipline

(1) $i = 0, j = 0, x = 0, y = 0$

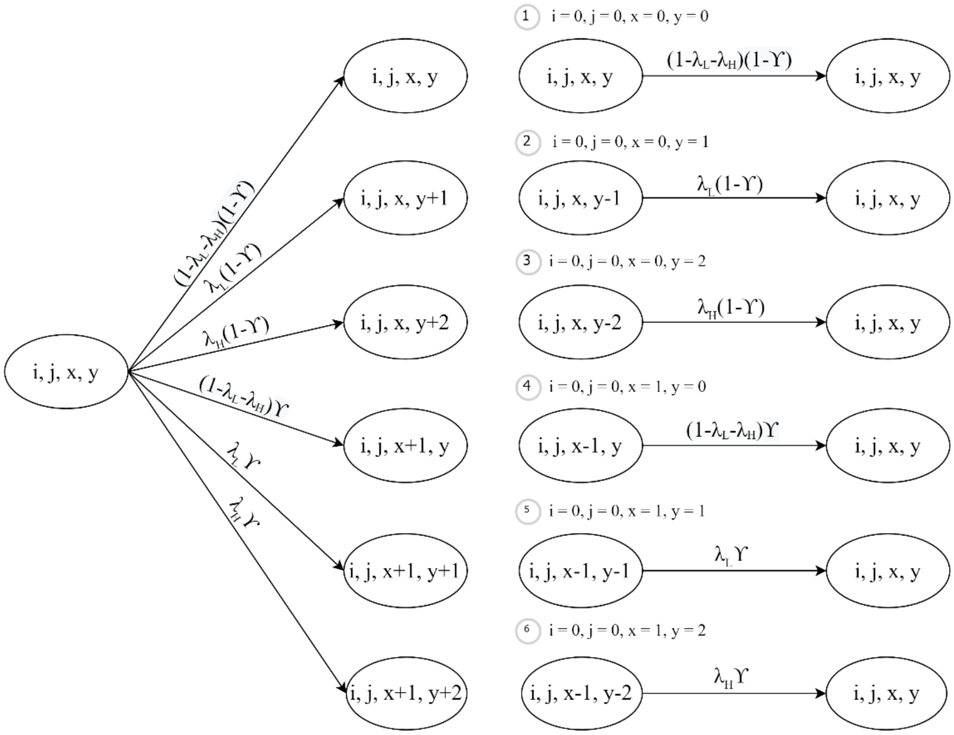


Fig 3. 15: The state diagram for $i = 0, j = 0, x = 0, y = 0$

(2) $0 \le i \le K-2, 0 \le j \le K-i-2, x = 0, y = 1$ 、2

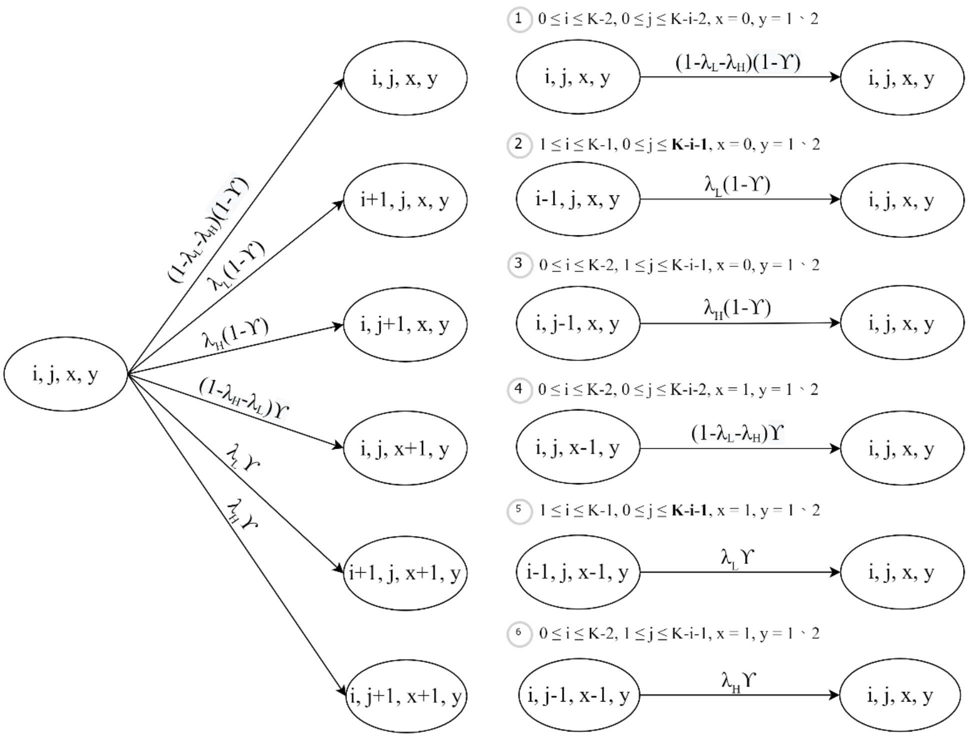


Fig 3. 16: The state diagram for $0 \le i \le K-2, 0 \le j \le K-i-2, x = 0, y = 1$ 、2

(3) $0 \le i \le K-1, j = K-i-1, x = 0, y = 1 、2$

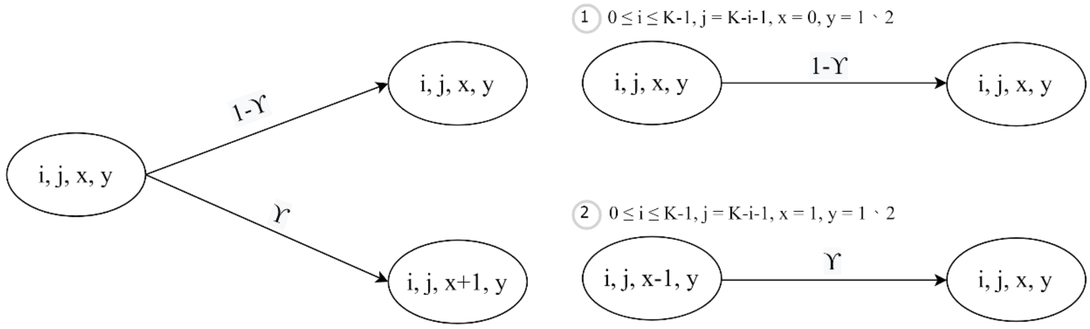


Fig 3. 17: The state diagram for $0 \le i \le K-1, j = K-i-1, x = 0, y = 1 、2$

(4) $i = 0, j = 0, x = 1, y = 0$

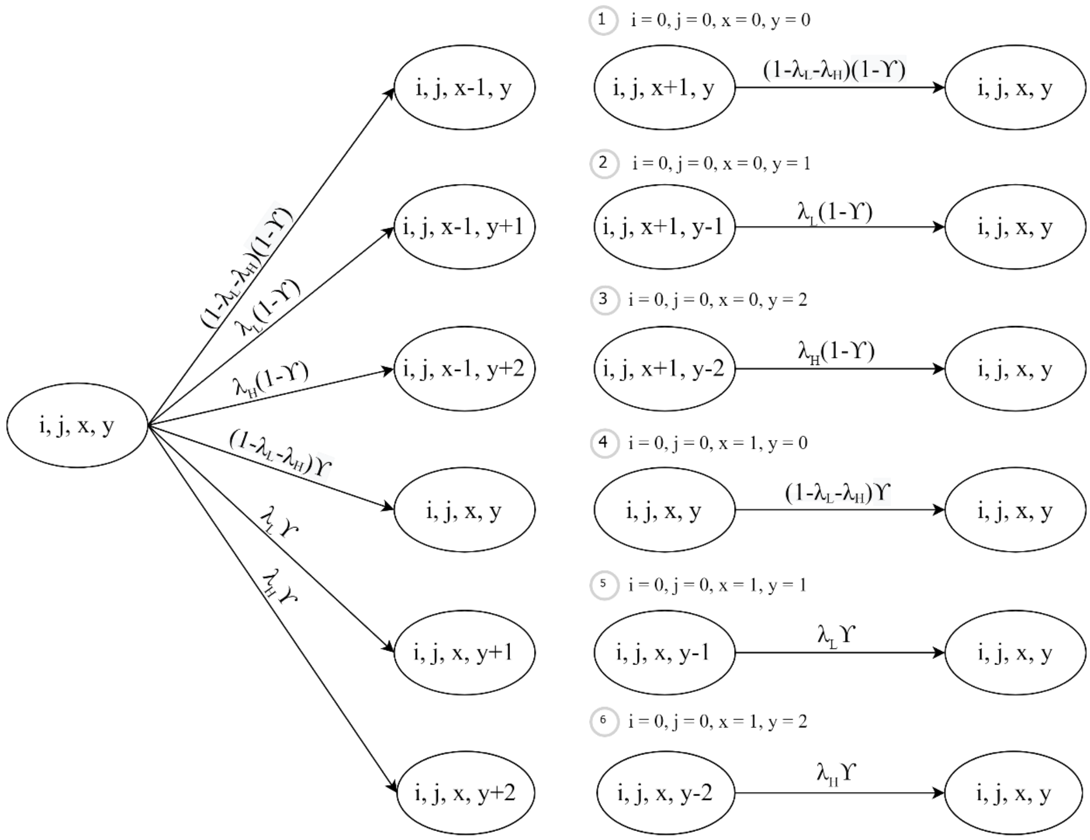


Fig 3. 18: The state diagram for $i = 0, j = 0, x = 1, y = 0$

(5) $i = 0, j = 0, x = 1, y = 1$

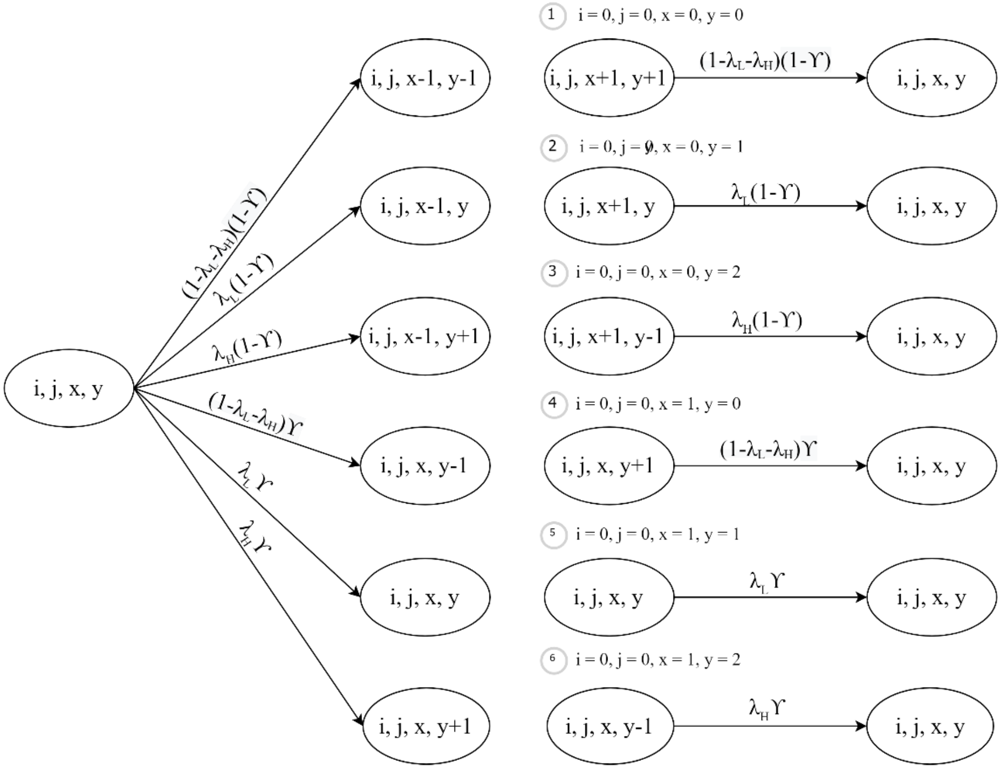


Fig 3. 19: The state diagram for $i = 0, j = 0, x = 1, y = 1$

(6) $i = 0, j = 0, x = 1, y = 2$

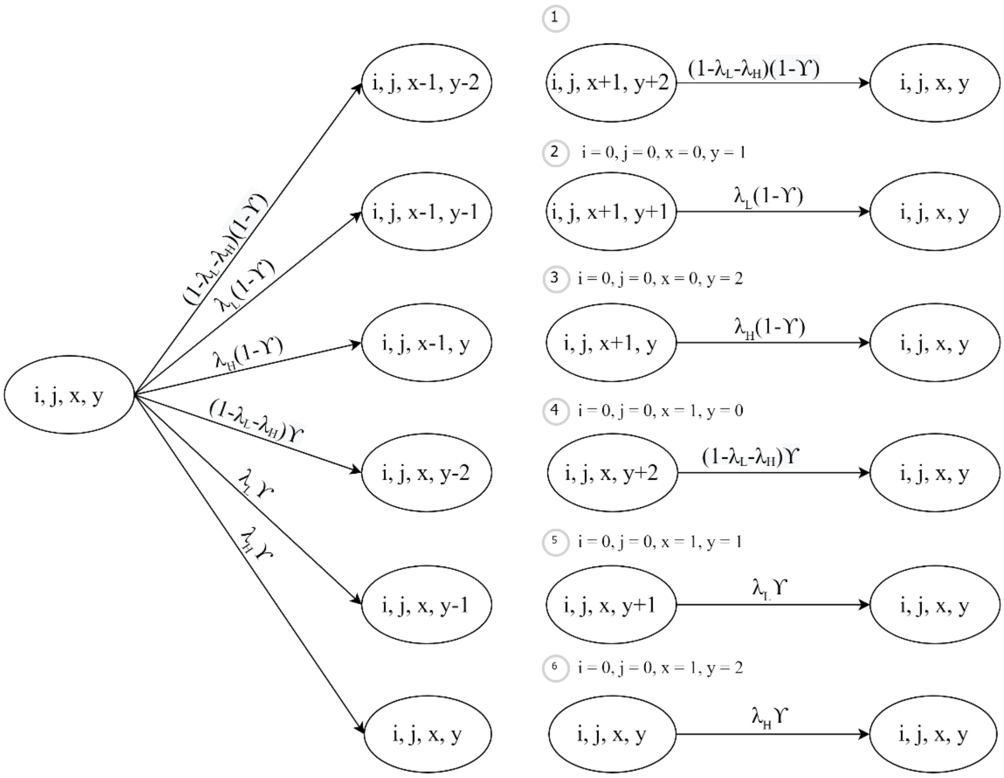


Fig 3. 20: The state diagram for $i = 0, j = 0, x = 1, y = 2$

(7) $i = 0, 1 \le j \le K-1, x = 1, y = 1$

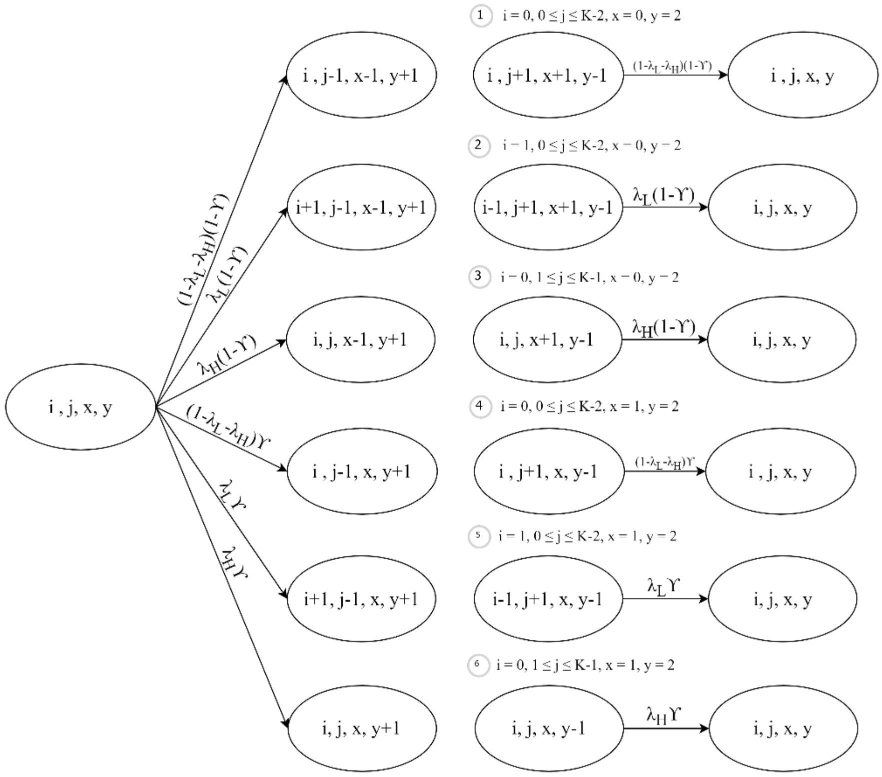


Fig 3. 21: The state diagram for $i = 0, 1 \le j \le K-1, x = 1, y = 1$

(8) $i = 0, 1 \le j \le K-1, x = 1, y = 2$

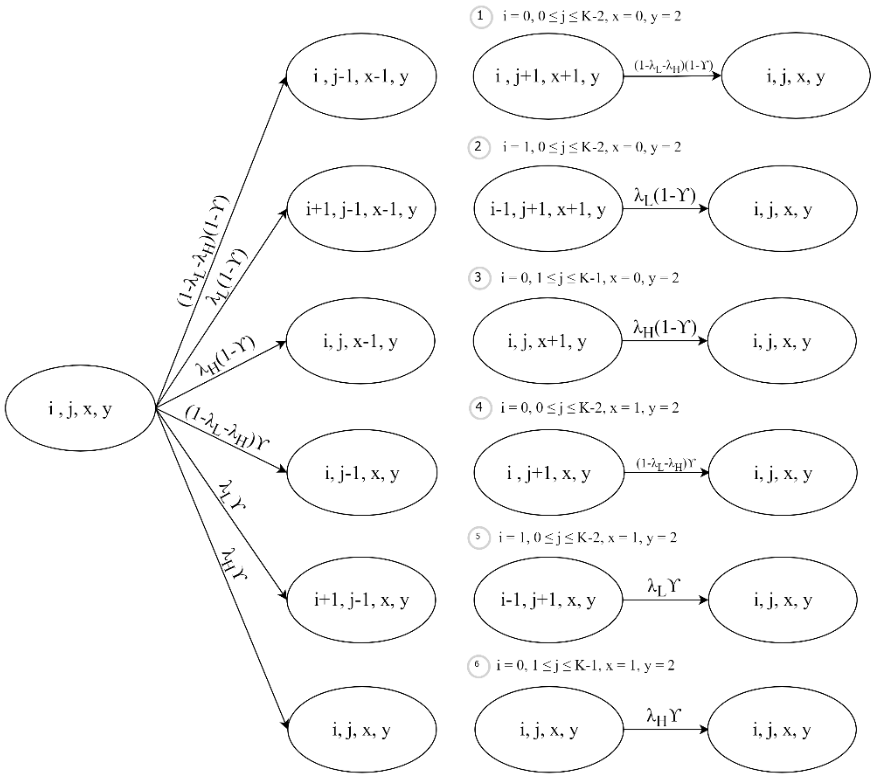


Fig 3. 22: The state diagram for $i = 0, 1 \le j \le K-1, x = 1, y = 2$

(9) $1 \le i \le K-1, j = 0, x = 1, y = 1$

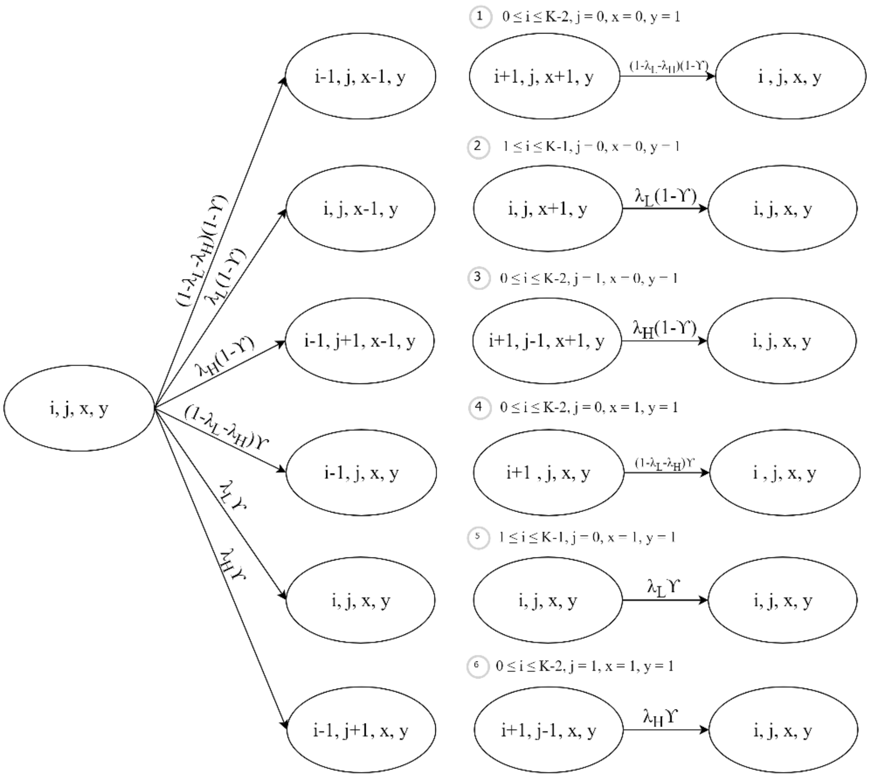


Fig 3. 23: The state diagram for $1 \le i \le K-1, j = 0, x = 1, y = 1$

(10) $1 \le i \le K-1, j = 0, x = 1, y = 2$

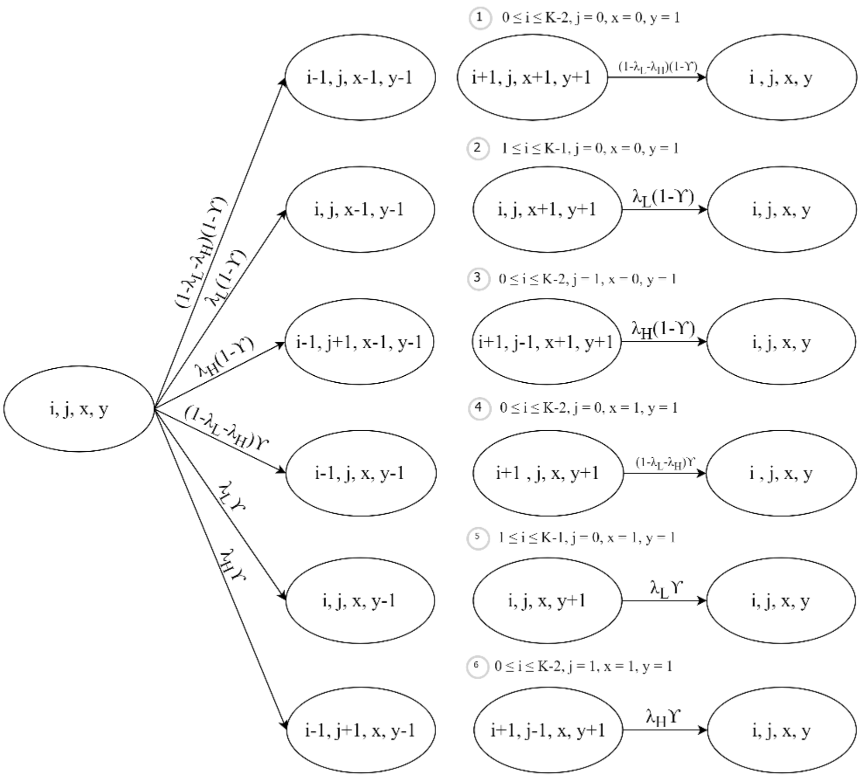
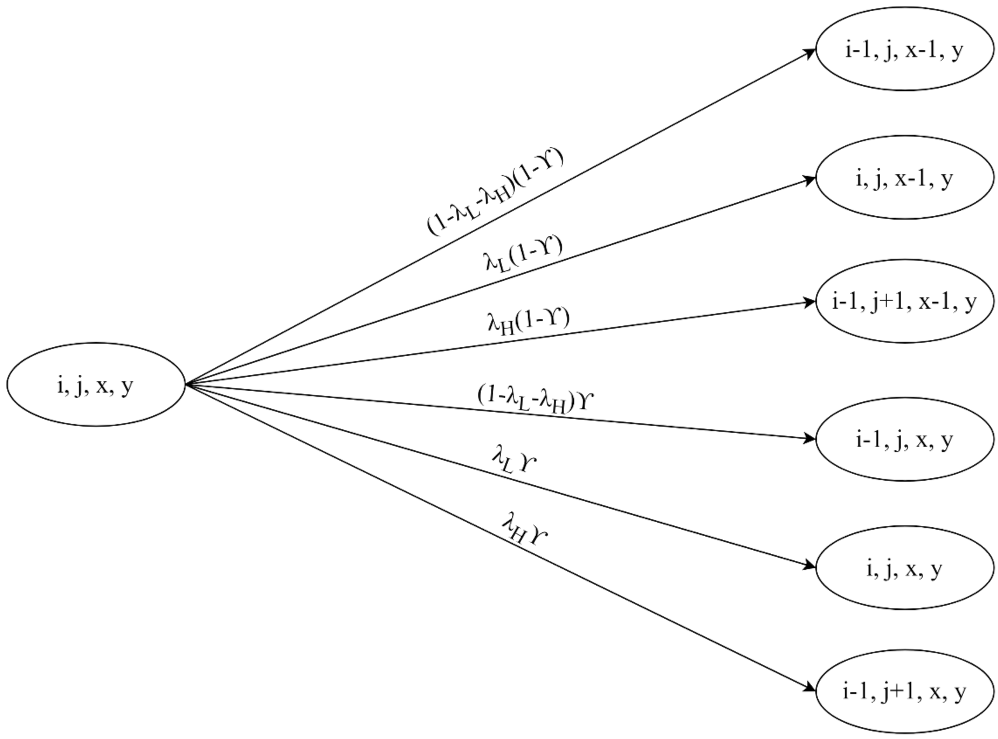


Fig 3. 24: The state diagram for $1 \le i \le K-1, j = 0, x = 1, y = 2$

(11) $1 \le i \le K-2, 1 \le j \le K-i-1, x=1, y=1$



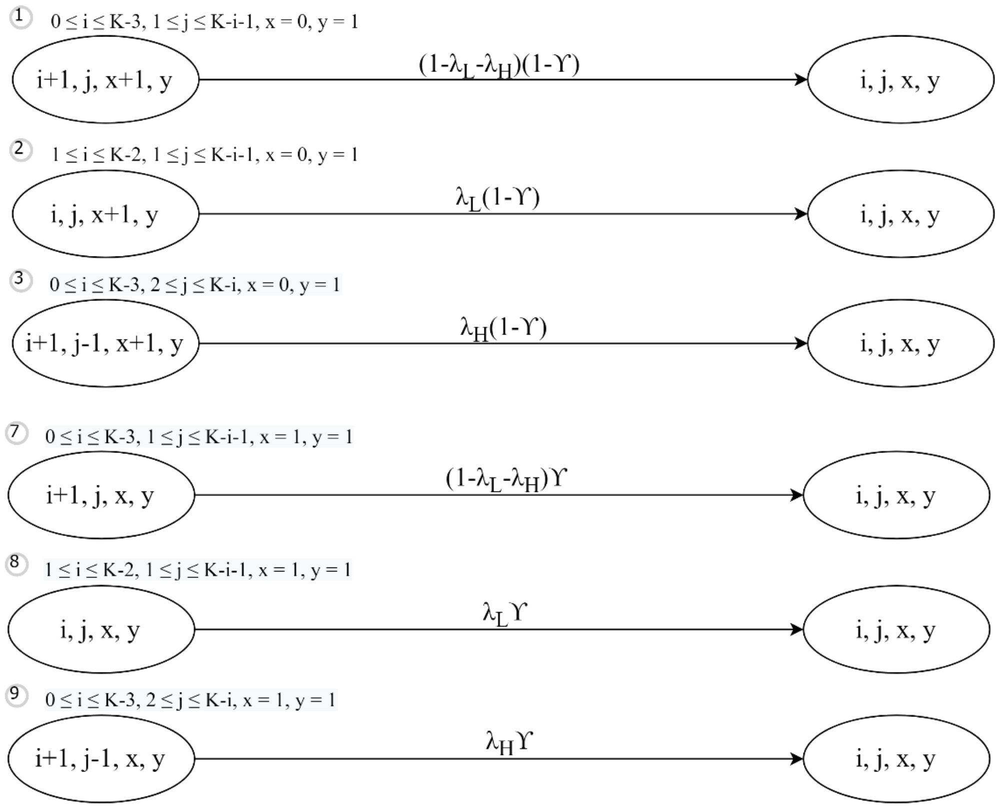
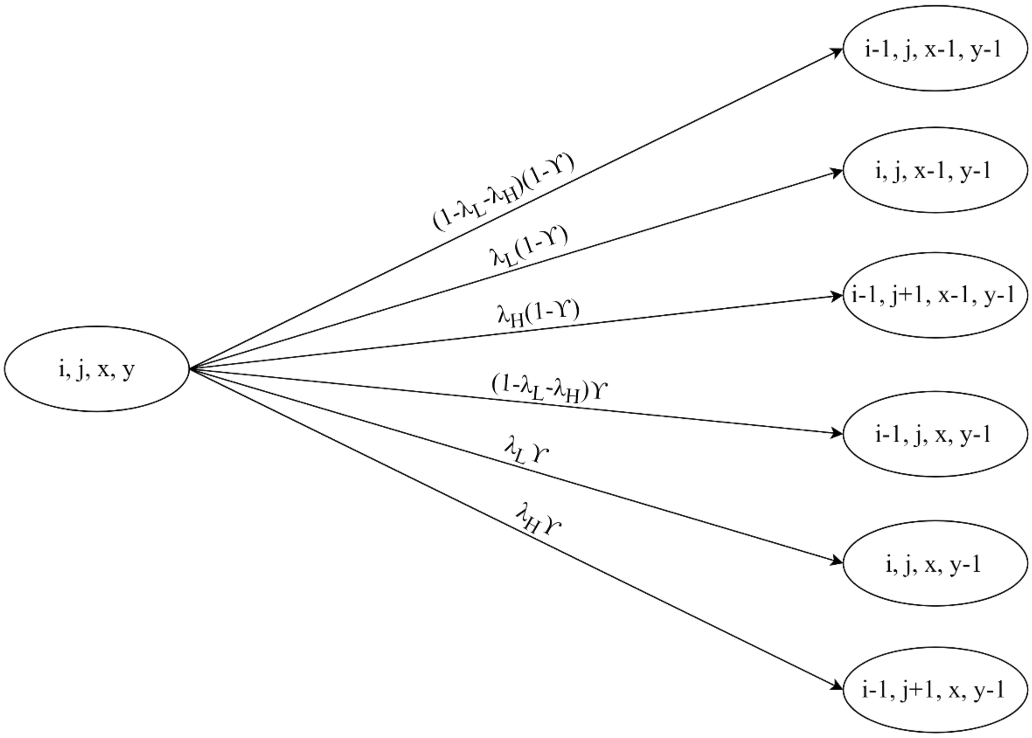


Fig 3. 25: The state diagram for $1 \le i \le K-2, 1 \le j \le K-i-1, x=1, y=1$

$(12)\ 1 \leq i \leq K-2, 1 \leq j \leq K-i-1, x=1, y=2$



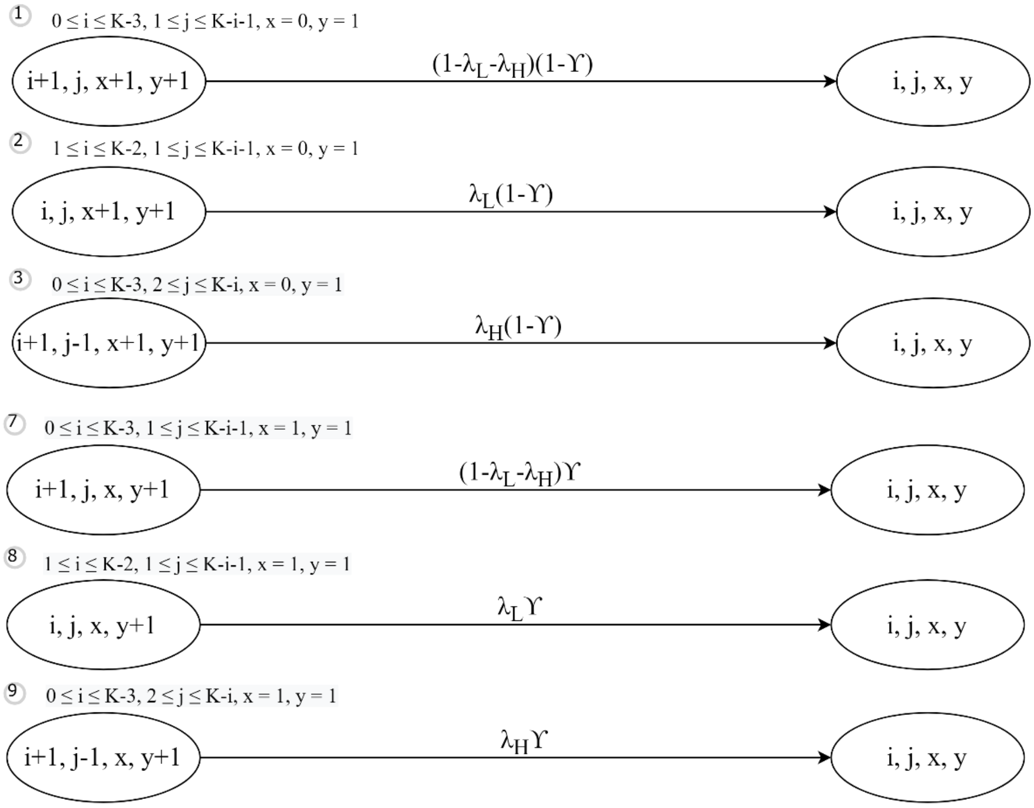


Fig 3. 26: The state diagram for $1 \leq i \leq K-2, 1 \leq j \leq K-i-1, x=1, y=2$

3.1.4 Iterative algorithm

In order to solve the state balance equations, we used the following iterative algorithm until the convergence is achieved. Consequently, we obtained the steady-state probability distribution of the system.

Iterative algorithm:

Step 1: Select the initial set of values for $\pi(i,j,x,y)^{old} = \frac{1}{|S|}$, $\forall i,j,x,y$, where $|S|$ is the total number of feasible states.

Step 2: Substitute $\pi(i,j,x,y)^{old}$ into Case 1 to Case 14 to find $\pi(i,j,x,y)^{new}$, $\forall i,j,x,y$.

Step 3: Normalize $\pi(i,j,x,y)^{new},\ \forall i,j,x,y$

Step 4: If $\sqrt{\sum\sum\sum\sum_{(i,j,x,y)\,\epsilon\, S}|\pi(i,j,x,y)^{old} - \pi(i,j,x,y)^{new}|^2} < \varepsilon$, stop the iteration, where ε is the stopping criterion. Otherwise, we set $\pi(i,j,x,y)^{old} = \pi(i,j,x,y)^{new}$ and return to step 2.

In our analytical analysis, the convergence criterion ε is set at $\varepsilon = 10^{-8}$, and the algorithm generally achieves convergence after about 200 iterations.

3.1.5 Performance index

In order to estimate the effectiveness of the whole system, we obtained various performance indices from the steady-state probability $\pi(i,j,x,y)$ which are summarized below.

First of all, the expected number of LBER (HBER) packets in the system, L_L (L_H), is given below.

$$L_L = \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}\sum_{y=0}^{2}[(i+1)\pi(i,j,x,1) + i\pi(i,j,x,2)] \qquad (3-4)$$

$$L_H = \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}\sum_{y=0}^{2}[j\pi(i,j,x,1) + (j+1)\pi(i,j,x,2)] \qquad (3-5)$$

The total number of packets in the system, L, is given below.

$$L = L_L + L_H \qquad (3-6)$$

Second, the expected number of LBER (HBER) packets in the queue L_{qL} (L_{qH}), is given below.

$$L_{qL} = \sum_{i=0}^{Q} \sum_{j=0}^{Q-i} \sum_{x=0}^{1} \sum_{y=0}^{2} i\pi(i,j,x,y) \tag{3-7}$$

$$L_{qH} = \sum_{i=0}^{Q} \sum_{j=0}^{Q-i} \sum_{x=0}^{1} \sum_{y=0}^{2} j\pi(i,j,x,y) \tag{3-8}$$

The summation of L_{qL} and L_{qH} will be the total number in queue L_q.

$$L_q = L_{qL} + L_{qH} \tag{3-9}$$

Third, the throughput of LBER (HBER) packets, TH_L (TH_H), is given below.

$$TH_L = \sum_{i=0}^{Q} \sum_{j=0}^{Q-i} \sum_{x=0}^{1} \gamma\pi(i,j,x,1) \tag{3-10}$$

$$TH_H = \sum_{i=0}^{Q} \sum_{j=0}^{Q-i} \sum_{x=0}^{1} \gamma\pi(i,j,x,2) \tag{3-11}$$

Thus, the throughput of the system, TH, is given below.

$$TH = \sum_{i=0}^{Q} \sum_{j=0}^{Q-i} \sum_{x=0}^{1} \sum_{y=1}^{2} \gamma\pi(i,j,x,y) \tag{3-12}$$

Fourth, the blocking probability of LBER (HBER) packets, P_{bL} (P_{bH}), is given below.

$$P_{bL} = \lambda_L \sum_{i=0}^{Q} \sum_{y=1}^{2} \pi(i,Q-i,0,y) \tag{3-13}$$

$$P_{bH} = \lambda_H \sum_{i=0}^{Q} \sum_{y=1}^{2} \pi(i,Q-i,0,y) \tag{3-14}$$

The blocking probability of the system, P_b, is given below.

$$P_b = \lambda \sum_{i=0}^{Q} \sum_{y=1}^{2} \pi(i, Q-i, 0, y) \tag{3-15}$$

Fifth, the average waiting time in the system, W, is given below.

$$W = \frac{L}{\lambda_{eff}} \tag{3-16}$$

$$\text{with } \lambda_{eff} = (1 - P_b)\lambda \tag{3-17}$$

Furthermore, the average waiting time of the LBER packets in the system, W_L, is given below.

$$W_L = \frac{L_L}{\lambda_{L\_eff}} \tag{3-18}$$

$$\text{with } \lambda_{L\_eff} = (1 - P_{bL})\lambda_L \tag{3-19}$$

On the other hand, the average waiting time of the HBER packets in the system, W_H, is given below.

$$W_H = \frac{L_H}{\lambda_{H\_eff}} \tag{3-20}$$

$$\text{with } \lambda_{H\_eff} = (1 - P_{bH})\lambda_H \tag{3-21}$$

Sixth, the average waiting time in queue, W_q, is given below.

$$W_q = \frac{L_q}{\lambda_{eff}} \tag{3-22}$$

The average waiting time in queue for LBER (HBER) packets is given below.

$$W_{qL} = \frac{L_{qL}}{\lambda_{eff}} \tag{3-23}$$

$$W_{qH} = \frac{L_{qH}}{\lambda_{eff}} \tag{3-24}$$

3.2. Adaptive Delivery Policy (ADP)

3.2.1 Model diagram

According to the results of PCCP, we find the transmission delay will be enormous due to the noisy environment. Thus, we try to do the trade-off between power consumption and time delay. We set the delivery probability α_L (α_H) for LBER (HBER) packets, respectively. While the channel is in state 0, i.e., $x[n] = 0$ in slot n, then the scheduler will detect the type of packet in the server and choose the corresponding delivery probability to transmit the packet. If the scheduler decides to transmit the packet in slot n, i.e., $S[n] = 1$, then the packet in the server will be transmitted no matter the channel is in state 0. Assume the system size is K, and the queue size is $K - 1$, and the arrival rates of LBER and HBER are λ_L and λ_H, respectively. Naturally, $0 < \lambda_L + \lambda_H < 1$. At the beginning of each slot, the channel will alter between state 0 and state 1 according to channel transition rate γ. In FIFO discipline, the probability that the HoL (head of line) packet is LBER can be obtained as follows:

$$\beta = nq_L / (nq_L + nq_H) \qquad (3-25)$$

(a) FIFO discipline

Table 3. 3: System parameter list of ADP with FIFO discipline

Parameters	Description
λ_L	Arrival rate of LBER packets at the queue
λ_H	Arrival rate of HBER packets at the queue
γ	The probability of good channel in each time slot
β	The probability of the HoL packet is LBER
nq_L	The number of LBER packets in queue
nq_H	The number of HBER packets in queue
α_L	The transmitted probability of LBER packet in state 0
α_H	The transmitted probability of HBER packet in state 0

(b) Priority discipline

Table 3. 4: System parameter list of ADP with priority discipline

Parameters	Description
$\boldsymbol{\lambda_L}$	Arrival rate of LBER packets at the queue
$\boldsymbol{\lambda_H}$	Arrival rate of HBER packets at the queue
$\boldsymbol{\gamma}$	The probability of good channel in each time slot
$\boldsymbol{\alpha_L}$	The transmitted probability of LBER packet in state 0
$\boldsymbol{\alpha_H}$	The transmitted probability of HBER packet in state 0

3.2.2 State balance equations

The system is modeled as a four-dimensional discrete time Markov chain with state (i, j, x, y), for both FIFO and priority disciplines, where i presents the number of LBER packets in queue, j presents the number of HBER packets in queue, x presents the channel state, and y presents the server state. While $x = 0$ means the channel state is bad (state 0), and $x = 1$ means the channel state is good (state 1). And $y = 0$ means there is no one in server, $y = 1$ means the LBER packet in server, and $y = 2$ means the HBER packet in server. The steady sate probability of the model is described as $\pi(i, j, x, y)$; thus, the state space can be denoted as follows:

$$S = \{(i, j, x, y) \mid 0 \le i \le Q, 0 \le j \le Q - i, 0 \le x \le 1, 0 \le y \le 2\} \qquad (3-26)$$

Hence, the number of feasible states is as follows:

$$|S| = 3(Q + 1)(Q + 2) \qquad (3-27)$$

Based on the assumption, we assume the Q is equal to 20, we can see the total number of feasible states is 1386. For both FIFO and priority disciplines, the feasible states can be classified into 32 cases as below.

(a) First-In-First-Out

Case 1 : $i = 0, j = 0, x = 0, y = 0$

$$\begin{aligned}\pi_{0,0,0,0} = {} & (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,0,0,0} + \alpha_L(1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,0,0,1} \\ & + \alpha_H(1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,0,0,2} + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,0,1,0} \\ & + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,0,1,1} + (1 - \lambda_L - \lambda_H)(1 - \gamma)\pi_{0,0,1,2}\end{aligned}$$

Case 2 : $i = 0, j = 0, x = 0, y = 1$

$$\begin{aligned}\pi_{0,0,0,1} = {} & \lambda_L(1-\gamma)\pi_{0,0,0,0} + (1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,0,0,1} \\ & + \alpha_L\lambda_L(1-\gamma)\pi_{0,0,0,1} + \alpha_L\lambda_L(1-\gamma)\pi_{0,0,0,2} \\ & + \alpha_L(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,0,0,1} + \alpha_H(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,0,0,2} \\ & + \lambda_L(1-\gamma)\pi_{0,0,1,0} + \lambda_L(1-\gamma)\pi_{0,0,1,1} + \lambda_L(1-\gamma)\pi_{0,0,1,2} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,0,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,0,1,2}\end{aligned}$$

Case 3 : $i = 0, j = 0, x = 0, y = 2$

$$\begin{aligned}\pi_{0,0,0,2} = {} & \lambda_H(1-\gamma)\pi_{0,0,0,0} + \alpha_L\lambda_H(1-\gamma)\pi_{0,0,0,1} \\ & + (1-\alpha_H)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,0,0,2} + \alpha_H\lambda_H(1-\gamma)\pi_{0,0,0,2} \\ & + \alpha_L(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,0,1} + \alpha_H(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,0,2} \\ & + \lambda_H(1-\gamma)\pi_{0,0,1,0} + \lambda_H(1-\gamma)\pi_{0,0,1,1} + \lambda_H(1-\gamma)\pi_{0,0,1,2} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,1,2}\end{aligned}$$

Case 4 : $i = 0, 1 \le j \le K-2, x = 0, y = 1$

$$\begin{aligned}\pi_{0,j,0,1} = {} & (1-\alpha_L)\lambda_H(1-\gamma)\pi_{0,0,0,1} + (1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,1} \\ & + (1-\alpha_L)\lambda_H(1-\gamma)\pi_{0,j-1,0,1} + \alpha_L\lambda_H(1-\gamma)\pi_{1,0,0,1} \\ & + \alpha_H\lambda_H(1-\gamma)\pi_{1,0,0,2} + \alpha_L\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,1} \\ & + \alpha_L\beta\lambda_H(1-\gamma)\pi_{1,j-1,0,1} + \alpha_H\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,2} \\ & + \alpha_H\beta\lambda_H(1-\gamma)\pi_{1,j-1,0,2} + \alpha_L\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,1} \\ & + \lambda_H(1-\gamma)\pi_{1,0,1,1} + \lambda_H(1-\gamma)\pi_{1,0,1,2} + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,1,1} \\ & + \beta\lambda_H(1-\gamma)\pi_{1,j-1,1,1} + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,1,2} \\ & + \beta\lambda_H(1-\gamma)\pi_{1,j-1,1,2}\end{aligned}$$

Case 5 : $i = 0, 1 \le j \le K-2, x = 0, y = 2$

$$\begin{aligned}\pi_{0,j,0,2} = {} & (1-\alpha_H)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,2} + (1-\alpha_H)\lambda_H(1-\gamma)\pi_{0,j-1,0,2} \\ & + \alpha_L(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,1} + \alpha_L\lambda_H(1-\gamma)\pi_{0,j,0,1} \\ & + \alpha_H(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,2} + \alpha_H\lambda_H(1-\gamma)\pi_{0,j,0,2} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,1} + \lambda_H(1-\gamma)\pi_{0,j,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,2} + \lambda_H(1-\gamma)\pi_{0,j,1,2}\end{aligned}$$

Case 6 : $1 \le i \le K-2, j=0, x=0, y=1$

$$\begin{aligned}\pi_{i,0,0,1} = {} & (1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,1} + (1-\alpha_L)\lambda_L(1-\gamma)\pi_{i-1,0,0,1} \\ & + \alpha_L(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,0,1} + \alpha_L\lambda_L(1-\gamma)\pi_{i,0,0,1} \\ & + \alpha_H\lambda_L(1-\gamma)\pi_{i+1,0,0,2} + \alpha_H\lambda_L(1-\gamma)\pi_{i,0,0,2} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,1} + \lambda_L(1-\gamma)\pi_{i,0,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,2} + \lambda_L(1-\gamma)\pi_{i,0,1,2}\end{aligned}$$

Case 7 : $1 \le i \le K-2, j=0, x=0, y=2$

$$\begin{aligned}\pi_{i,0,0,2} = {} & (1-\alpha_H)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,2} + (1-\alpha_H)\lambda_L(1-\gamma)\pi_{i-1,0,0,2} \\ & + \alpha_L(1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i-1,1,0,1} \\ & + \alpha_L(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,0,1} + \alpha_H(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,0,2} \\ & + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,1,1,1} + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,1,1} \\ & + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,1,1,2} + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,1,2}\end{aligned}$$

Case 8 : $i=0, j=K-1, x=0, y=1$

$$\begin{aligned}\pi_{0,j,0,1} = {} & (1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,1} + (1-\alpha_L)\lambda_H(1-\gamma)\pi_{0,j-1,0,1} \\ & + \alpha_L\beta\lambda_H(1-\gamma)\pi_{1,j-1,0,1} + \alpha_H\beta\lambda_H(1-\gamma)\pi_{1,j-1,0,2} \\ & + \beta\lambda_H(1-\gamma)\pi_{1,j-1,1,1} + \beta\lambda_H(1-\gamma)\pi_{1,j-1,1,2}\end{aligned}$$

Case 9 : $i=0, j=K-1, x=0, y=2$

$$\begin{aligned}\pi_{0,j,0,2} = {} & (1-\alpha_H)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,2} + (1-\alpha_H)\lambda_H(1-\gamma)\pi_{0,j-1,0,2} \\ & + \alpha_L(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,1} + \alpha_L\lambda_H(1-\gamma)\pi_{0,j,0,1} \\ & + \alpha_H(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,2} + \alpha_H\lambda_H(1-\gamma)\pi_{0,j,0,2} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,1} + \lambda_H(1-\gamma)\pi_{0,j,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,2} + \lambda_H(1-\gamma)\pi_{0,j,1,2}\end{aligned}$$

Case 10 : $i=K-1, j=0, x=0, y=1$

$$\begin{aligned}\pi_{i,0,0,1} = {} & (1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,1} + (1-\alpha_L)\lambda_L(1-\gamma)\pi_{i-1,0,0,1} \\ & + \alpha_L(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,0,1} + \alpha_L\lambda_L(1-\gamma)\pi_{i,0,0,1} \\ & + \alpha_H(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,0,2} + \alpha_H\lambda_L(1-\gamma)\pi_{i,0,0,2} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,1} + \lambda_L(1-\gamma)\pi_{i,0,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,2} + \lambda_L(1-\gamma)\pi_{i,0,1,2}\end{aligned}$$

Case 11 : $i = K - 1, j = 0, x = 0, y = 2$

$$\begin{aligned}\pi_{i,0,0,2} = {} & (1-\alpha_H)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,2} + (1-\alpha_H)\lambda_L(1-\gamma)\pi_{i-1,0,0,2} \\ & + \alpha_L(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,0,1} + \alpha_H(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,0,2} \\ & + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,1,1} + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,1,2}\end{aligned}$$

Case 12 : $1 \le i \le K - 2, 1 \le j \le K - i - 2, x = 0, y = 1$

$$\begin{aligned}\pi_{i,j,0,1} = {} & (1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,1} + (1-\alpha_L)\lambda_L(1-\gamma)\pi_{i-1,j,0,1} \\ & + (1-\alpha_L)\lambda_H(1-\gamma)\pi_{i,j-1,0,1} + \alpha_L\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,1} \\ & + \alpha_L\beta\lambda_L(1-\gamma)\pi_{i,j,0,1} + \alpha_L\beta\lambda_H(1-\gamma)\pi_{i+1,j-1,0,1} \\ & + \alpha_H\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,2} + \alpha_H\beta\lambda_L(1-\gamma)\pi_{i,j,0,2} \\ & + \alpha_H\beta\lambda_L(1-\gamma)\pi_{i+1,j-1,0,2} + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,1} \\ & + \beta\lambda_L(1-\gamma)\pi_{i,j,1,1} + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,1} \\ & + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,2} + \beta\lambda_L(1-\gamma)\pi_{i,j,1,2} \\ & + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 13 : $1 \le i \le K - 2, 1 \le j \le K - i - 2, x = 0, y = 2$

$$\begin{aligned}\pi_{i,j,0,2} = {} & (1-\alpha_H)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,2} + (1-\alpha_H)\lambda_L(1-\gamma)\pi_{i-1,j,0,2} \\ & + (1-\alpha_H)\lambda_H(1-\gamma)\pi_{i,j-1,0,2} \\ & + \alpha_L(1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,0,1} \\ & + \alpha_L(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,0,1} + \alpha_L(1-\beta)\lambda_H(1-\gamma)\pi_{i,j,0,1} \\ & + \alpha_H(1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,0,2} \\ & + \alpha_H(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,0,2} + \alpha_H(1-\beta)\lambda_H(1-\gamma)\pi_{i,j,0,2} \\ & + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,1,1} + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,1,1} \\ & + (1-\beta)\lambda_H(1-\gamma)\pi_{i,j,1,1} + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,1,2} \\ & + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,1,2} + (1-\beta)\lambda_H(1-\gamma)\pi_{i,j,1,2}\end{aligned}$$

Case 14 : $1 \le i \le K-2, j = K-i-1, x = 0, y = 1$

$$\pi_{i,j,0,1} = (1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,1} + (1-\alpha_L)\lambda_L(1-\gamma)\pi_{i-1,j,0,1} + (1-\alpha_L)\lambda_H(1-\gamma)\pi_{i,j-1,0,1} + \alpha_L\beta\lambda_L(1-\gamma)\pi_{i,j,0,1} + \alpha_L\beta\lambda_H(1-\gamma)\pi_{i+1,j-1,0,1} + \alpha_H\beta\lambda_L(1-\gamma)\pi_{i,j,0,2} + \alpha_H\beta\lambda_H(1-\gamma)\pi_{i+1,j-1,0,2} + \beta\lambda_L(1-\gamma)\pi_{i,j,1,1} + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,1} + \beta\lambda_L(1-\gamma)\pi_{i,j,1,2} + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,2}$$

Case 15 : $1 \le i \le K-2, j = K-i-1, x = 0, y = 2$

$$\pi_{i,j,0,2} = (1-\alpha_H)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,2} + (1-\alpha_H)\lambda_L(1-\gamma)\pi_{i-1,j,0,2} + (1-\alpha_H)\lambda_H(1-\gamma)\pi_{i,j-1,0,2} + \alpha_L(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,0,1} + \alpha_L(1-\beta)\lambda_H(1-\gamma)\pi_{i,j,0,1} + \alpha_H(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,0,2} + \alpha_H(1-\beta)\lambda_H(1-\gamma)\pi_{i,j,0,2} + (1-\beta)\lambda_L(1-\gamma)\pi_{i,j,1,1} + (1-\beta)\lambda_H(1-\gamma)\pi_{i+1,j-1,1,1} + (1-\beta)\lambda_L(1-\gamma)\pi_{i,j,1,2} + (1-\beta)\lambda_H(1-\gamma)\pi_{i+1,j-1,1,2}$$

Case 16 : $i = 0, j = 0, x = 1, y = 0$

$$\pi_{0,0,1,0} = (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,0} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,0} + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,1} + \alpha_H(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,2}$$

Case 17 : $i = 0, j = 0, x = 1, y = 1$

$$\pi_{0,0,1,1} = (1-\alpha_L)(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,0,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,0,1,2} + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{1,0,0,1} + \alpha_H(1-\lambda_L-\lambda_H)\gamma\pi_{1,0,0,2} + \lambda_L\gamma\pi_{0,0,0,0}$$

Case 18 : $i = 0, j = 0, x = 1, y = 2$

$$\pi_{0,0,1,2} = (1-\alpha_H)(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,1,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,1,1,2} + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{0,1,0,1} + \alpha_H(1-\lambda_L-\lambda_H)\gamma\pi_{0,1,0,2} + \lambda_H\gamma\pi_{0,0,0,0}$$

Case 19 : $i = 0, 1 \le j \le K-1, x = 1, y = 1$

$$\pi_{0,j,1,1} = (1-\alpha_L)(1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,1} + (1-\alpha_L)\lambda_H\gamma\pi_{0,j-1,0,1} + \alpha_L\beta\lambda_H\gamma\pi_{1,j-1,0,1} + \alpha_H\beta\lambda_H\gamma\pi_{1,j-1,0,2} + \alpha_L\beta(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,1} + \alpha_H\beta(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,2} + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,1,1} + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,1,2} + \beta\lambda_H\gamma\pi_{1,j-1,1,1} + \beta\lambda_H\gamma\pi_{1,j-1,1,2}$$

Case 20 : $i = 0, 1 \le j \le K-1, x = 1, y = 2$

$$\pi_{0,j,1,2} = (1-\alpha_H)(1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,2} + (1-\alpha_H)\lambda_H\gamma\pi_{0,j-1,0,2} + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,0,1} + \alpha_H(1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,0,2} + \alpha_L\lambda_H\gamma\pi_{0,j,0,1} + \alpha_H\lambda_H\gamma\pi_{0,j,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,1,2} + \lambda_H\gamma\pi_{0,j,1,1} + \lambda_H\gamma\pi_{0,j,1,2}$$

Case 21 : $1 \le i \le K-1, j = 0, x = 1, y = 1$

$$\pi_{i,0,1,1} = (1-\alpha_L)(1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,1} + (1-\alpha_L)\lambda_L\gamma\pi_{i-1,0,0,1} + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,0,1} + \alpha_H(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,0,2} + \alpha_L\lambda_L\gamma\pi_{i,0,0,1} + \alpha_H\lambda_L\gamma\pi_{i,0,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,1,2} + \lambda_L\gamma\pi_{i,0,1,1} + \lambda_L\gamma\pi_{i,0,1,2}$$

Case 22 : $1 \le i \le K-1, j = 0, x = 1, y = 2$

$$\pi_{i,0,1,2} = (1-\alpha_H)(1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,2} + (1-\alpha_H)\lambda_L\gamma\pi_{i-1,0,0,2} + \alpha_L(1-\beta)\lambda_L\gamma\pi_{i-1,1,0,1} + \alpha_H(1-\beta)\lambda_L\gamma\pi_{i-1,1,0,2} + \alpha_L(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,1,0,1} + \alpha_H(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,1,0,2} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,1,1,1} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,1,1,2} + (1-\beta)\lambda_L\gamma\pi_{i-1,1,1,1} + (1-\beta)\lambda_L\gamma\pi_{i-1,1,1,2}$$

Case 23 : $1 \le i \le K-2, 1 \le j \le K-i-1, x = 1, y = 1$

$$\pi_{i,j,1,1} = (1-\alpha_L)(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,1} + \alpha_L\beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,1} + \alpha_H\beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,2} + \alpha_L\beta\lambda_L\gamma\pi_{i,j,0,1} + \alpha_L\beta\lambda_H\gamma\pi_{i+1,j-1,0,1} + \alpha_H\beta\lambda_L\gamma\pi_{i,j,0,2} + \alpha_H\beta\lambda_H\gamma\pi_{i+1,j-1,0,2} + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,1} + \beta\lambda_L\gamma\pi_{i,j,1,1} + \beta\lambda_H\gamma\pi_{i+1,j-1,1,1} + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,2} + \beta\lambda_L\gamma\pi_{i,j,1,2} + \beta\lambda_H\gamma\pi_{i+1,j-1,1,2}$$

Case 24 : $1 \leq i \leq K-2, 1 \leq j \leq K-i-1, x=1, y=2$

$$\pi_{i,j,1,2} = (1-\alpha_H)(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,2} + \alpha_L(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,0,1} + \alpha_H(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,0,2} + \alpha_L(1-\beta)\lambda_L\gamma\pi_{i-1,j+1,0,1} + \alpha_L(1-\beta)\lambda_H\gamma\pi_{i,j,0,1} + \alpha_H(1-\beta)\lambda_L\gamma\pi_{i-1,j+1,0,2} + \alpha_H(1-\beta)\lambda_H\gamma\pi_{i,j,0,2} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,1,1} + (1-\beta)\lambda_L\gamma\pi_{i-1,j+1,1,1} + (1-\beta)\lambda_H\gamma\pi_{i,j,1,1} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,1,2} + (1-\beta)\lambda_L\gamma\pi_{i-1,j+1,1,2} + (1-\beta)\lambda_H\gamma\pi_{i,j,1,2}$$

(b) Priority discipline

Case 1 : $i=0, j=0, x=0, y=0$

$$\pi_{0,0,0,0} = (1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,0,0} + \alpha_L(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,0,1} + \alpha_H(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,1,0} + (1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,1,2}$$

Case 2 : $i=0, j=0, x=0, y=1$

$$\pi_{0,0,0,1} = \lambda_L(1-\gamma)\,\pi_{0,0,0,0} + (1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,0,1} + \alpha_L\lambda_L(1-\gamma)\,\pi_{0,0,0,1} + \alpha_H\lambda_L(1-\gamma)\,\pi_{0,0,0,2} + \alpha_L(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{1,0,0,1} + \alpha_H(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{1,0,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,0,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,0,1,2} + \lambda_L(1-\gamma)\pi_{0,0,1,1} + \lambda_L(1-\gamma)\pi_{0,0,1,2}$$

Case 3 : $i=0, j=0, x=0, y=2$

$$\pi_{0,0,0,2} = \lambda_H(1-\gamma)\,\pi_{0,0,0,0} + (1-\alpha_H)(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,0,2} + \alpha_L\lambda_H(1-\gamma)\,\pi_{0,0,0,1} + \alpha_H\lambda_H(1-\gamma)\,\pi_{0,0,0,2} + \alpha_L(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,0,1} + \alpha_H(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,1,2} + \lambda_H(1-\gamma)\pi_{0,0,1,1} + \lambda_H(1-\gamma)\pi_{0,0,1,2}$$

Case 4 : $i = 0, 1 \leq j \leq K-2, x = 0, y = 1$

$$
\begin{aligned}
\pi_{0,j,0,1} = {} & (1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,1} + (1-\alpha_L)\lambda_H(1-\gamma)\pi_{0,j-1,0,1} \\
& + \alpha_L(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,1} + \alpha_H(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,2} \\
& + \alpha_L\lambda_H(1-\gamma)\pi_{1,j-1,0,1} + \alpha_H\lambda_H(1-\gamma)\pi_{1,j-1,0,2} \\
& + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,1,2} \\
& + \lambda_H(1-\gamma)\pi_{1,j-1,1,1} + \lambda_H(1-\gamma)\pi_{1,j-1,1,2}
\end{aligned}
$$

Case 5 : $i = 0, 1 \leq j \leq K-2, x = 0, y = 2$

$$
\begin{aligned}
\pi_{0,j,0,2} = {} & (1-\alpha_H)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,2} + (1-\alpha_H)\lambda_H(1-\gamma)\pi_{0,j-1,0,2} \\
& + \alpha_L(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,1} + \alpha_H(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,2} \\
& + \alpha_L\lambda_H(1-\gamma)\pi_{0,j,0,1} + \alpha_H\lambda_H(1-\gamma)\pi_{0,j,0,2} \\
& + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,2} \\
& + \lambda_H(1-\gamma)\pi_{0,j,1,1} + \lambda_H(1-\gamma)\pi_{0,j,1,2}
\end{aligned}
$$

Case 6 : $1 \leq i \leq K-2, j = 0, x = 0, y = 1$

$$
\begin{aligned}
\pi_{i,0,0,1} = {} & (1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,1} + (1-\alpha_L)\lambda_L(1-\gamma)\pi_{i-1,0,0,1} \\
& + \alpha_L(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,0,1} + \alpha_H(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,0,2} \\
& + \alpha_L\lambda_L(1-\gamma)\pi_{i,0,0,1} + \alpha_H\lambda_L(1-\gamma)\pi_{i,0,0,2} \\
& + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,2} \\
& + \lambda_L(1-\gamma)\pi_{i,0,1,1} + \lambda_L(1-\gamma)\pi_{i,0,1,2}
\end{aligned}
$$

Case 7 : $1 \leq i \leq K-2, j = 0, x = 0, y = 2$

$$
\begin{aligned}
\pi_{i,0,0,2} = {} & (1-\alpha_H)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,2} + (1-\alpha_H)\lambda_L(1-\gamma)\pi_{i-1,0,0,2} \\
& + \alpha_L\lambda_L(1-\gamma)\pi_{0,1,0,1} + \alpha_H\lambda_L(1-\gamma)\pi_{0,1,0,2} + \lambda_L(1-\gamma)\pi_{0,1,1,1} \\
& + \lambda_L(1-\gamma)\pi_{0,1,1,2}
\end{aligned}
$$

Case 8 : $i = 0, j = K-1, x = 0, y = 1$

$$\begin{aligned}\pi_{0,j,0,1} = {} & (1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,1} + (1-\alpha_L)\lambda_H(1-\gamma)\pi_{0,j-1,0,1} \\ & + \alpha_L(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j-1,0,1} + \alpha_H(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j-1,0,2} \\ & + \alpha_L\lambda_H(1-\gamma)\pi_{1,j,0,1} + \alpha_H\lambda_H(1-\gamma)\pi_{1,j,0,2} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j-1,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j-1,1,2} \\ & + \lambda_H(1-\gamma)\pi_{1,j,1,1} + \lambda_H(1-\gamma)\pi_{1,j,1,2}\end{aligned}$$

Case 9 : $i = 0, j = K-1, x = 0, y = 2$

$$\begin{aligned}\pi_{0,j,0,2} = {} & (1-\alpha_H)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,2} + (1-\alpha_H)\lambda_H(1-\gamma)\pi_{0,j-1,0,2} \\ & + \alpha_L\lambda_H(1-\gamma)\pi_{0,j,0,1} + \alpha_H\lambda_H(1-\gamma)\pi_{0,j,0,2} + \lambda_H(1-\gamma)\pi_{0,j,1,1} \\ & + \lambda_H(1-\gamma)\pi_{0,j,1,2}\end{aligned}$$

Case 10 : $i = K-1, j = 0, x = 0, y = 1$

$$\begin{aligned}\pi_{i,0,0,1} = {} & (1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,1} + (1-\alpha_L)\lambda_L(1-\gamma)\pi_{i-1,0,0,1} \\ & + \alpha_L\lambda_L(1-\gamma)\pi_{i,0,0,1} + \alpha_H\lambda_L(1-\gamma)\pi_{i,0,0,2} + \lambda_L(1-\gamma)\pi_{i,0,1,1} \\ & + \lambda_L(1-\gamma)\pi_{i,0,1,2}\end{aligned}$$

Case 11 : $i = K-1, j = 0, x = 0, y = 2$

$$\begin{aligned}\pi_{i,0,0,2} = {} & (1-\alpha_H)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,2} + (1-\alpha_H)\lambda_L(1-\gamma)\pi_{i-1,0,0,2} \\ & + \alpha_L\lambda_L(1-\gamma)\pi_{0,1,0,1} + \alpha_H\lambda_L(1-\gamma)\pi_{0,1,0,2} + \lambda_L(1-\gamma)\pi_{0,1,1,1} \\ & + \lambda_L(1-\gamma)\pi_{0,1,1,2}\end{aligned}$$

Case 12 : $1 \le i \le K-2, 1 \le j \le K-i-2, x = 0, y = 1$

$$\begin{aligned}\pi_{i,j,0,1} = {} & (1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,1} + (1-\alpha_L)\lambda_L(1-\gamma)\pi_{i-1,j,0,1} \\ & + (1-\alpha_L)\lambda_H(1-\gamma)\pi_{i,j-1,0,1} + \alpha_L(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,1} \\ & + \alpha_L\lambda_L(1-\gamma)\pi_{i,j,0,1} + \alpha_L\lambda_H(1-\gamma)\pi_{i+1,j-1,0,1} \\ & + \alpha_H(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,2} + \alpha_H\lambda_L(1-\gamma)\pi_{i,j,0,2} \\ & + \alpha_H\lambda_H(1-\gamma)\pi_{i+1,j-1,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,1} \\ & + \lambda_L(1-\gamma)\pi_{i,j,1,1} + \lambda_H(1-\gamma)\pi_{i+1,j-1,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,2} + \lambda_L(1-\gamma)\pi_{i,j,1,2} \\ & + \lambda_H(1-\gamma)\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 13 : $1 \le i \le K-2, 1 \le j \le K-i-2, x=0, y=2$

$$\begin{aligned}\pi_{i,j,0,2} = {} & (1-\alpha_H)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,2} + (1-\alpha_H)\lambda_L(1-\gamma)\pi_{i-1,j,0,2} \\ & + (1-\alpha_H)\lambda_H(1-\gamma)\pi_{i,j-1,0,2} + \alpha_L\lambda_L(1-\gamma)\pi_{0,j+1,0,1} \\ & + \alpha_H\lambda_L(1-\gamma)\pi_{0,j+1,0,2} + \lambda_L(1-\gamma)\pi_{0,j+1,1,1} + \lambda_L(1-\gamma)\pi_{0,j+1,1,2}\end{aligned}$$

Case 14 : $1 \le i \le K-2, j = K-i-1, x=0, y=1$

$$\begin{aligned}\pi_{i,j,0,1} = {} & (1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,1} + (1-\alpha_L)\lambda_L(1-\gamma)\pi_{i-1,j,0,1} \\ & + (1-\alpha_L)\lambda_H(1-\gamma)\pi_{i,j-1,0,1} + \alpha_L\lambda_L(1-\gamma)\pi_{i,j,0,1} \\ & + \alpha_H\lambda_L(1-\gamma)\pi_{i,j,0,2} + \alpha_L\lambda_H(1-\gamma)\pi_{i+1,j-1,0,1} \\ & + \alpha_H\lambda_H(1-\gamma)\pi_{i+1,j-1,0,2}\end{aligned}$$

Case 15 : $1 \le i \le K-2, j = K-i-1, x=0, y=2$

$$\begin{aligned}\pi_{i,j,0,2} = {} & (1-\alpha_H)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,2} + (1-\alpha_H)\lambda_L(1-\gamma)\pi_{i-1,j,0,2} \\ & + (1-\alpha_H)\lambda_H(1-\gamma)\pi_{i,j-1,0,2} + \alpha_L\lambda_L(1-\gamma)\pi_{0,j,0,1} \\ & + \alpha_H\lambda_L(1-\gamma)\pi_{0,j,0,2} + \lambda_L(1-\gamma)\pi_{0,j+1,1,1} + \lambda_L(1-\gamma)\pi_{0,j+1,1,2}\end{aligned}$$

Case 16 : $i=0, j=0, x=1, y=0$

$$\begin{aligned}\pi_{0,0,1,0} = {} & (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,0} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,0} + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,1} \\ & + \alpha_H(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,1} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,2}\end{aligned}$$

Case 17 : $i=0, j=0, x=1, y=1$

$$\begin{aligned}\pi_{0,0,1,1} = {} & (1-\alpha_L)(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,1} + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{1,0,0,1} \\ & + \alpha_H(1-\lambda_L-\lambda_H)\gamma\pi_{1,0,0,2} + \lambda_L\gamma\pi_{0,0,0,0} + \lambda_L\gamma\pi_{0,0,0,1} + \lambda_L\gamma\pi_{0,0,0,2} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{1,0,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,0,1,2}\end{aligned}$$

Case 18 : $i=0, j=0, x=1, y=2$

$$\begin{aligned}\pi_{0,0,1,2} = {} & \lambda_H\gamma\pi_{0,0,0,0} + \lambda_H\gamma\pi_{0,0,1,1} + \lambda_H\gamma\pi_{0,0,1,2} + (1-\alpha_H)(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,2} \\ & + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{0,1,0,1} + \alpha_H(1-\lambda_L-\lambda_H)\gamma\pi_{0,1,0,2} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{0,1,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,1,1,2}\end{aligned}$$

Case 19 : $i = 0, 1 \leq j \leq K-1, x = 1, y = 1$

$$\begin{aligned}\pi_{0,j,1,1} = {} & (1-\alpha_L)(1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,1} + (1-\alpha_L)\lambda_H\gamma\pi_{0,j-1,0,1} \\ & + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{0,j-1,0,1} + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,1} \\ & + \alpha_L\lambda_H\gamma\pi_{1,j-1,0,1} + \alpha_H\lambda_H\gamma\pi_{1,j-1,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,j,1,1} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{1,j,1,2} + \lambda_H\gamma\pi_{1,j-1,1,1} + \lambda_H\gamma\pi_{1,j-1,1,2}\end{aligned}$$

Case 20 : $i = 0, 1 \leq j \leq K-1, x = 1, y = 2$

$$\begin{aligned}\pi_{0,j,1,2} = {} & (1-\alpha_H)(1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,2} + (1-\alpha_H)\lambda_H\gamma\pi_{0,j-1,0,2} \\ & + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,0,1} + \alpha_L\lambda_H\gamma\pi_{0,j,0,1} \\ & + \alpha_L\lambda_H(1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,0,2} + \alpha_H\lambda_H\gamma\pi_{0,j,0,2} \\ & + (1-\lambda_L-\lambda_H)\pi_{0,j+1,1,1} + (1-\lambda_L-\lambda_H)\pi_{0,j+1,1,2} + \lambda_H\gamma\pi_{0,j,1,1} \\ & + \lambda_H\gamma\pi_{0,j,1,2}\end{aligned}$$

Case 21 : $1 \leq i \leq K-1, j = 0, x = 1, y = 1$

$$\begin{aligned}\pi_{i,0,1,1} = {} & (1-\alpha_L)(1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,1} + (1-\alpha_L)\lambda_L\gamma\pi_{i-1,0,0,1} \\ & + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,0,1} + \alpha_H(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,0,2} \\ & + \alpha_L\lambda_L\gamma\pi_{i,0,0,1} + \alpha_H\lambda_L\gamma\pi_{i,0,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,1,1} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,1,2} + \lambda_L\gamma\pi_{i,0,1,1} + \lambda_L\gamma\pi_{i,0,1,2}\end{aligned}$$

Case 22 : $1 \leq i \leq K-1, j = 0, x = 1, y = 2$

$$\begin{aligned}\pi_{i,0,1,2} = {} & (1-\alpha_H)(1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,2} + (1-\alpha_H)\lambda_L\gamma\pi_{i-1,0,0,2} + \alpha_L\lambda_L\gamma\pi_{0,1,0,1} \\ & + \alpha_H\lambda_L\gamma\pi_{0,1,0,2} + \lambda_L\gamma\pi_{0,1,1,1} + \lambda_L\gamma\pi_{0,1,1,2}\end{aligned}$$

Case 23 : $1 \leq i \leq K-2, 1 \leq j \leq K-i-1, x = 1, y = 1$

$$\begin{aligned}\pi_{i,j,1,1} = {} & (1-\alpha_L)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j,0,1} + (1-\alpha_L)\lambda_L\gamma\pi_{i-1,j,0,1} \\ & + (1-\alpha_L)\lambda_H\gamma\pi_{i,j-1,0,1} + \alpha_L\lambda_L\gamma\pi_{i,j,0,1} + \alpha_L\lambda_H\gamma\pi_{i+1,j-1,0,1} \\ & + \alpha_H(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,2} + \alpha_H\lambda_L\gamma\pi_{i,j,0,2} + \alpha_H\lambda_H\gamma\pi_{i+1,j-1,0,2} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,1} + \lambda_L\gamma\pi_{i,j,1,1} + \lambda_H\gamma\pi_{i+1,j-1,1,1} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,2} + \lambda_L\gamma\pi_{i,j,1,2} + \lambda_H\gamma\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 24 : $1 \leq i \leq K-2, 1 \leq j \leq K-i-1, x=1, y=2$

$$\pi_{i,j,1,2} = (1-\alpha_H)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j,0,2} + (1-\alpha_H)\lambda_L\gamma\pi_{i-1,j,0,2} + (1-\alpha_H)\lambda_H\gamma\pi_{i,j-1,0,2} + \alpha_L\lambda_L\gamma\pi_{0,j+1,0,1} + \alpha_H\lambda_L\gamma\pi_{0,j+1,0,2} + \lambda_L\gamma\pi_{0,j+1,1,1} + \lambda_L\gamma\pi_{0,j+1,1,2}$$

3.2.3 State diagram

(a) First-In-First-Out

(1) $i=0, j=0, x=0, y=0$

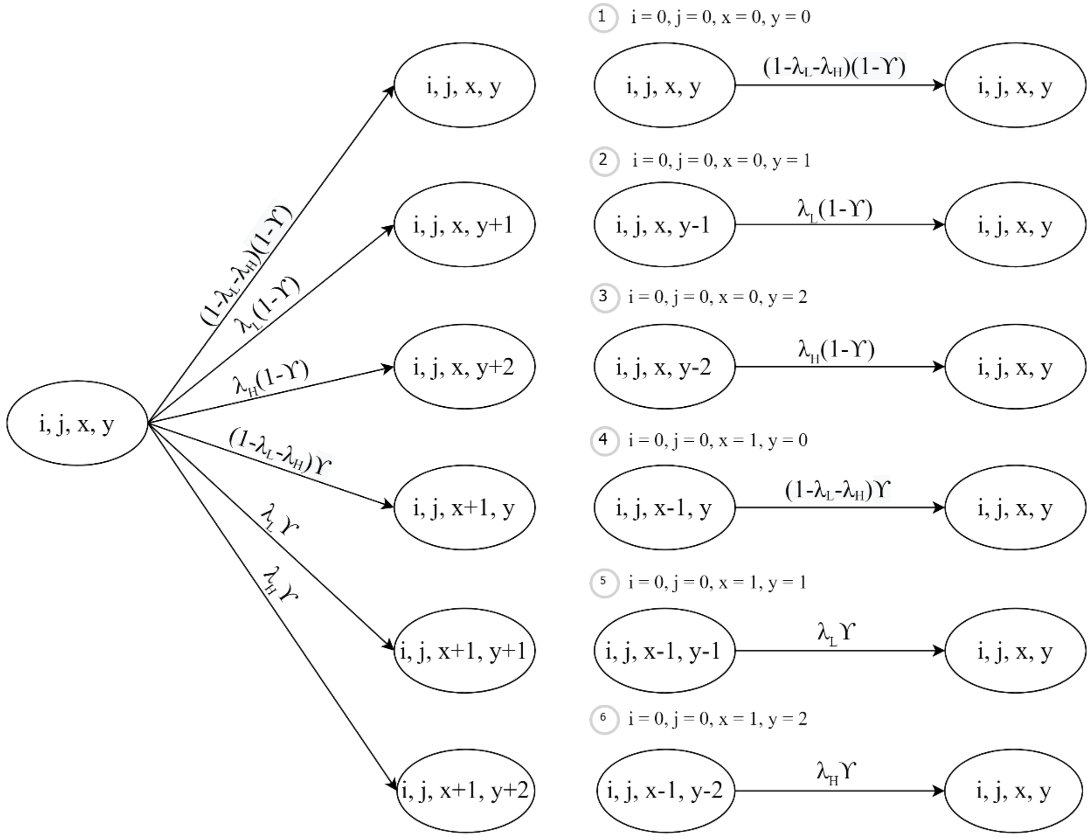
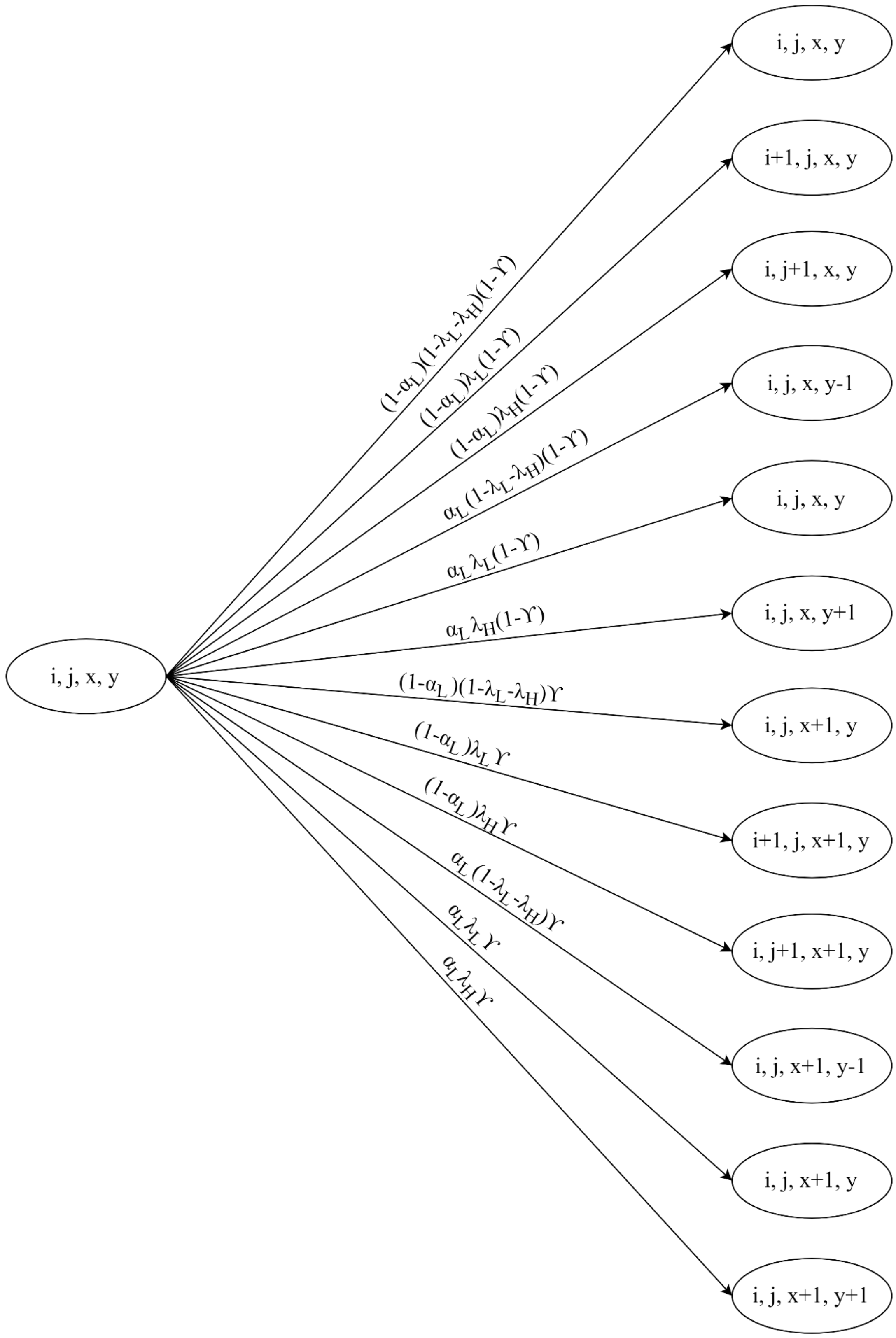


Fig 3. 27: The state diagram for $i=0, j=0, x=0, y=0$

(2) $i = 0, j = 0, x = 0, y = 1$


i, j, x, y
i, j, x, y
i+1, j, x, y
i, j+1, x, y
i, j, x, y-1
i, j, x, y
i, j, x, y+1
i, j, x+1, y
i+1, j, x+1, y
i, j+1, x+1, y
i, j, x+1, y-1
i, j, x+1, y
i, j, x+1, y+1
$(1-\alpha_L)(1-\lambda_L-\lambda_H)(1-\Upsilon)$
$(1-\alpha_L)\lambda_L(1-\Upsilon)$
$(1-\alpha_L)\lambda_H(1-\Upsilon)$
$\alpha_L(1-\lambda_L-\lambda_H)(1-\Upsilon)$
$\alpha_L\lambda_L(1-\Upsilon)$
$\alpha_L\lambda_H(1-\Upsilon)$
$(1-\alpha_L)(1-\lambda_L-\lambda_H)\Upsilon$
$(1-\alpha_L)\lambda_L\Upsilon$
$(1-\alpha_L)\lambda_H\Upsilon$
$\alpha_L(1-\lambda_L-\lambda_H)\Upsilon$
$\alpha_L\lambda_L\Upsilon$
$\alpha_L\lambda_H\Upsilon$

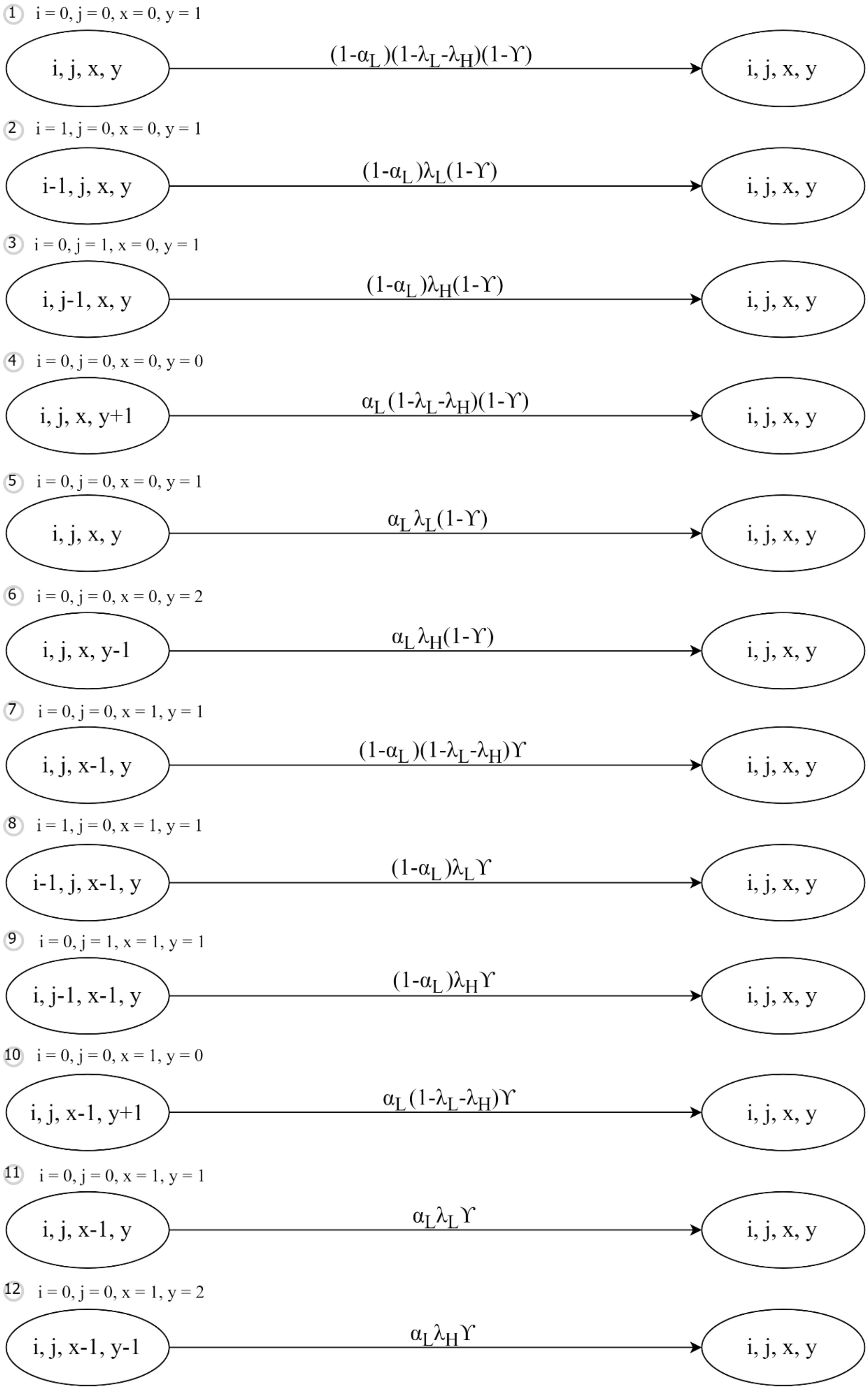
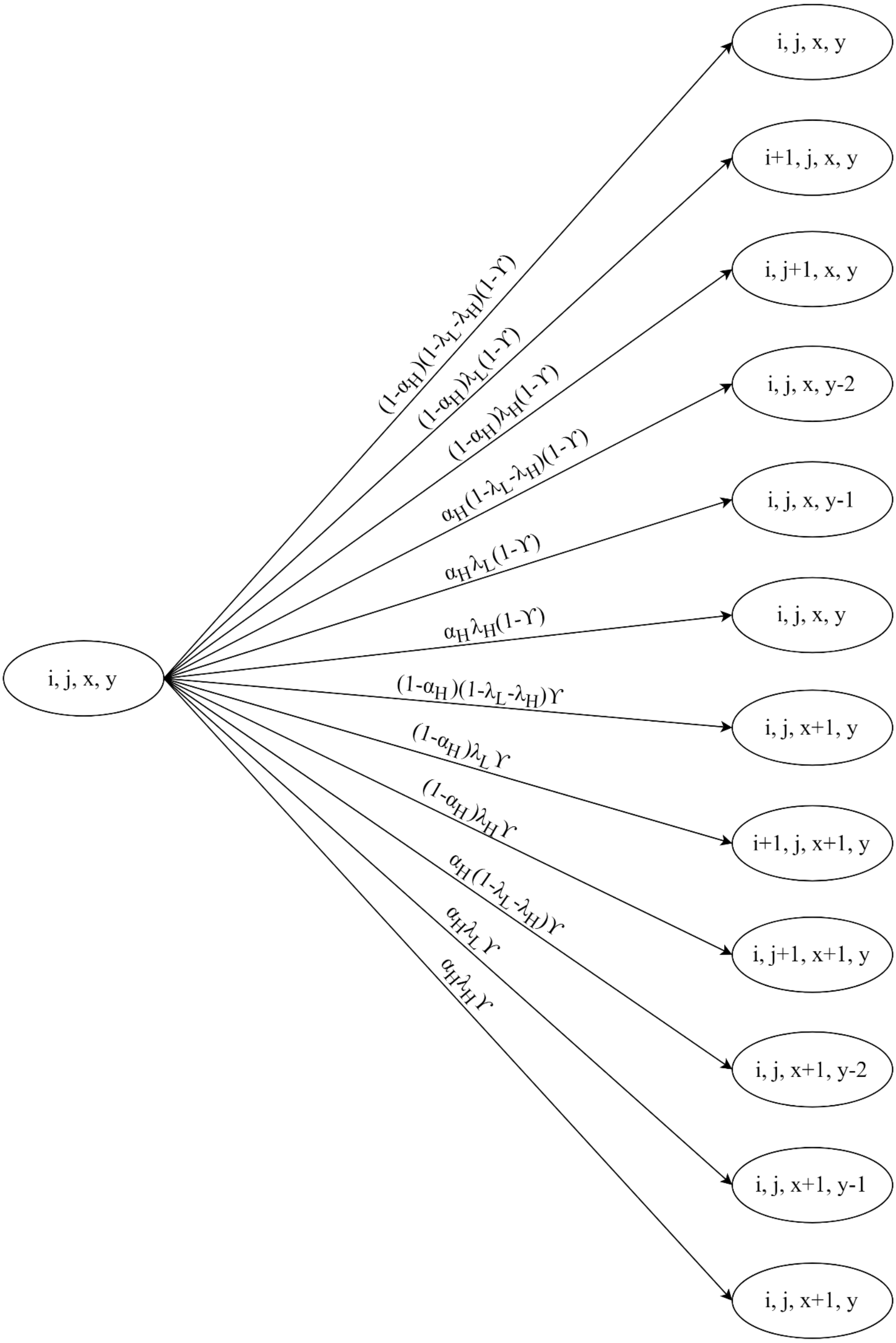


Fig 3. 28: The state diagram for $i = 0, j = 0, x = 0, y = 1$

(3) $i = 0, j = 0, x = 0, y = 2$


i, j, x, y
i, j, x, y
i+1, j, x, y
i, j+1, x, y
i, j, x, y-2
i, j, x, y-1
i, j, x, y
i, j, x+1, y
i+1, j, x+1, y
i, j+1, x+1, y
i, j, x+1, y-2
i, j, x+1, y-1
i, j, x+1, y
(1-αH)(1-λL-λH)(1-ϒ)
(1-αH)λL(1-ϒ)
(1-αH)λH(1-ϒ)
αH(1-λL-λH)(1-ϒ)
αHλL(1-ϒ)
αHλH(1-ϒ)
(1-αH)(1-λL-λH)ϒ
(1-αH)λLϒ
(1-αH)λHϒ
αH(1-λL-λH)ϒ
αHλLϒ
αHλHϒ

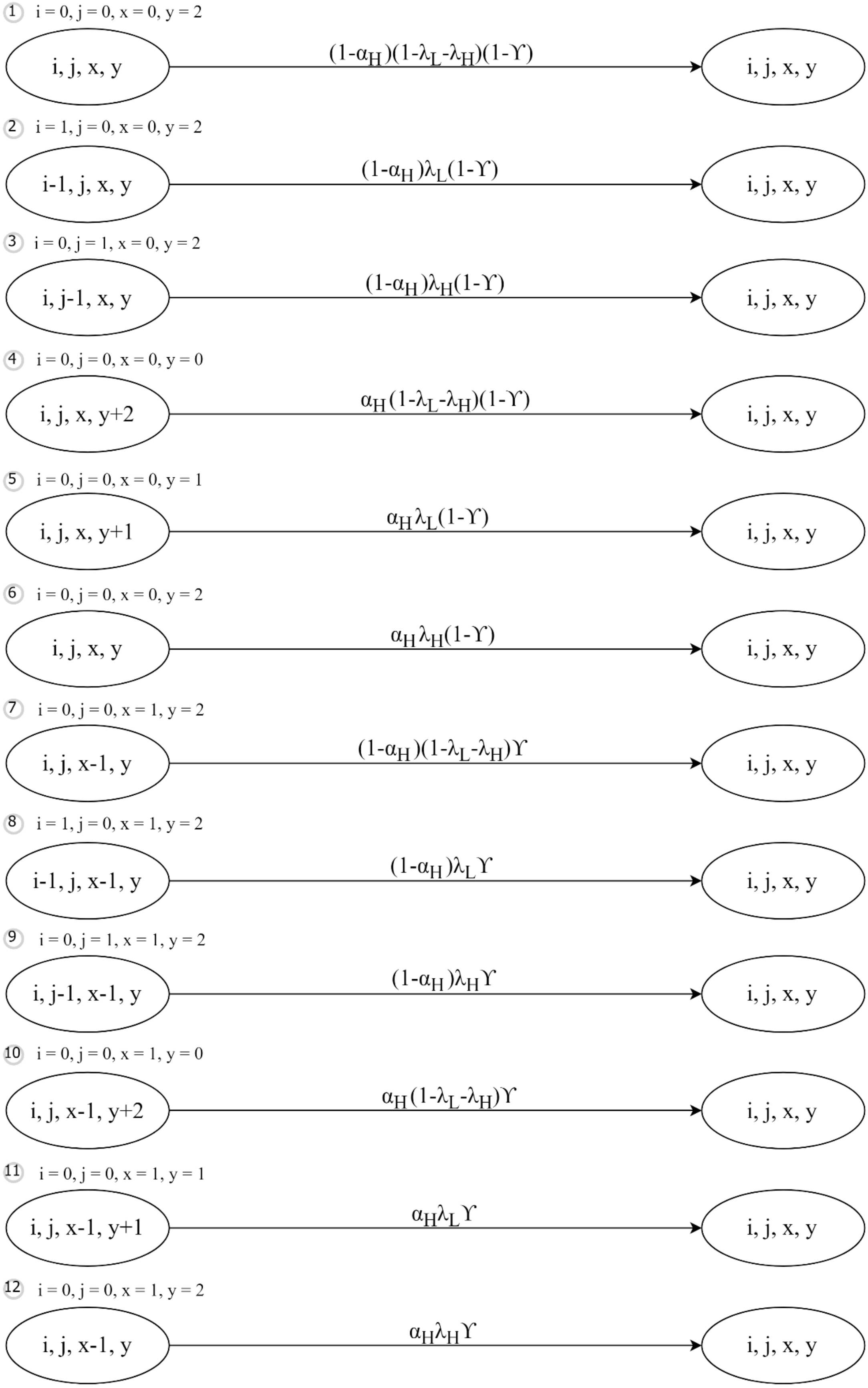
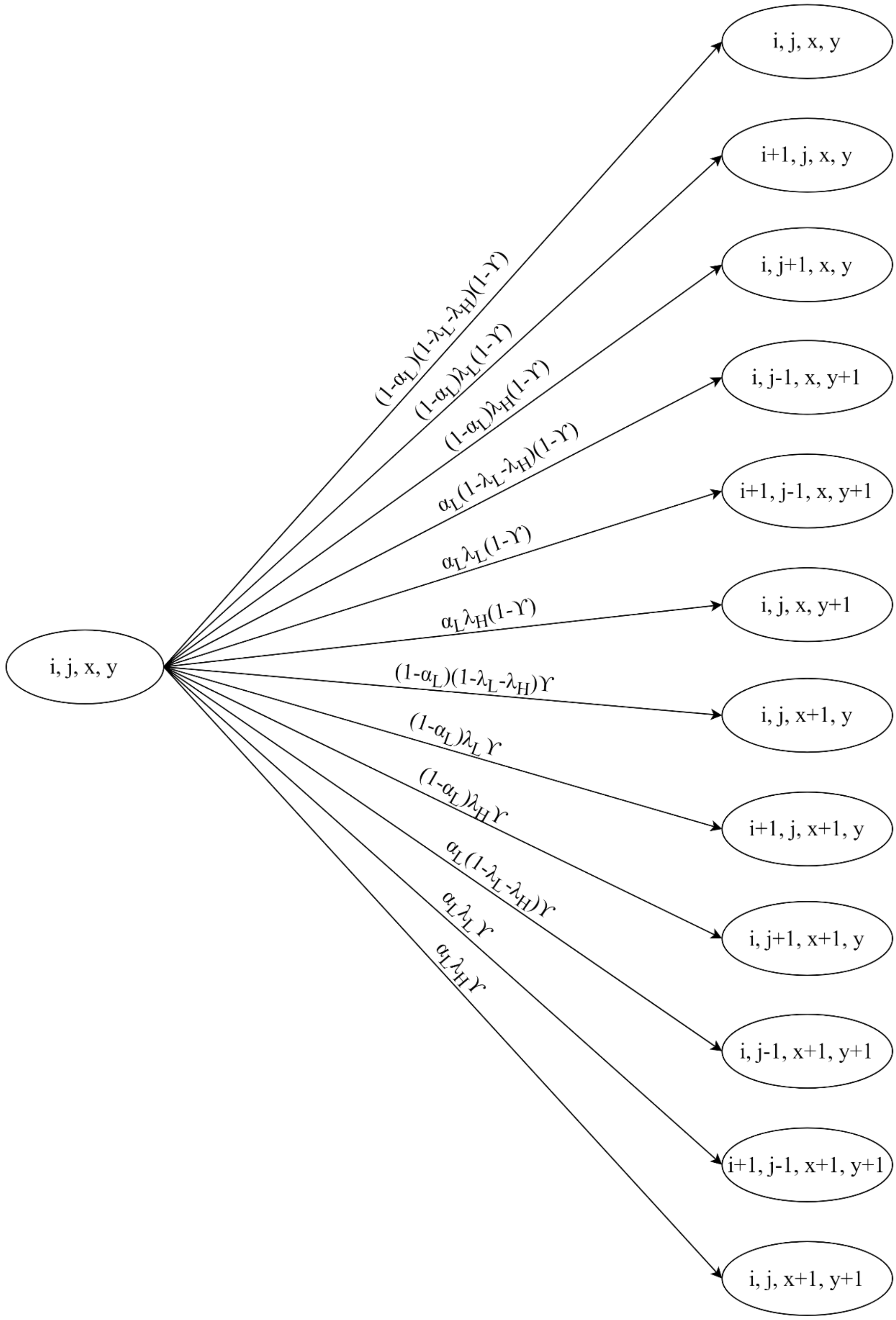


Fig 3. 29: The state diagram for $i = 0, j = 0, x = 0, y = 2$

(4) $i = 0, 1 \leq j \leq K - 2, x = 0, y = 1$



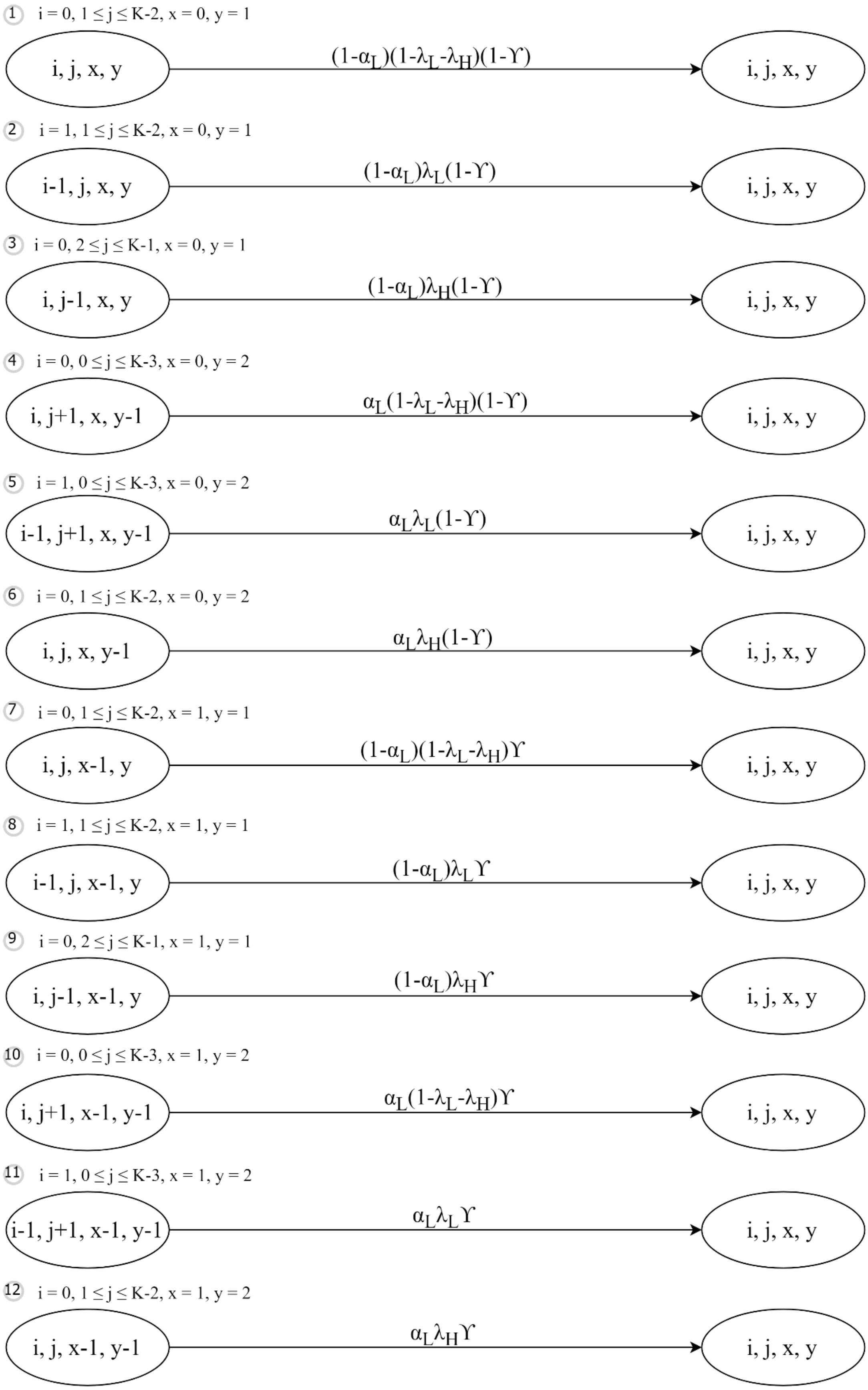
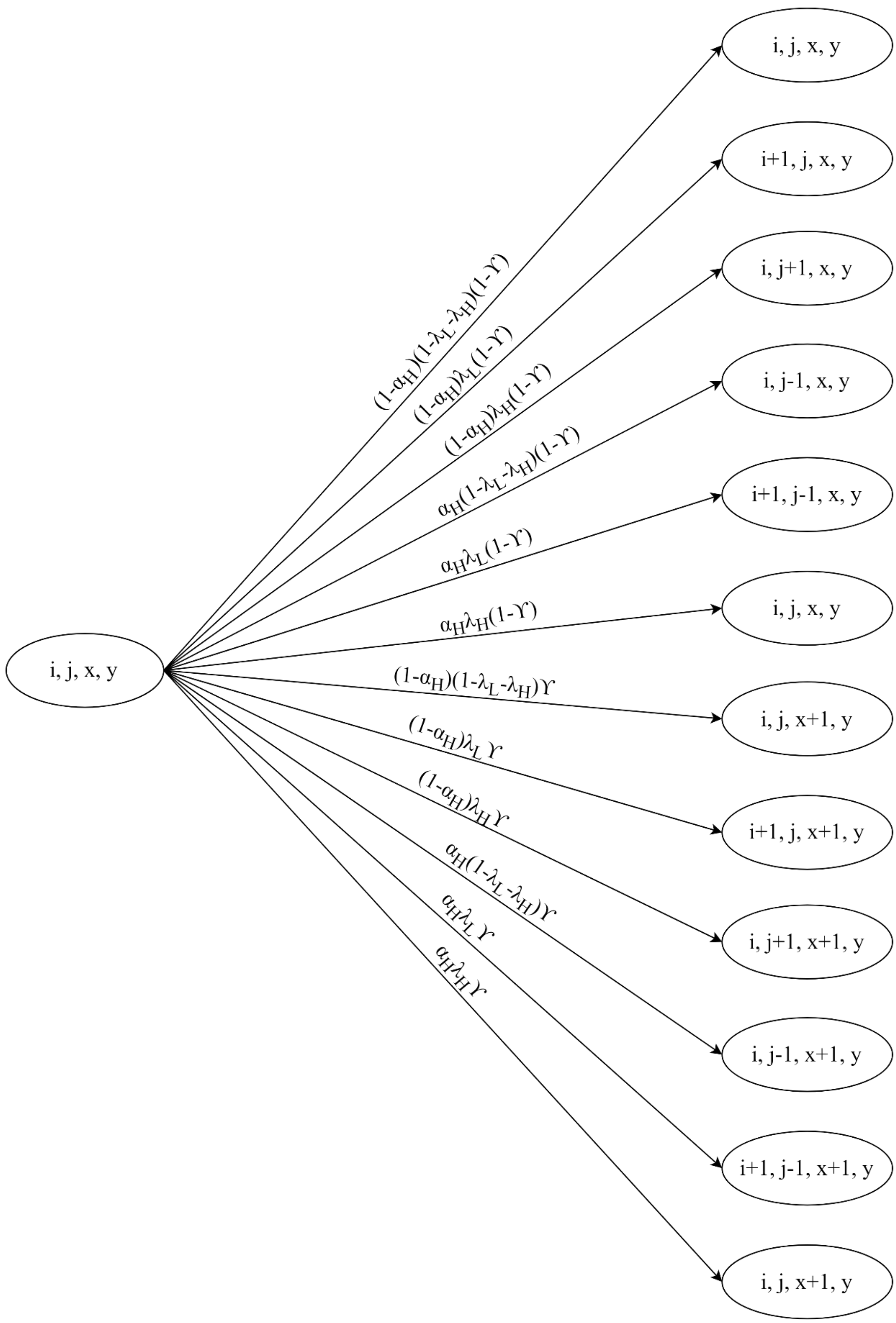


Fig 3. 30: The state diagram for $i = 0, 1 \leq j \leq K-2, x = 0, y = 1$

(5) $i = 0, 1 \leq j \leq K-2, x = 0, y = 2$



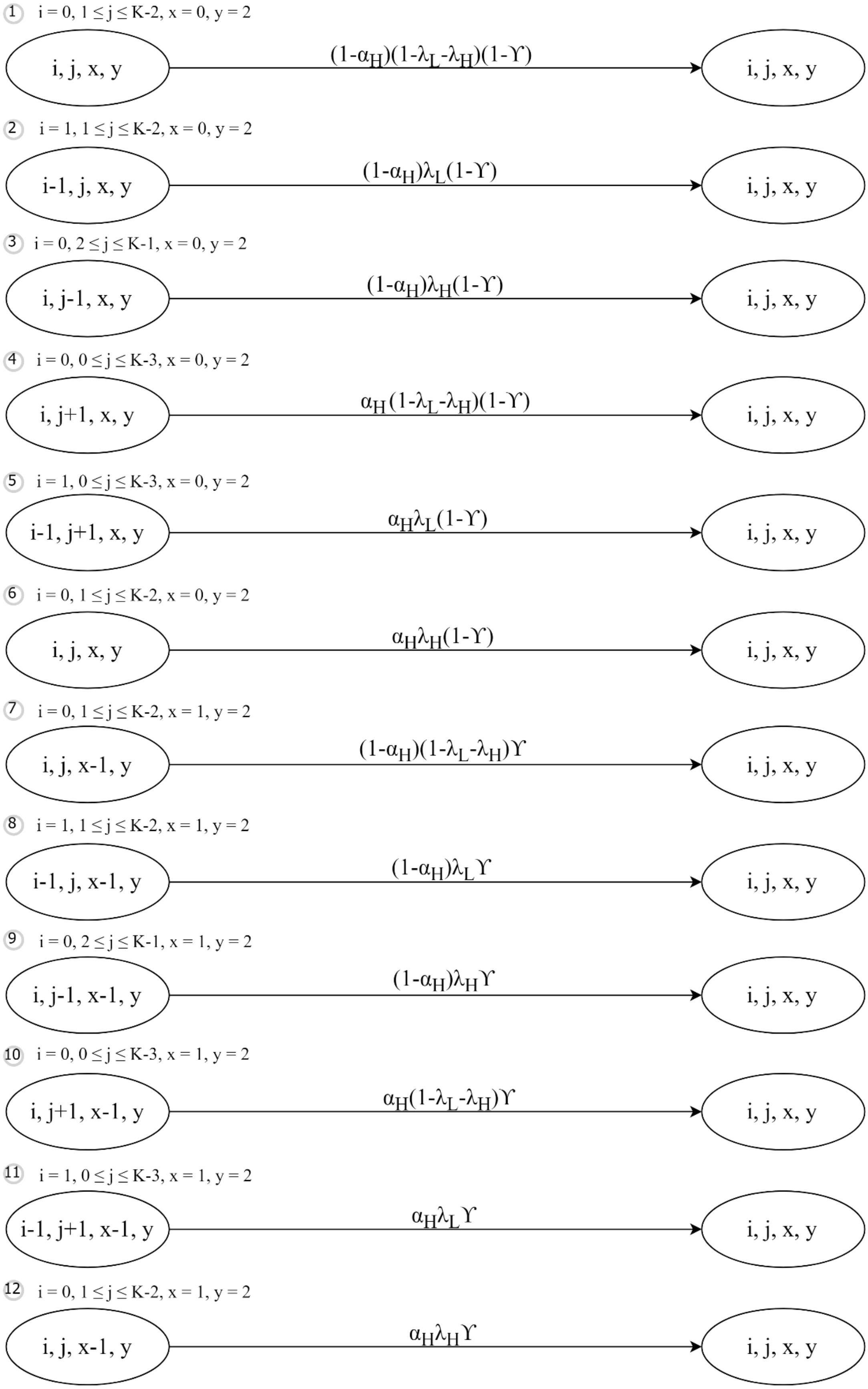
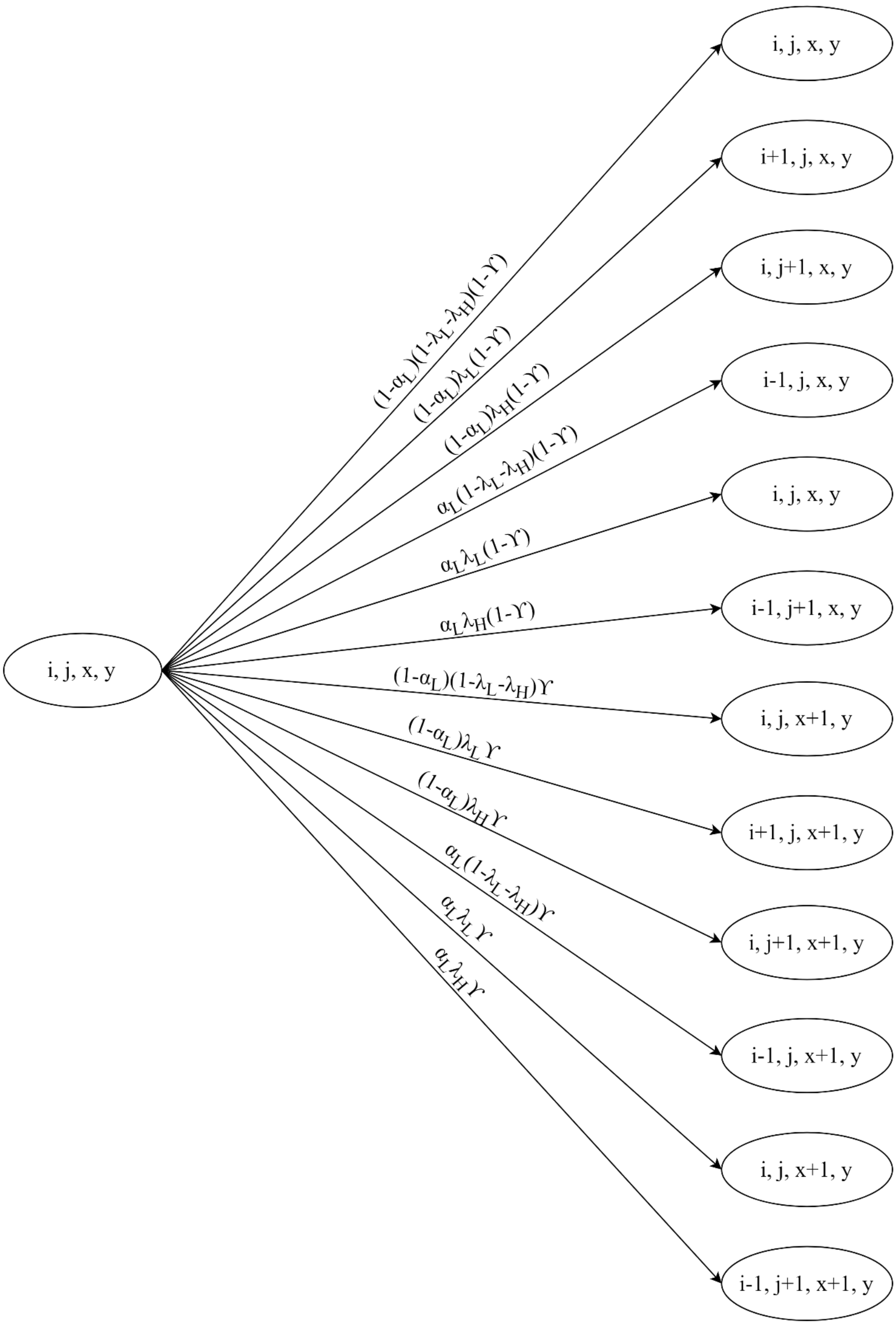


Fig 3. 31: The state diagram for $i = 0, 1 \leq j \leq K-2, x = 0, y = 2$

(6) $1 \leq i \leq K-2, j=0, x=0, y=1$



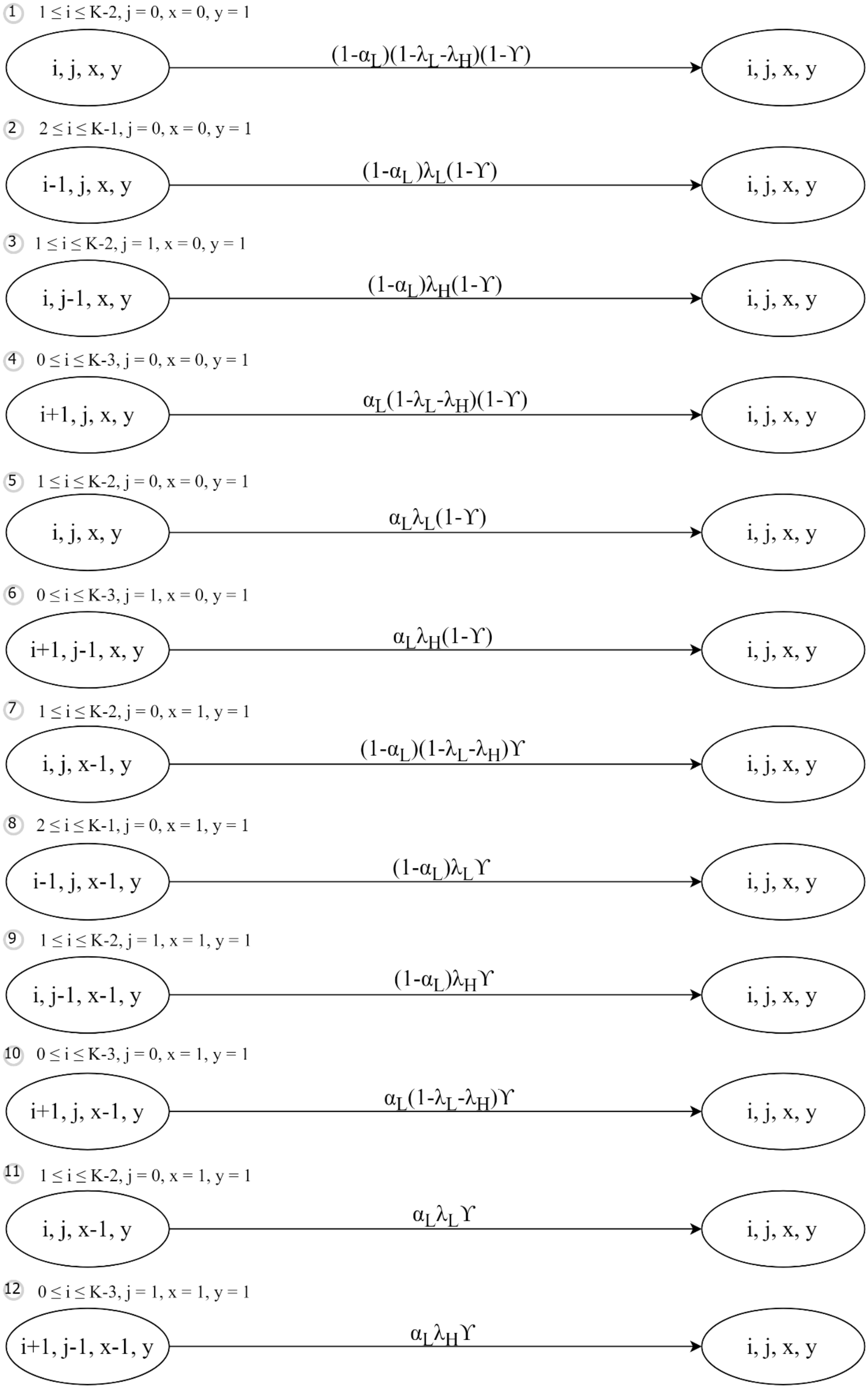
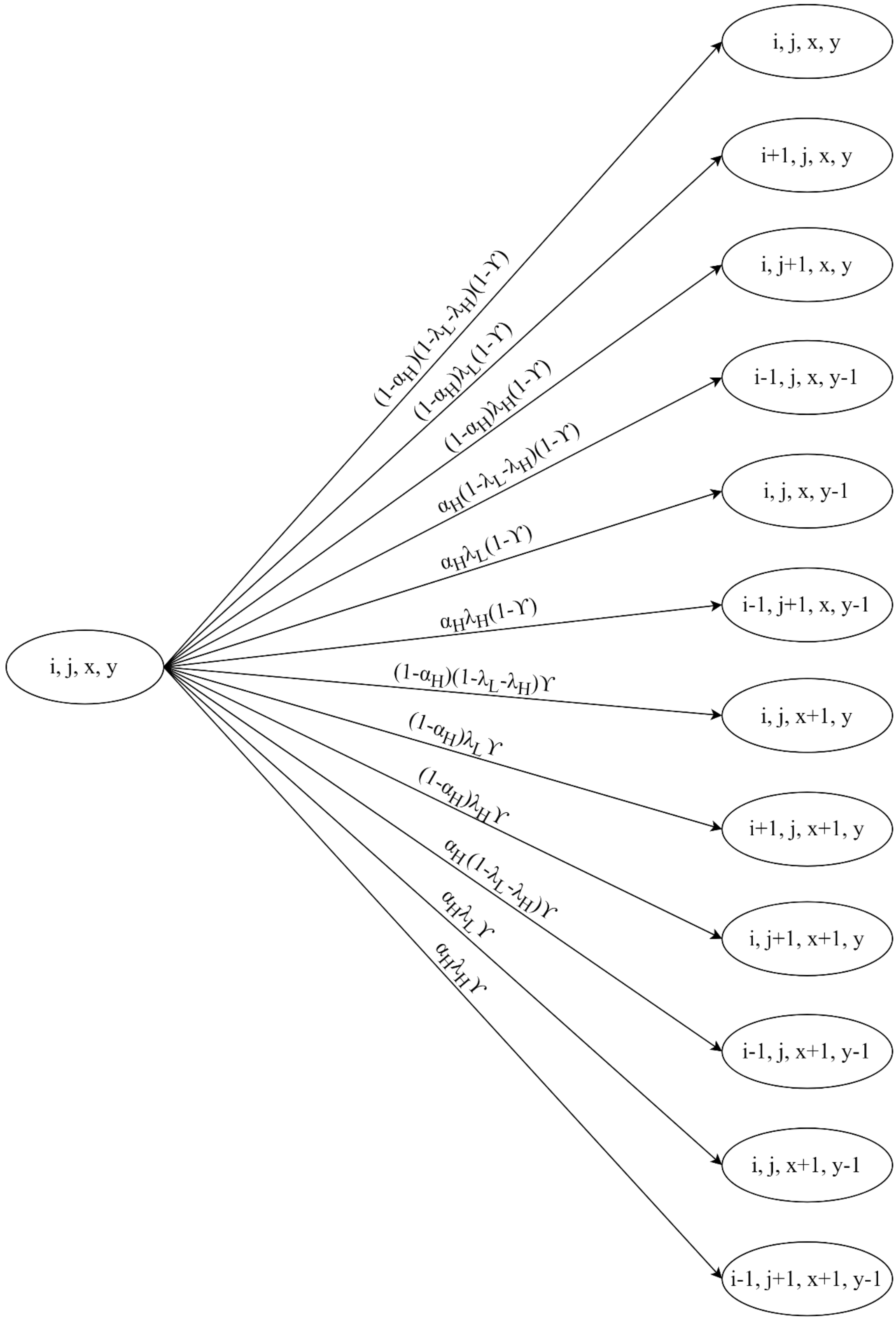


Fig 3. 32: The state diagram for $1 \leq i \leq K-2, j = 0, x = 0, y = 1$

(7) $1 \le i \le K-2, j = 0, x = 0, y = 2$



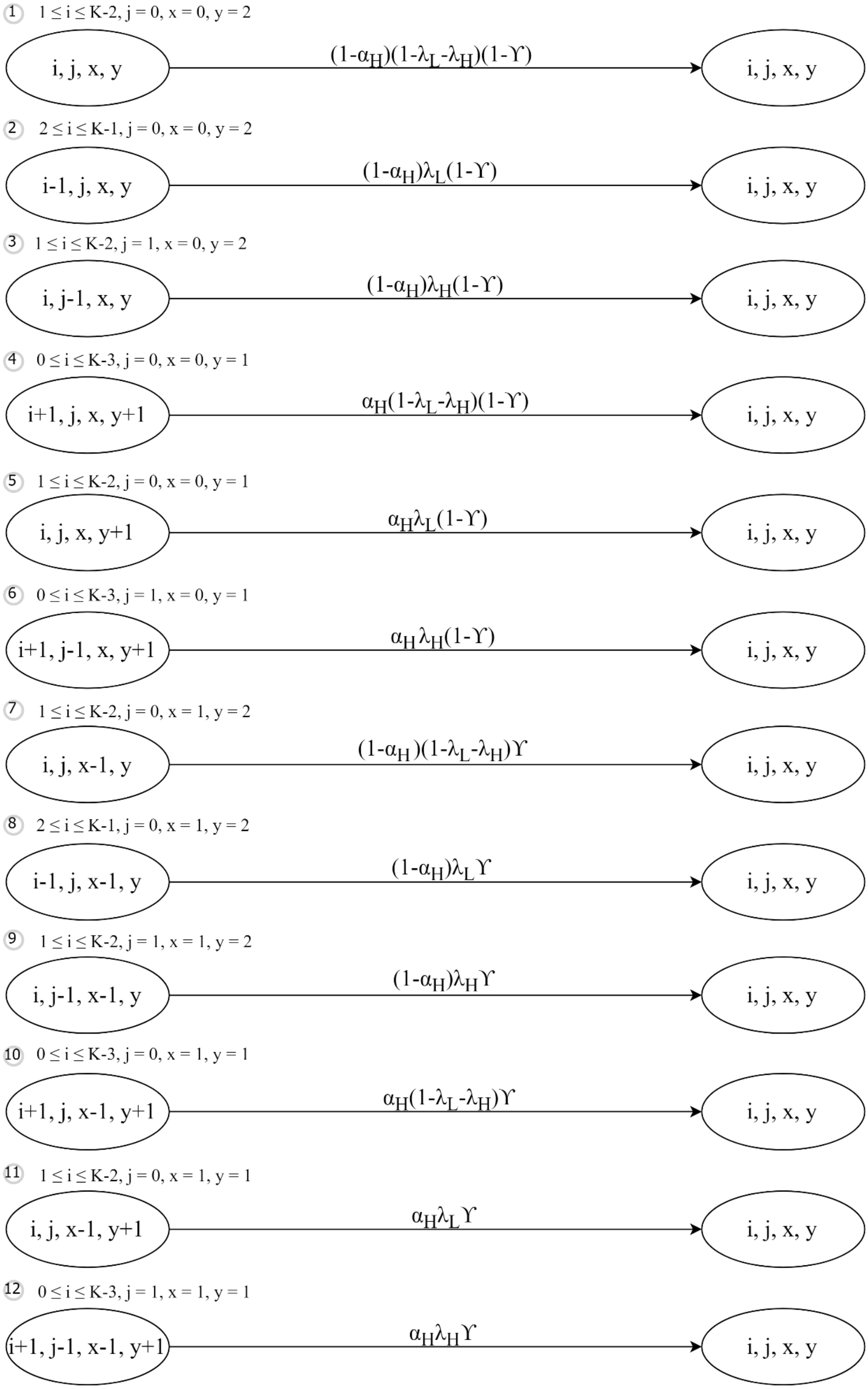
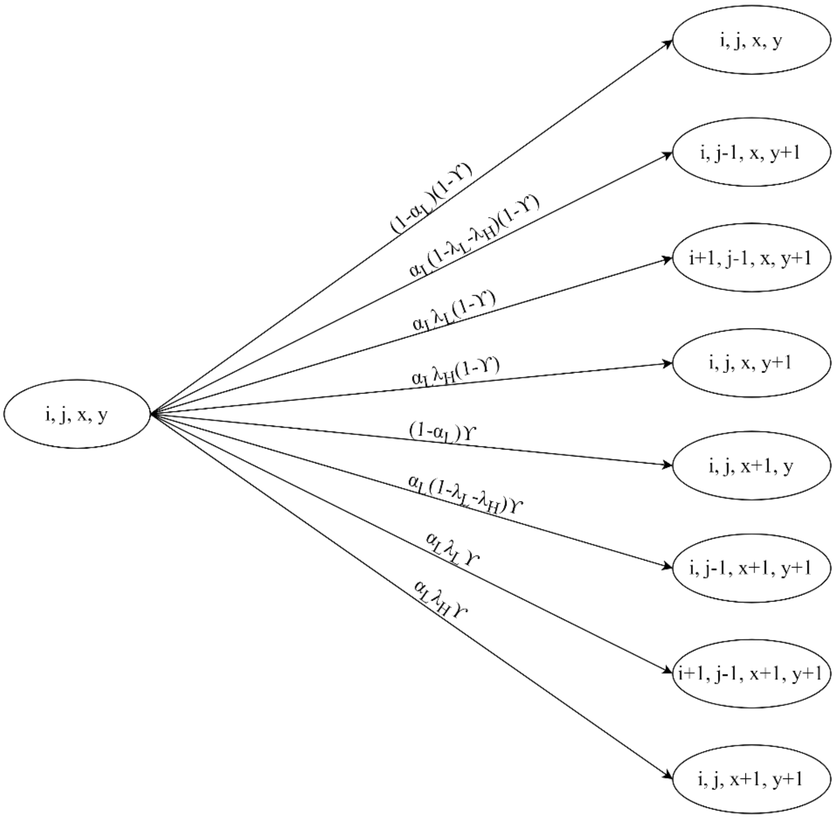


Fig 3. 33: The state diagram for $1 \leq i \leq K-2, j = 0, x = 0, y = 2$

(8) $i = 0, j = K - 1, x = 0, y = 1$



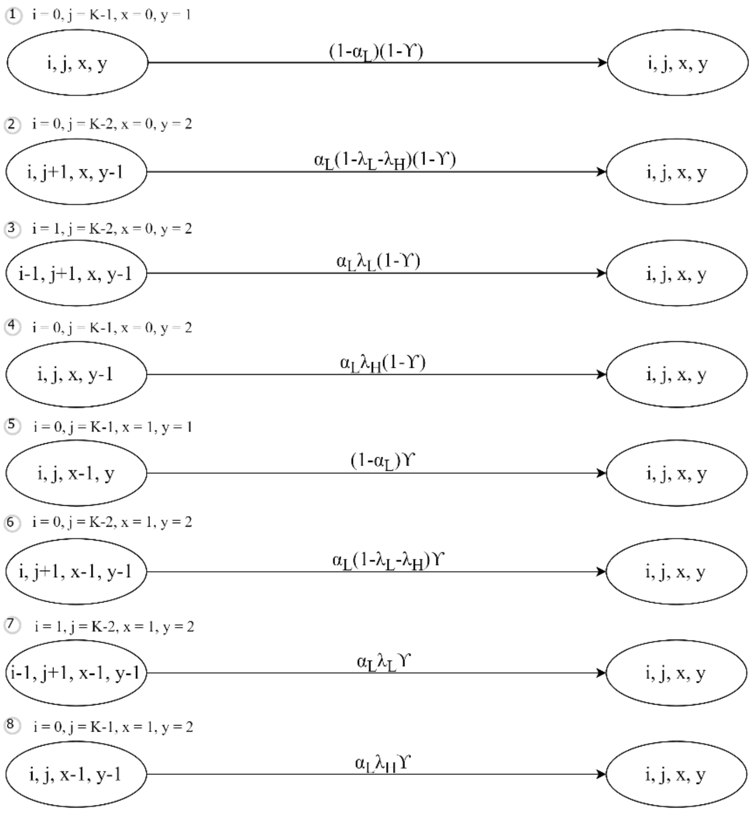
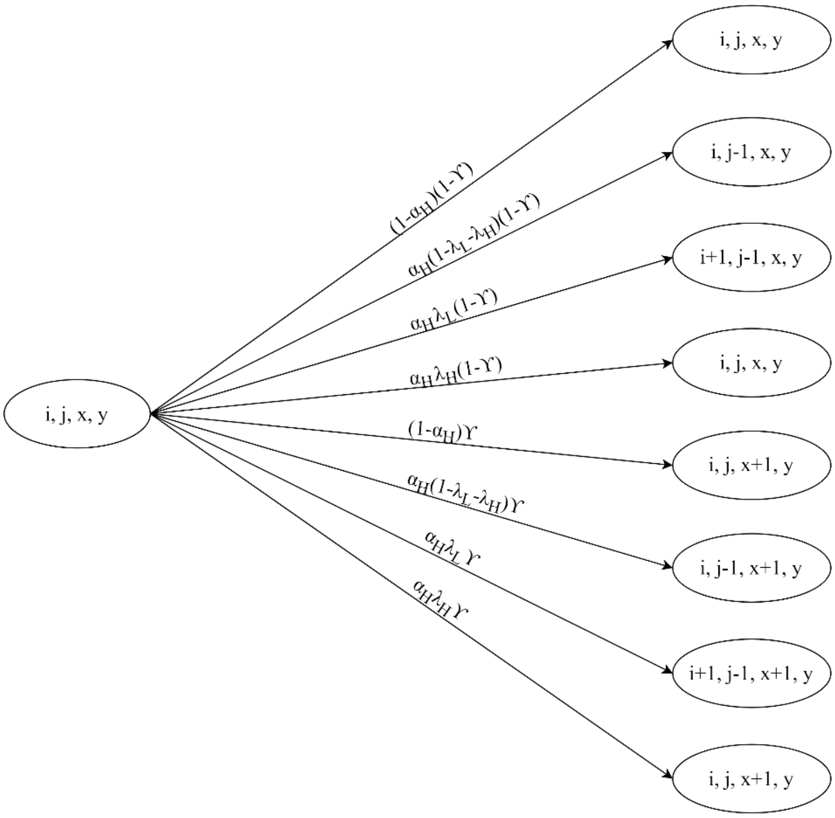


Fig 3. 34: The state diagram for $i = 0, j = K - 1, x = 0, y = 1$

(9) $i = 0, j = K - 1, x = 0, y = 2$



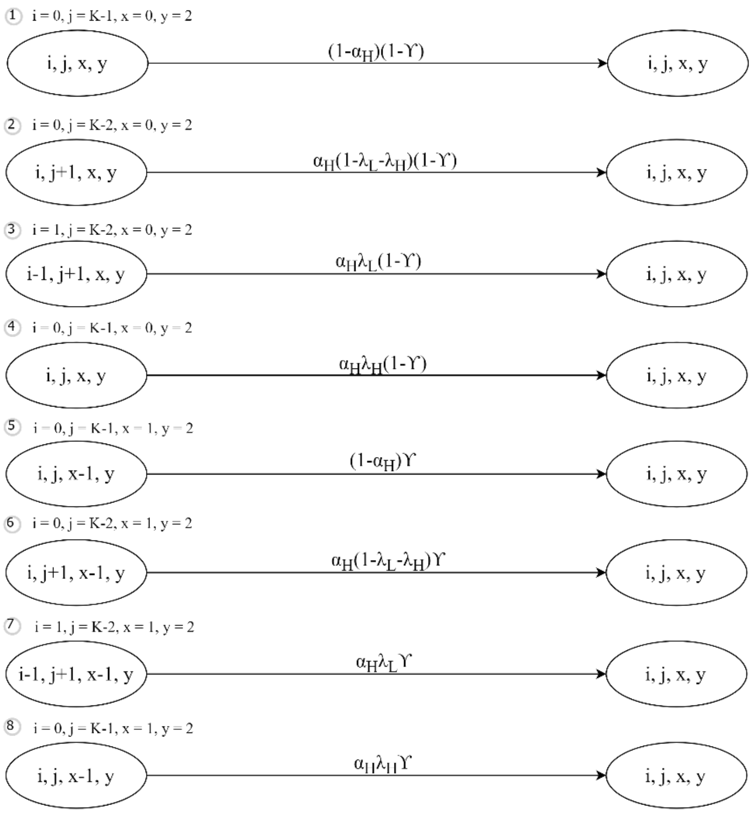
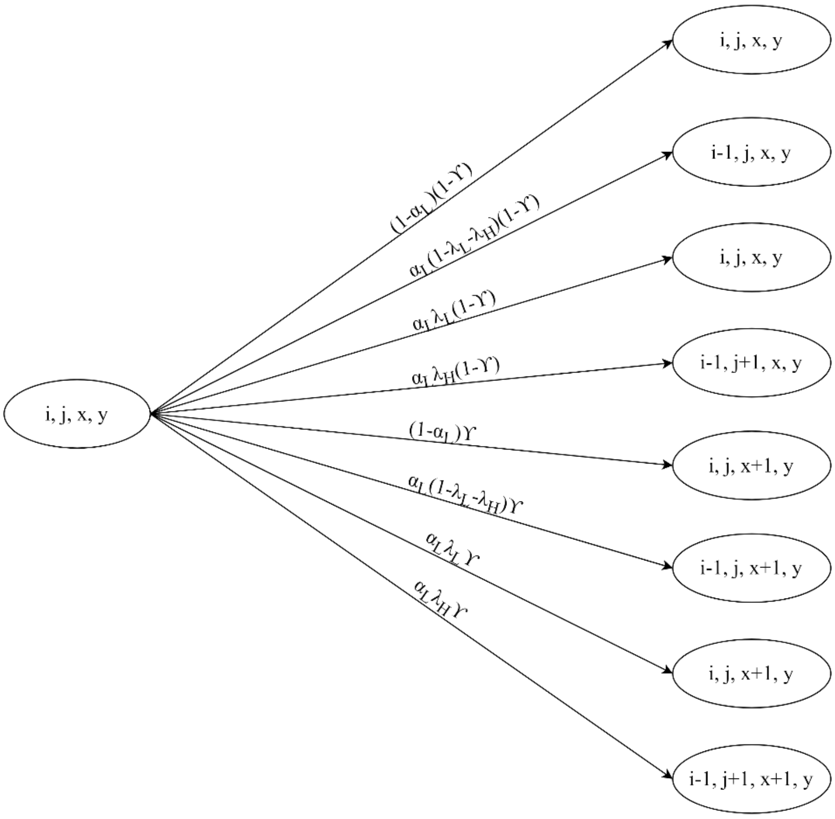


Fig 3. 35: The state diagram for $i = 0, j = K - 1, x = 0, y = 2$

(10) $i = K - 1, j = 0, x = 0, y = 1$



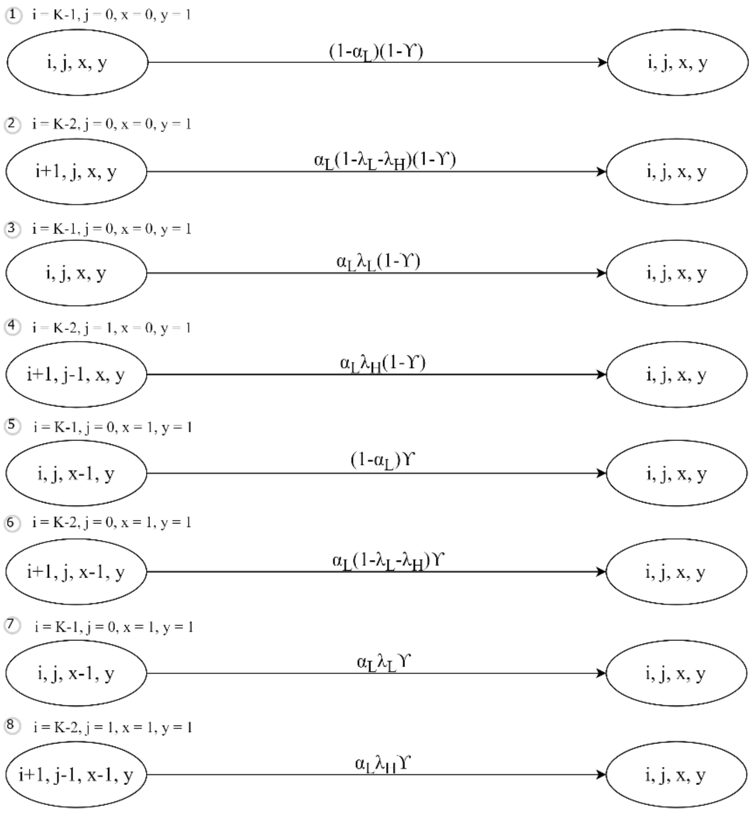
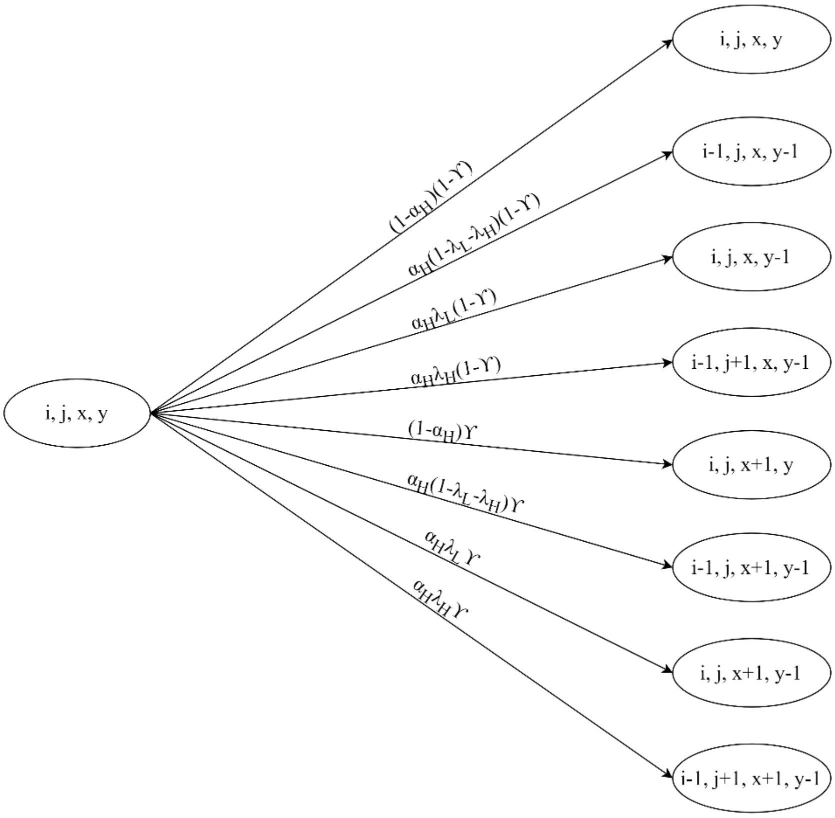


Fig 3. 36: The state diagram for $i = K - 1, j = 0, x = 0, y = 1$

(11) $i = K-1, j = 0, x = 0, y = 2$



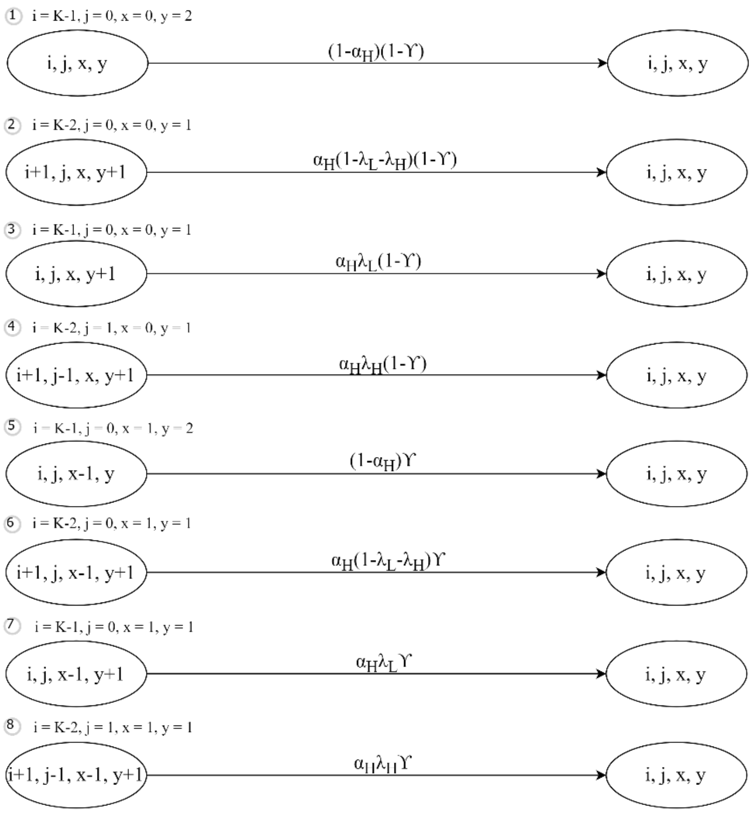
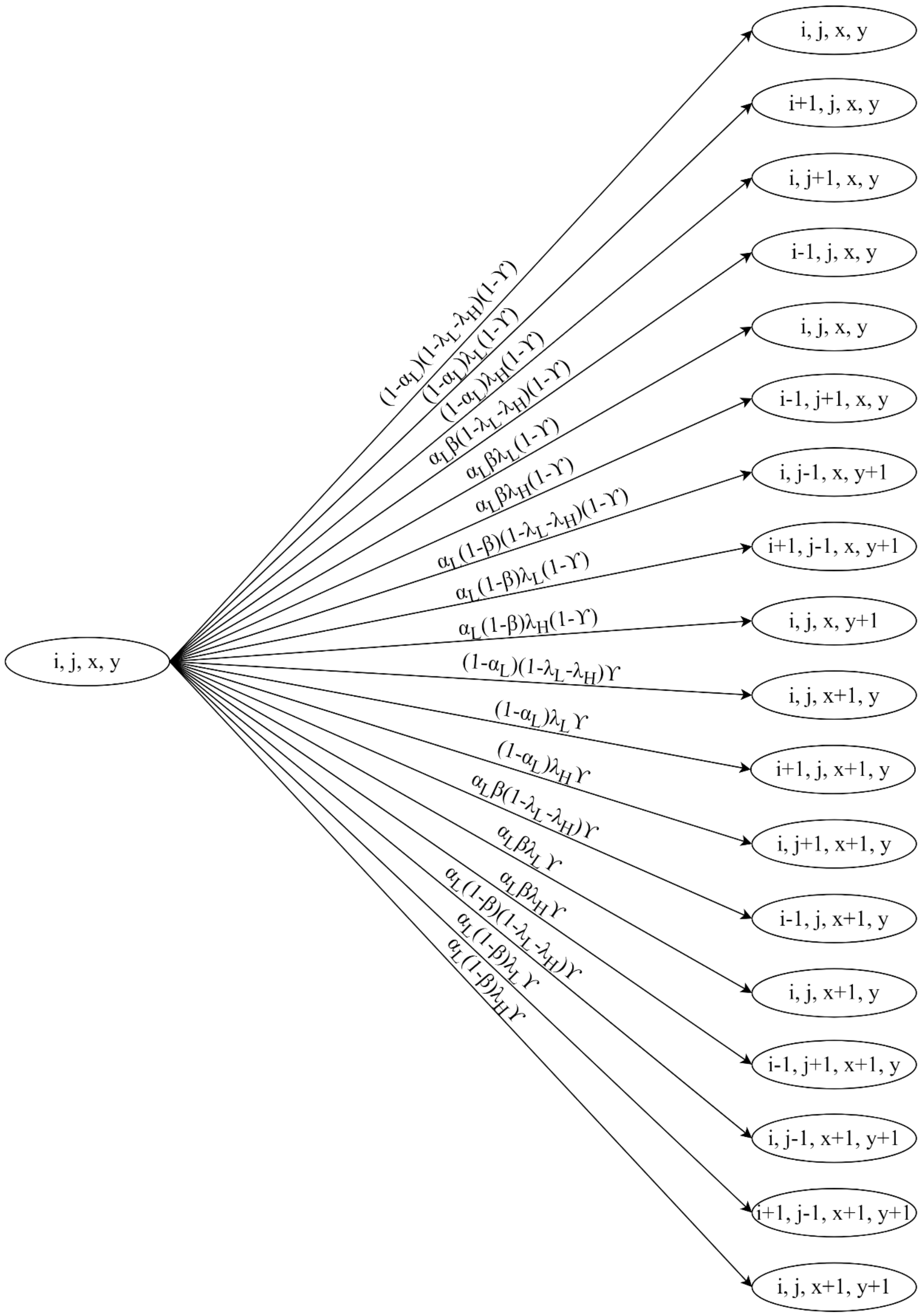


Fig 3. 37: The state diagram for $i = K-1, j = 0, x = 0, y = 2$

(12) $1 \le i \le K-2, 1 \le j \le K-i-2, x=0, y=1$



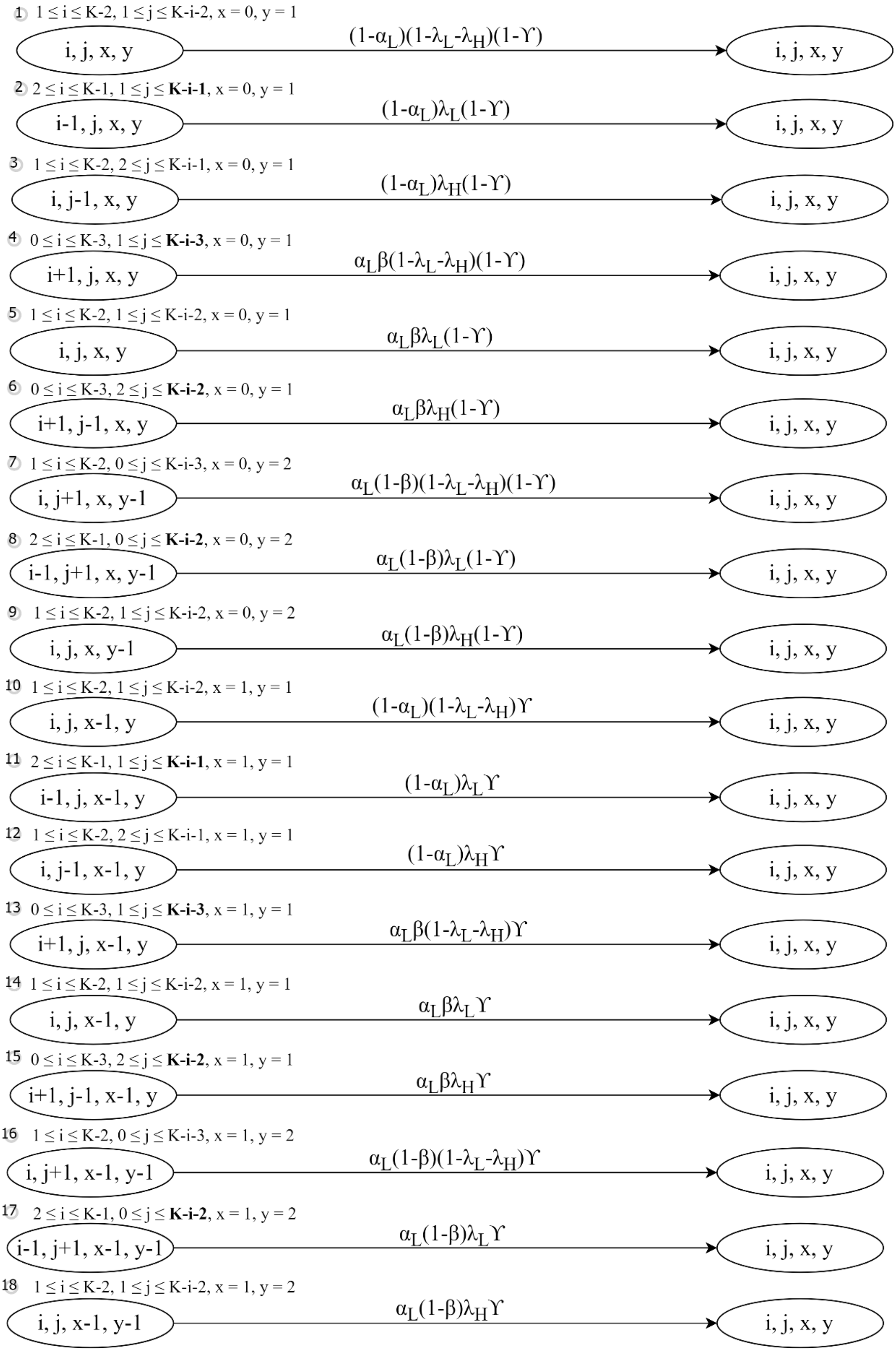
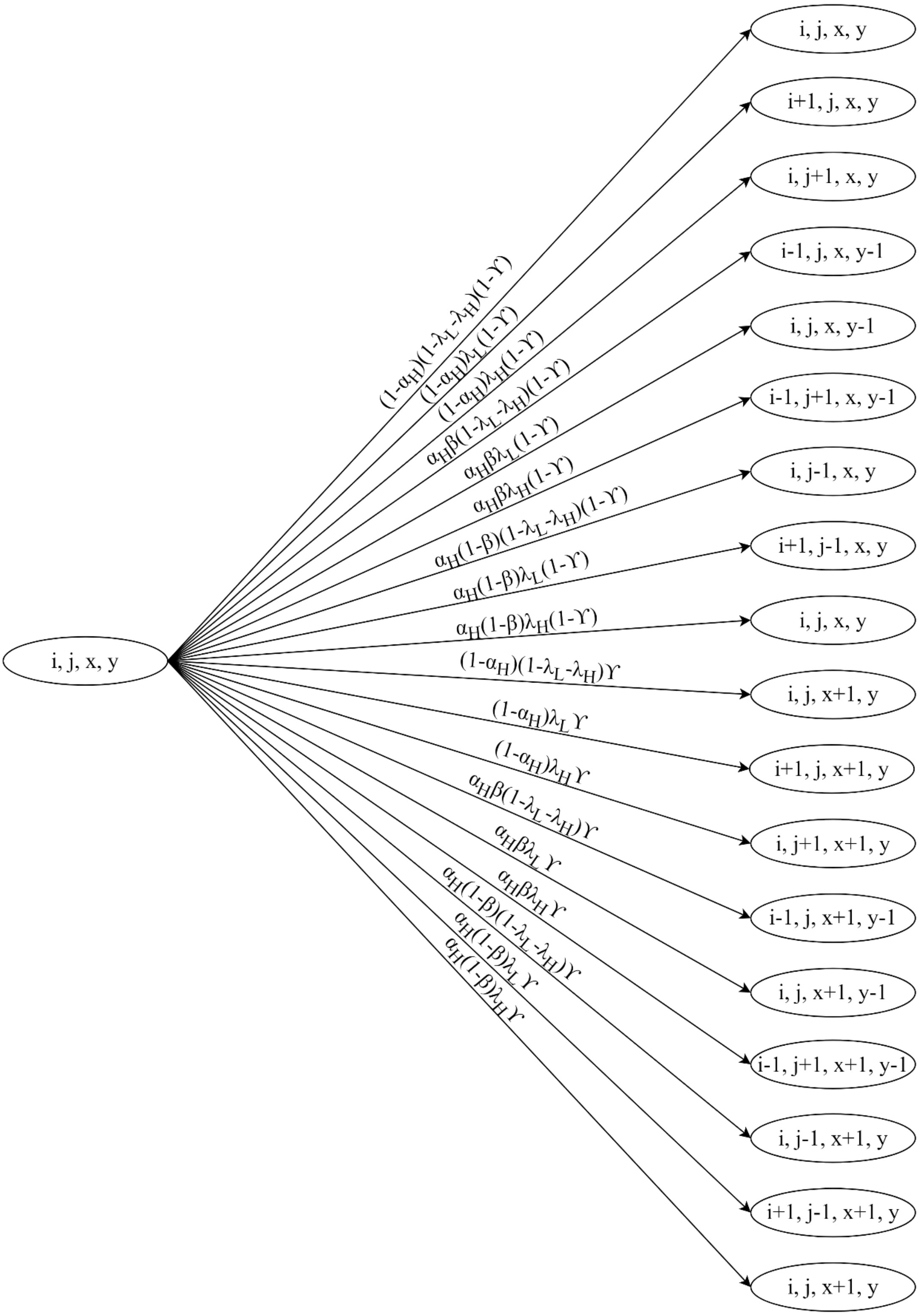


Fig 3. 38: The state diagram for $1 \le i \le K-2, 1 \le j \le K-i-2, x = 0, y = 1$

(13) $1 \le i \le K-2, 1 \le j \le K-i-2, x = 0, y = 2$



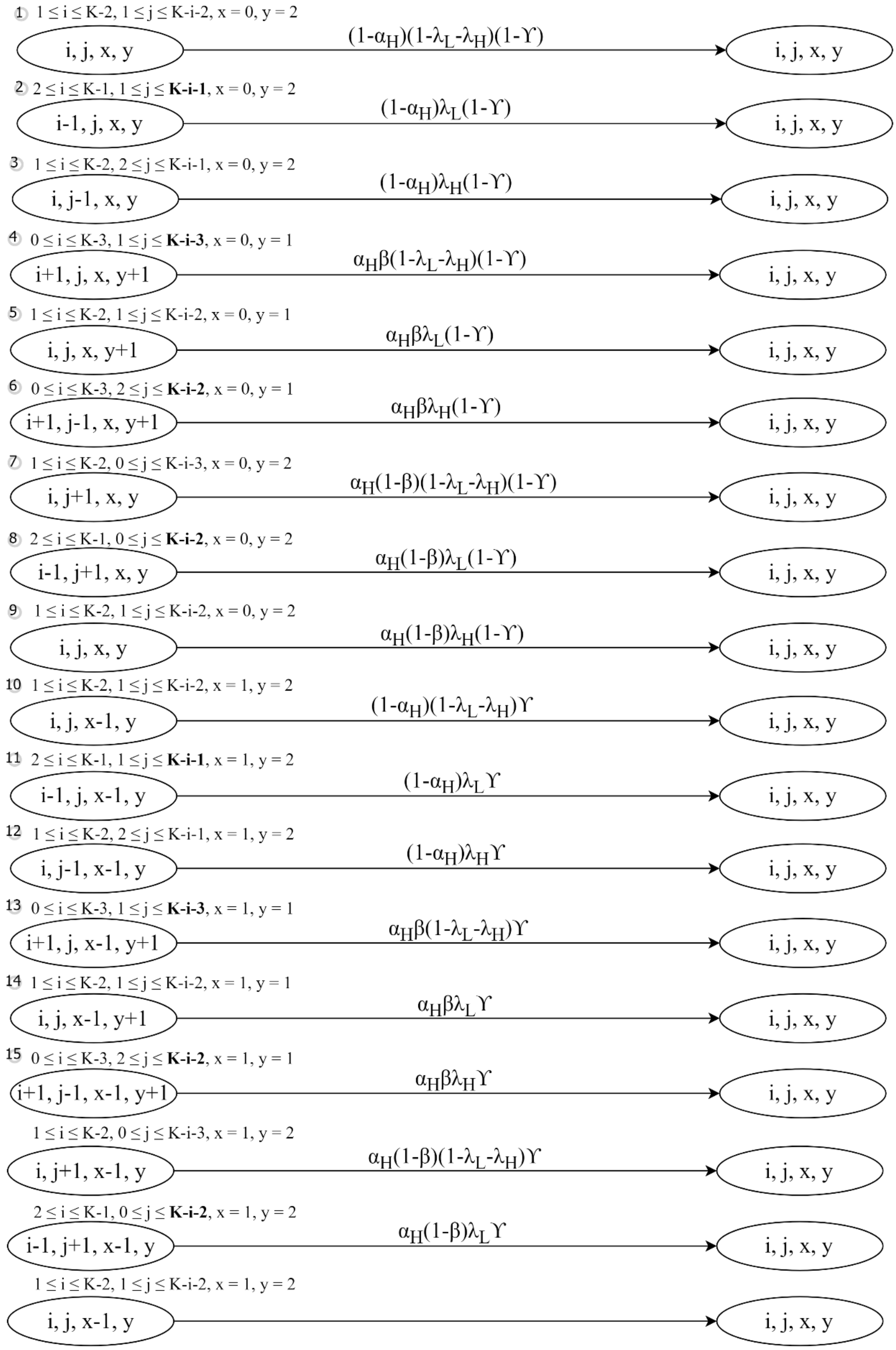
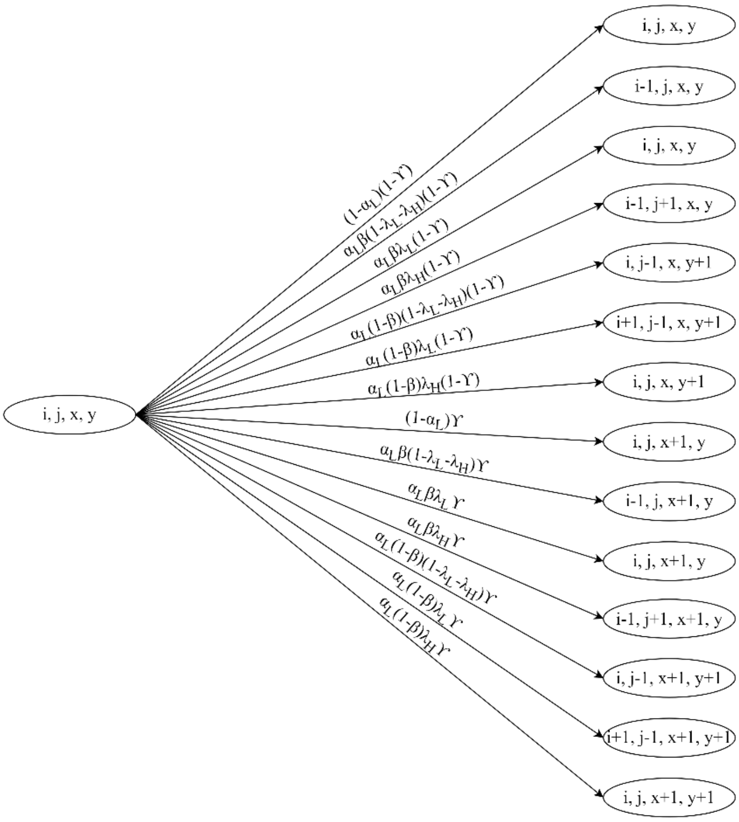


Fig 3. 39: The state diagram for $1 \le i \le K-2, 1 \le j \le K-i-2, x = 0, y = 2$

(14) $1 \le i \le K-2, j = K-i-1, x = 0, y = 1$



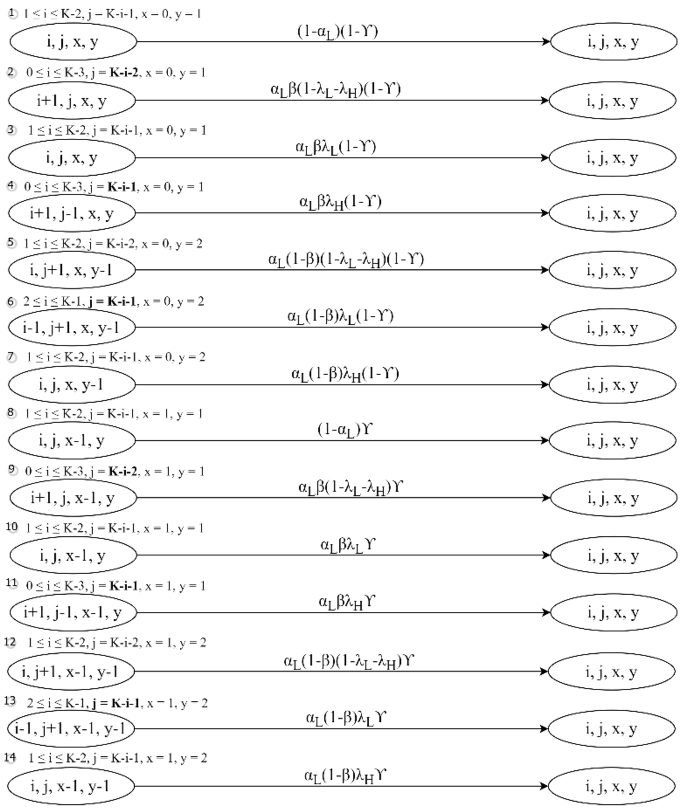
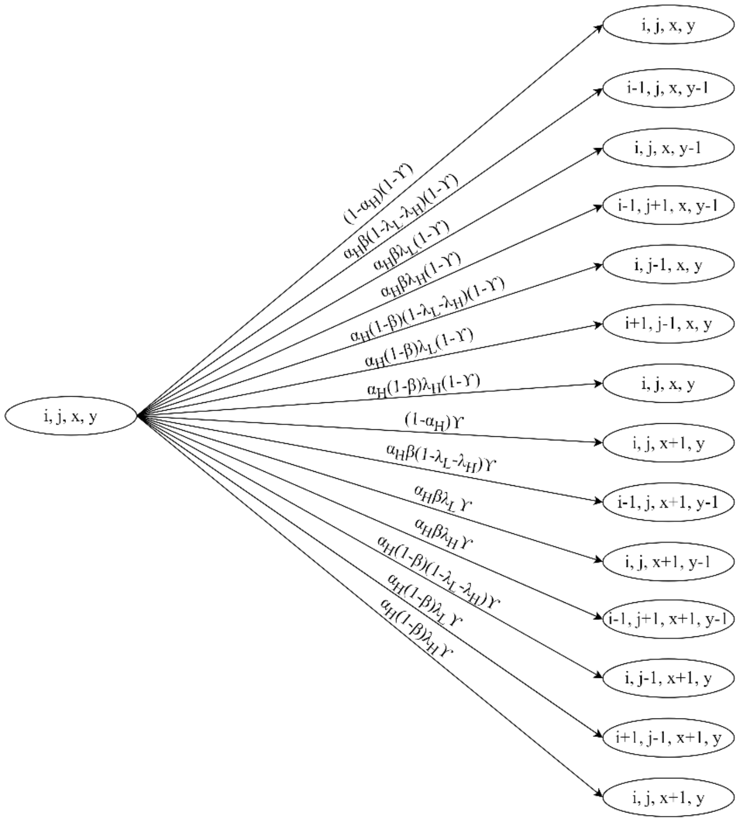


Fig 3. 40: The state diagram for $1 \le i \le K-2, j = K-i-1, x = 0, y = 1$

(15) $1 \le i \le K-2, j = K-i-1, x = 0, y = 2$



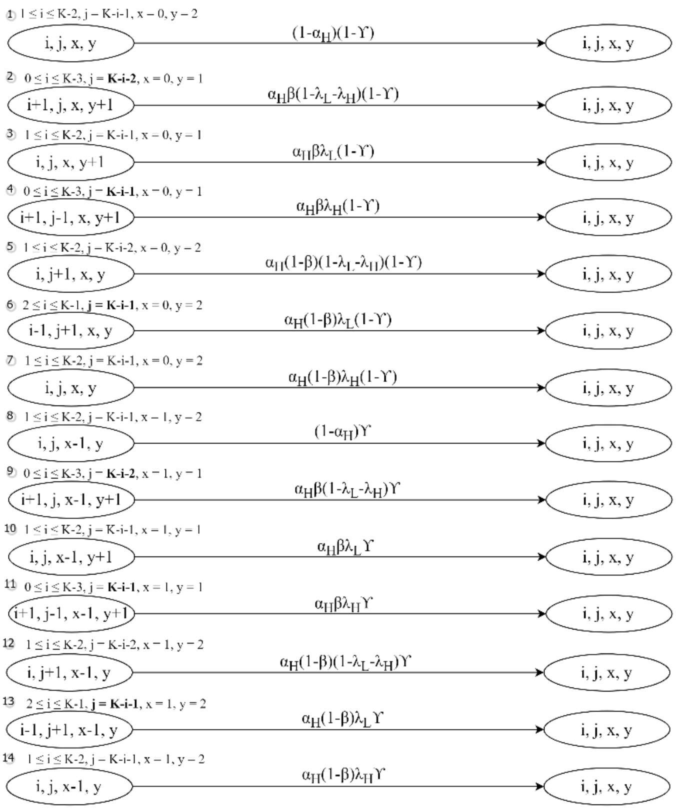


Fig 3. 41: The state diagram for $1 \le i \le K-2, j = K-i-1, x = 0, y = 2$

(16) $i = 0, j = 0, x = 1, y = 0$

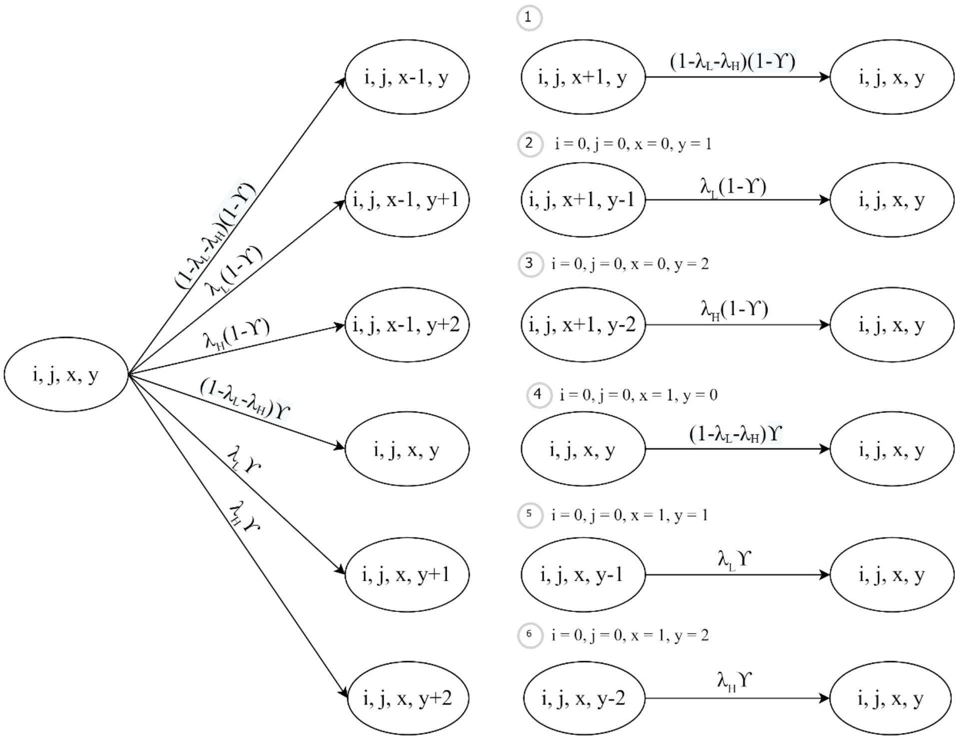


Fig 3. 42: The state diagram for $i = 0, j = 0, x = 1, y = 0$

(17) $i = 0, j = 0, x = 1, y = 1$

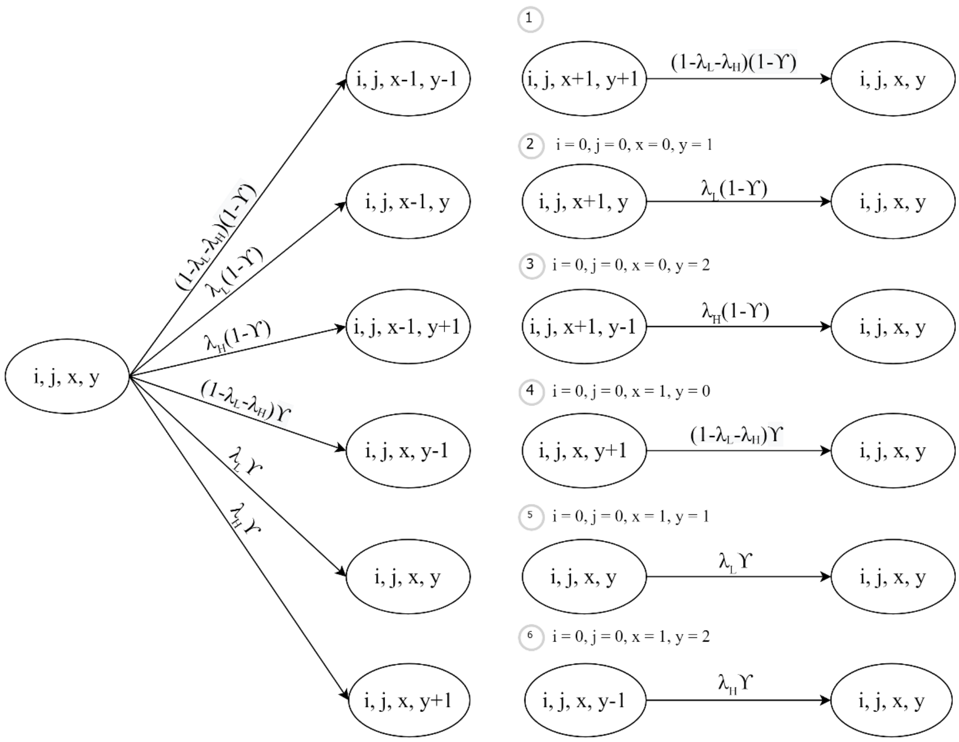


Fig 3. 43: The state diagram for $i = 0, j = 0, x = 1, y = 1$

(18) $i = 0, j = 0, x = 1, y = 2$

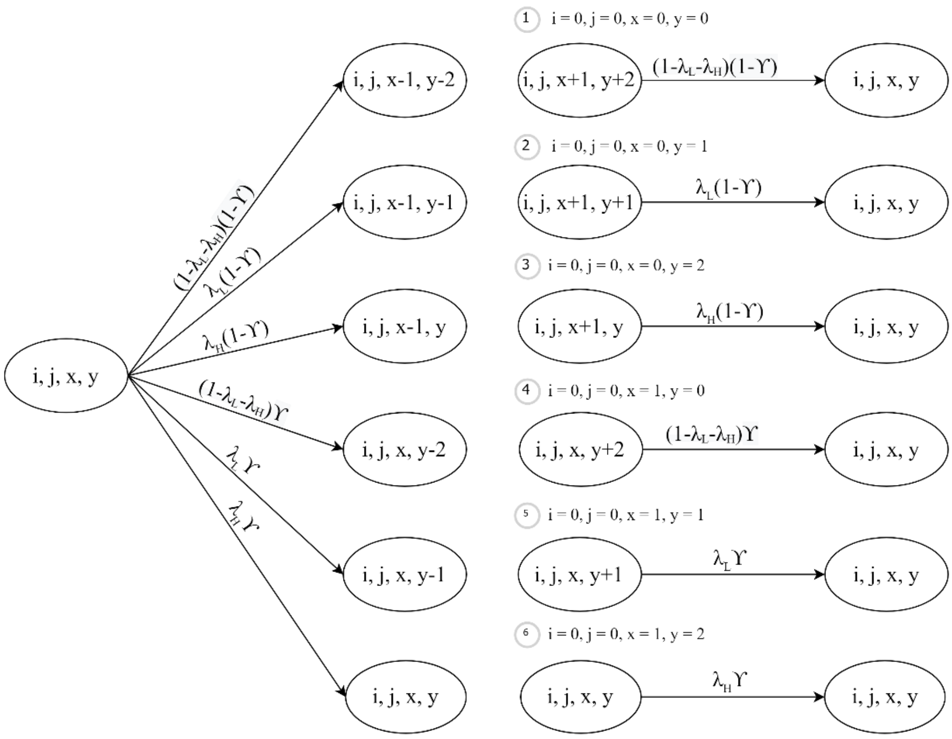


Fig 3. 44: The state diagram for $i = 0, j = 0, x = 1, y = 2$

(19) $i = 0, 1 \leq j \leq K - 1, x = 1, y = 1$

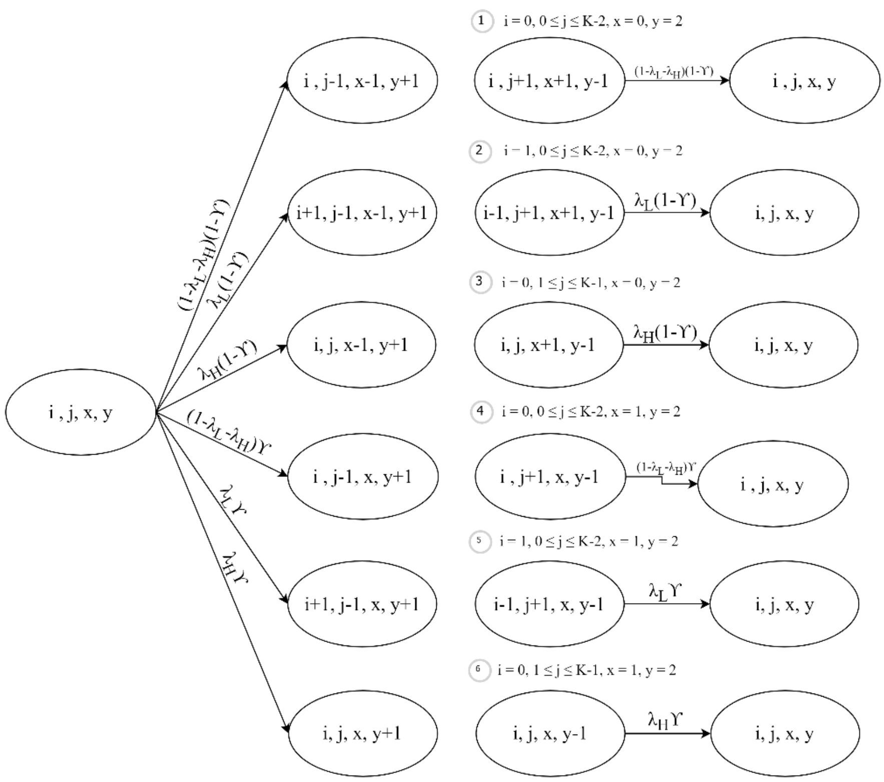


Fig 3. 45: The state diagram for $i = 0, 1 \leq j \leq K - 1, x = 1, y = 1$

(20) $i = 0, 1 \leq j \leq K-1, x = 1, y = 2$

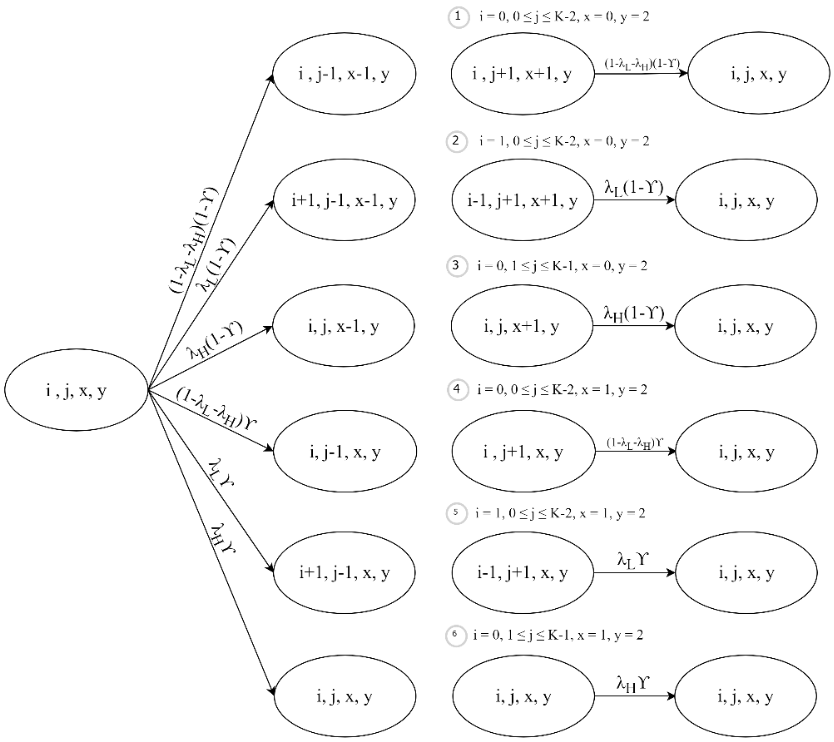


Fig 3. 46: The state diagram for $i = 0, 1 \leq j \leq K-1, x = 1, y = 2$

(21) $1 \leq i \leq K-1, j = 0, x = 1, y = 1$

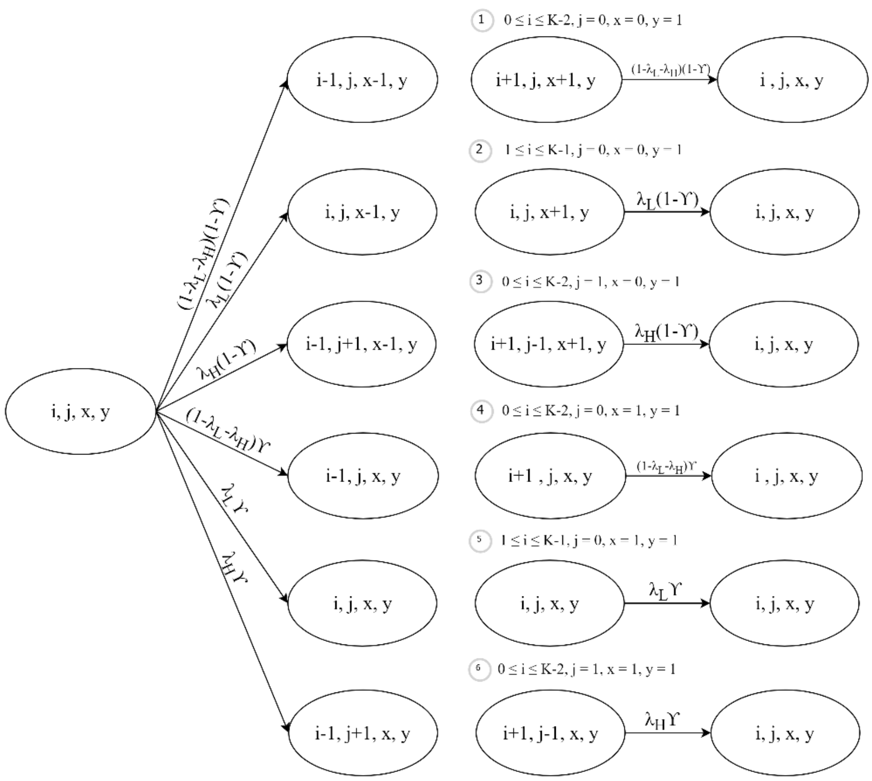


Fig 3. 47: The state diagram for $1 \leq i \leq K-1, j = 0, x = 1, y = 1$

(22) $1 \le i \le K-1, j=0, x=1, y=2$

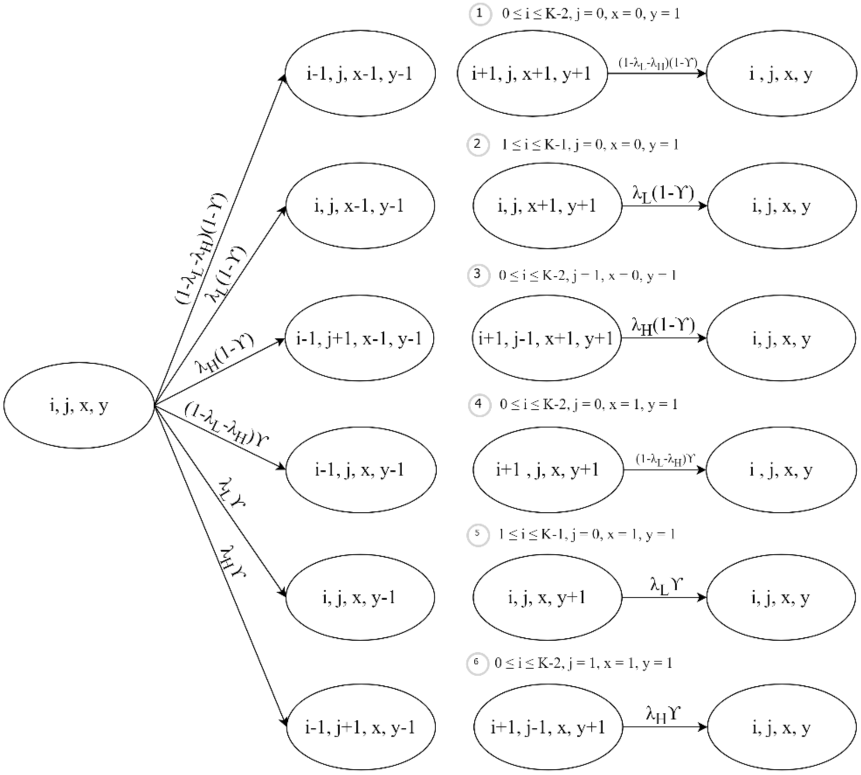
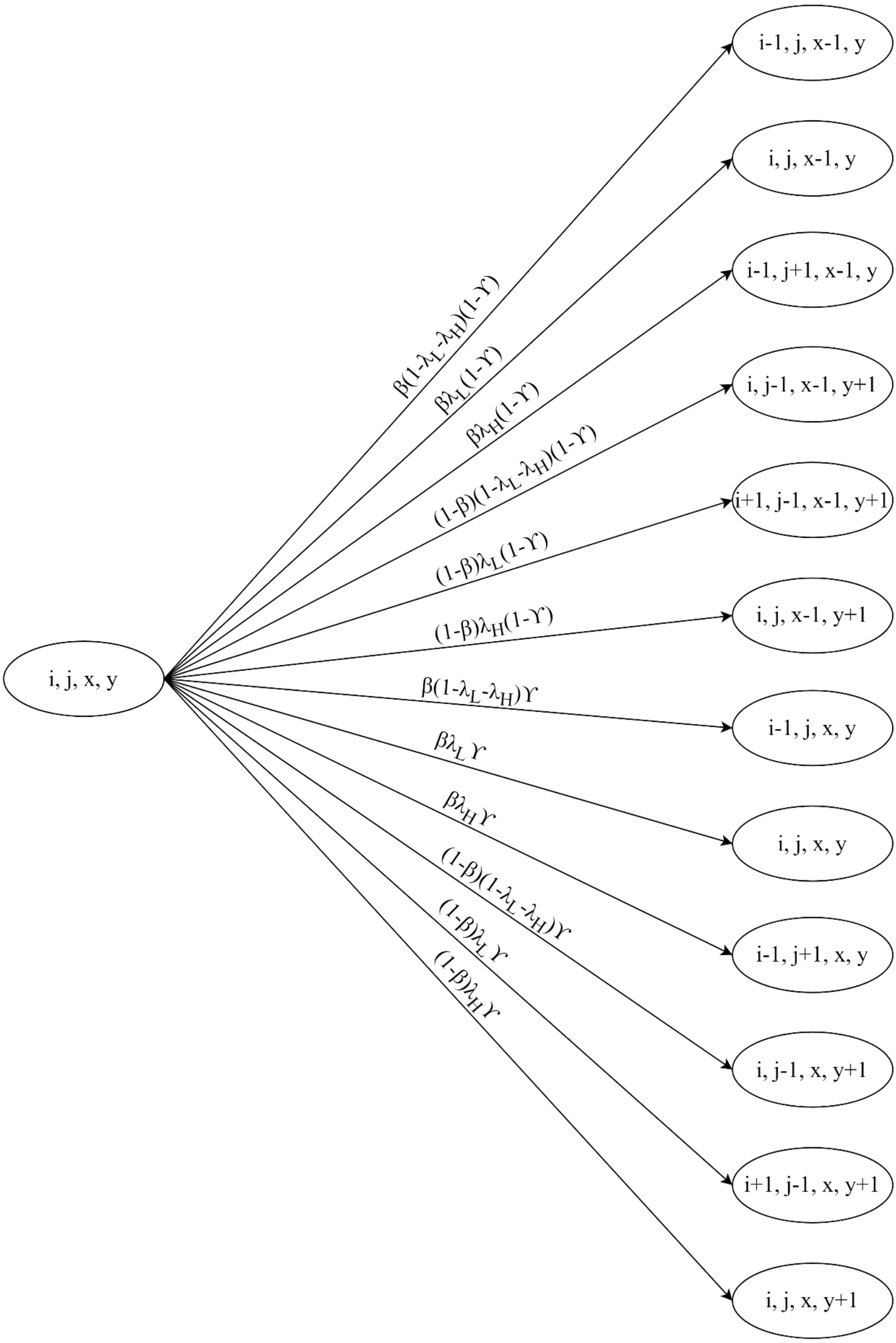


Fig 3. 48: The state diagram for $1 \le i \le K-1, j=0, x=1, y=2$

(23) $1 \le i \le K-2, , 1 \le j \le K-i-1, x=1, y=1$



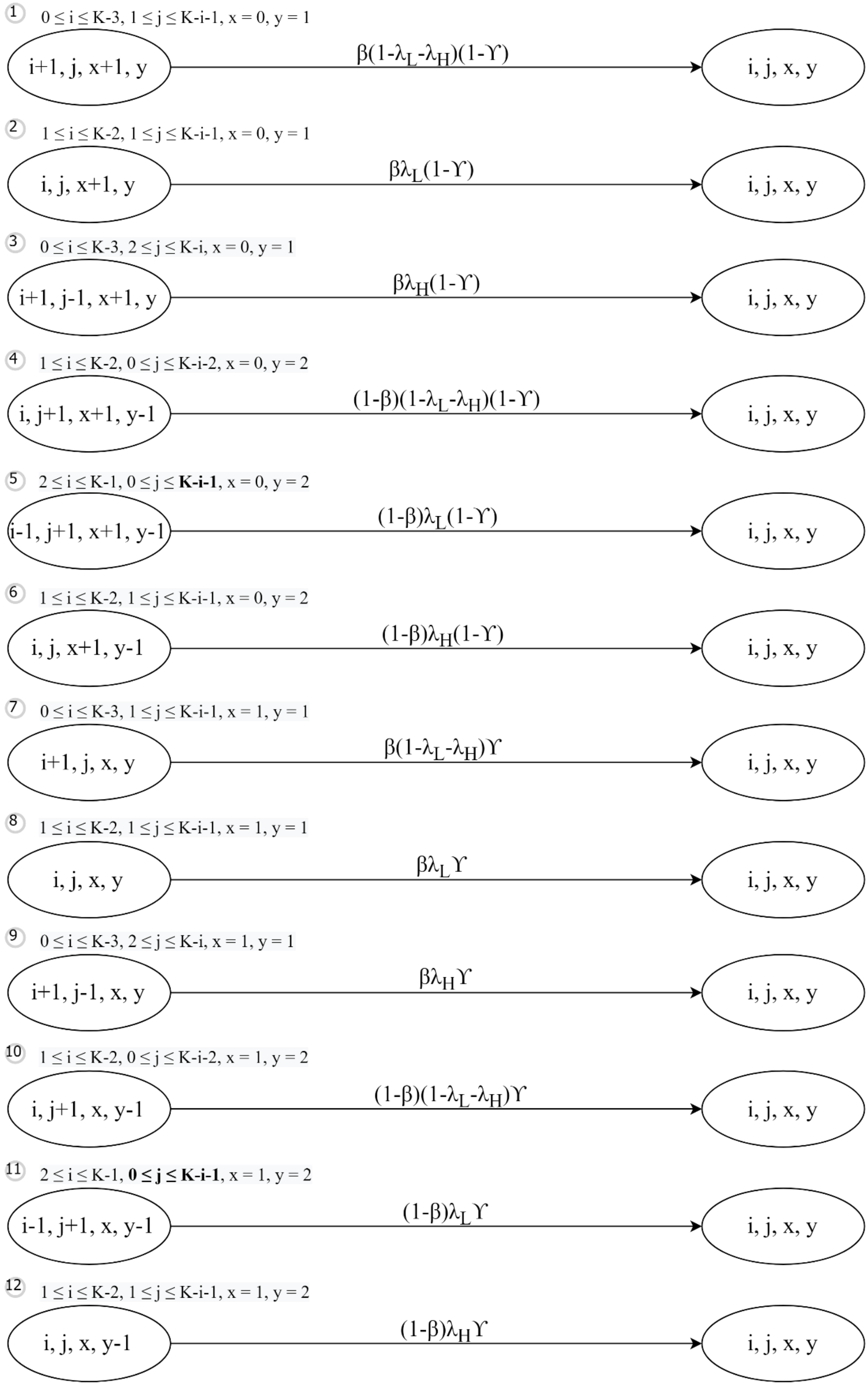
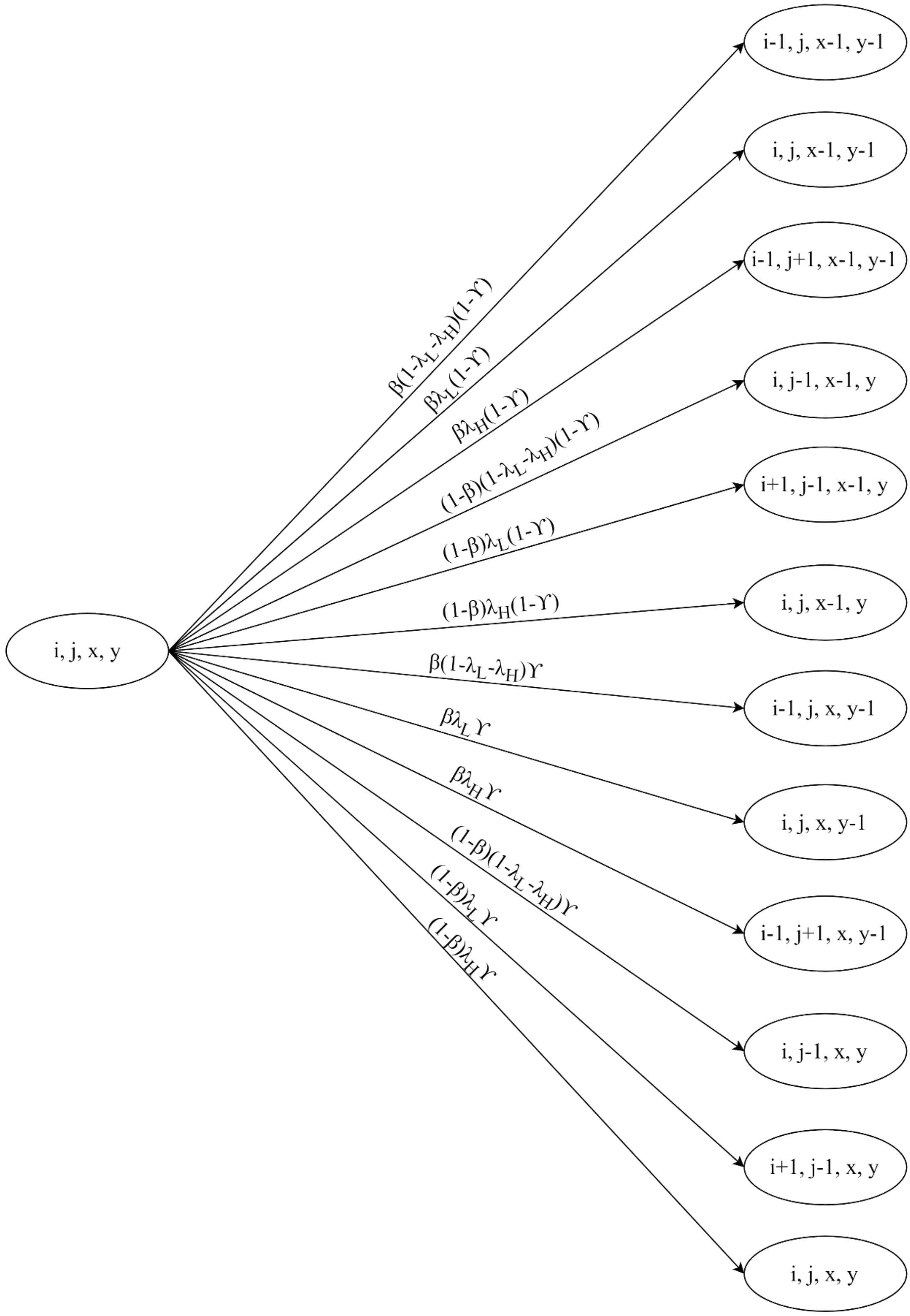


Fig 3. 49: The state diagram for $1 \leq i \leq K-2, ,1 \leq j \leq K-i-1, x=1, y=1$

(24) $1 \leq i \leq K-2, , 1 \leq j \leq K-i-1, x=1, y=2$



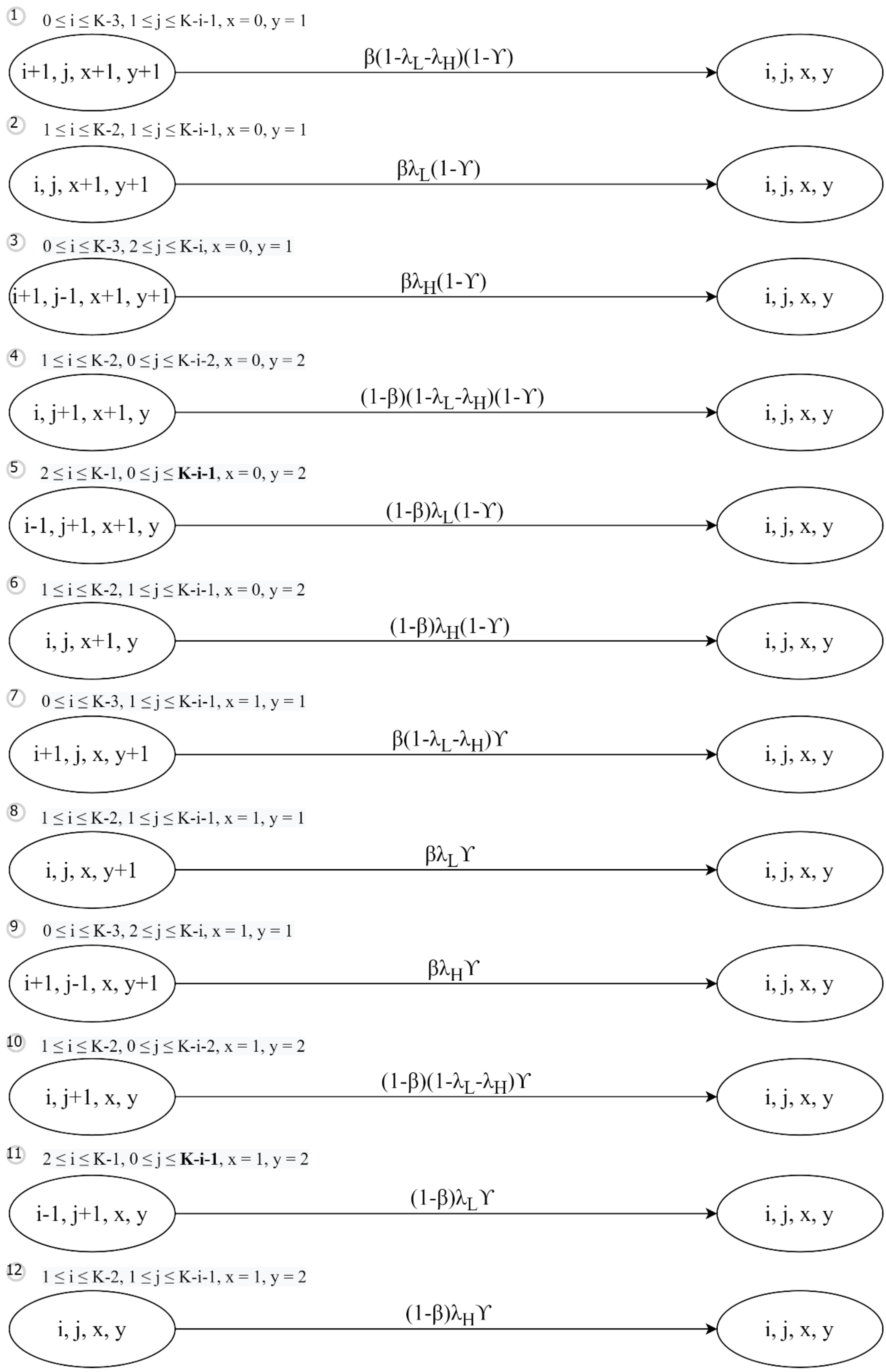


Fig 3. 50: The state diagram for $1 \le i \le K-2, ,1 \le j \le K-i-1, x=1, y=1$

(b) Priority discipline

(1) $i = 0, j = 0, x = 0, y = 0$

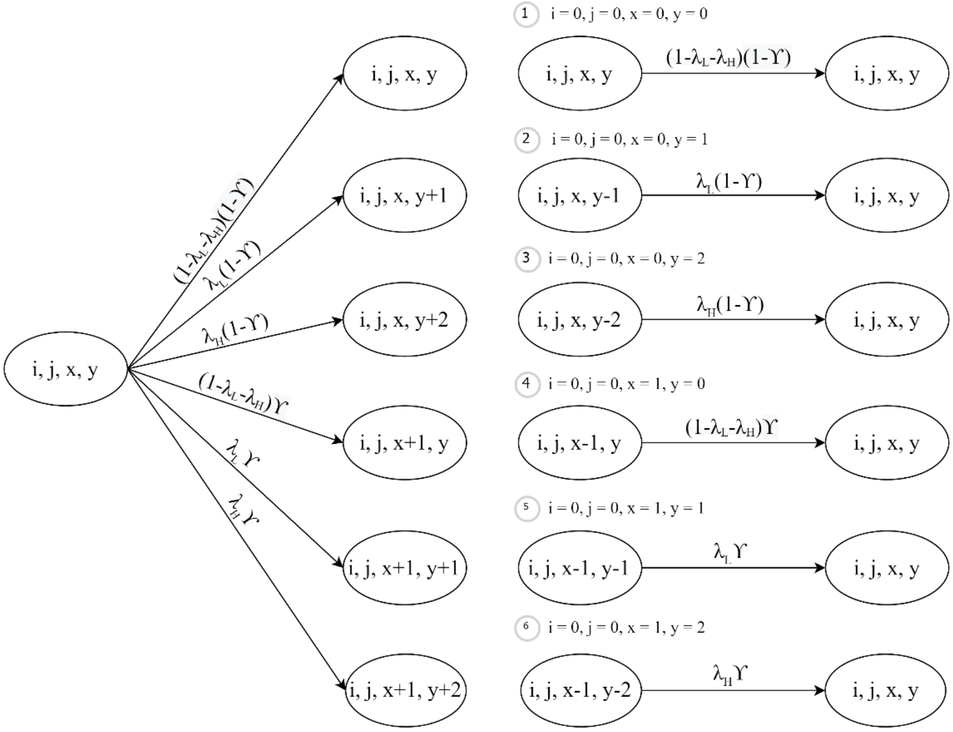


Fig 3. 51: The state diagram for $i = 0, j = 0, x = 0, y = 0$

(2) $i = 0, j = 0, x = 0, y = 1$

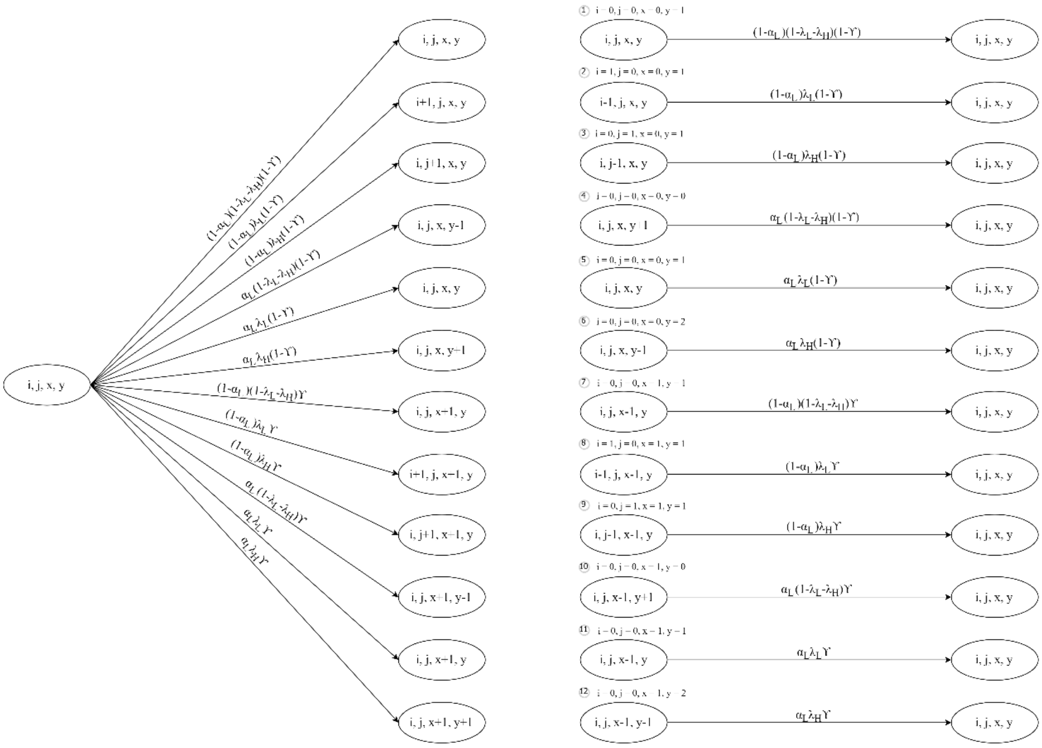


Fig 3. 52: The state diagram for $i = 0, j = 0, x = 0, y = 1$

(3) $i = 0, j = 0, x = 0, y = 2$

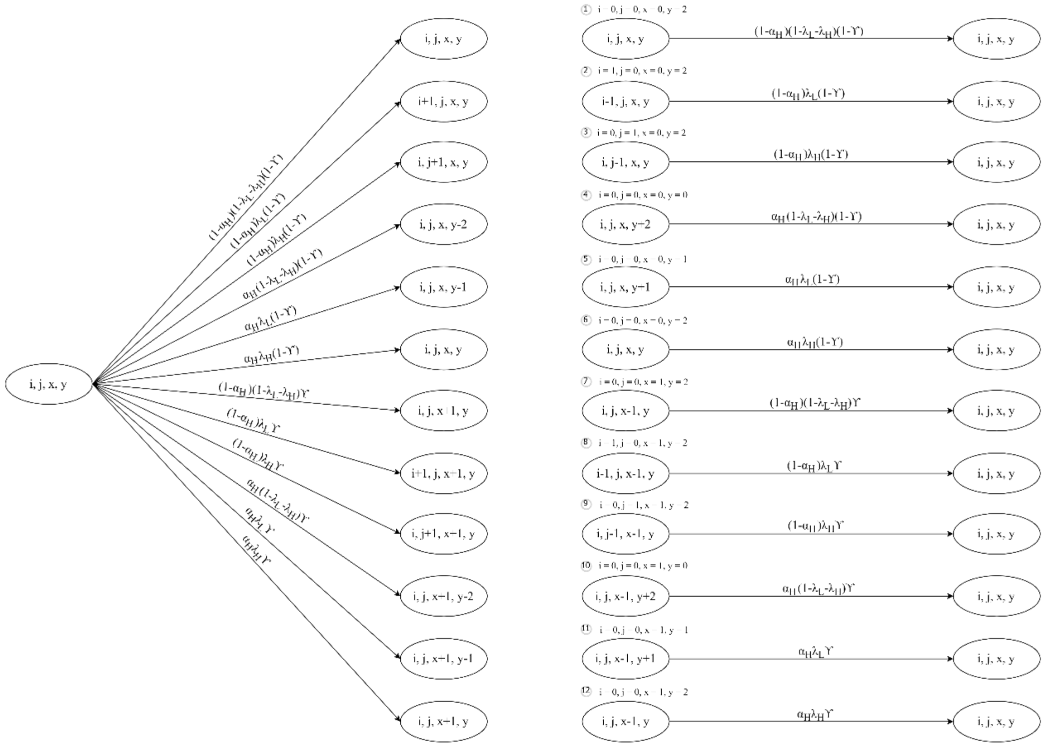


Fig 3. 53: The state diagram for $i = 0, j = 0, x = 0, y = 2$

(4) $i = 0, 1 \leq j \leq K - 2, x = 0, y = 1$

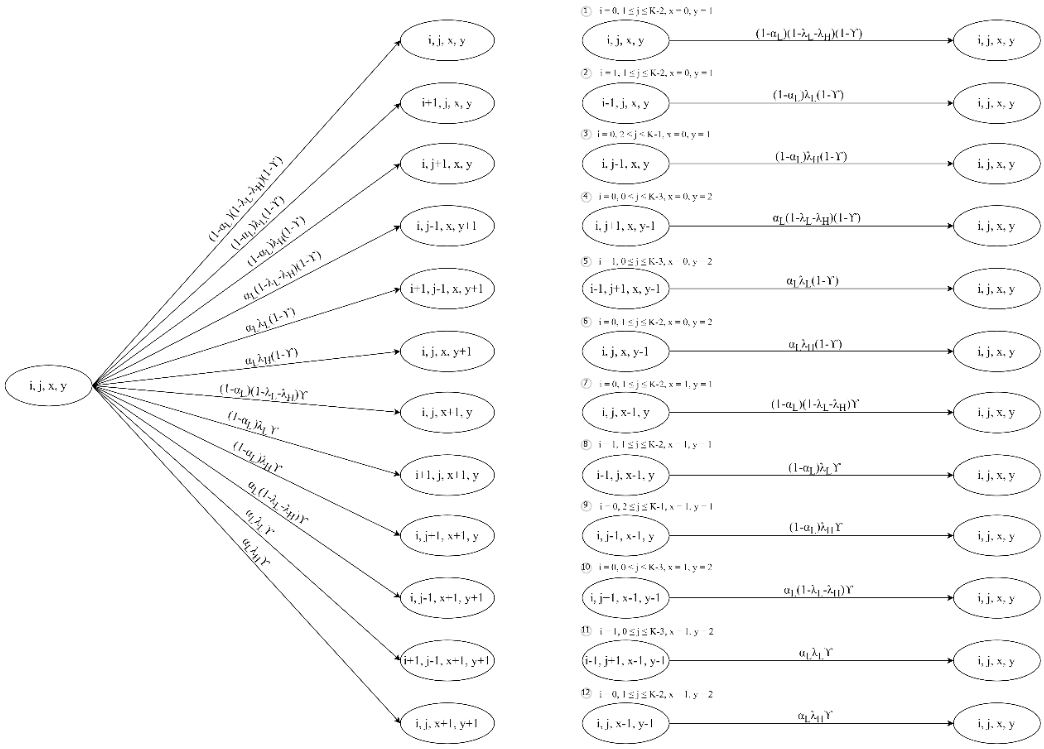


Fig 3. 54: The state diagram for $i = 0, 1 \leq j \leq K - 2, x = 0, y = 1$

(5) $i = 0, 1 \leq j \leq K-2, x = 0, y = 2$

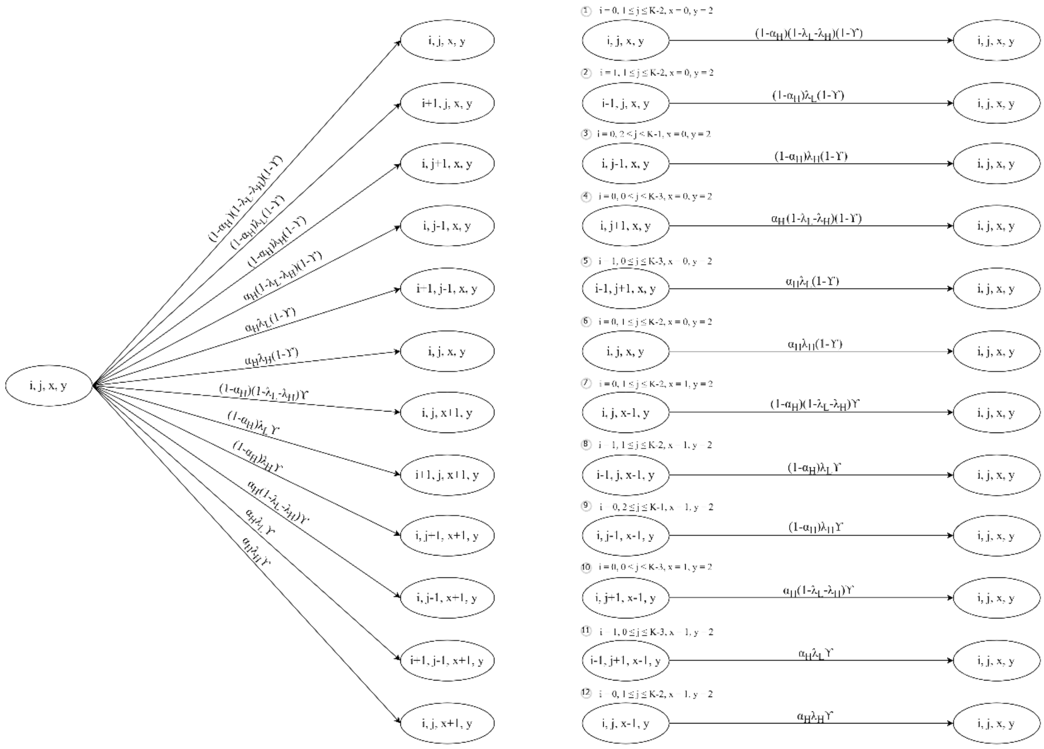


Fig 3. 55: The state diagram for $i = 0, 1 \leq j \leq K-2, x = 0, y = 2$

(6) $1 \leq i \leq K-2, j = 0, x = 0, y = 1$

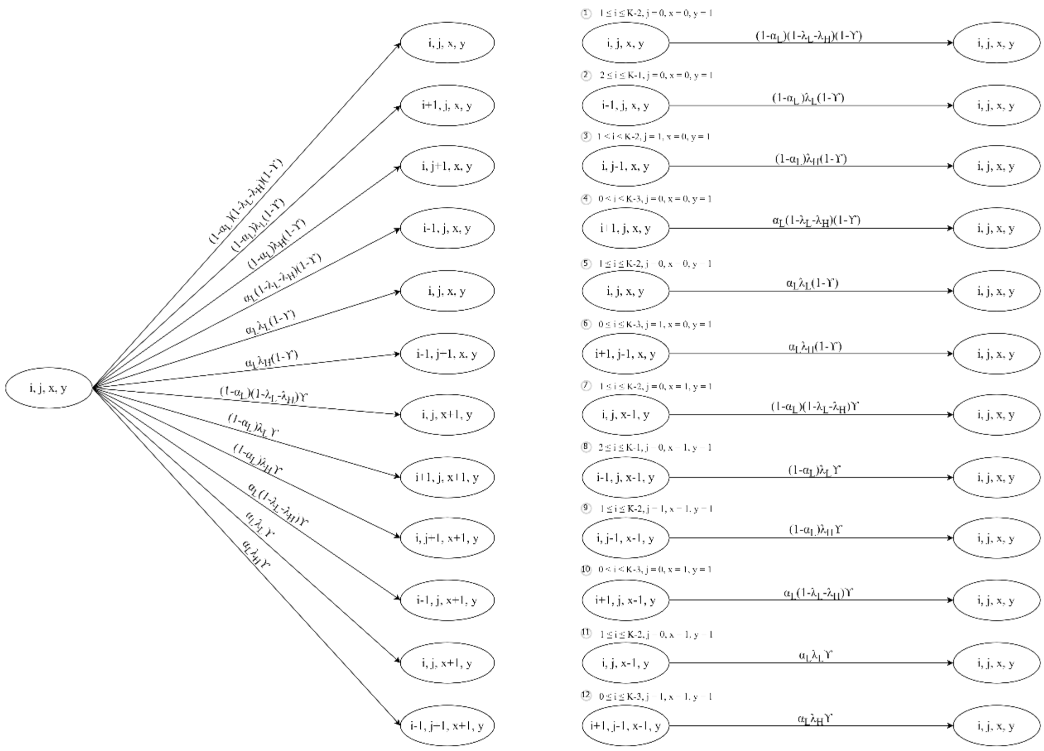


Fig 3. 56: The state diagram for $1 \leq i \leq K-2, j = 0, x = 0, y = 1$

(7) $1 \le i \le K-2, j = 0, x = 0, y = 2$

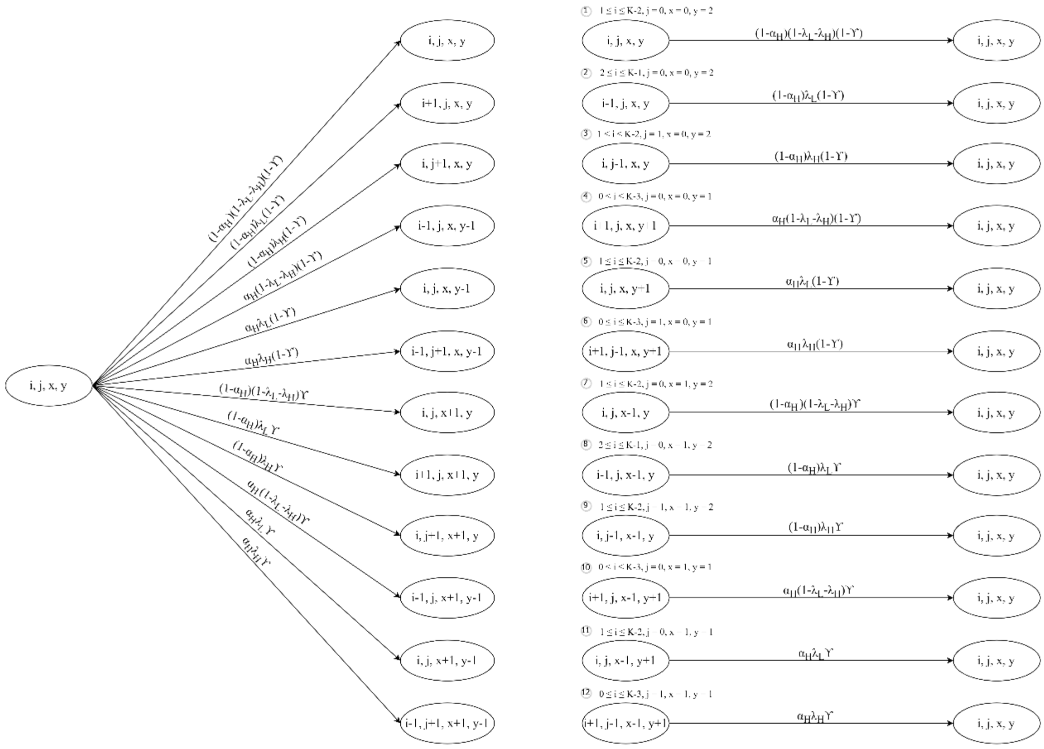


Fig 3. 57: The state diagram for $1 \le i \le K-2, j = 0, x = 0, y = 2$

(8) $i = 0, j = K-1, x = 0, y = 1$

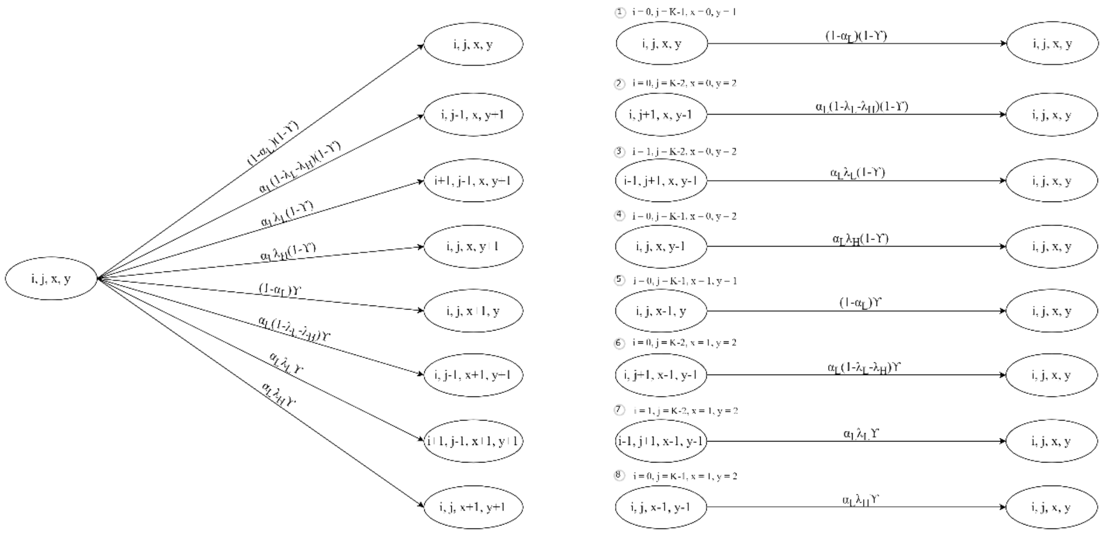


Fig 3. 58: The state diagram for $i = 0, j = K-1, x = 0, y = 1$

(9) $i = 0, j = K - 1, x = 0, y = 2$

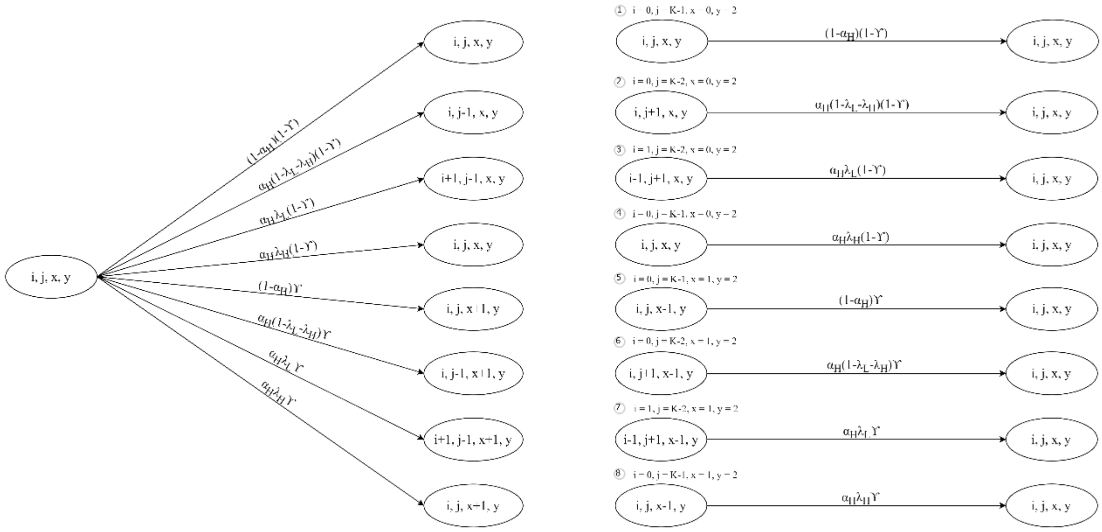


Fig 3. 59: The state diagram for $i = 0, j = K - 1, x = 0, y = 2$

(10) $i = K - 1, j = 0, x = 0, y = 1$

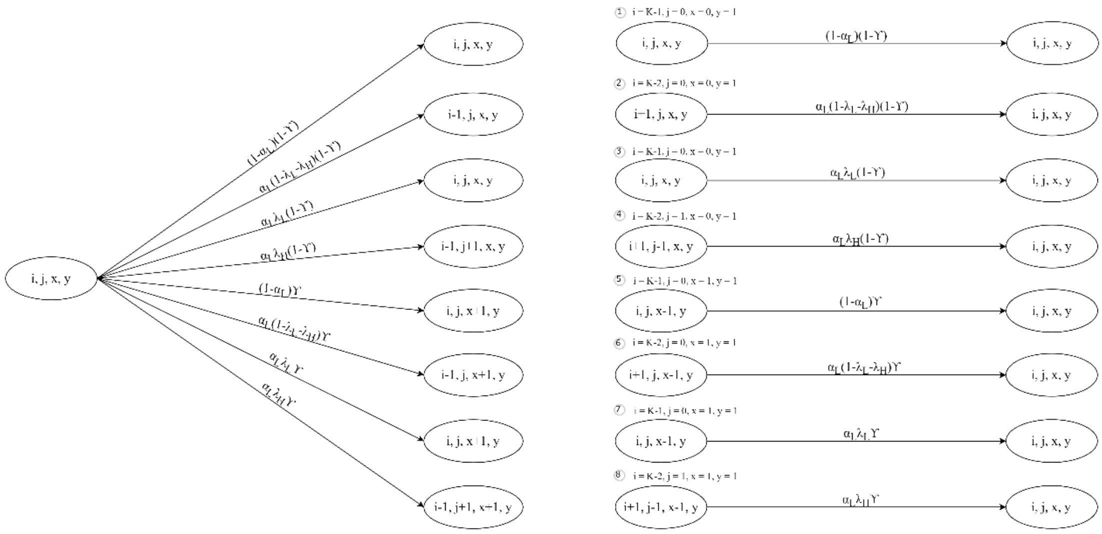


Fig 3. 60: The state diagram for $i = K - 1, j = 0, x = 0, y = 1$

(11) $i = K - 1, j = 0, x = 0, y = 2$

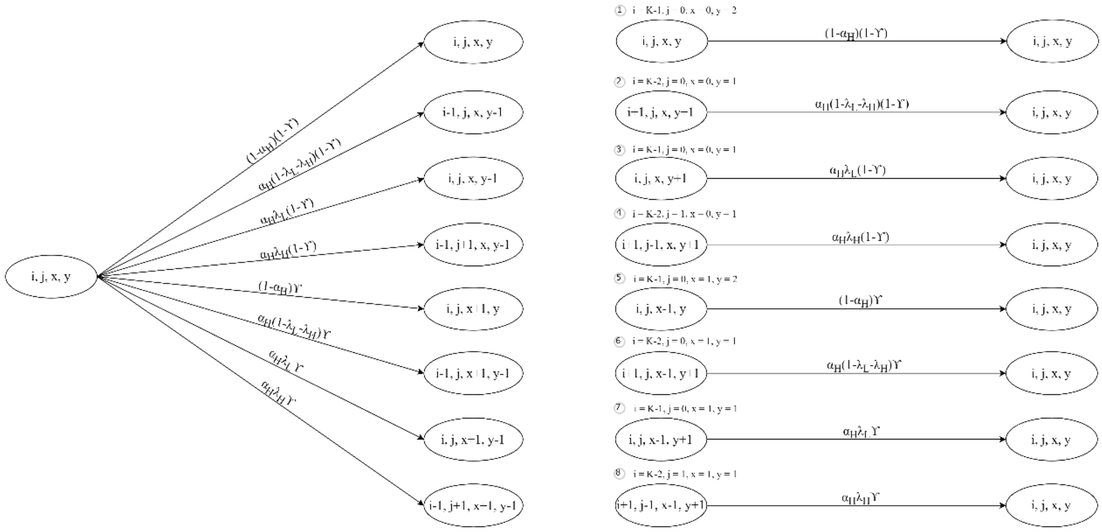
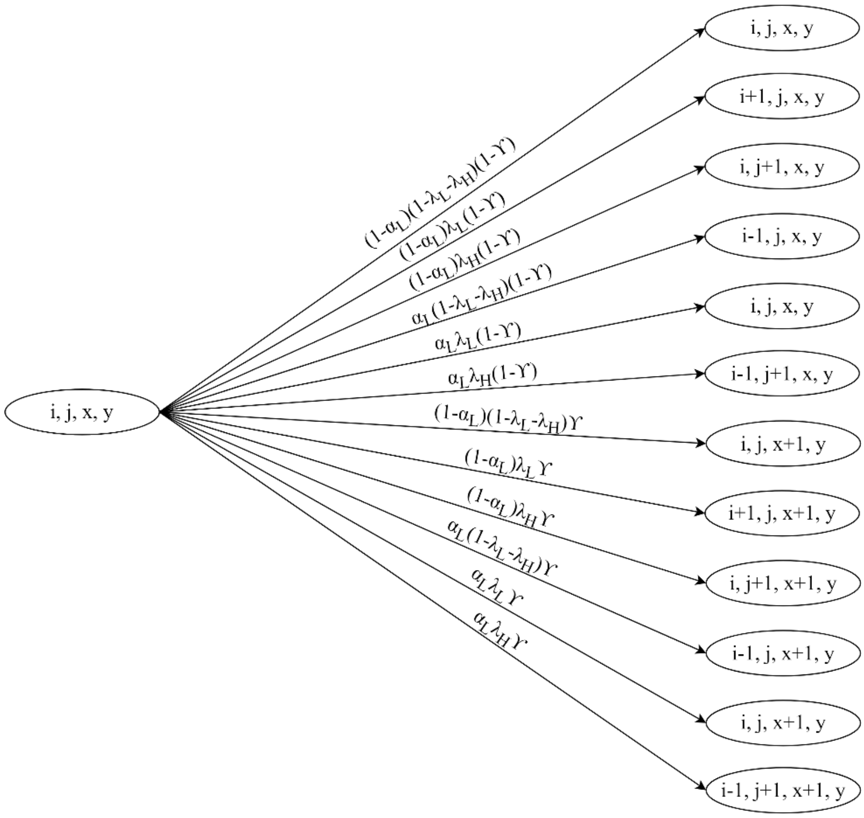


Fig 3. 61: The state diagram for $i = K - 1, j = 0, x = 0, y = 2$

(12) $1 \leq i \leq K-2, 1 \leq j \leq K-i-2, x=0, y=1$



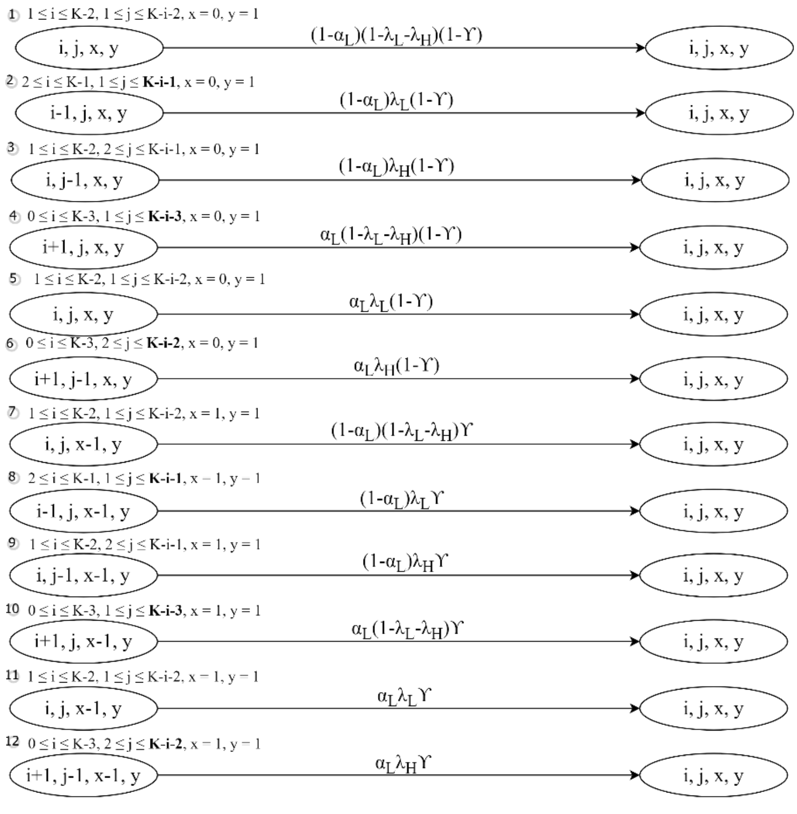
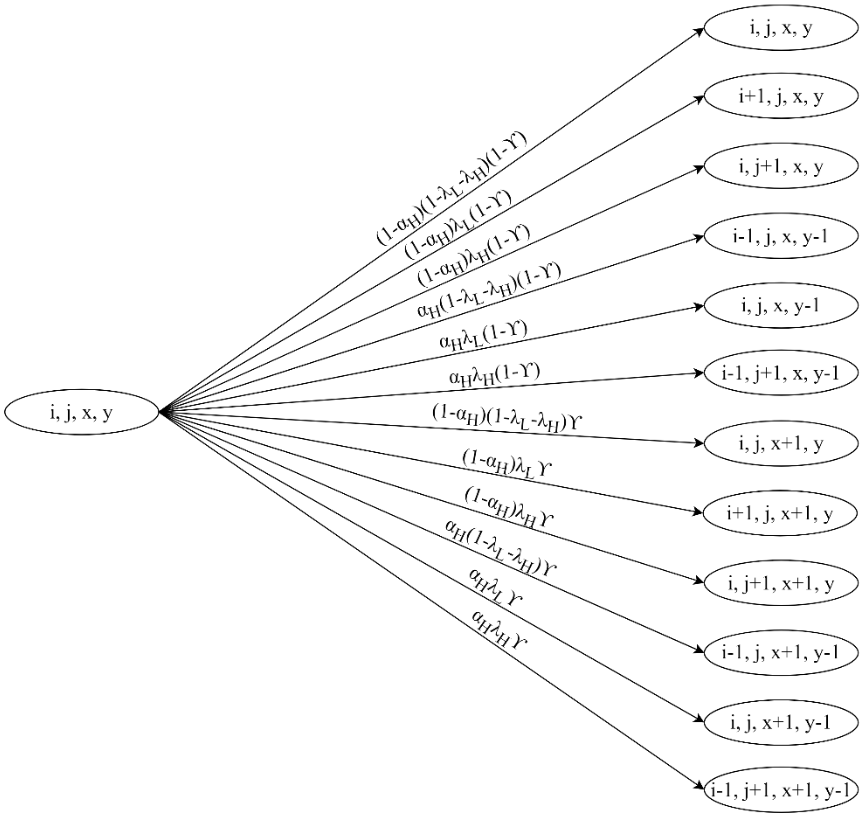


Fig 3. 62: The state diagram for $1 \leq i \leq K-2, 1 \leq j \leq K-i-2, x=0, y=1$

(13) $1 \leq i \leq K-2, 1 \leq j \leq K-i-2, x=0, y=2$



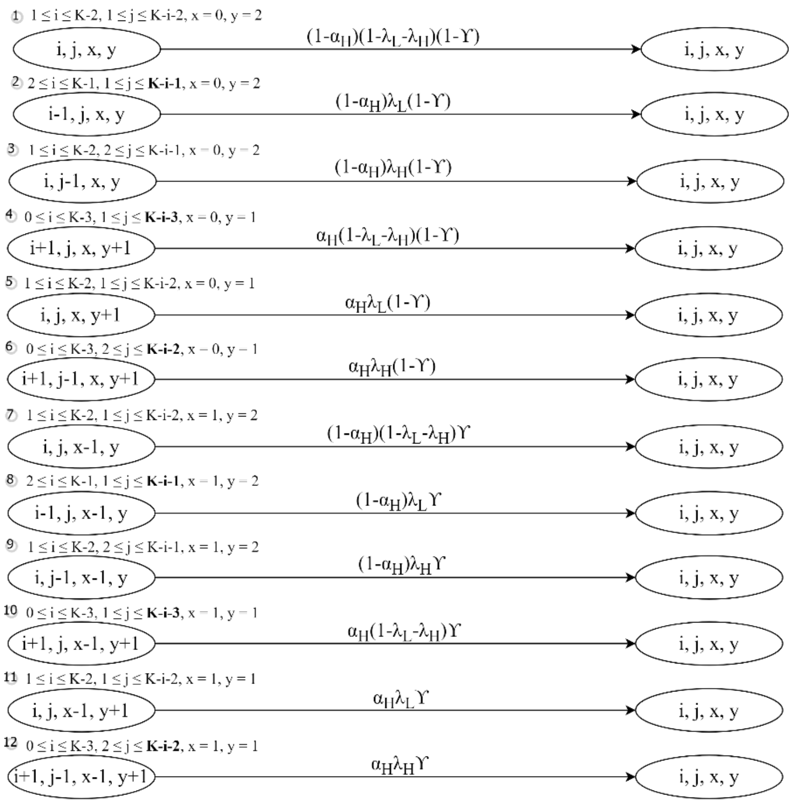


Fig 3. 63: The state diagram for $1 \leq i \leq K-2, 1 \leq j \leq K-i-2, x=0, y=2$

$(14)\ 1 \le i \le K-2, j = K-i-1, x = 0, y = 1$

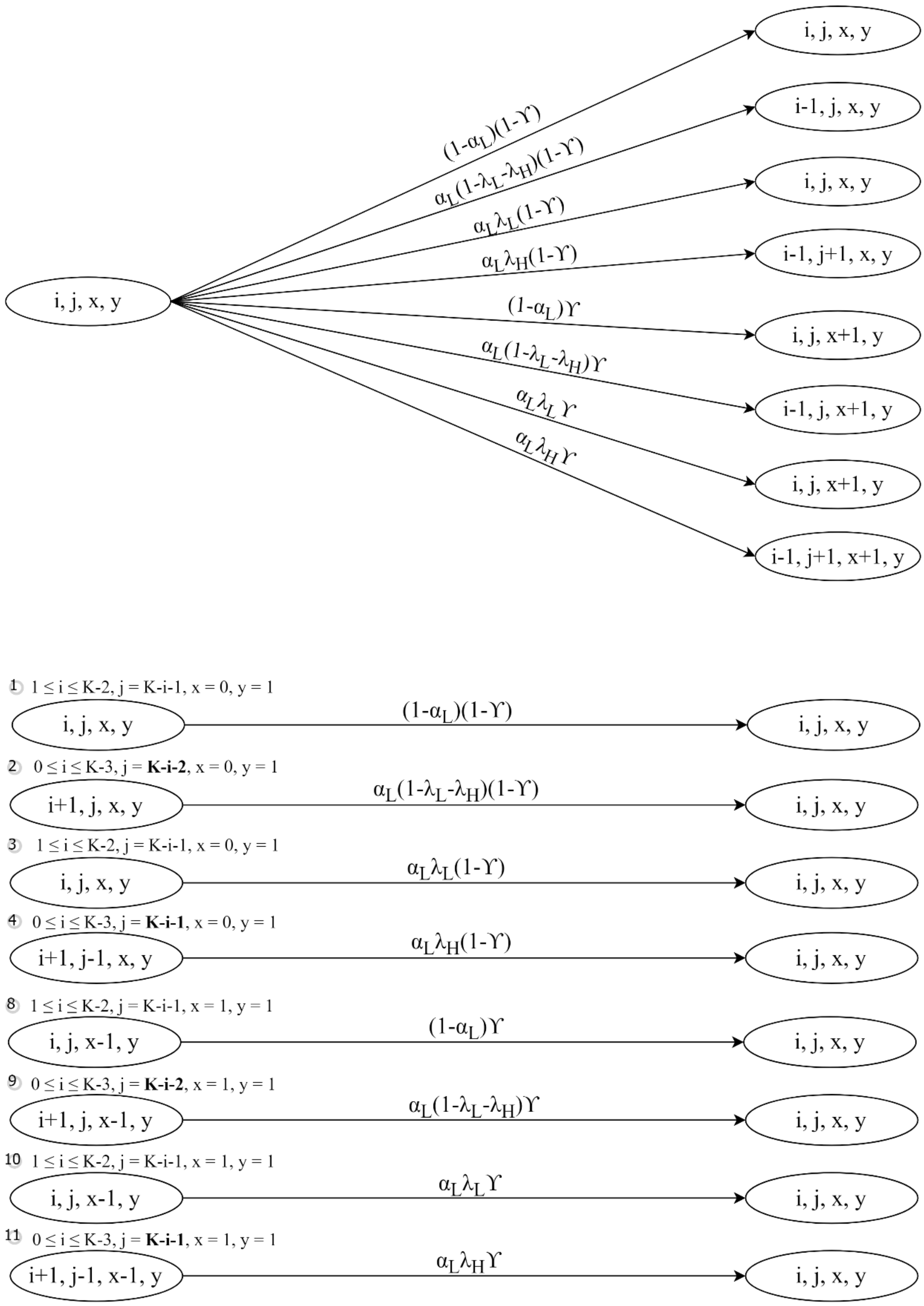
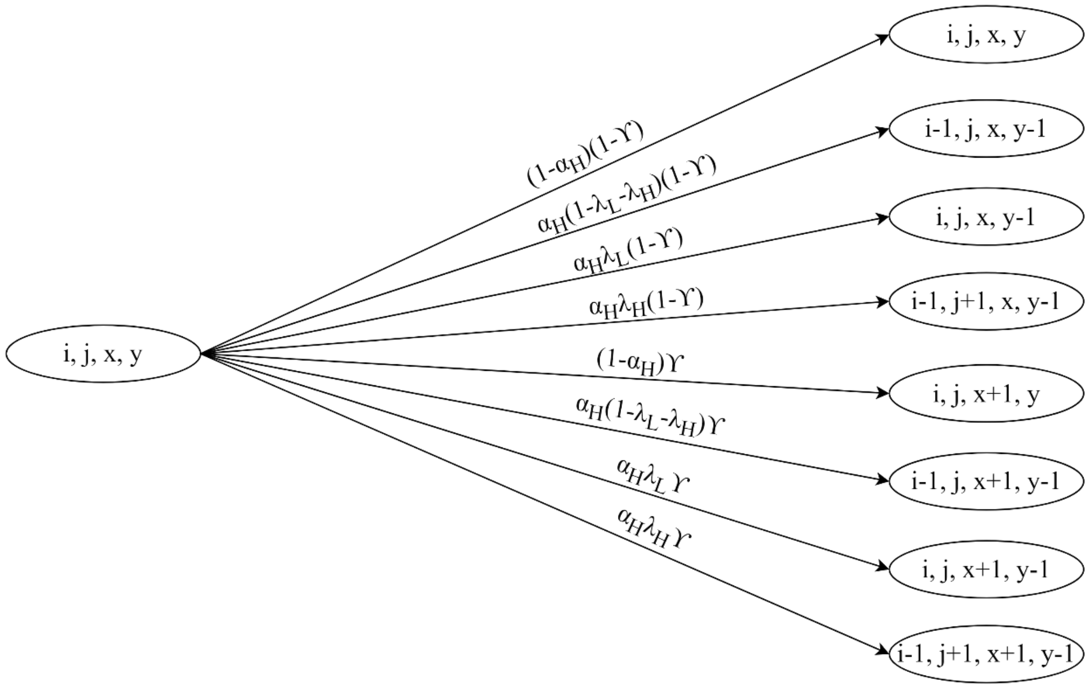


Fig 3. 64: The state diagram for $1 \le i \le K-2, j = K-i-1, x = 0, y = 1$

(15) $1 \le i \le K-2, j = K-i-1, x = 0, y = 2$



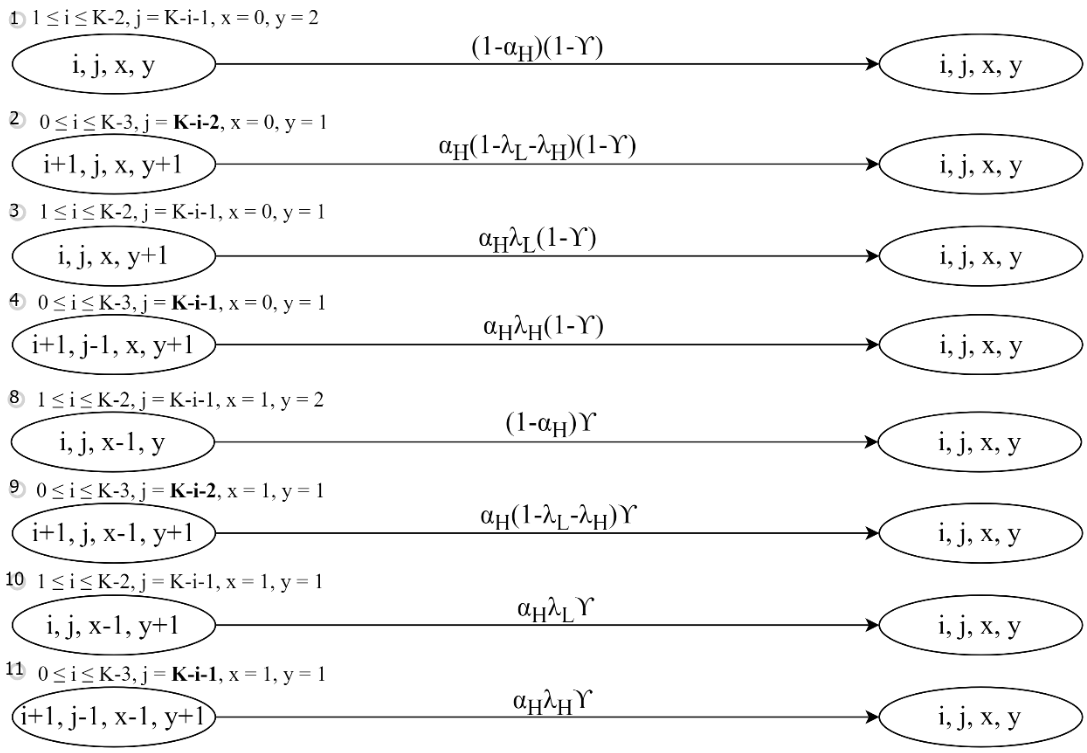


Fig 3. 65: The state diagram for $1 \le i \le K-2, j = K-i-1, x = 0, y = 2$

(16) $i = 0, j = 0, x = 1, y = 0$

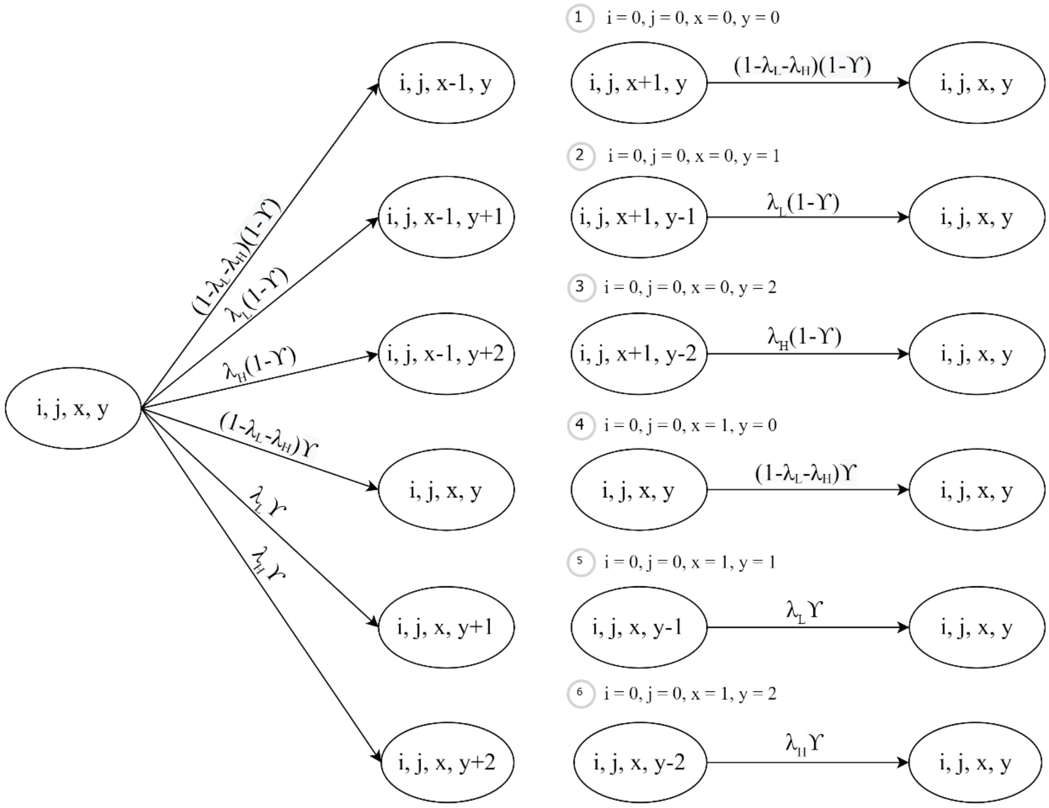


Fig 3. 66: The state diagram for $i = 0, j = 0, x = 1, y = 0$

(17) $i = 0, j = 0, x = 1, y = 1$

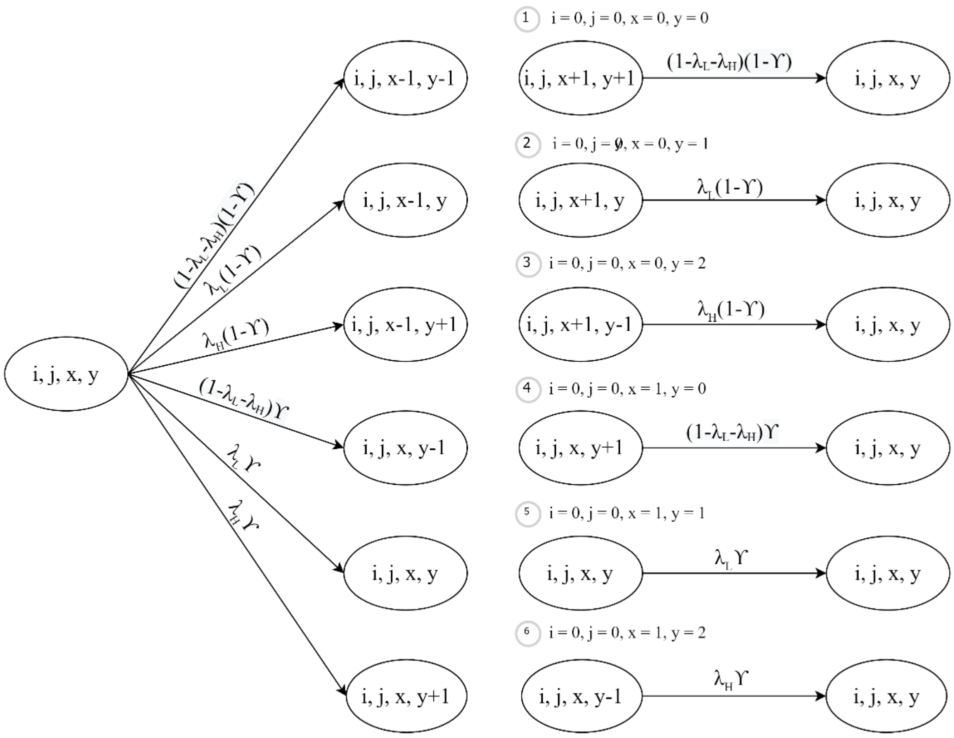


Fig 3. 67: The state diagram for $i = 0, j = 0, x = 1, y = 1$

(18) $i = 0, j = 0, x = 1, y = 2$

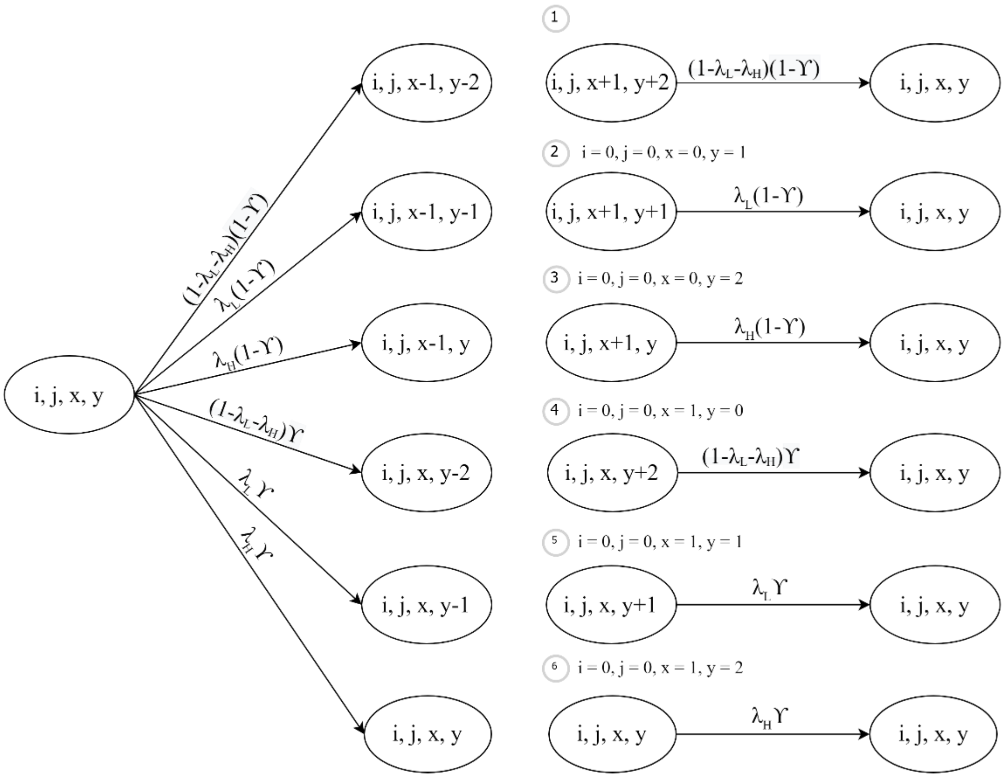


Fig 3. 68: The state diagram for $i = 0, j = 0, x = 1, y = 2$

(19) $\mathrm{i} = 0, 1 \leq \mathrm{j} \leq \mathrm{K} - 1, \mathrm{x} = 1, \mathrm{y} = 1$

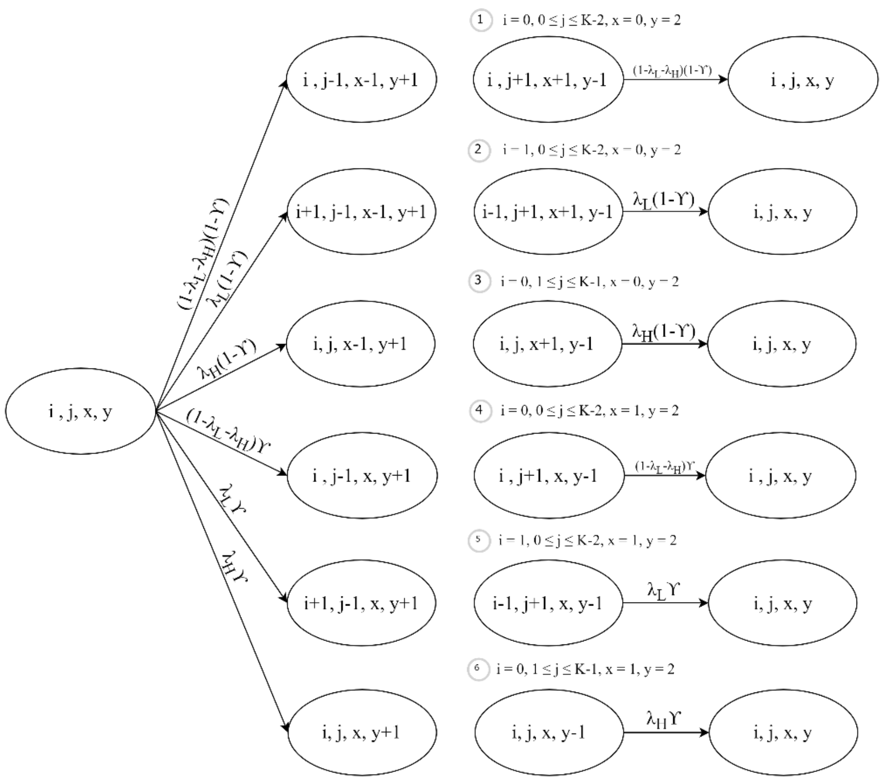


Fig 3. 69: The state diagram for $i = 0, 1 \leq j \leq K - 1, x = 1, y = 1$

(20) $i = 0, 1 \leq j \leq K-1, x = 1, y = 2$

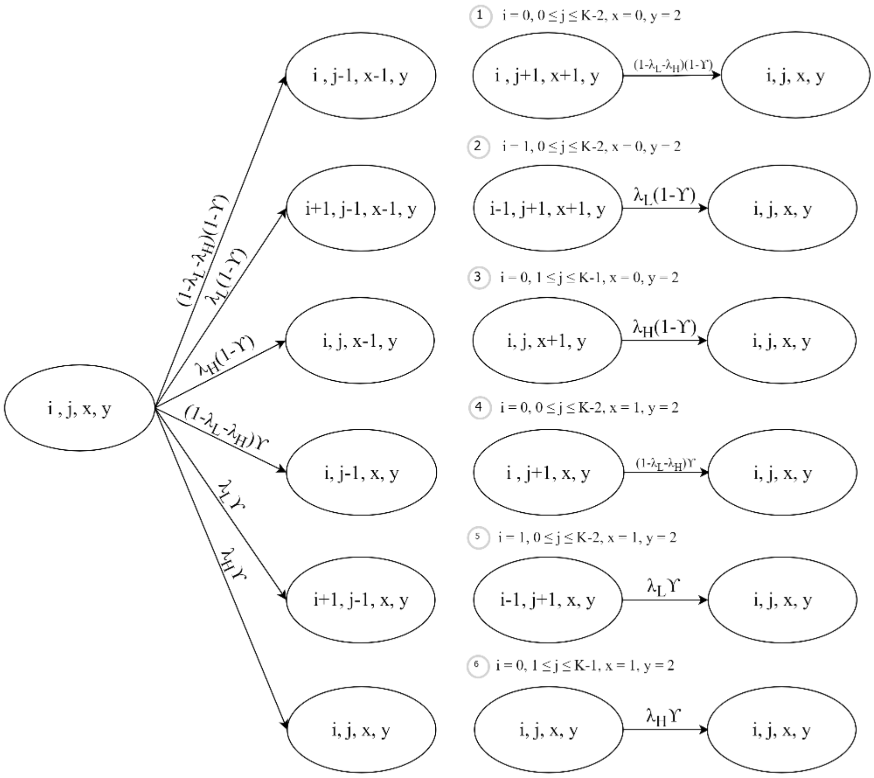


Fig 3. 70: The state diagram for $i = 0, 1 \leq j \leq K-1, x = 1, y = 2$

(21) $1 \leq i \leq K-1, j = 0, x = 1, y = 1$

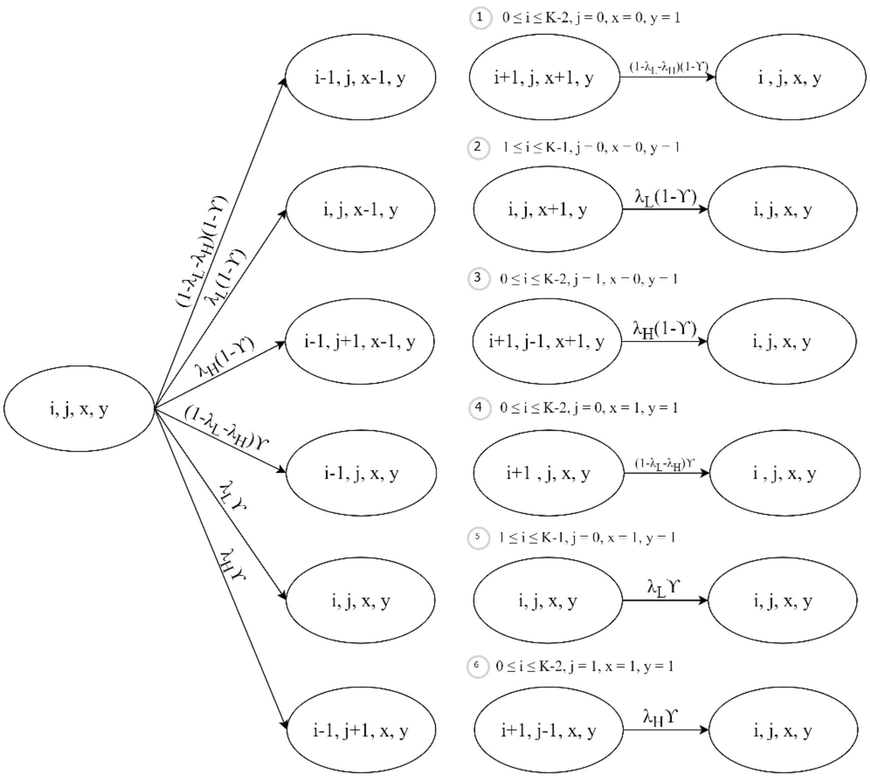


Fig 3. 71: The state diagram for $1 \leq i \leq K-1, j = 0, x = 1, y = 1$

(22) $1 \le i \le K-1, j=0, x=1, y=2$

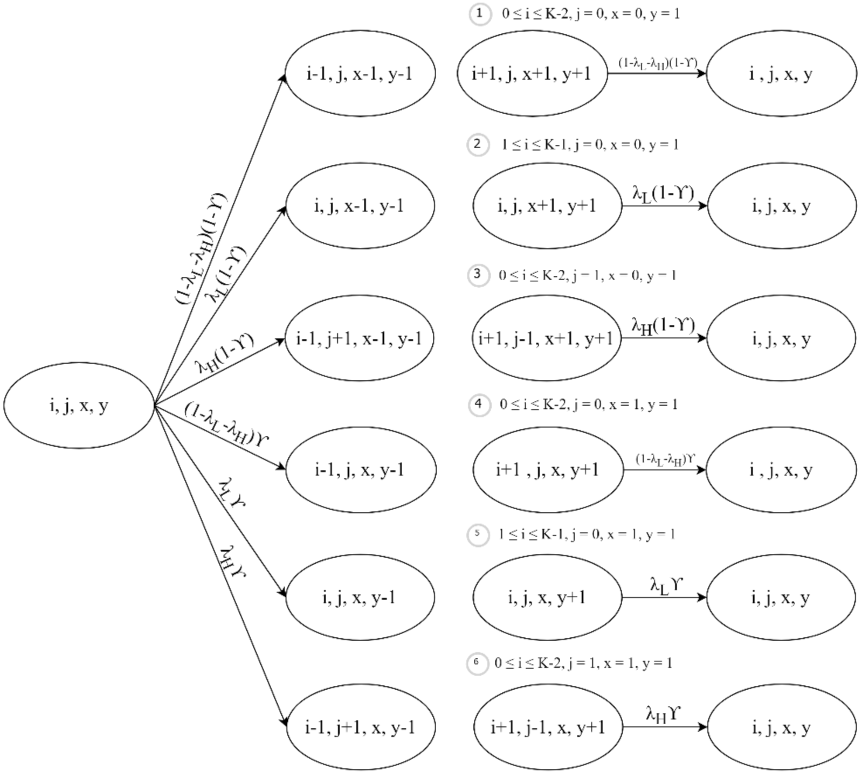


Fig 3. 72: The state diagram for $1 \le i \le K-1, j=0, x=1, y=2$

(23) $1 \le i \le K-2, 1 \le j \le K-i-1, x=1, y=1$

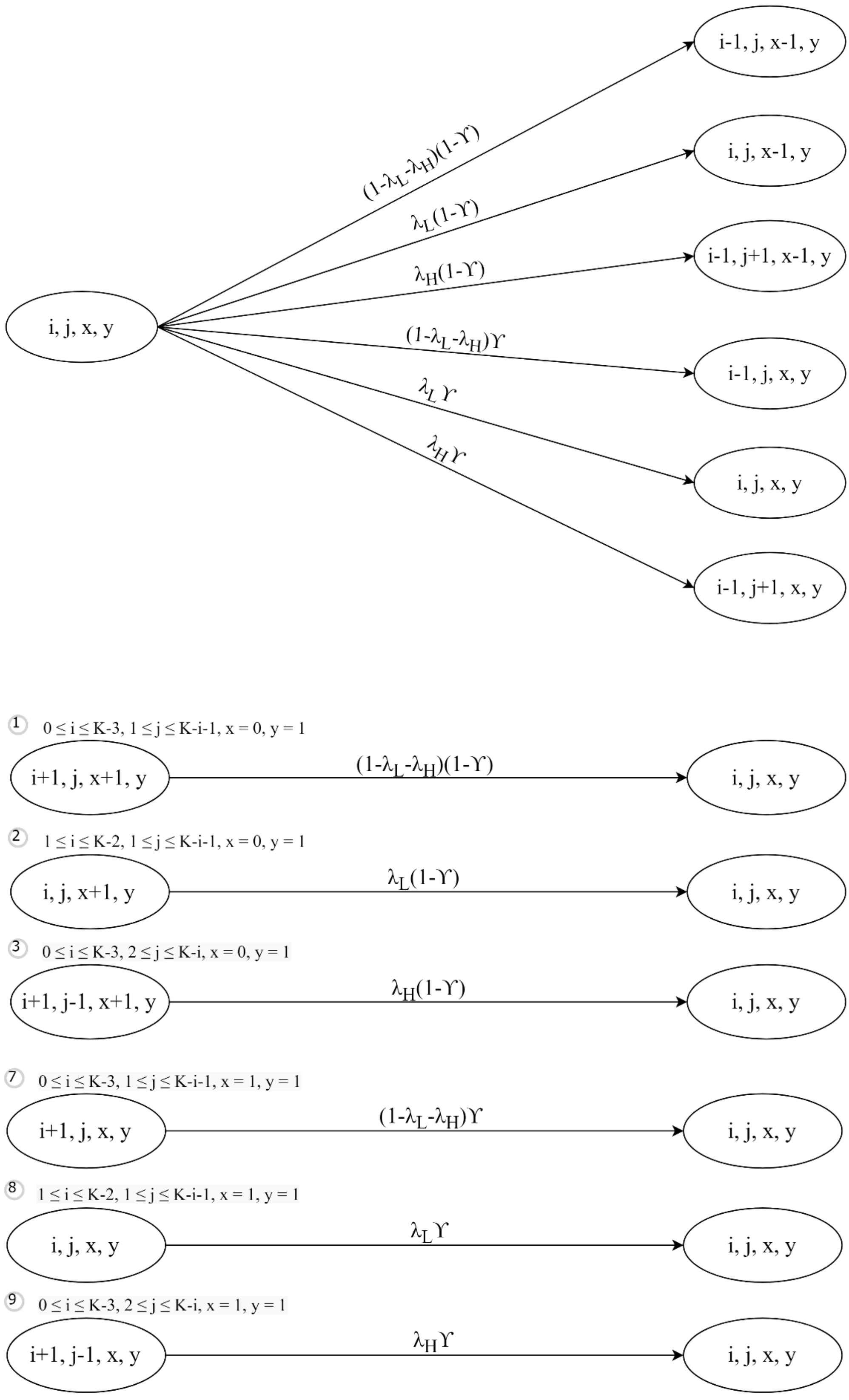
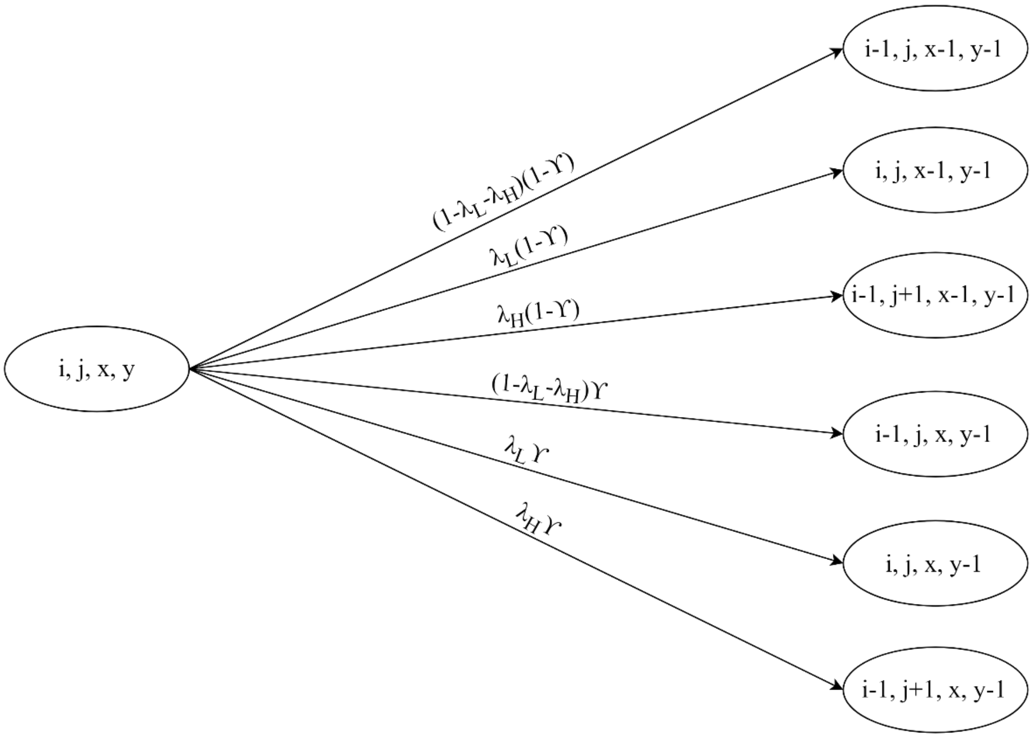


Fig 3. 73: The state diagram for $1 \le i \le K-2, 1 \le j \le K-i-1, x=1, y=1$

(24) $1 \le i \le K-2, 1 \le j \le K-i-1, x = 1, y = 2$



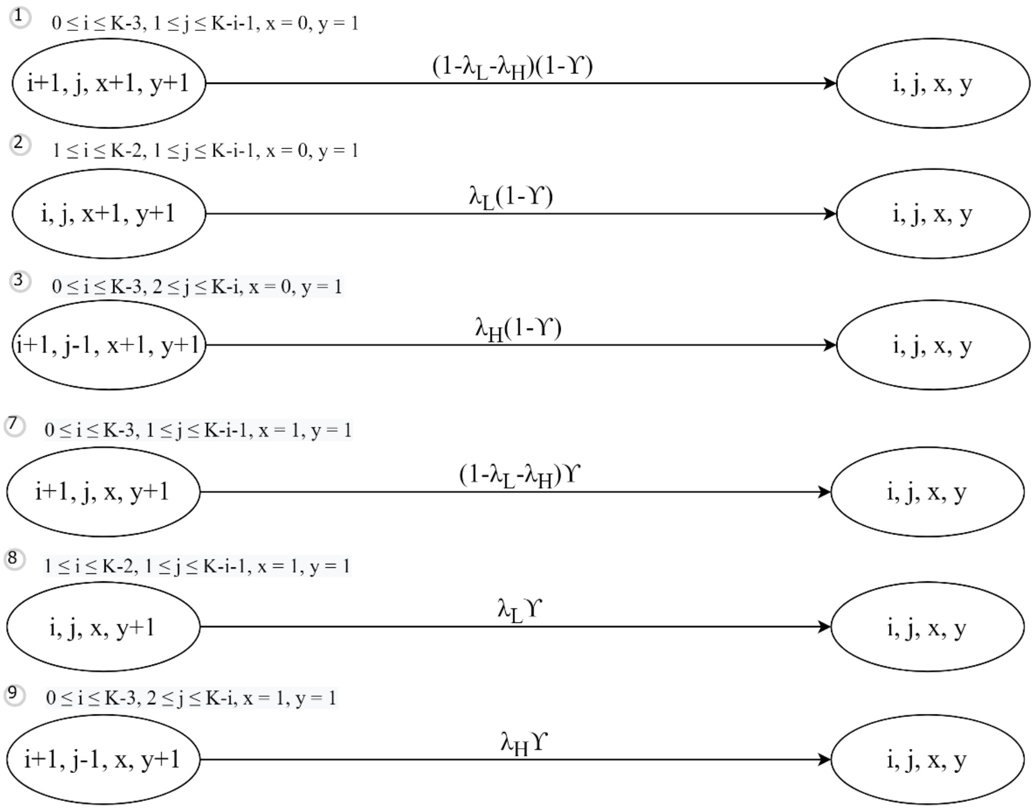


Fig 3. 74: The state diagram for $1 \le i \le K-2, 1 \le j \le K-i-1, x = 1, y = 2$

3.2.4 Iterative algorithm

In order to solve the state balance equations, we used the following iterative algorithm until the convergence is achieved. Consequently, we obtained the steady-state probability distribution of the system.

Iterative algorithm:

Step 1: Select the initial set of values for $\pi(i,j,x,y)^{old} = \frac{1}{|S|}$, $\forall i,j,x,y$, where $|S|$ is the total number of feasible states.

Step 2: Substitute $\pi(i,j,x,y)^{old}$ into Case 1 to Case 24 to find $\pi(i,j,x,y)^{new}$, $\forall i,j,x,y$.

Step 3: Normalize $\pi(i,j,x,y)^{new},\ \forall i,j,x,y$

Step 4: If $\sqrt{\sum\sum\sum\sum_{(i,j,x,y)\,\epsilon\,S}|\pi(i,j,x,y)^{old} - \pi(i,j,x,y)^{new}|^2} < \varepsilon$, stop the iteration, where ε is the stopping criterion. Or we set $\pi(i,j,x,y)^{old} = \pi(i,j,x,y)^{new}$ and return to step 2.

In our analytical analysis, the convergence criterion ε is set at ε = 10^{-8}, and the algorithm generally achieves convergence after about 350 iterations.

3.2.5 Performance index

In order to estimate the effectiveness of the whole system, we obtained various performance indexes from the steady-state probability $\pi(i,j,x,y)$ which are summarized below.

First of all, the expected number of LBER (HBER) packets in the system, L_L (L_H), is given below.

$$L_L = \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}\sum_{y=0}^{2}[(i+1)\pi(i,j,x,1) + i\pi(i,j,x,2)] \qquad (3-28)$$

$$L_H = \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}\sum_{y=0}^{2}[j\pi(i,j,x,1) + (j+1)\pi(i,j,x,2)] \qquad (3-29)$$

The total number of packets in the system, L, is given below.

$$L = L_L + L_H \qquad (3-30)$$

Second, the expected number of LBER (HBER) packets in the queue L_{qL} (L_{qH}), is given below.

$$L_{qL} = \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}\sum_{y=0}^{2} i\pi(i,j,x,y) \qquad (3-31)$$

$$L_{qH} = \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}\sum_{y=0}^{2} j\pi(i,j,x,y) \qquad (3-32)$$

The summation of L_{qL} and L_{qH} will be the total number in queue L_q.

$$L_q = L_{qL} + L_{qH} \qquad (3-33)$$

Third, the blocking probability of LBER (HBER) packets, P_{bL} (P_{bH}), is given below.

$$P_{bL} = \lambda_L(1-\alpha_L)\sum_{i=0}^{Q}\pi(i,Q-i,0,1) + \lambda_L(1-\alpha_H)\sum_{i=0}^{Q}\pi(i,Q-i,0,2) \qquad (3-34)$$

$$P_{bH} = \lambda_H(1-\alpha_L)\sum_{i=0}^{Q}\pi(i,Q-i,0,1) + \lambda_H(1-\alpha_H)\sum_{i=0}^{Q}\pi(i,Q-i,0,2) \qquad (3-35)$$

The blocking probability of the system, P_b, is given below.

$$P_b = \lambda(1-\alpha_L)\sum_{i=0}^{Q}\pi(i,Q-i,0,1) + \lambda(1-\alpha_H)\sum_{i=0}^{Q}\pi(i,Q-i,0,2) \qquad (3-36)$$

Fourth, the throughput of LBER (HBER) packets, TH_L (TH_H), is given below.

$$TH_L = \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}\gamma\pi(i,j,x,1) + \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}(1-\gamma)\alpha_L\pi(i,j,x,1) \qquad (3-37)$$

$$TH_H = \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}\gamma\pi(i,j,x,2) + \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}(1-\gamma)\alpha_H\pi(i,j,x,2) \qquad (3-38)$$

Thus, the throughput of the system, TH, is given below.

$$TH = TH_L + TH_H \qquad (3-39)$$

Fifth, the average waiting time in the system, W, is given below.

$$W = \frac{L}{\lambda_{eff}} \qquad (3-40)$$

$$\text{with } \lambda_{eff} = (1 - P_b)\lambda \qquad (3-41)$$

Furthermore, the average waiting time of the LBER packets in the system, W_L, is given below.

$$W_L = \frac{L_L}{\lambda_{L\_eff}} \qquad (3-42)$$

$$\text{with } \lambda_{L\_eff} = (1 - P_{bL})\lambda_L \qquad (3-43)$$

On the other hand, the average waiting time of the HBER packets in the system, W_H, is given below.

$$W_H = \frac{L_H}{\lambda_{H\_eff}} \qquad (3-44)$$

$$\text{with } \lambda_{H\_eff} = (1 - P_{bH})\lambda_H \qquad (3-45)$$

Sixth, the average waiting time in queue, W_q, is given below.

$$W_q = \frac{L_q}{\lambda_{eff}} \qquad (3-46)$$

The average waiting time in queue for LBER (HBER) packets is given below.

$$W_{qL} = \frac{L_{qL}}{\lambda_{eff}} \qquad (3-47)$$

$$W_{qH} = \frac{L_{qH}}{\lambda_{eff}} \qquad (3-48)$$

3.3. Threshold-based Transmission Policy (TTP)

3.3.1 Model diagram

In order to do the trade-off between the power consumption and the time delay of the system, we set the different delivery probabilities for LBER (HBER) packets, which are α_{L1}, α_{L2} $(\alpha_{H1}, \alpha_{H2})$, $0 < \alpha_{L1}, \alpha_{L2}, \alpha_{H1}, \alpha_{H2} < 1$. The scheduler will directly transmit the packet in server while the channel state is in state 1, i.e., $x[n] = 1$. On the other hand, if the channel state is in state 0, i.e., $x[n] = 0$, in the beginning of every time slot, the scheduler will detect the number in queue. If the number in queue is less than and equal to the transmission threshold ε, the scheduler will choose the delivery probability α_{L1}(α_{H1}) to decide whether to transmit the LBER (HBER) packet in server. In other words, if the number in queue exceeds the transmission threshold θ, then the scheduler will switch to another delivery probability α_{L2} (α_{H2}) and use the corresponding delivery probability to decide whether to transmit the LBER (HBER) packet in server. Assume the system size is K, the queue size is $K - 1$, and the arrival rates of LBER and HBER are λ_L and λ_H, respectively. Naturally, $0 < \lambda_L + \lambda_H < 1$. At the beginning of each slot, the channel will alter between state 0 and state 1 according to channel transition rate γ. In FIFO discipline, the probability that the HoL (head of line) packet is LBER can be obtained as follows:

$$\beta = nq_L / (nq_L + nq_H) \qquad (3-49)$$

(a) FIFO discipline

Table 3. 5: System parameter list of TTP with FIFO discipline

Parameters	Description
$\boldsymbol{\lambda_L}$	Arrival rate of LBER packets at the queue
$\boldsymbol{\lambda_H}$	Arrival rate of HBER packets at the queue
$\boldsymbol{\gamma}$	The probability of good channel in each time slot
$\boldsymbol{\beta}$	The probability of the HoL packet is LBER
$\boldsymbol{\theta}$	Transmission threshold of the system
$\boldsymbol{nq_L}$	The number of LBER packets in queue
$\boldsymbol{nq_H}$	The number of HBER packets in queue

α_{L1}	The transmitted probability of LBER packet in state 0 if $\boldsymbol{nq} \le \boldsymbol{\theta}$
α_{L2}	The transmitted probability of LBER packet in state 0 if $\boldsymbol{nq} > \boldsymbol{\theta}$
α_{H1}	The transmitted probability of HBER packet in state 0 if $\boldsymbol{nq} \le \boldsymbol{\theta}$
α_{H2}	The transmitted probability of HBER packet in state 0 if $\boldsymbol{nq} > \boldsymbol{\theta}$

(b) Priority discipline

Table 3. 6: System parameter list of TTP with priority discipline

Parameters	**Description**
$\boldsymbol{\lambda_L}$	Arrival rate of LBER packets at the queue
$\boldsymbol{\lambda_H}$	Arrival rate of HBER packets at the queue
$\boldsymbol{\gamma}$	The probability of good channel in each time slot
$\boldsymbol{\theta}$	Transmission threshold of the system
α_{L1}	The transmitted probability of LBER packet in state 0 if $\boldsymbol{nq} \le \boldsymbol{\theta}$
α_{L2}	The transmitted probability of LBER packet in state 0 if $\boldsymbol{nq} > \boldsymbol{\theta}$
α_{H1}	The transmitted probability of HBER packet in state 0 if $\boldsymbol{nq} \le \boldsymbol{\theta}$
α_{H2}	The transmitted probability of HBER packet in state 0 if $\boldsymbol{nq} > \boldsymbol{\theta}$

3.3.2 State balance equations

The system is modeled as a four-dimensional discrete time Markov chain with state (i,j,x,y), for both FIFO and priority disciplines, where i presents the number of LBER packets in queue, j presents the number of HBER packets in queue, x presents the channel state, and y presents the server state. While $x = 0$ means the channel state is bad (state 0), and $x = 1$ means the channel state is good (state 1). And $y = 0$ means there is no one in server, $y = 1$ means the LBER packet in server, and $y = 2$ means the HBER packet in server. The steady sate probability of the model is described as $\pi(i,j,x,y)$; thus, the state space can be denoted as follows:

$$S = \{(i,j,x,y) |\ 0 \le i \le Q, 0 \le j \le Q - i, 0 \le x \le 1, 0 \le y \le 2\} \qquad (3-50)$$

Hence, the number of feasible states is as follows:

$$|S| = 3(Q+1)(Q+2) \qquad (3-51)$$

As an example, if Q is equal to 20, we can see the total number of feasible states is 1386.

For both FIFO and priority disciplines, the feasible states can be classified into 32 cases as below.

(a) First-In-First-Out

Case 1 : $i = 0, j = 0, x = 0, y = 0$

$$\begin{aligned}\pi_{0,0,0,0} = &(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,0,0,0} + \alpha_{L1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,0,0,1}\\ &+ \alpha_{H1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,0,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,0,1,0}\\ &+ (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,0,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,0,1,2}\end{aligned}$$

Case 2 : $i = 0, j = 0, x = 0, y = 1$

$$\begin{aligned}\pi_{0,0,0,1} = &\lambda_L(1-\gamma)\pi_{0,0,0,0} + (1-\alpha_{L1})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,0,0,1}\\ &+ \alpha_{L1}\lambda_L(1-\gamma)\pi_{0,0,0,1} + \alpha_{L1}\lambda_L(1-\gamma)\pi_{0,0,0,2}\\ &+ \alpha_{L1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,0,0,1} + \alpha_{H1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,0,0,2}\\ &+ \lambda_L(1-\gamma)\pi_{0,0,1,0} + \lambda_L(1-\gamma)\pi_{0,0,1,1} + \lambda_L(1-\gamma)\pi_{0,0,1,2}\\ &+ (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,0,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,0,1,2}\end{aligned}$$

Case 3 : $i = 0, j = 0, x = 0, y = 2$

$$\begin{aligned}\pi_{0,0,0,2} = &\lambda_H(1-\gamma)\pi_{0,0,0,0} + \alpha_{L1}\lambda_H(1-\gamma)\pi_{0,0,0,1}\\ &+ (1-\alpha_{H1})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,0,0,2} + \alpha_{H1}\lambda_H(1-\gamma)\pi_{0,0,0,2}\\ &+ \alpha_{L1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,0,1} + \alpha_{H1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,0,2}\\ &+ \lambda_H(1-\gamma)\pi_{0,0,1,0} + \lambda_H(1-\gamma)\pi_{0,0,1,1} + \lambda_H(1-\gamma)\pi_{0,0,1,2}\\ &+ (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,1,2}\end{aligned}$$

Case 4 : $i = 0, 1 \le j \le \theta, x = 0, y = 1$

$$\begin{aligned}\pi_{0,j,0,1} = &(1-\alpha_{L1})\lambda_H(1-\gamma)\pi_{0,0,0,1} + (1-\alpha_{L1})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,1}\\ &+ (1-\alpha_{L1})\lambda_H(1-\gamma)\pi_{0,j-1,0,1} + \alpha_{L1}\lambda_H(1-\gamma)\pi_{1,0,0,1}\\ &+ \alpha_{H1}\lambda_H(1-\gamma)\pi_{1,0,0,2} + \alpha_{L1}\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,1}\\ &+ \alpha_{L1}\beta\lambda_H(1-\gamma)\pi_{1,j-1,0,1} + \alpha_{H1}\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,2}\\ &+ \alpha_{H1}\beta\lambda_H(1-\gamma)\pi_{1,j-1,0,2} + \alpha_{L1}\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,1}\\ &+ \lambda_H(1-\gamma)\pi_{1,0,1,1} + \lambda_H(1-\gamma)\pi_{1,0,1,2} + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,1,1}\\ &+ \beta\lambda_H(1-\gamma)\pi_{1,j-1,1,1} + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,1,2}\\ &+ \beta\lambda_H(1-\gamma)\pi_{1,j-1,1,2}\end{aligned}$$

Case 5 : $i = 0, \theta < j \leq K-2, x = 0, y = 1$

$$\begin{aligned}\pi_{0,j,0,1} = {} & (1-\alpha_{L2})\lambda_H(1-\gamma)\pi_{0,0,0,1} + (1-\alpha_{L2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,1} \\ & + (1-\alpha_{L2})\lambda_H(1-\gamma)\pi_{0,j-1,0,1} + \alpha_{L2}\lambda_H(1-\gamma)\pi_{1,0,0,1} \\ & + \alpha_{H2}\lambda_H(1-\gamma)\pi_{1,0,0,2} + \alpha_{L2}\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,1} \\ & + \alpha_{L2}\beta\lambda_H(1-\gamma)\pi_{1,j-1,0,1} + \alpha_{H2}\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,2} \\ & + \alpha_{H2}\beta\lambda_H(1-\gamma)\pi_{1,j-1,0,2} + \alpha_{L2}\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,1} \\ & + \lambda_H(1-\gamma)\pi_{1,0,1,1} + \lambda_H(1-\gamma)\pi_{1,0,1,2} + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,1,1} \\ & + \beta\lambda_H(1-\gamma)\pi_{1,j-1,1,1} + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,1,2} \\ & + \beta\lambda_H(1-\gamma)\pi_{1,j-1,1,2}\end{aligned}$$

Case 6 : $i = 0, 1 \leq j \leq \theta, x = 0, y = 2$

$$\begin{aligned}\pi_{0,j,0,2} = {} & (1-\alpha_{H1})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,2} + (1-\alpha_{H1})\lambda_H(1-\gamma)\pi_{0,j-1,0,2} \\ & + \alpha_{L1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,1} + \alpha_{L1}\lambda_H(1-\gamma)\pi_{0,j,0,1} \\ & + \alpha_{H1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,2} + \alpha_{H1}\lambda_H(1-\gamma)\pi_{0,j,0,2} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,1} + \lambda_H(1-\gamma)\pi_{0,j,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,2} + \lambda_H(1-\gamma)\pi_{0,j,1,2}\end{aligned}$$

Case 7 : $i = 0, \theta < j \leq K-2, x = 0, y = 2$

$$\begin{aligned}\pi_{0,j,0,2} = {} & (1-\alpha_{H2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,2} + (1-\alpha_{H2})\lambda_H(1-\gamma)\pi_{0,j-1,0,2} \\ & + \alpha_{L2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,1} + \alpha_{L2}\lambda_H(1-\gamma)\pi_{0,j,0,1} \\ & + \alpha_{H2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,2} + \alpha_{H2}\lambda_H(1-\gamma)\pi_{0,j,0,2} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,1} + \lambda_H(1-\gamma)\pi_{0,j,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,2} + \lambda_H(1-\gamma)\pi_{0,j,1,2}\end{aligned}$$

Case 8 : $1 \leq i \leq \theta, j = 0, x = 0, y = 1$

$$\begin{aligned}\pi_{i,0,0,1} = {} & (1-\alpha_{L1})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,1} + (1-\alpha_{L1})\lambda_L(1-\gamma)\pi_{i-1,0,0,1} \\ & + \alpha_{L1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,0,1} + \alpha_{L1}\lambda_L(1-\gamma)\pi_{i,0,0,1} \\ & + \alpha_{H1}\lambda_L(1-\gamma)\pi_{i+1,0,0,2} + \alpha_{H1}\lambda_L(1-\gamma)\pi_{i,0,0,2} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,1} + \lambda_L(1-\gamma)\pi_{i,0,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,2} + \lambda_L(1-\gamma)\pi_{i,0,1,2}\end{aligned}$$

Case 9 : $\theta < i \leq K-2, j=0, x=0, y=1$

$$\begin{aligned}\pi_{i,0,0,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,1} + (1-\alpha_{L2})\lambda_L(1-\gamma)\pi_{i-1,0,0,1} \\ & + \alpha_{L2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,0,1} + \alpha_{L2}\lambda_L(1-\gamma)\pi_{i,0,0,1} \\ & + \alpha_{H2}\lambda_L(1-\gamma)\pi_{i+1,0,0,2} + \alpha_{H2}\lambda_L(1-\gamma)\pi_{i,0,0,2} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,1} + \lambda_L(1-\gamma)\pi_{i,0,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,2} + \lambda_L(1-\gamma)\pi_{i,0,1,2}\end{aligned}$$

Case 10 : $1 \leq i \leq \theta, j=0, x=0, y=2$

$$\begin{aligned}\pi_{i,0,0,2} = {} & (1-\alpha_{H1})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,2} + (1-\alpha_{H1})\lambda_L(1-\gamma)\pi_{i-1,0,0,2} \\ & + \alpha_{L1}(1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i-1,1,0,1} \\ & + \alpha_{L1}(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,0,1} + \alpha_{H1}(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,0,2} \\ & + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,1,1,1} + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,1,1} \\ & + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,1,1,2} + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,1,2}\end{aligned}$$

Case 11 : $\theta < i \leq K-2, j=0, x=0, y=2$

$$\begin{aligned}\pi_{i,0,0,2} = {} & (1-\alpha_{H2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,2} + (1-\alpha_{H2})\lambda_L(1-\gamma)\pi_{i-1,0,0,2} \\ & + \alpha_{L2}(1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i-1,1,0,1} \\ & + \alpha_{L2}(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,0,1} + \alpha_{H2}(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,0,2} \\ & + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,1,1,1} + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,1,1} \\ & + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,1,1,2} + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,1,2}\end{aligned}$$

Case 12 : $i=0, j=K-1, x=0, y=1$

$$\begin{aligned}\pi_{0,j,0,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,1} + (1-\alpha_{L2})\lambda_H(1-\gamma)\pi_{0,j-1,0,1} \\ & + \alpha_{L2}\beta\lambda_H(1-\gamma)\pi_{1,j-1,0,1} + \alpha_{H2}\beta\lambda_H(1-\gamma)\pi_{1,j-1,0,2} \\ & + \beta\lambda_H(1-\gamma)\pi_{1,j-1,1,1} + \beta\lambda_H(1-\gamma)\pi_{1,j-1,1,2}\end{aligned}$$

Case 13 : $i=0, j=K-1, x=0, y=2$

$$\begin{aligned}\pi_{0,j,0,2} = {} & (1-\alpha_{H2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,2} + (1-\alpha_{H2})\lambda_H(1-\gamma)\pi_{0,j-1,0,2} \\ & + \alpha_{L2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,1} + \alpha_{L2}\lambda_H(1-\gamma)\pi_{0,j,0,1} \\ & + \alpha_{H2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,2} + \alpha_{H2}\lambda_H(1-\gamma)\pi_{0,j,0,2} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,1} + \lambda_H(1-\gamma)\pi_{0,j,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,2} + \lambda_H(1-\gamma)\pi_{0,j,1,2}\end{aligned}$$

Case 14 : $i = K - 1, j = 0, x = 0, y = 1$

$$
\begin{aligned}
\pi_{i,0,0,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,1} + (1-\alpha_{L2})\lambda_L(1-\gamma)\pi_{i-1,0,0,1} \\
& + \alpha_{L2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,0,1} + \alpha_{L2}\lambda_L(1-\gamma)\pi_{i,0,0,1} \\
& + \alpha_{H2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,0,2} + \alpha_{H2}\lambda_L(1-\gamma)\pi_{i,0,0,2} \\
& + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,1} + \lambda_L(1-\gamma)\pi_{i,0,1,1} \\
& + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,2} + \lambda_L(1-\gamma)\pi_{i,0,1,2}
\end{aligned}
$$

Case 15 : $i = K - 1, j = 0, x = 0, y = 2$

$$
\begin{aligned}
\pi_{i,0,0,2} = {} & (1-\alpha_{H2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,2} + (1-\alpha_{H2})\lambda_L(1-\gamma)\pi_{i-1,0,0,2} \\
& + \alpha_{L2}(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,0,1} + \alpha_{H2}(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,0,2} \\
& + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,1,1} + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,1,1,2}
\end{aligned}
$$

Case 16 : $1 \le i \le \theta, 1 \le j \le \theta - i, x = 0, y = 1$

$$
\begin{aligned}
\pi_{i,j,0,1} = {} & (1-\alpha_{L1})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,1} + (1-\alpha_{L1})\lambda_L(1-\gamma)\pi_{i-1,j,0,1} \\
& + (1-\alpha_{L1})\lambda_H(1-\gamma)\pi_{i,j-1,0,1} + \alpha_{L1}\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,1} \\
& + \alpha_{L1}\beta\lambda_L(1-\gamma)\pi_{i,j,0,1} + \alpha_{L1}\beta\lambda_H(1-\gamma)\pi_{i+1,j-1,0,1} \\
& + \alpha_{H1}\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,2} + \alpha_{H1}\beta\lambda_L(1-\gamma)\pi_{i,j,0,2} \\
& + \alpha_{H1}\beta\lambda_L(1-\gamma)\pi_{i+1,j-1,0,2} + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,1} \\
& + \beta\lambda_L(1-\gamma)\pi_{i,j,1,1} + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,1} \\
& + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,2} + \beta\lambda_L(1-\gamma)\pi_{i,j,1,2} \\
& + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,2}
\end{aligned}
$$

Case 17 : $1 \le i \le \theta, \theta - i < j < K - i - 1, x = 0, y = 1$

$$
\begin{aligned}
\pi_{i,j,0,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,1} + (1-\alpha_{L2})\lambda_L(1-\gamma)\pi_{i-1,j,0,1} \\
& + (1-\alpha_{L2})\lambda_H(1-\gamma)\pi_{i,j-1,0,1} + \alpha_{L2}\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,1} \\
& + \alpha_{L2}\beta\lambda_L(1-\gamma)\pi_{i,j,0,1} + \alpha_{L2}\beta\lambda_H(1-\gamma)\pi_{i+1,j-1,0,1} \\
& + \alpha_{H2}\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,2} + \alpha_{H2}\beta\lambda_L(1-\gamma)\pi_{i,j,0,2} \\
& + \alpha_{H2}\beta\lambda_L(1-\gamma)\pi_{i+1,j-1,0,2} + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,1} \\
& + \beta\lambda_L(1-\gamma)\pi_{i,j,1,1} + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,1} \\
& + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,2} + \beta\lambda_L(1-\gamma)\pi_{i,j,1,2} \\
& + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,2}
\end{aligned}
$$

Case 18 : $\theta \le i \le K-2, 1 \le j < K-i-1, x=0, y=1$

$$
\begin{aligned}
\pi_{i,j,0,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,1} + (1-\alpha_{L2})\lambda_L(1-\gamma)\pi_{i-1,j,0,1} \\
& + (1-\alpha_{L2})\lambda_H(1-\gamma)\pi_{i,j-1,0,1} + \alpha_{L2}\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,1} \\
& + \alpha_{L2}\beta\lambda_L(1-\gamma)\pi_{i,j,0,1} + \alpha_{L2}\beta\lambda_H(1-\gamma)\pi_{i+1,j-1,0,1} \\
& + \alpha_{H2}\beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,2} + \alpha_{H2}\beta\lambda_L(1-\gamma)\pi_{i,j,0,2} \\
& + \alpha_{H2}\beta\lambda_L(1-\gamma)\pi_{i+1,j-1,0,2} + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,1} \\
& + \beta\lambda_L(1-\gamma)\pi_{i,j,1,1} + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,1} \\
& + \beta(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,2} + \beta\lambda_L(1-\gamma)\pi_{i,j,1,2} \\
& + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,2}
\end{aligned}
$$

Case 19 : $1 \le i \le K-2, j = K-i-1, x=0, y=1$

$$
\begin{aligned}
\pi_{i,j,0,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,1} + (1-\alpha_{L2})\lambda_L(1-\gamma)\pi_{i-1,j,0,1} \\
& + (1-\alpha_{L2})\lambda_H(1-\gamma)\pi_{i,j-1,0,1} + \alpha_{L2}\beta\lambda_L(1-\gamma)\pi_{i,j,0,1} \\
& + \alpha_{L2}\beta\lambda_H(1-\gamma)\pi_{i+1,j-1,0,1} + \alpha_{H2}\beta\lambda_L(1-\gamma)\pi_{i,j,0,2} \\
& + \alpha_{H2}\beta\lambda_H(1-\gamma)\pi_{i+1,j-1,0,2} + \beta\lambda_L(1-\gamma)\pi_{i,j,1,1} \\
& + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,1} + \beta\lambda_L(1-\gamma)\pi_{i,j,1,2} + \beta\lambda_H(1-\gamma)\pi_{i+1,j-1,1,2}
\end{aligned}
$$

Case 20 : $1 \le i \le \theta, 1 \le j \le \theta - i, x=0, y=2$

$$
\begin{aligned}
\pi_{i,j,0,2} = {} & (1-\alpha_{H1})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,2} + (1-\alpha_{H1})\lambda_L(1-\gamma)\pi_{i-1,j,0,2} \\
& + (1-\alpha_{H1})\lambda_H(1-\gamma)\pi_{i,j-1,0,2} \\
& + \alpha_{L1}(1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,0,1} \\
& + \alpha_{L1}(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,0,1} + \alpha_{L1}(1-\beta)\lambda_H(1-\gamma)\pi_{i,j,0,1} \\
& + \alpha_{H1}(1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,0,2} \\
& + \alpha_{H1}(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,0,2} + \alpha_{H1}(1-\beta)\lambda_H(1-\gamma)\pi_{i,j,0,2} \\
& + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,1,1} + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,1,1} \\
& + (1-\beta)\lambda_H(1-\gamma)\pi_{i,j,1,1} + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,1,2} \\
& + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,1,2} + (1-\beta)\lambda_H(1-\gamma)\pi_{i,j,1,2}
\end{aligned}
$$

Case 21 : $1 \leq i \leq \theta, \theta - i < j < K - i - 1, x = 0, y = 2$

$$
\begin{aligned}
\pi_{i,j,0,2} = {} & (1-\alpha_{H2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,2} + (1-\alpha_{H2})\lambda_L(1-\gamma)\pi_{i-1,j,0,2} \\
& + (1-\alpha_{H2})\lambda_H(1-\gamma)\pi_{i,j-1,0,2} \\
& + \alpha_{L2}(1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,0,1} \\
& + \alpha_{L2}(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,0,1} + \alpha_{L2}(1-\beta)\lambda_H(1-\gamma)\pi_{i,j,0,1} \\
& + \alpha_{H2}(1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,0,2} \\
& + \alpha_{H2}(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,0,2} + \alpha_{H2}(1-\beta)\lambda_H(1-\gamma)\pi_{i,j,0,2} \\
& + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,1,1} + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,1,1} \\
& + (1-\beta)\lambda_H(1-\gamma)\pi_{i,j,1,1} + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,1,2} \\
& + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,1,2} + (1-\beta)\lambda_H(1-\gamma)\pi_{i,j,1,2}
\end{aligned}
$$

Case 22 : $\theta < i \leq K - 2, 1 \leq j \leq K - i - 2, x = 0, y = 2$

$$
\begin{aligned}
\pi_{i,j,0,2} = {} & (1-\alpha_{H2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,2} + (1-\alpha_{H2})\lambda_L(1-\gamma)\pi_{i-1,j,0,2} \\
& + (1-\alpha_{H2})\lambda_H(1-\gamma)\pi_{i,j-1,0,2} \\
& + \alpha_{L2}(1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,0,1} \\
& + \alpha_{L2}(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,0,1} + \alpha_{L2}(1-\beta)\lambda_H(1-\gamma)\pi_{i,j,0,1} \\
& + \alpha_{H2}(1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,0,2} \\
& + \alpha_{H2}(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,0,2} + \alpha_{H2}(1-\beta)\lambda_H(1-\gamma)\pi_{i,j,0,2} \\
& + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,1,1} + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,1,1} \\
& + (1-\beta)\lambda_H(1-\gamma)\pi_{i,j,1,1} + (1-\beta)(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j+1,1,2} \\
& + (1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,1,2} + (1-\beta)\lambda_H(1-\gamma)\pi_{i,j,1,2}
\end{aligned}
$$

Case 23 : $1 \leq i \leq K - 2, j = K - i - 1, x = 0, y = 2$

$$
\begin{aligned}
\pi_{i,j,0,2} = {} & (1-\alpha_{H2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,2} + (1-\alpha_{H2})\lambda_L(1-\gamma)\pi_{i-1,j,0,2} \\
& + (1-\alpha_{H2})\lambda_H(1-\gamma)\pi_{i,j-1,0,2} + \alpha_{L2}(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,0,1} \\
& + \alpha_{L2}(1-\beta)\lambda_H(1-\gamma)\pi_{i,j,0,1} + \alpha_{H2}(1-\beta)\lambda_L(1-\gamma)\pi_{i-1,j+1,0,2} \\
& + \alpha_{H2}(1-\beta)\lambda_H(1-\gamma)\pi_{i,j,0,2} + (1-\beta)\lambda_L(1-\gamma)\pi_{i,j,1,1} \\
& + (1-\beta)\lambda_H(1-\gamma)\pi_{i+1,j-1,1,1} + (1-\beta)\lambda_L(1-\gamma)\pi_{i,j,1,2} \\
& + (1-\beta)\lambda_H(1-\gamma)\pi_{i+1,j-1,1,2}
\end{aligned}
$$

Case 24 : $i = 0, j = 0, x = 1, y = 0$

$$\pi_{0,0,1,0} = (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,0} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,0} + \alpha_{L1}(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,1}$$
$$+ \alpha_{H1}(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,1}$$
$$+ (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,2}$$

Case 25 : $i = 0, j = 0, x = 1, y = 1$

$$\pi_{0,0,1,1} = (1-\alpha_{L1})(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,0,1,1}$$
$$+ (1-\lambda_L-\lambda_H)\gamma\pi_{1,0,1,2} + \alpha_{L1}(1-\lambda_L-\lambda_H)\gamma\pi_{1,0,0,1}$$
$$+ \alpha_{H1}(1-\lambda_L-\lambda_H)\gamma\pi_{1,0,0,2} + \lambda_L\gamma\pi_{0,0,0,0}$$

Case 26 : $i = 0, j = 0, x = 1, y = 2$

$$\pi_{0,0,1,2} = (1-\alpha_{H1})(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,1,1,1}$$
$$+ (1-\lambda_L-\lambda_H)\gamma\pi_{0,1,1,2} + \alpha_{L1}(1-\lambda_L-\lambda_H)\gamma\pi_{0,1,0,1}$$
$$+ \alpha_{H1}(1-\lambda_L-\lambda_H)\gamma\pi_{0,1,0,2} + \lambda_H\gamma\pi_{0,0,0,0}$$

Case 27 : $i = 0, 1 \le j \le \theta, x = 1, y = 1$

$$\pi_{0,j,1,1} = (1-\alpha_{L1})(1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,1} + (1-\alpha_{L1})\lambda_H\gamma\pi_{0,j-1,0,1}$$
$$+ \alpha_{L1}\beta\lambda_H\gamma\pi_{1,j-1,0,1} + \alpha_{H1}\beta\lambda_H\gamma\pi_{1,j-1,0,2} + \alpha_{L1}\beta(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,1}$$
$$+ \alpha_{H1}\beta(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,2} + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,1,1}$$
$$+ \beta(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,1,2} + \beta\lambda_H\gamma\pi_{1,j-1,1,1} + \beta\lambda_H\gamma\pi_{1,j-1,1,2}$$

Case 28 : $i = 0, \theta < j \le K-1, x = 1, y = 1$

$$\pi_{0,j,1,1} = (1-\alpha_{L2})(1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,1} + (1-\alpha_{L2})\lambda_H\gamma\pi_{0,j-1,0,1}$$
$$+ \alpha_{L2}\beta\lambda_H\gamma\pi_{1,j-1,0,1} + \alpha_{H2}\beta\lambda_H\gamma\pi_{1,j-1,0,2} + \alpha_{L2}\beta(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,1}$$
$$+ \alpha_{H2}\beta(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,2} + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,1,1}$$
$$+ \beta(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,1,2} + \beta\lambda_H\gamma\pi_{1,j-1,1,1} + \beta\lambda_H\gamma\pi_{1,j-1,1,2}$$

Case 29 : $i = 0, 1 \le j \le \theta, x = 1, y = 2$

$$\pi_{0,j,1,2} = (1-\alpha_{H1})(1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,2} + (1-\alpha_{H1})\lambda_H\gamma\pi_{0,j-1,0,2}$$
$$+ \alpha_{L1}(1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,0,1} + \alpha_{H1}(1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,0,2}$$
$$+ \alpha_{L1}\lambda_H\gamma\pi_{0,j,0,1} + \alpha_{H2}\lambda_H\gamma\pi_{0,j,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,1,1}$$
$$+ (1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,1,2} + \lambda_H\gamma\pi_{0,j,1,1} + \lambda_H\gamma\pi_{0,j,1,2}$$

Case 30 : $i = 0, \theta < j \leq K-1, x = 1, y = 2$

$$\pi_{0,j,1,2} = (1-\alpha_{H2})(1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,2} + (1-\alpha_{H2})\lambda_H\gamma\pi_{0,j-1,0,2} + \alpha_{L2}(1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,0,1} + \alpha_{H2}(1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,0,2} + \alpha_{L2}\lambda_H\gamma\pi_{0,j,0,1} + \alpha_{H2}\lambda_H\gamma\pi_{0,j,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,1,2} + \lambda_H\gamma\pi_{0,j,1,1} + \lambda_H\gamma\pi_{0,j,1,2}$$

Case 31 : $1 \leq i \leq \theta, j = 0, x = 1, y = 1$

$$\pi_{i,0,1,1} = (1-\alpha_{L1})(1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,1} + (1-\alpha_{L1})\lambda_L\gamma\pi_{i-1,0,0,1} + \alpha_{L1}(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,0,1} + \alpha_{H1}(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,0,2} + \alpha_{L1}\lambda_L\gamma\pi_{i,0,0,1} + \alpha_{H1}\lambda_L\gamma\pi_{i,0,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,1,2} + \lambda_L\gamma\pi_{i,0,1,1} + \lambda_L\gamma\pi_{i,0,1,2}$$

Case 32 : $\theta < i \leq K-1, j = 0, x = 1, y = 1$

$$\pi_{i,0,1,1} = (1-\alpha_{L2})(1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,1} + (1-\alpha_{L2})\lambda_L\gamma\pi_{i-1,0,0,1} + \alpha_{L2}(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,0,1} + \alpha_{H2}(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,0,2} + \alpha_{L2}\lambda_L\gamma\pi_{i,0,0,1} + \alpha_{H2}\lambda_L\gamma\pi_{i,0,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,1,2} + \lambda_L\gamma\pi_{i,0,1,1} + \lambda_L\gamma\pi_{i,0,1,2}$$

Case 33 : $1 \leq i \leq \theta, j = 0, x = 1, y = 2$

$$\pi_{i,0,1,2} = (1-\alpha_{H1})(1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,2} + (1-\alpha_{H1})\lambda_L\gamma\pi_{i-1,0,0,2} + \alpha_{L1}(1-\beta)\lambda_L\gamma\pi_{i-1,1,0,1} + \alpha_{H1}(1-\beta)\lambda_L\gamma\pi_{i-1,1,0,2} + \alpha_{L1}(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,1,0,1} + \alpha_{H1}(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,1,0,2} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,1,1,1} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,1,1,2} + (1-\beta)\lambda_L\gamma\pi_{i-1,1,1,1} + (1-\beta)\lambda_L\gamma\pi_{i-1,1,1,2}$$

Case 34 : $\theta < i \leq K-1, j = 0, x = 1, y = 2$

$$\pi_{i,0,1,2} = (1-\alpha_{H2})(1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,2} + (1-\alpha_{H2})\lambda_L\gamma\pi_{i-1,0,0,2} + \alpha_{L2}(1-\beta)\lambda_L\gamma\pi_{i-1,1,0,1} + \alpha_{H2}(1-\beta)\lambda_L\gamma\pi_{i-1,1,0,2} + \alpha_{L2}(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,1,0,1} + \alpha_{H2}(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,1,0,2} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,1,1,1} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,1,1,2} + (1-\beta)\lambda_L\gamma\pi_{i-1,1,1,1} + (1-\beta)\lambda_L\gamma\pi_{i-1,1,1,2}$$

Case 35 : $1 \le i \le \theta, 1 \le j \le \theta - i, x = 1, y = 1$

$$\begin{aligned}\pi_{i,j,1,1} = {} & (1-\alpha_{L1})(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,1} + \alpha_{L1}\beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,1} \\ & + \alpha_{H1}\beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,2} + \alpha_{L1}\beta\lambda_L\gamma\pi_{i,j,0,1} \\ & + \alpha_{L1}\beta\lambda_H\gamma\pi_{i+1,j-1,0,1} + \alpha_{H1}\beta\lambda_L\gamma\pi_{i,j,0,2} + \alpha_{H1}\beta\lambda_H\gamma\pi_{i+1,j-1,0,2} \\ & + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,1} + \beta\lambda_L\gamma\pi_{i,j,1,1} + \beta\lambda_H\gamma\pi_{i+1,j-1,1,1} \\ & + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,2} + \beta\lambda_L\gamma\pi_{i,j,1,2} + \beta\lambda_H\gamma\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 36 : $1 \le i \le \theta, \theta - i < j < K - i - 1, x = 1, y = 1$

$$\begin{aligned}\pi_{i,j,1,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,1} + \alpha_{L2}\beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,1} \\ & + \alpha_{H2}\beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,2} + \alpha_{L2}\beta\lambda_L\gamma\pi_{i,j,0,1} \\ & + \alpha_{L2}\beta\lambda_H\gamma\pi_{i+1,j-1,0,1} + \alpha_{H2}\beta\lambda_L\gamma\pi_{i,j,0,2} + \alpha_{H2}\beta\lambda_H\gamma\pi_{i+1,j-1,0,2} \\ & + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,1} + \beta\lambda_L\gamma\pi_{i,j,1,1} + \beta\lambda_H\gamma\pi_{i+1,j-1,1,1} \\ & + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,2} + \beta\lambda_L\gamma\pi_{i,j,1,2} + \beta\lambda_H\gamma\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 37 : $\theta < i \le K - 2, 1 \le j \le K - i - 2, x = 1, y = 1$

$$\begin{aligned}\pi_{i,j,1,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,1} + \alpha_{L2}\beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,1} \\ & + \alpha_{H2}\beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,2} + \alpha_{L2}\beta\lambda_L\gamma\pi_{i,j,0,1} \\ & + \alpha_{L2}\beta\lambda_H\gamma\pi_{i+1,j-1,0,1} + \alpha_{H2}\beta\lambda_L\gamma\pi_{i,j,0,2} + \alpha_{H2}\beta\lambda_H\gamma\pi_{i+1,j-1,0,2} \\ & + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,1} + \beta\lambda_L\gamma\pi_{i,j,1,1} + \beta\lambda_H\gamma\pi_{i+1,j-1,1,1} \\ & + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,2} + \beta\lambda_L\gamma\pi_{i,j,1,2} + \beta\lambda_H\gamma\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 38 : $1 \le i \le K - 2, j = K - i - 1, x = 1, y = 1$

$$\begin{aligned}\pi_{i,j,1,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,1} + \alpha_{L2}\beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,1} \\ & + \alpha_{H2}\beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,2} + \alpha_{L2}\beta\lambda_L\gamma\pi_{i,j,0,1} \\ & + \alpha_{L2}\beta\lambda_H\gamma\pi_{i+1,j-1,0,1} + \alpha_{H2}\beta\lambda_L\gamma\pi_{i,j,0,2} + \alpha_{H2}\beta\lambda_H\gamma\pi_{i+1,j-1,0,2} \\ & + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,1} + \beta\lambda_L\gamma\pi_{i,j,1,1} + \beta\lambda_H\gamma\pi_{i+1,j-1,1,1} \\ & + \beta(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,2} + \beta\lambda_L\gamma\pi_{i,j,1,2} + \beta\lambda_H\gamma\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 39 : $1 \leq i \leq \theta, 1 \leq j \leq \theta - i, x = 1, y = 2$

$$\pi_{i,j,1,2} = (1-\alpha_{H1})(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,2} + \alpha_{L1}(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,0,1} + \alpha_{H1}(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,0,2} + \alpha_{L1}(1-\beta)\lambda_L\gamma\pi_{i-1,j+1,0,1} + \alpha_{L1}(1-\beta)\lambda_H\gamma\pi_{i,j,0,1} + \alpha_{H1}(1-\beta)\lambda_L\gamma\pi_{i-1,j+1,0,2} + \alpha_{H1}(1-\beta)\lambda_H\gamma\pi_{i,j,0,2} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,1,1} + (1-\beta)\lambda_L\gamma\pi_{i-1,j+1,1,1} + (1-\beta)\lambda_H\gamma\pi_{i,j,1,1} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,1,2} + (1-\beta)\lambda_L\gamma\pi_{i-1,j+1,1,2} + (1-\beta)\lambda_H\gamma\pi_{i,j,1,2}$$

Case 40 : $1 \leq i \leq \theta, \theta - i < j < K - i - 1, x = 1, y = 2$

$$\pi_{i,j,1,2} = (1-\alpha_{H2})(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,2} + \alpha_{L2}(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,0,1} + \alpha_{H2}(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,0,2} + \alpha_{L2}(1-\beta)\lambda_L\gamma\pi_{i-1,j+1,0,1} + \alpha_{L2}(1-\beta)\lambda_H\gamma\pi_{i,j,0,1} + \alpha_{H2}(1-\beta)\lambda_L\gamma\pi_{i-1,j+1,0,2} + \alpha_{H2}(1-\beta)\lambda_H\gamma\pi_{i,j,0,2} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,1,1} + (1-\beta)\lambda_L\gamma\pi_{i-1,j+1,1,1} + (1-\beta)\lambda_H\gamma\pi_{i,j,1,1} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,1,2} + (1-\beta)\lambda_L\gamma\pi_{i-1,j+1,1,2} + (1-\beta)\lambda_H\gamma\pi_{i,j,1,2}$$

Case 41 : $\theta < i \leq K - 2, 1 \leq j \leq K - i - 2, x = 1, y = 2$

$$\pi_{i,j,1,2} = (1-\alpha_{H2})(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,2} + \alpha_{L2}(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,0,1} + \alpha_{H2}(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,0,2} + \alpha_{L2}(1-\beta)\lambda_L\gamma\pi_{i-1,j+1,0,1} + \alpha_{L2}(1-\beta)\lambda_H\gamma\pi_{i,j,0,1} + \alpha_{H2}(1-\beta)\lambda_L\gamma\pi_{i-1,j+1,0,2} + \alpha_{H2}(1-\beta)\lambda_H\gamma\pi_{i,j,0,2} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,1,1} + (1-\beta)\lambda_L\gamma\pi_{i-1,j+1,1,1} + (1-\beta)\lambda_H\gamma\pi_{i,j,1,1} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,1,2} + (1-\beta)\lambda_L\gamma\pi_{i-1,j+1,1,2} + (1-\beta)\lambda_H\gamma\pi_{i,j,1,2}$$

Case 42 : $1 \leq i \leq K-2, j = K-i-1, x = 1, y = 2$

$$\pi_{i,j,1,2} = (1-\alpha_{H2})(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,2} + \alpha_{L2}(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,0,1} + \alpha_{H2}(1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,0,2} + \alpha_{L2}(1-\beta)\lambda_L\gamma\pi_{i-1,j+1,0,1} + \alpha_{L2}(1-\beta)\lambda_H\gamma\pi_{i,j,0,1} + \alpha_{H2}(1-\beta)\lambda_L\gamma\pi_{i-1,j+1,0,2} + \alpha_{H2}(1-\beta)\lambda_H\gamma\pi_{i,j,0,2} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,1,1} + (1-\beta)\lambda_L\gamma\pi_{i-1,j+1,1,1} + (1-\beta)\lambda_H\gamma\pi_{i,j,1,1} + (1-\beta)(1-\lambda_L-\lambda_H)\gamma\pi_{i,j+1,1,2} + (1-\beta)\lambda_L\gamma\pi_{i-1,j+1,1,2} + (1-\beta)\lambda_H\gamma\pi_{i,j,1,2}$$

(b) Priority discipline

Case 1 : $i = 0, j = 0, x = 0, y = 0$

$$\pi_{0,0,0,0} = (1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,0,0} + \alpha_{L1}(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,0,1} + \alpha_{H1}(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,1,0} + (1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,1,2}$$

Case 2 : $i = 0, j = 0, x = 0, y = 1$

$$\pi_{0,0,0,1} = \lambda_L(1-\gamma)\,\pi_{0,0,0,0} + (1-\alpha_{L1})(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,0,1} + \alpha_{L1}\lambda_L(1-\gamma)\,\pi_{0,0,0,1} + \alpha_{H1}\lambda_L(1-\gamma)\,\pi_{0,0,0,2} + \alpha_{L1}(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{1,0,0,1} + \alpha_{H1}(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{1,0,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,0,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,0,1,2} + \lambda_L(1-\gamma)\pi_{0,0,1,1} + \lambda_L(1-\gamma)\pi_{0,0,1,2}$$

Case 3 : $i = 0, j = 0, x = 0, y = 2$

$$\pi_{0,0,0,2} = \lambda_H(1-\gamma)\,\pi_{0,0,0,0} + (1-\alpha_{H1})(1-\lambda_L-\lambda_H)(1-\gamma)\,\pi_{0,0,0,2} + \alpha_{L1}\lambda_H(1-\gamma)\,\pi_{0,0,0,1} + \alpha_{H1}\lambda_H(1-\gamma)\,\pi_{0,0,0,2} + \alpha_{L1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,0,1} + \alpha_{H1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,1,1,2} + \lambda_H(1-\gamma)\pi_{0,0,1,1} + \lambda_H(1-\gamma)\pi_{0,0,1,2}$$

Case 4 : $i = 0, 1 \le j \le \theta, x = 0, y = 1$

$$\pi_{0,j,0,1} = (1-\alpha_{L1})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,1} + (1-\alpha_{L1})\lambda_H(1-\gamma)\pi_{0,j-1,0,1} + \alpha_{L1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,1} + \alpha_{H1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,2} + \alpha_{L1}\lambda_H(1-\gamma)\pi_{1,j-1,0,1} + \alpha_{H1}\lambda_H(1-\gamma)\pi_{1,j-1,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,1,2} + \lambda_H(1-\gamma)\pi_{1,j-1,1,1} + \lambda_H(1-\gamma)\pi_{1,j-1,1,2}$$

Case 5 : $i = 0, \theta < j \leq K - 2, x = 0, y = 1$

$$\begin{aligned}
\pi_{0,j,0,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,1} + (1-\alpha_{L2})\lambda_H(1-\gamma)\pi_{0,j-1,0,1} \\
& + \alpha_{L2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,1} + \alpha_{H2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,0,2} \\
& + \alpha_{L2}\lambda_H(1-\gamma)\pi_{1,j-1,0,1} + \alpha_{H2}\lambda_H(1-\gamma)\pi_{1,j-1,0,2} \\
& + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,1,1} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j,1,2} \\
& + \lambda_H(1-\gamma)\pi_{1,j-1,1,1} + \lambda_H(1-\gamma)\pi_{1,j-1,1,2}
\end{aligned}$$

Case 6 : $i = 0, 1 \leq j \leq \theta, x = 0, y = 2$

$$\begin{aligned}
\pi_{0,j,0,2} = {} & (1-\alpha_{H1})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,2} + (1-\alpha_{H1})\lambda_H(1-\gamma)\pi_{0,j-1,0,2} \\
& + \alpha_{L1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,1} \\
& + \alpha_{H1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,2} + \alpha_{L1}\lambda_H(1-\gamma)\pi_{0,j,0,1} \\
& + \alpha_{H1}\lambda_H(1-\gamma)\pi_{0,j,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,1} \\
& + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,2} + \lambda_H(1-\gamma)\pi_{0,j,1,1} \\
& + \lambda_H(1-\gamma)\pi_{0,j,1,2}
\end{aligned}$$

Case 7 : $i = 0, \theta < j \leq K - 2, x = 0, y = 2$

$$\begin{aligned}
\pi_{0,j,0,2} = {} & (1-\alpha_{H2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,2} + (1-\alpha_{H2})\lambda_H(1-\gamma)\pi_{0,j-1,0,2} \\
& + \alpha_{L2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,1} \\
& + \alpha_{H2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,0,2} + \alpha_{L2}\lambda_H(1-\gamma)\pi_{0,j,0,1} \\
& + \alpha_{H2}\lambda_H(1-\gamma)\pi_{0,j,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,1} \\
& + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j+1,1,2} + \lambda_H(1-\gamma)\pi_{0,j,1,1} \\
& + \lambda_H(1-\gamma)\pi_{0,j,1,2}
\end{aligned}$$

Case 8 : $1 \leq i \leq \theta, j = 0, x = 0, y = 1$

$$\begin{aligned}
\pi_{i,0,0,1} = {} & (1-\alpha_{L1})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,1} + (1-\alpha_{L1})\lambda_L(1-\gamma)\pi_{i-1,0,0,1} \\
& + \alpha_{L1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,0,1} \\
& + \alpha_{H1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,0,2} + \alpha_{L1}\lambda_L(1-\gamma)\pi_{i,0,0,1} \\
& + \alpha_{H1}\lambda_L(1-\gamma)\pi_{i,0,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,1} \\
& + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,2} + \lambda_L(1-\gamma)\pi_{i,0,1,1} + \lambda_L(1-\gamma)\pi_{i,0,1,2}
\end{aligned}$$

Case 9 : $\theta < i \le K-2, j=0, x=0, y=1$

$$\begin{aligned}\pi_{i,0,0,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,1} + (1-\alpha_{L2})\lambda_L(1-\gamma)\pi_{i-1,0,0,1} \\ & + \alpha_{L2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,0,1} \\ & + \alpha_{H2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,0,2} + \alpha_{L2}\lambda_L(1-\gamma)\pi_{i,0,0,1} \\ & + \alpha_{H2}\lambda_L(1-\gamma)\pi_{i,0,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,0,1,2} + \lambda_L(1-\gamma)\pi_{i,0,1,1} + \lambda_L(1-\gamma)\pi_{i,0,1,2}\end{aligned}$$

Case 10 : $1 \le i \le \theta, j=0, x=0, y=2$

$$\begin{aligned}\pi_{i,0,0,2} = {} & (1-\alpha_{H1})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,2} + (1-\alpha_{H1})\lambda_L(1-\gamma)\pi_{i-1,0,0,2} \\ & + \alpha_{L1}\lambda_L(1-\gamma)\pi_{0,1,0,1} + \alpha_{H1}\lambda_L(1-\gamma)\pi_{0,1,0,2} + \lambda_L(1-\gamma)\pi_{0,1,1,1} \\ & + \lambda_L(1-\gamma)\pi_{0,1,1,2}\end{aligned}$$

Case 11 : $\theta < i \le K-2, j=0, x=0, y=2$

$$\begin{aligned}\pi_{i,0,0,2} = {} & (1-\alpha_{H2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,2} + (1-\alpha_{H2})\lambda_L(1-\gamma)\pi_{i-1,0,0,2} \\ & + \alpha_{L2}\lambda_L(1-\gamma)\pi_{0,1,0,1} + \alpha_{H2}\lambda_L(1-\gamma)\pi_{0,1,0,2} + \lambda_L(1-\gamma)\pi_{0,1,1,1} \\ & + \lambda_L(1-\gamma)\pi_{0,1,1,2}\end{aligned}$$

Case 12 : $i=0, j=K-1, x=0, y=1$

$$\begin{aligned}\pi_{0,j,0,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,1} + (1-\alpha_{L2})\lambda_H(1-\gamma)\pi_{0,j-1,0,1} \\ & + \alpha_{L2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j-1,0,1} \\ & + \alpha_{H2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j-1,0,2} + \alpha_{L2}\lambda_H(1-\gamma)\pi_{1,j,0,1} \\ & + \alpha_{H2}\lambda_H(1-\gamma)\pi_{1,j,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j-1,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{1,j-1,1,2} + \lambda_H(1-\gamma)\pi_{1,j,1,1} \\ & + \lambda_H(1-\gamma)\pi_{1,j,1,2}\end{aligned}$$

Case 13 : $i=0, j=K-1, x=0, y=2$

$$\begin{aligned}\pi_{0,j,0,2} = {} & (1-\alpha_{H2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{0,j,0,2} + (1-\alpha_{H2})\lambda_H(1-\gamma)\pi_{0,j-1,0,2} \\ & + \alpha_{L2}\lambda_H(1-\gamma)\pi_{0,j,0,1} + \alpha_{H2}\lambda_H(1-\gamma)\pi_{0,j,0,2} + \lambda_H(1-\gamma)\pi_{0,j,1,1} \\ & + \lambda_H(1-\gamma)\pi_{0,j,1,2}\end{aligned}$$

Case 14 : $i = K - 1, j = 0, x = 0, y = 1$

$$\begin{aligned}\pi_{i,0,0,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,1} + (1-\alpha_{L2})\lambda_L(1-\gamma)\pi_{i-1,0,0,1} \\ & + \alpha_{L2}\lambda_L(1-\gamma)\pi_{i,0,0,1} + \alpha_{H2}\lambda_L(1-\gamma)\pi_{i,0,0,2} + \lambda_L(1-\gamma)\pi_{i,0,1,1} \\ & + \lambda_L(1-\gamma)\pi_{i,0,1,2}\end{aligned}$$

Case 15 : $i = K - 1, j = 0, x = 0, y = 2$

$$\begin{aligned}\pi_{i,0,0,2} = {} & (1-\alpha_{H2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,0,0,2} + (1-\alpha_{H2})\lambda_L(1-\gamma)\pi_{i-1,0,0,2} \\ & + \alpha_{L2}\lambda_L(1-\gamma)\pi_{0,1,0,1} + \alpha_{H2}\lambda_L(1-\gamma)\pi_{0,1,0,2} + \lambda_L(1-\gamma)\pi_{0,1,1,1} \\ & + \lambda_L(1-\gamma)\pi_{0,1,1,2}\end{aligned}$$

Case 16 : $1 \le i \le \theta, 1 \le j \le \theta - i, x = 0, y = 1$

$$\begin{aligned}\pi_{i,j,0,1} = {} & (1-\alpha_{L1})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,1} + (1-\alpha_{L1})\lambda_L(1-\gamma)\pi_{i-1,j,0,1} \\ & + (1-\alpha_{L1})\lambda_H(1-\gamma)\pi_{i,j-1,0,1} + \alpha_{L1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,1} \\ & + \alpha_{L1}\lambda_L(1-\gamma)\pi_{i,j,0,1} + \alpha_{L1}\lambda_H(1-\gamma)\pi_{i+1,j-1,0,1} \\ & + \alpha_{H1}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,2} + \alpha_{H1}\lambda_L(1-\gamma)\pi_{i,j,0,2} \\ & + \alpha_{H1}\lambda_H(1-\gamma)\pi_{i+1,j-1,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,1} \\ & + \lambda_L(1-\gamma)\pi_{i,j,1,1} + \lambda_H(1-\gamma)\pi_{i+1,j-1,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,2} + \lambda_L(1-\gamma)\pi_{i,j,1,2} \\ & + \lambda_H(1-\gamma)\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 17 : $1 \le i \le \theta, \theta - i < j < K - i - 1, x = 0, y = 1$

$$\begin{aligned}\pi_{i,j,0,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,1} + (1-\alpha_{L2})\lambda_L(1-\gamma)\pi_{i-1,j,0,1} \\ & + (1-\alpha_{L2})\lambda_H(1-\gamma)\pi_{i,j-1,0,1} + \alpha_{L2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,1} \\ & + \alpha_{L2}\lambda_L(1-\gamma)\pi_{i,j,0,1} + \alpha_{L2}\lambda_H(1-\gamma)\pi_{i+1,j-1,0,1} \\ & + \alpha_{H2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,2} + \alpha_{H2}\lambda_L(1-\gamma)\pi_{i,j,0,2} \\ & + \alpha_{H2}\lambda_H(1-\gamma)\pi_{i+1,j-1,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,1} \\ & + \lambda_L(1-\gamma)\pi_{i,j,1,1} + \lambda_H(1-\gamma)\pi_{i+1,j-1,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,2} + \lambda_L(1-\gamma)\pi_{i,j,1,2} \\ & + \lambda_H(1-\gamma)\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 18 : $\theta < i \leq K-2, 1 \leq j < K-i-1, x=0, y=1$

$$\begin{aligned}\pi_{i,j,0,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,1} + (1-\alpha_{L2})\lambda_L(1-\gamma)\pi_{i-1,j,0,1} \\ & + (1-\alpha_{L2})\lambda_H(1-\gamma)\pi_{i,j-1,0,1} + \alpha_{L2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,1} \\ & + \alpha_{L2}\lambda_L(1-\gamma)\pi_{i,j,0,1} + \alpha_{L2}\lambda_H(1-\gamma)\pi_{i+1,j-1,0,1} \\ & + \alpha_{H2}(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,0,2} + \alpha_{H2}\lambda_L(1-\gamma)\pi_{i,j,0,2} \\ & + \alpha_{H2}\lambda_H(1-\gamma)\pi_{i+1,j-1,0,2} + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,1} \\ & + \lambda_L(1-\gamma)\pi_{i,j,1,1} + \lambda_H(1-\gamma)\pi_{i+1,j-1,1,1} \\ & + (1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i+1,j,1,2} + \lambda_L(1-\gamma)\pi_{i,j,1,2} \\ & + \lambda_H(1-\gamma)\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 19 : $1 \leq i \leq K-2, j = K-i-1, x=0, y=1$

$$\begin{aligned}\pi_{i,j,0,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,1} + (1-\alpha_{L2})\lambda_L(1-\gamma)\pi_{i-1,j,0,1} \\ & + (1-\alpha_{L2})\lambda_H(1-\gamma)\pi_{i,j-1,0,1} + \alpha_{L2}\lambda_L(1-\gamma)\pi_{i,j,0,1} \\ & + \alpha_{H2}\lambda_L(1-\gamma)\pi_{i,j,0,2} + \alpha_{L2}\lambda_H(1-\gamma)\pi_{i+1,j-1,0,1} \\ & + \alpha_{H2}\lambda_H(1-\gamma)\pi_{i+1,j-1,0,2}\end{aligned}$$

Case 20 : $1 \leq i \leq \theta, 1 \leq j \leq \theta-i, x=0, y=2$

$$\begin{aligned}\pi_{i,j,0,2} = {} & (1-\alpha_{H1})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,2} + (1-\alpha_{H1})\lambda_L(1-\gamma)\pi_{i-1,j,0,2} \\ & + (1-\alpha_{H1})\lambda_H(1-\gamma)\pi_{i,j-1,0,2} + \alpha_{L1}\lambda_L(1-\gamma)\pi_{0,j+1,0,1} \\ & + \alpha_{H1}\lambda_L(1-\gamma)\pi_{0,j+1,0,2} + \lambda_L(1-\gamma)\pi_{0,j+1,1,1} + \lambda_L(1-\gamma)\pi_{0,j+1,1,2}\end{aligned}$$

Case 21 : $1 \leq i \leq \theta, \theta-i < j < K-i-1, x=0, y=2$

$$\begin{aligned}\pi_{i,j,0,2} = {} & (1-\alpha_{H2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,2} + (1-\alpha_{H2})\lambda_L(1-\gamma)\pi_{i-1,j,0,2} \\ & + (1-\alpha_{H2})\lambda_H(1-\gamma)\pi_{i,j-1,0,2} + \alpha_{L2}\lambda_L(1-\gamma)\pi_{0,j+1,0,1} \\ & + \alpha_{H2}\lambda_L(1-\gamma)\pi_{0,j+1,0,2} + \lambda_L(1-\gamma)\pi_{0,j+1,1,1} + \lambda_L(1-\gamma)\pi_{0,j+1,1,2}\end{aligned}$$

Case 22 : $\theta < i \leq K-2, 1 \leq j \leq K-i-1, x=0, y=2$

$$\begin{aligned}\pi_{i,j,0,2} = {} & (1-\alpha_{H2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,2} + (1-\alpha_{H2})\lambda_L(1-\gamma)\pi_{i-1,j,0,2} \\ & + (1-\alpha_{H2})\lambda_H(1-\gamma)\pi_{i,j-1,0,2} + \alpha_{L2}\lambda_L(1-\gamma)\pi_{0,j+1,0,1} \\ & + \alpha_{H2}\lambda_L(1-\gamma)\pi_{0,j+1,0,2} + \lambda_L(1-\gamma)\pi_{0,j+1,1,1} + \lambda_L(1-\gamma)\pi_{0,j+1,1,2}\end{aligned}$$

Case 23 : $1 \leq i \leq K-2, j = K-i-1, x = 0, y = 2$

$$\pi_{i,j,0,2} = (1-\alpha_{H2})(1-\lambda_L-\lambda_H)(1-\gamma)\pi_{i,j,0,2} + (1-\alpha_{H2})\lambda_L(1-\gamma)\pi_{i-1,j,0,2} + (1-\alpha_{H2})\lambda_H(1-\gamma)\pi_{i,j-1,0,2} + \alpha_{L2}\lambda_L(1-\gamma)\pi_{0,j,0,1} + \alpha_{H2}\lambda_L(1-\gamma)\pi_{0,j,0,2} + \lambda_L(1-\gamma)\pi_{0,j+1,1,1} + \lambda_L(1-\gamma)\pi_{0,j+1,1,2}$$

Case 24 : $i = 0, j = 0, x = 1, y = 0$

$$\pi_{0,0,1,0} = (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,0} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,0} + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,1} + \alpha_H(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,0,1,2}$$

Case 25 : $i = 0, j = 0, x = 1, y = 1$

$$\pi_{0,0,1,1} = (1-\alpha_L)(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,1} + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{1,0,0,1} + \alpha_H(1-\lambda_L-\lambda_H)\gamma\pi_{1,0,0,2} + \lambda_L\gamma\pi_{0,0,0,0} + \lambda_L\gamma\pi_{0,0,0,1} + \lambda_L\gamma\pi_{0,0,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,0,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,0,1,2}$$

Case 26 : $i = 0, j = 0, x = 1, y = 2$

$$\pi_{0,0,1,2} = \lambda_H\gamma\pi_{0,0,0,0} + \lambda_H\gamma\pi_{0,0,1,1} + \lambda_H\gamma\pi_{0,0,1,2} + (1-\alpha_H)(1-\lambda_L-\lambda_H)\gamma\pi_{0,0,0,2} + \alpha_L(1-\lambda_L-\lambda_H)\gamma\pi_{0,1,0,1} + \alpha_H(1-\lambda_L-\lambda_H)\gamma\pi_{0,1,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,1,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{0,1,1,2}$$

Case 27 : $i = 0, 1 \leq j \leq \theta, x = 1, y = 1$

$$\pi_{0,j,1,1} = (1-\alpha_{L1})(1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,1} + (1-\alpha_{L1})\lambda_H\gamma\pi_{0,j-1,0,1} + \alpha_{L1}(1-\lambda_L-\lambda_H)\gamma\pi_{0,j-1,0,1} + \alpha_{L1}(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,1} + \alpha_{L1}\lambda_H\gamma\pi_{1,j-1,0,1} + \alpha_{H1}\lambda_H\gamma\pi_{1,j-1,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,j,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,j,1,2} + \lambda_H\gamma\pi_{1,j-1,1,1} + \lambda_H\gamma\pi_{1,j-1,1,2}$$

Case 28 : $i = 0, \theta < j \leq \mathrm{K}-1, x = 1, y = 1$

$$\pi_{0,j,1,1} = (1-\alpha_{L2})(1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,1} + (1-\alpha_{L2})\lambda_H\gamma\pi_{0,j-1,0,1} + \alpha_{L2}(1-\lambda_L-\lambda_H)\gamma\pi_{0,j-1,0,1} + \alpha_{L2}(1-\lambda_L-\lambda_H)\gamma\pi_{1,j,0,1} + \alpha_{L2}\lambda_H\gamma\pi_{1,j-1,0,1} + \alpha_{H2}\lambda_H\gamma\pi_{1,j-1,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,j,1,1} + (1-\lambda_L-\lambda_H)\gamma\pi_{1,j,1,2} + \lambda_H\gamma\pi_{1,j-1,1,1} + \lambda_H\gamma\pi_{1,j-1,1,2}$$

Case 29 : $i = 0, 1 \leq j \leq \theta, x = 1, y = 2$

$$\begin{aligned}\pi_{0,j,1,2} = {} & (1-\alpha_{H1})(1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,2} + (1-\alpha_{H1})\lambda_H\gamma\pi_{0,j-1,0,2} \\ & + \alpha_{L1}(1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,0,1} + \alpha_{L1}\lambda_H\gamma\pi_{0,j,0,1} \\ & + \alpha_{L1}\lambda_H(1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,0,2} + \alpha_{H1}\lambda_H\gamma\pi_{0,j,0,2} \\ & + (1-\lambda_L-\lambda_H)\pi_{0,j+1,1,1} + (1-\lambda_L-\lambda_H)\pi_{0,j+1,1,2} + \lambda_H\gamma\pi_{0,j,1,1} \\ & + \lambda_H\gamma\pi_{0,j,1,2}\end{aligned}$$

Case 30 : $i = 0, \theta < j \leq K-1, x = 1, y = 2$

$$\begin{aligned}\pi_{0,j,1,2} = {} & (1-\alpha_{H2})(1-\lambda_L-\lambda_H)\gamma\pi_{0,j,0,2} + (1-\alpha_{H2})\lambda_H\gamma\pi_{0,j-1,0,2} \\ & + \alpha_{L2}(1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,0,1} + \alpha_{L2}\lambda_H\gamma\pi_{0,j,0,1} \\ & + \alpha_{L2}\lambda_H(1-\lambda_L-\lambda_H)\gamma\pi_{0,j+1,0,2} + \alpha_{H2}\lambda_H\gamma\pi_{0,j,0,2} \\ & + (1-\lambda_L-\lambda_H)\pi_{0,j+1,1,1} + (1-\lambda_L-\lambda_H)\pi_{0,j+1,1,2} + \lambda_H\gamma\pi_{0,j,1,1} \\ & + \lambda_H\gamma\pi_{0,j,1,2}\end{aligned}$$

Case 31 : $1 \leq i \leq \theta, j = 0, x = 1, y = 1$

$$\begin{aligned}\pi_{i,0,1,1} = {} & (1-\alpha_{L1})(1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,1} + (1-\alpha_{L1})\lambda_L\gamma\pi_{i-1,0,0,1} \\ & + \alpha_{L1}(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,0,1} + \alpha_{H1}(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,0,2} \\ & + \alpha_{L1}\lambda_L\gamma\pi_{i,0,0,1} + \alpha_H\lambda_L\gamma\pi_{i,0,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,1,1} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,1,2} + \lambda_L\gamma\pi_{i,0,1,1} + \lambda_L\gamma\pi_{i,0,1,2}\end{aligned}$$

Case 32 : $\theta < i \leq K-1, j = 0, x = 1, y = 1$

$$\begin{aligned}\pi_{i,0,1,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,1} + (1-\alpha_{L2})\lambda_L\gamma\pi_{i-1,0,0,1} \\ & + \alpha_{L2}(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,0,1} + \alpha_{H2}(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,0,2} \\ & + \alpha_{L2}\lambda_L\gamma\pi_{i,0,0,1} + \alpha_H\lambda_L\gamma\pi_{i,0,0,2} + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,1,1} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,0,1,2} + \lambda_L\gamma\pi_{i,0,1,1} + \lambda_L\gamma\pi_{i,0,1,2}\end{aligned}$$

Case 33 : $1 \leq i \leq \theta, j = 0, x = 1, y = 2$

$$\begin{aligned}\pi_{i,0,1,2} = {} & (1-\alpha_{H1})(1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,2} + (1-\alpha_{H1})\lambda_L\gamma\pi_{i-1,0,0,2} + \alpha_{L1}\lambda_L\gamma\pi_{0,1,0,1} \\ & + \alpha_{H1}\lambda_L\gamma\pi_{0,1,0,2} + \lambda_L\gamma\pi_{0,1,1,1} + \lambda_L\gamma\pi_{0,1,1,2}\end{aligned}$$

Case 34 : $\theta < i \le K-1, j=0, x=1, y=2$

$$\pi_{i,0,1,2} = (1-\alpha_{H2})(1-\lambda_L-\lambda_H)\gamma\pi_{i,0,0,2} + (1-\alpha_{H2})\lambda_L\gamma\pi_{i-1,0,0,2} + \alpha_{L2}\lambda_L\gamma\pi_{0,1,0,1} + \alpha_{H2}\lambda_L\gamma\pi_{0,1,0,2} + \lambda_L\gamma\pi_{0,1,1,1} + \lambda_L\gamma\pi_{0,1,1,2}$$

Case 35 : $1 \le i \le \theta, 1 \le j \le \theta - i, x=1, y=1$

$$\begin{aligned}\pi_{i,j,1,1} = {} & (1-\alpha_{L1})(1-\lambda_L-\lambda_H)\gamma\pi_{i,j,0,1} + (1-\alpha_{L1})\lambda_L\gamma\pi_{i-1,j,0,1} \\ & + (1-\alpha_{L1})\lambda_H\gamma\pi_{i,j-1,0,1} + \alpha_{L1}\lambda_L\gamma\pi_{i,j,0,1} + \alpha_{L1}\lambda_H\gamma\pi_{i+1,j-1,0,1} \\ & + \alpha_{H1}(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,2} + \alpha_{H1}\lambda_L\gamma\pi_{i,j,0,2} + \alpha_{H1}\lambda_H\gamma\pi_{i+1,j-1,0,2} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,1} + \lambda_L\gamma\pi_{i,j,1,1} + \lambda_H\gamma\pi_{i+1,j-1,1,1} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,2} + \lambda_L\gamma\pi_{i,j,1,2} + \lambda_H\gamma\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 36 : $1 \le i \le \theta, \theta - i < j \le K-i-1, x=1, y=1$

$$\begin{aligned}\pi_{i,j,1,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)\gamma\pi_{i,j,0,1} + (1-\alpha_{L2})\lambda_L\gamma\pi_{i-1,j,0,1} \\ & + (1-\alpha_{L2})\lambda_H\gamma\pi_{i,j-1,0,1} + \alpha_{L2}\lambda_L\gamma\pi_{i,j,0,1} + \alpha_{L2}\lambda_H\gamma\pi_{i+1,j-1,0,1} \\ & + \alpha_{H2}(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,2} + \alpha_{H2}\lambda_L\gamma\pi_{i,j,0,2} + \alpha_{H2}\lambda_H\gamma\pi_{i+1,j-1,0,2} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,1} + \lambda_L\gamma\pi_{i,j,1,1} + \lambda_H\gamma\pi_{i+1,j-1,1,1} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,2} + \lambda_L\gamma\pi_{i,j,1,2} + \lambda_H\gamma\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 37 : $\theta < i \le K-2, 1 \le j \le K-i-2, x=1, y=1$

$$\begin{aligned}\pi_{i,j,1,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)\gamma\pi_{i,j,0,1} + (1-\alpha_{L2})\lambda_L\gamma\pi_{i-1,j,0,1} \\ & + (1-\alpha_{L2})\lambda_H\gamma\pi_{i,j-1,0,1} + \alpha_{L2}\lambda_L\gamma\pi_{i,j,0,1} + \alpha_{L2}\lambda_H\gamma\pi_{i+1,j-1,0,1} \\ & + \alpha_{H2}(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,2} + \alpha_{H2}\lambda_L\gamma\pi_{i,j,0,2} + \alpha_{H2}\lambda_H\gamma\pi_{i+1,j-1,0,2} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,1} + \lambda_L\gamma\pi_{i,j,1,1} + \lambda_H\gamma\pi_{i+1,j-1,1,1} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,2} + \lambda_L\gamma\pi_{i,j,1,2} + \lambda_H\gamma\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 38 : $1 < i \le K-2, j = K-i-1, x=1, y=1$

$$\begin{aligned}\pi_{i,j,1,1} = {} & (1-\alpha_{L2})(1-\lambda_L-\lambda_H)\gamma\pi_{i,j,0,1} + (1-\alpha_{L2})\lambda_L\gamma\pi_{i-1,j,0,1} \\ & + (1-\alpha_{L2})\lambda_H\gamma\pi_{i,j-1,0,1} + \alpha_{L2}\lambda_L\gamma\pi_{i,j,0,1} + \alpha_{L2}\lambda_H\gamma\pi_{i+1,j-1,0,1} \\ & + \alpha_{H2}(1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,0,2} + \alpha_{H2}\lambda_L\gamma\pi_{i,j,0,2} + \alpha_{H2}\lambda_H\gamma\pi_{i+1,j-1,0,2} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,1} + \lambda_L\gamma\pi_{i,j,1,1} + \lambda_H\gamma\pi_{i+1,j-1,1,1} \\ & + (1-\lambda_L-\lambda_H)\gamma\pi_{i+1,j,1,2} + \lambda_L\gamma\pi_{i,j,1,2} + \lambda_H\gamma\pi_{i+1,j-1,1,2}\end{aligned}$$

Case 39 : $1 \leq i \leq \theta, 1 \leq j \leq \theta - i, x = 1, y = 2$

$$\pi_{i,j,1,2} = (1-\alpha_{H1})(1-\lambda_L-\lambda_H)\gamma\pi_{i,j,0,2} + (1-\alpha_{H1})\lambda_L\gamma\pi_{i-1,j,0,2} + (1-\alpha_{H1})\lambda_H\gamma\pi_{i,j-1,0,2} + \alpha_{L1}\lambda_L\gamma\pi_{0,j+1,0,1} + \alpha_{H1}\lambda_L\gamma\pi_{0,j+1,0,2} + \lambda_L\gamma\pi_{0,j+1,1,1} + \lambda_L\gamma\pi_{0,j+1,1,2}$$

Case 40 : $1 \leq i \leq \theta, \theta - i < j < K - i - 1, x = 1, y = 2$

$$\pi_{i,j,1,2} = (1-\alpha_{H2})(1-\lambda_L-\lambda_H)\gamma\pi_{i,j,0,2} + (1-\alpha_{H2})\lambda_L\gamma\pi_{i-1,j,0,2} + (1-\alpha_{H2})\lambda_H\gamma\pi_{i,j-1,0,2} + \alpha_{L2}\lambda_L\gamma\pi_{0,j+1,0,1} + \alpha_{H2}\lambda_L\gamma\pi_{0,j+1,0,2} + \lambda_L\gamma\pi_{0,j+1,1,1} + \lambda_L\gamma\pi_{0,j+1,1,2}$$

Case 41 : $\theta < i \leq K - 2, 1 \leq j \leq K - i - 2, x = 1, y = 2$

$$\pi_{i,j,1,2} = (1-\alpha_{H2})(1-\lambda_L-\lambda_H)\gamma\pi_{i,j,0,2} + (1-\alpha_{H2})\lambda_L\gamma\pi_{i-1,j,0,2} + (1-\alpha_{H2})\lambda_H\gamma\pi_{i,j-1,0,2} + \alpha_{L2}\lambda_L\gamma\pi_{0,j+1,0,1} + \alpha_{H2}\lambda_L\gamma\pi_{0,j+1,0,2} + \lambda_L\gamma\pi_{0,j+1,1,1} + \lambda_L\gamma\pi_{0,j+1,1,2}$$

Case 42 : $1 \leq i \leq K - 2, j = K - i - 1, x = 1, y = 2$

$$\pi_{i,j,1,2} = (1-\alpha_{H2})(1-\lambda_L-\lambda_H)\gamma\pi_{i,j,0,2} + (1-\alpha_{H2})\lambda_L\gamma\pi_{i-1,j,0,2} + (1-\alpha_{H2})\lambda_H\gamma\pi_{i,j-1,0,2} + \alpha_{L2}\lambda_L\gamma\pi_{0,j+1,0,1} + \alpha_{H2}\lambda_L\gamma\pi_{0,j+1,0,2} + \lambda_L\gamma\pi_{0,j+1,1,1} + \lambda_L\gamma\pi_{0,j+1,1,2}$$

3.3.3 State diagram

(a) First-In-First-Out

(1) $i = 0, j = 0, x = 0, y = 0$

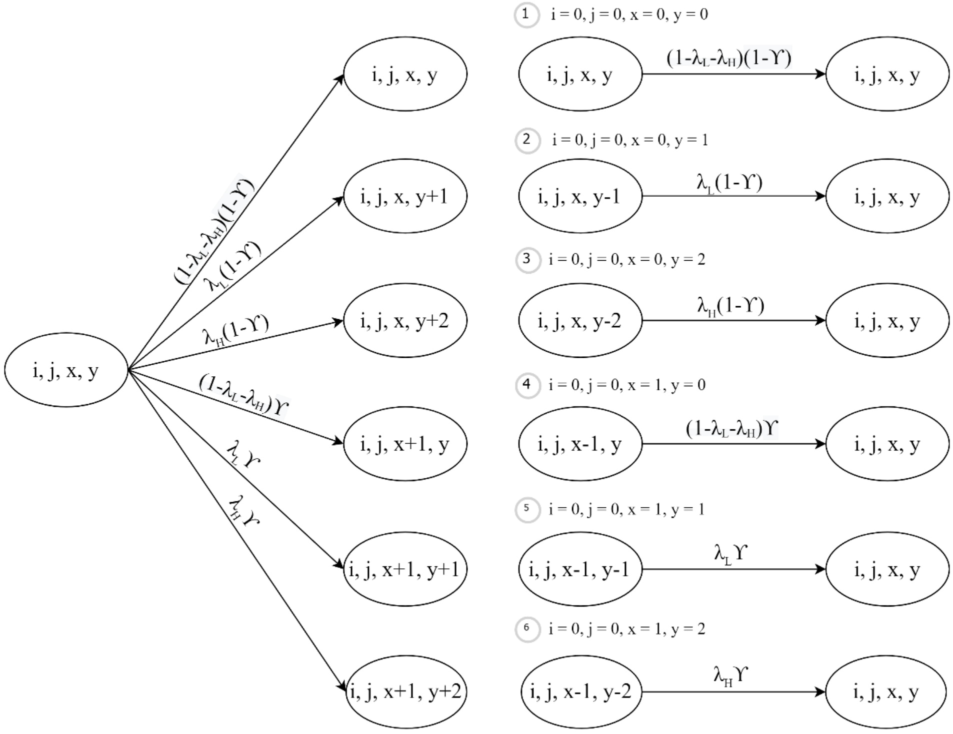
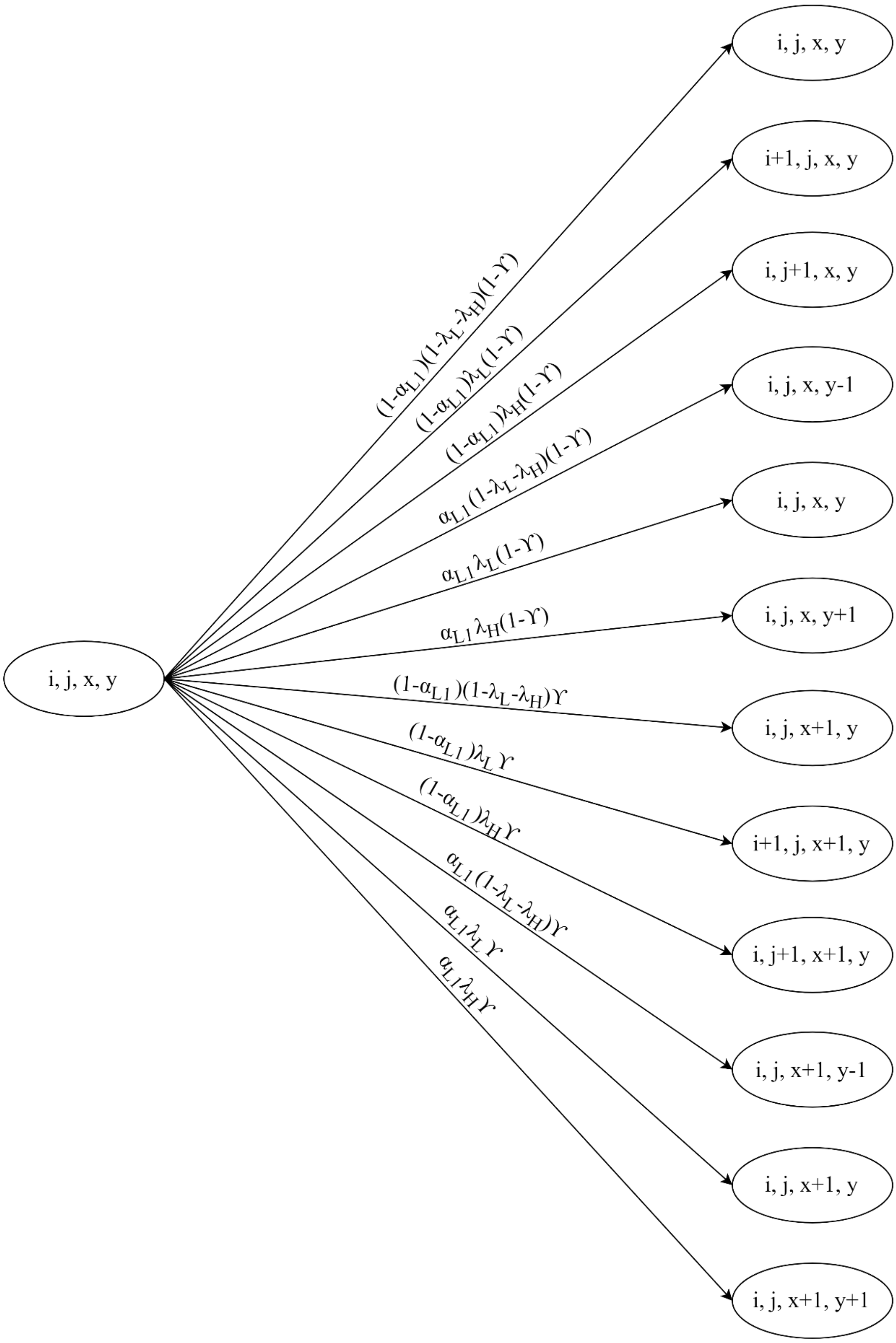


Fig 3. 75: The state diagram for $i = 0, j = 0, x = 0, y = 0$

(2) $i = 0, j = 0, x = 0, y = 1$


i, j, x, y
i, j, x, y
i+1, j, x, y
i, j+1, x, y
i, j, x, y-1
i, j, x, y
i, j, x, y+1
i, j, x+1, y
i+1, j, x+1, y
i, j+1, x+1, y
i, j, x+1, y-1
i, j, x+1, y
i, j, x+1, y+1
(1-αL1)(1-λL-λH)(1-ϒ)
(1-αL1)λL(1-ϒ)
(1-αL1)λH(1-ϒ)
αL1(1-λL-λH)(1-ϒ)
αL1λL(1-ϒ)
αL1λH(1-ϒ)
(1-αL1)(1-λL-λH)ϒ
(1-αL1)λLϒ
(1-αL1)λHϒ
αL1(1-λL-λH)ϒ
αL1λLϒ
αL1λHϒ

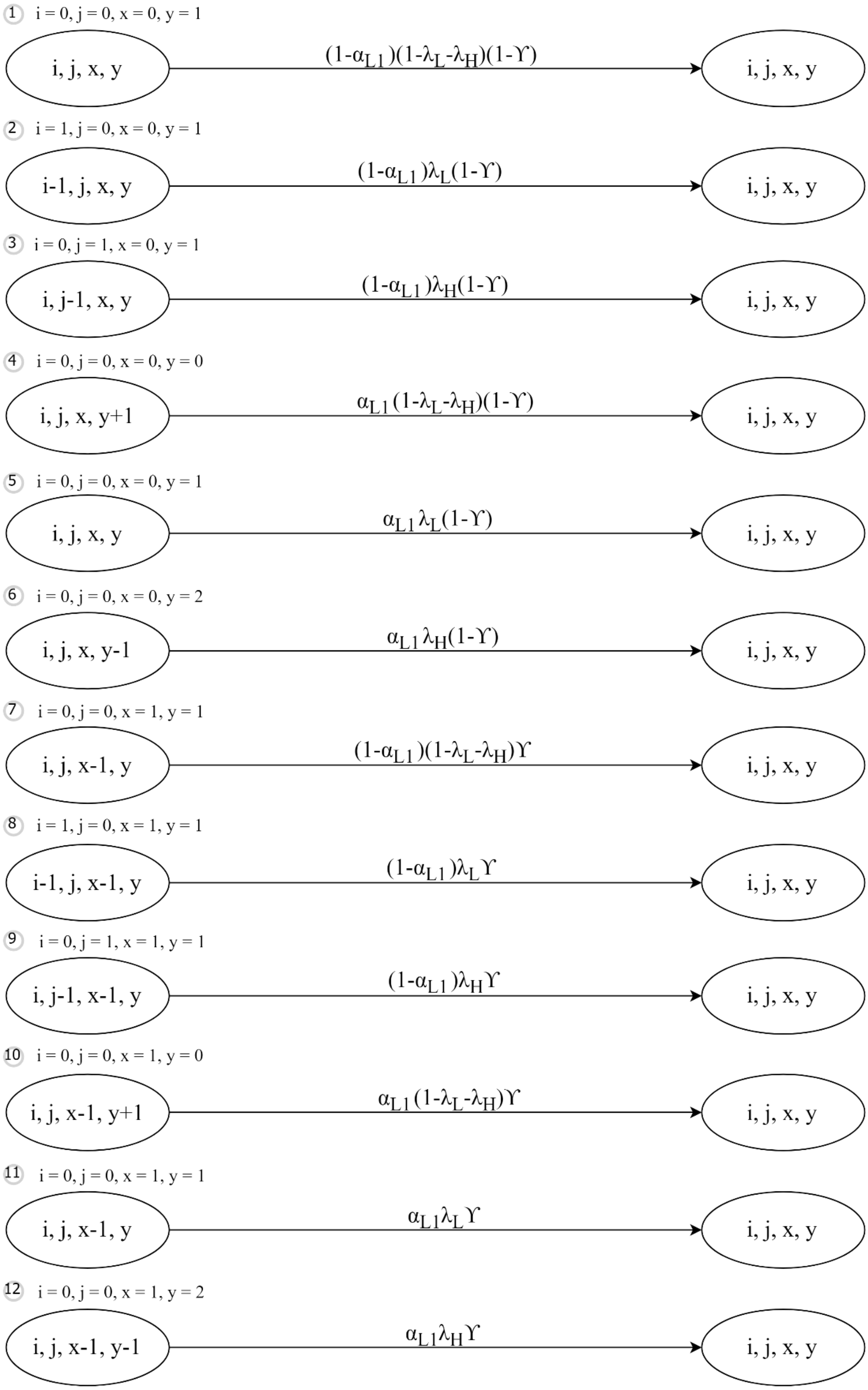
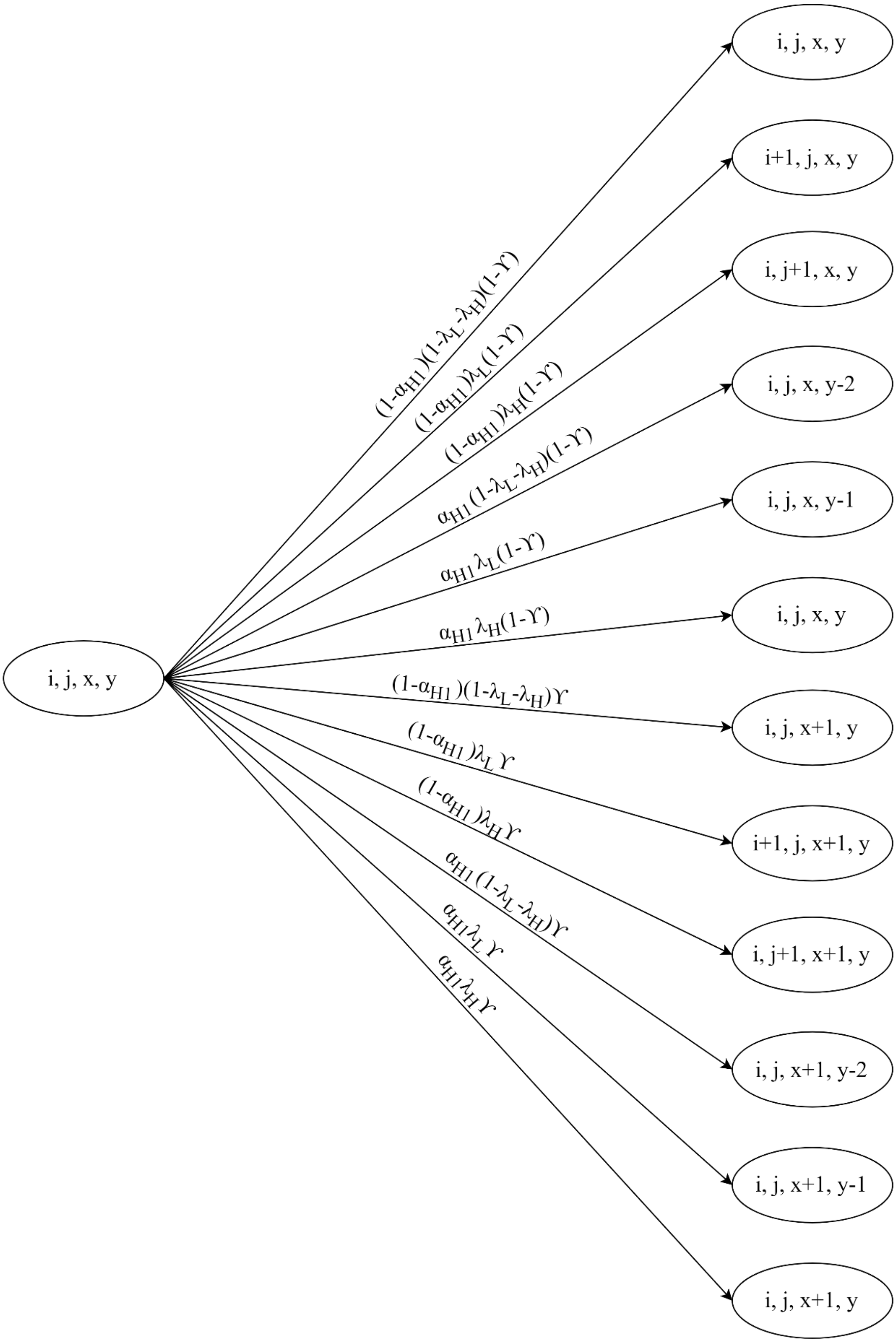


Fig 3. 76: The state diagram for $i = 0, j = 0, x = 0, y = 1$

(3) $i = 0, j = 0, x = 0, y = 2$



i, j, x, y
i, j, x, y
i+1, j, x, y
i, j+1, x, y
i, j, x, y-2
i, j, x, y-1
i, j, x, y
i, j, x+1, y
i+1, j, x+1, y
i, j+1, x+1, y
i, j, x+1, y-2
i, j, x+1, y-1
i, j, x+1, y
(1-αH1)(1-λL-λH)(1-ϒ)
(1-αH1)λL(1-ϒ)
(1-αH1)λH(1-ϒ)
αH1(1-λL-λH)(1-ϒ)
αH1λL(1-ϒ)
αH1λH(1-ϒ)
(1-αH1)(1-λL-λH)ϒ
(1-αH1)λLϒ
(1-αH1)λHϒ
αH1(1-λL-λH)ϒ
αH1λLϒ
αH1λHϒ

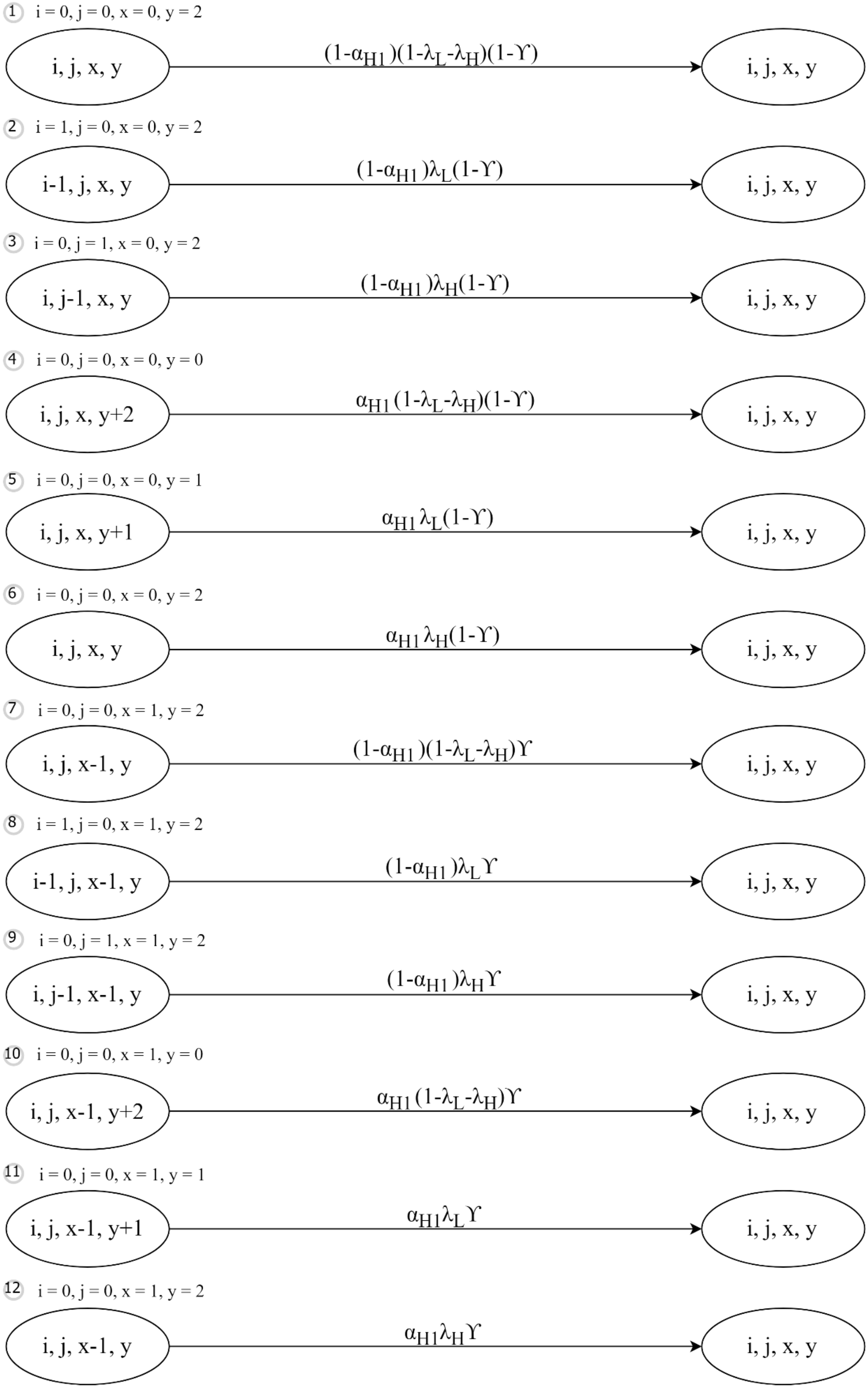
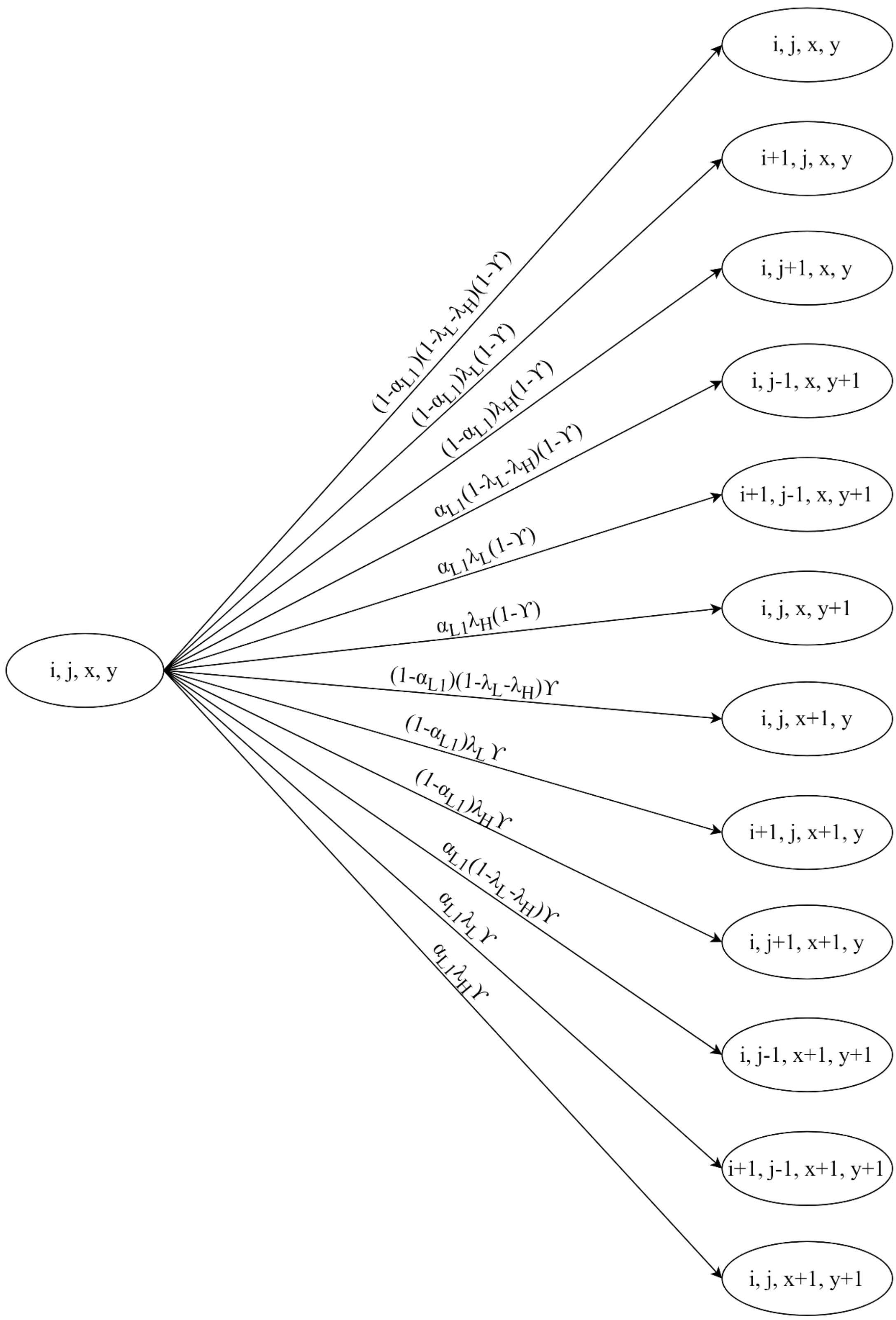


Fig 3. 77: The state diagram for $i = 0, j = 0, x = 0, y = 2$

(4) $i = 0, 1 \leq j \leq \theta, x = 0, y = 1$



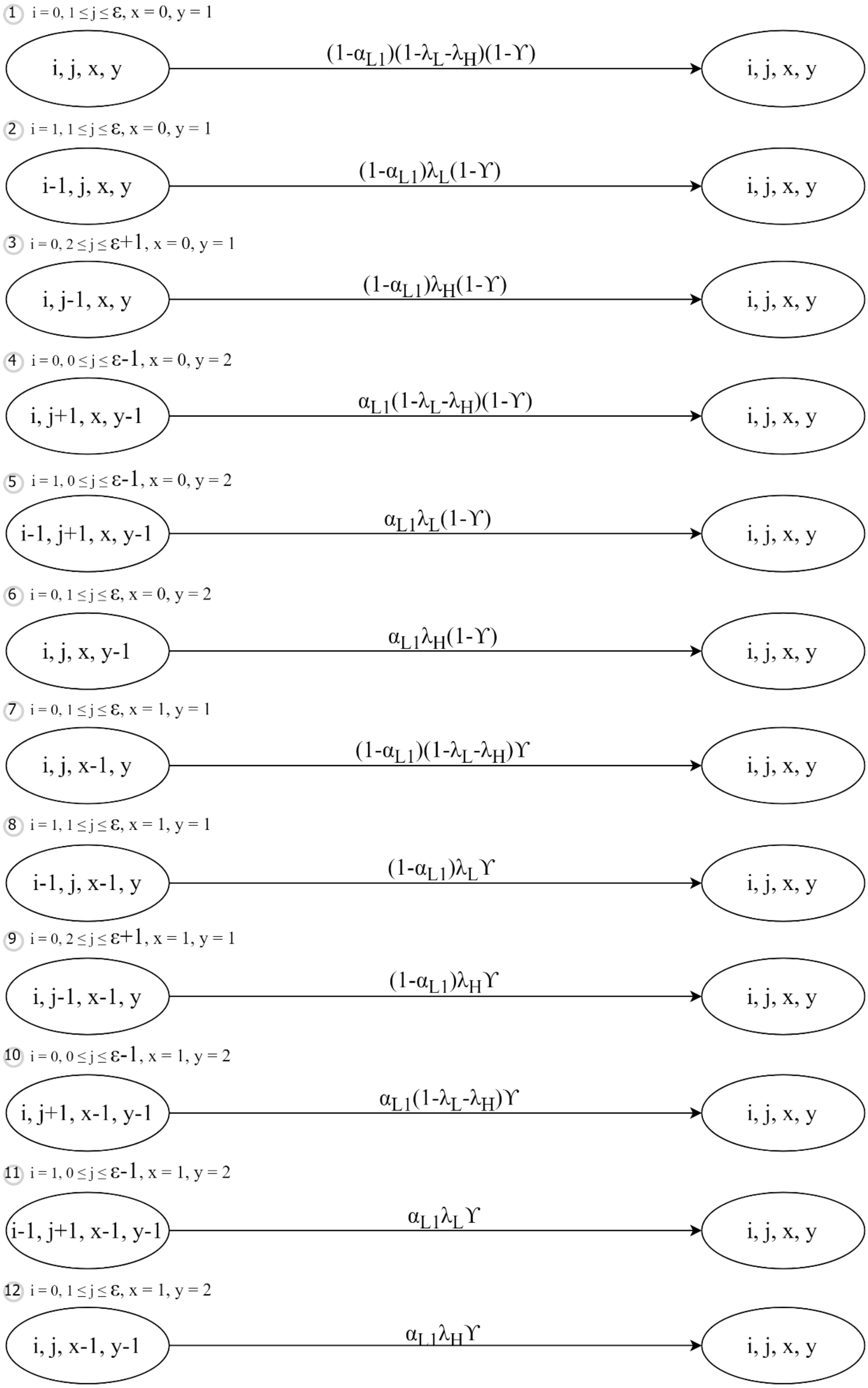
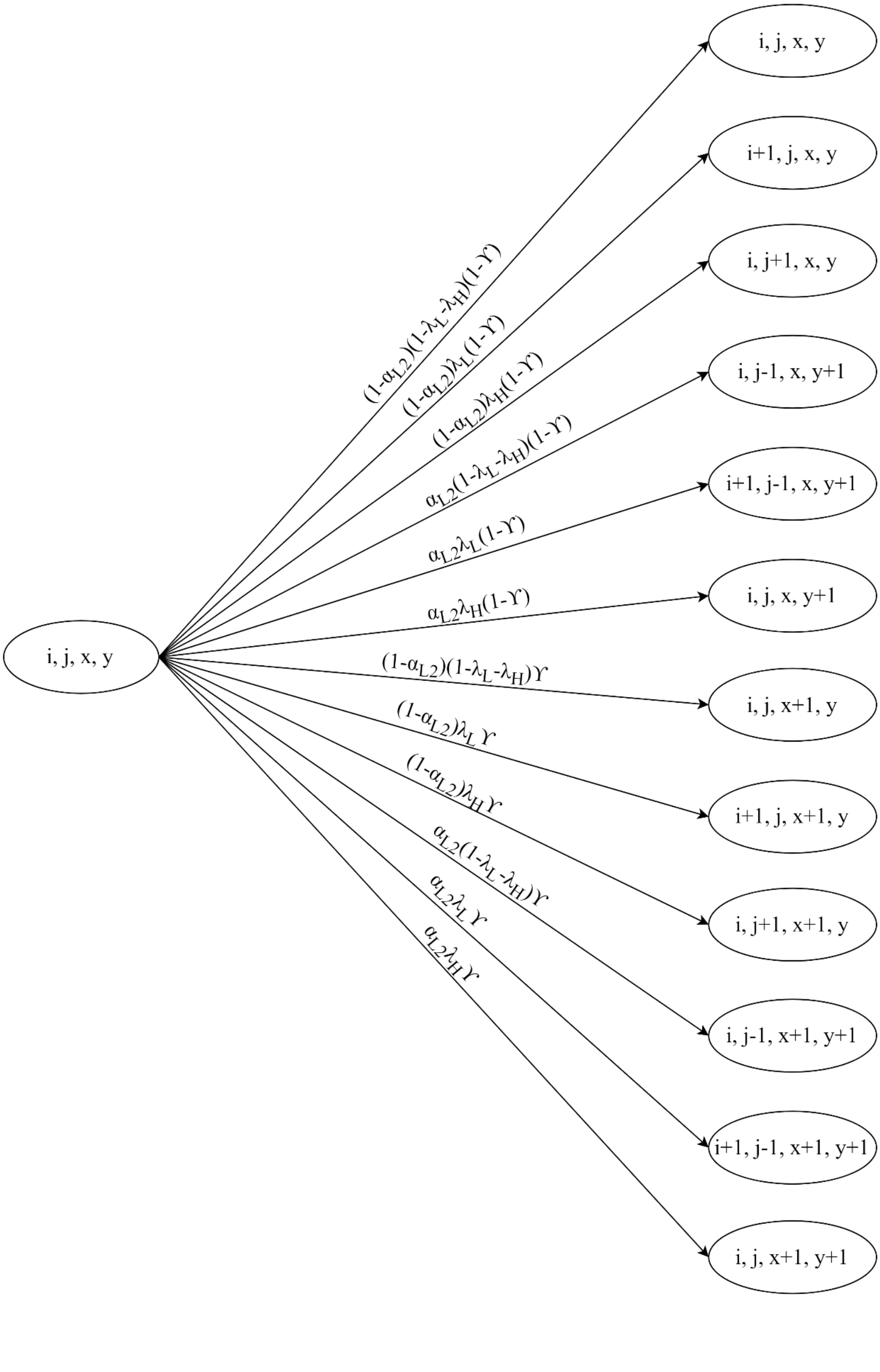


Fig 3. 78: The state diagram for $i = 0, 1 \leq j \leq \theta, x = 0, y = 1$

(5) $i = 0, \theta < j \leq K-2, x = 0, y = 1$



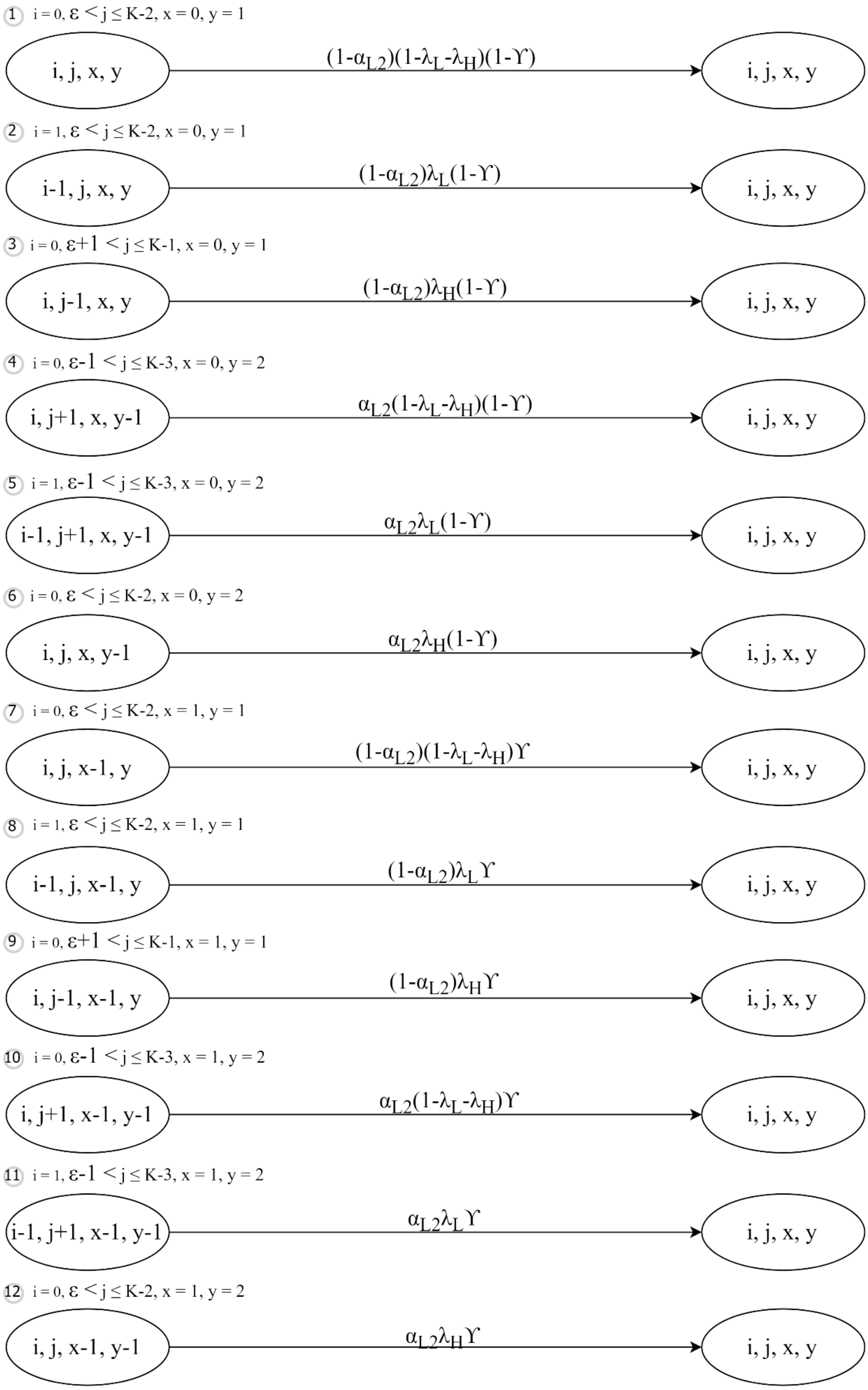
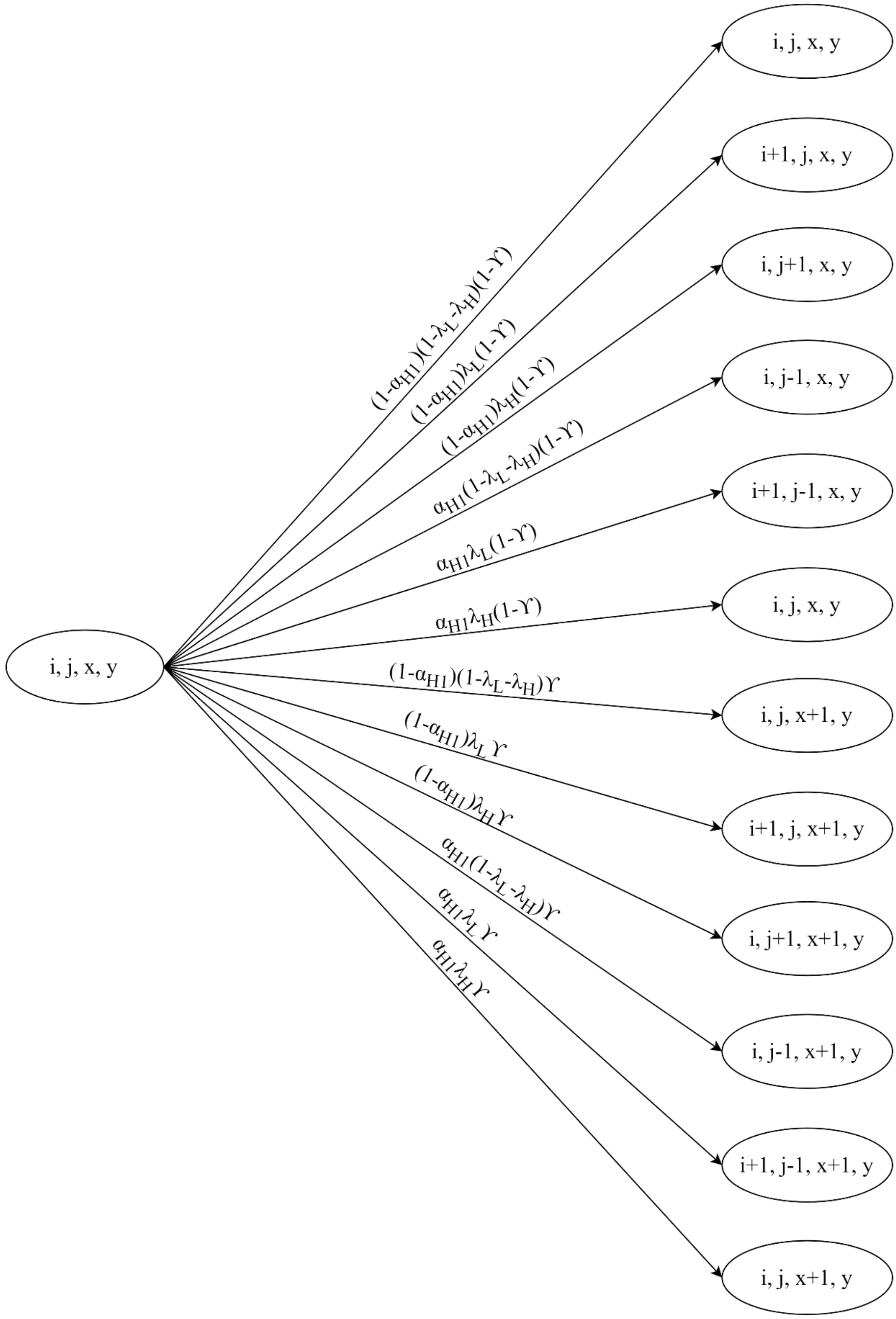


Fig 3. 79: The state diagram for $i = 0, \theta < j \leq K - 2, x = 0, y = 1$

(6) $i = 0, 1 \leq j \leq \theta, x = 0, y = 2$



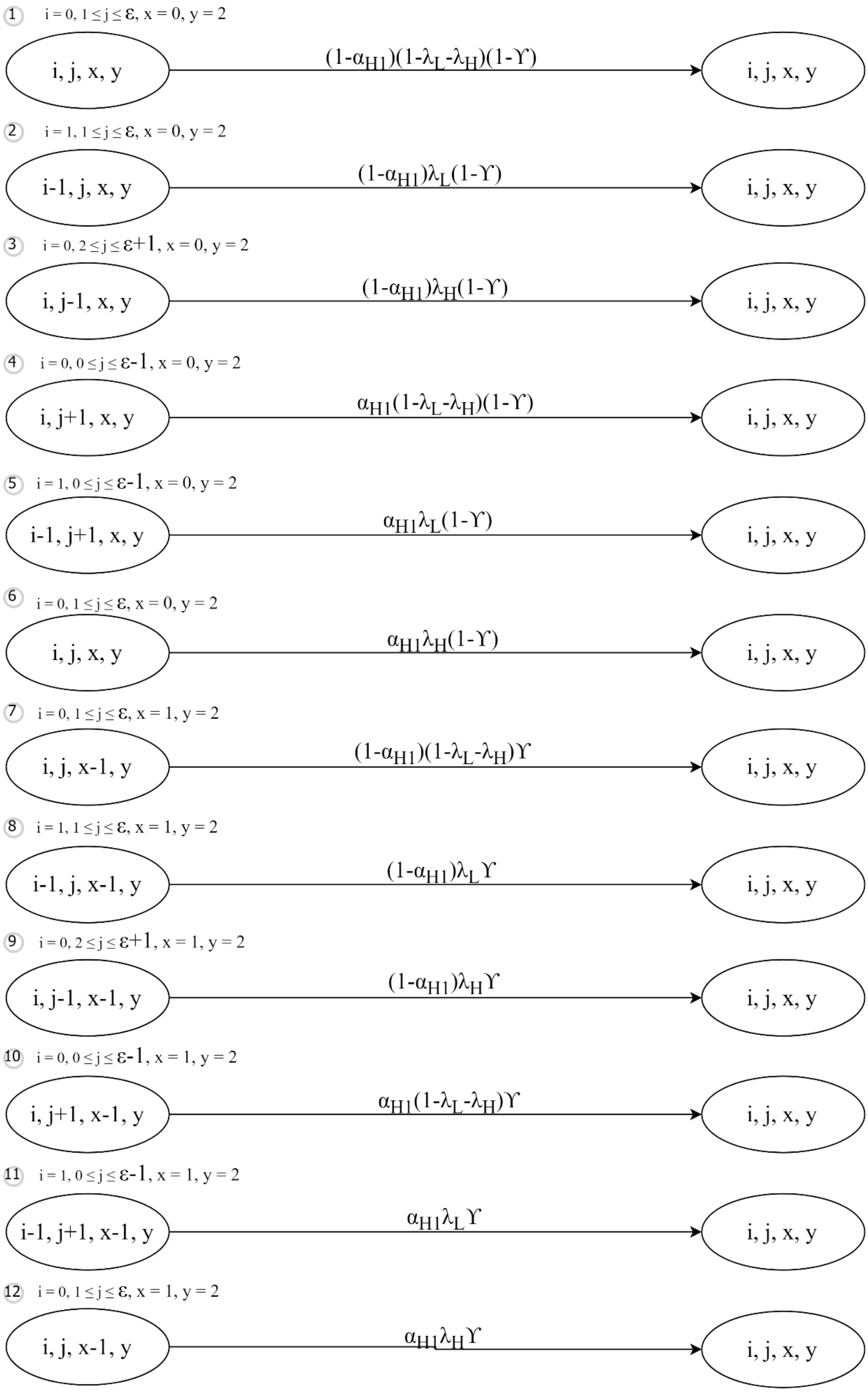
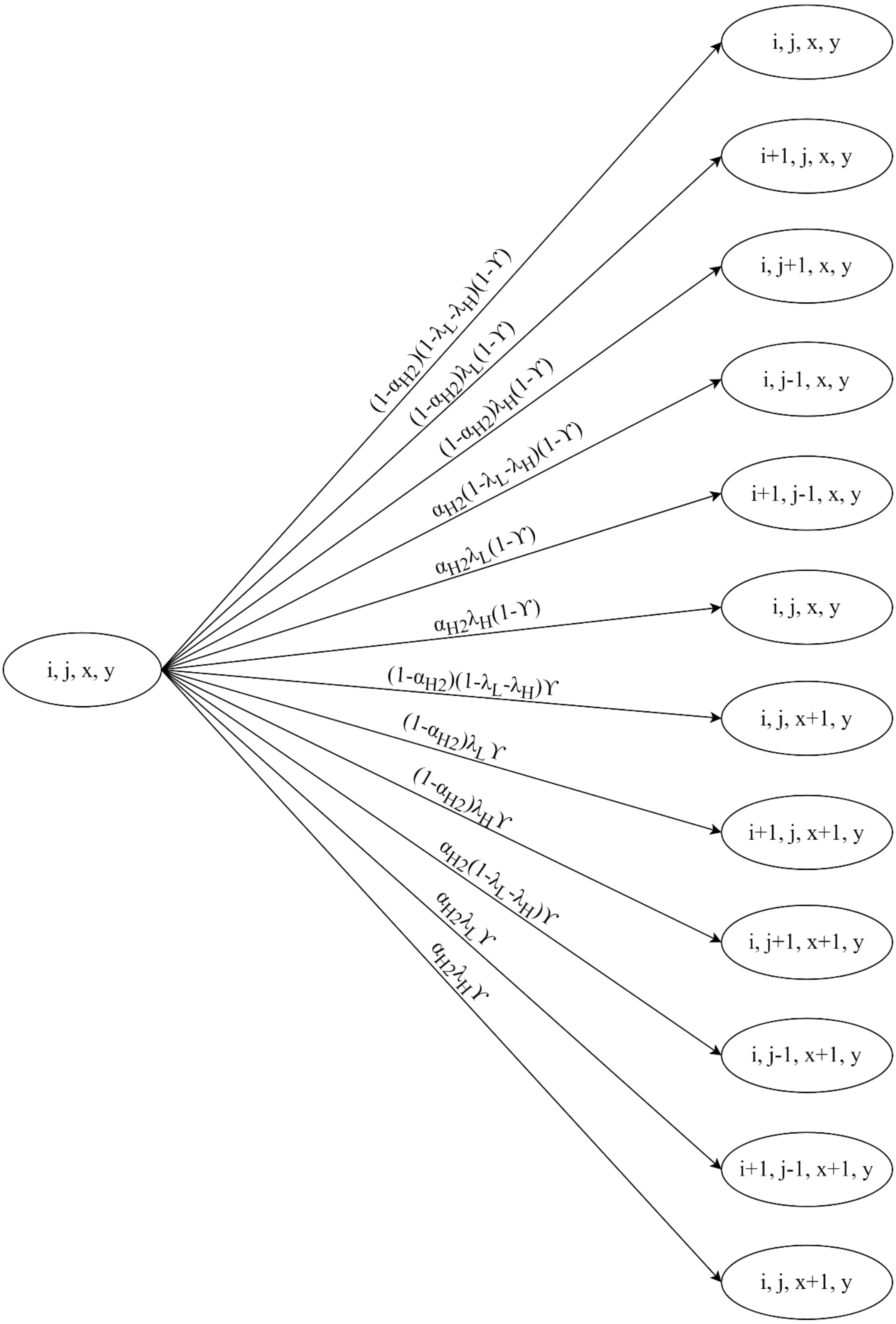


Fig 3. 80: The state diagram for $i = 0, 1 \leq j \leq \theta, x = 0, y = 2$

(7) $i = 0, \theta < j \leq K - 2, x = 0, y = 2$



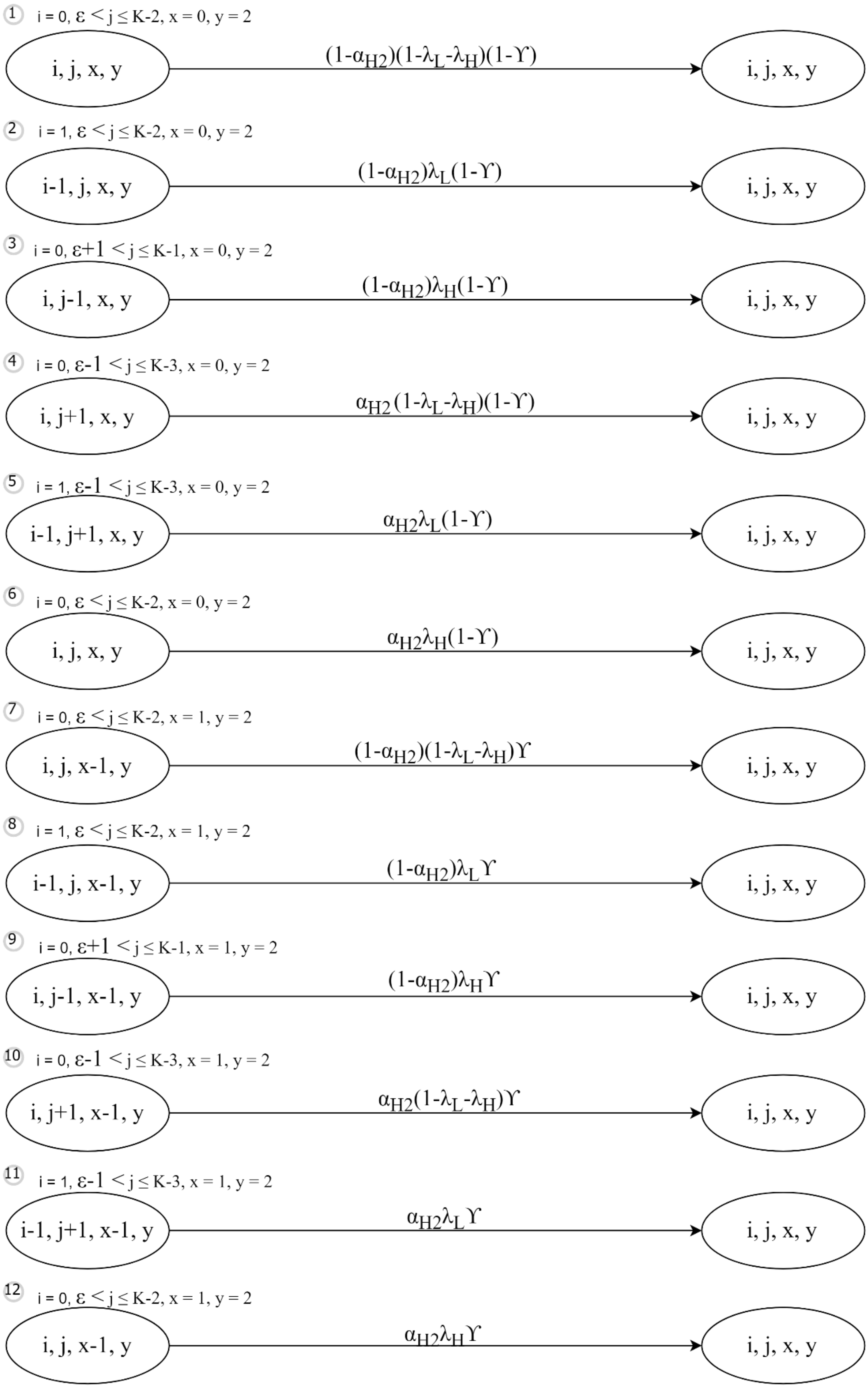
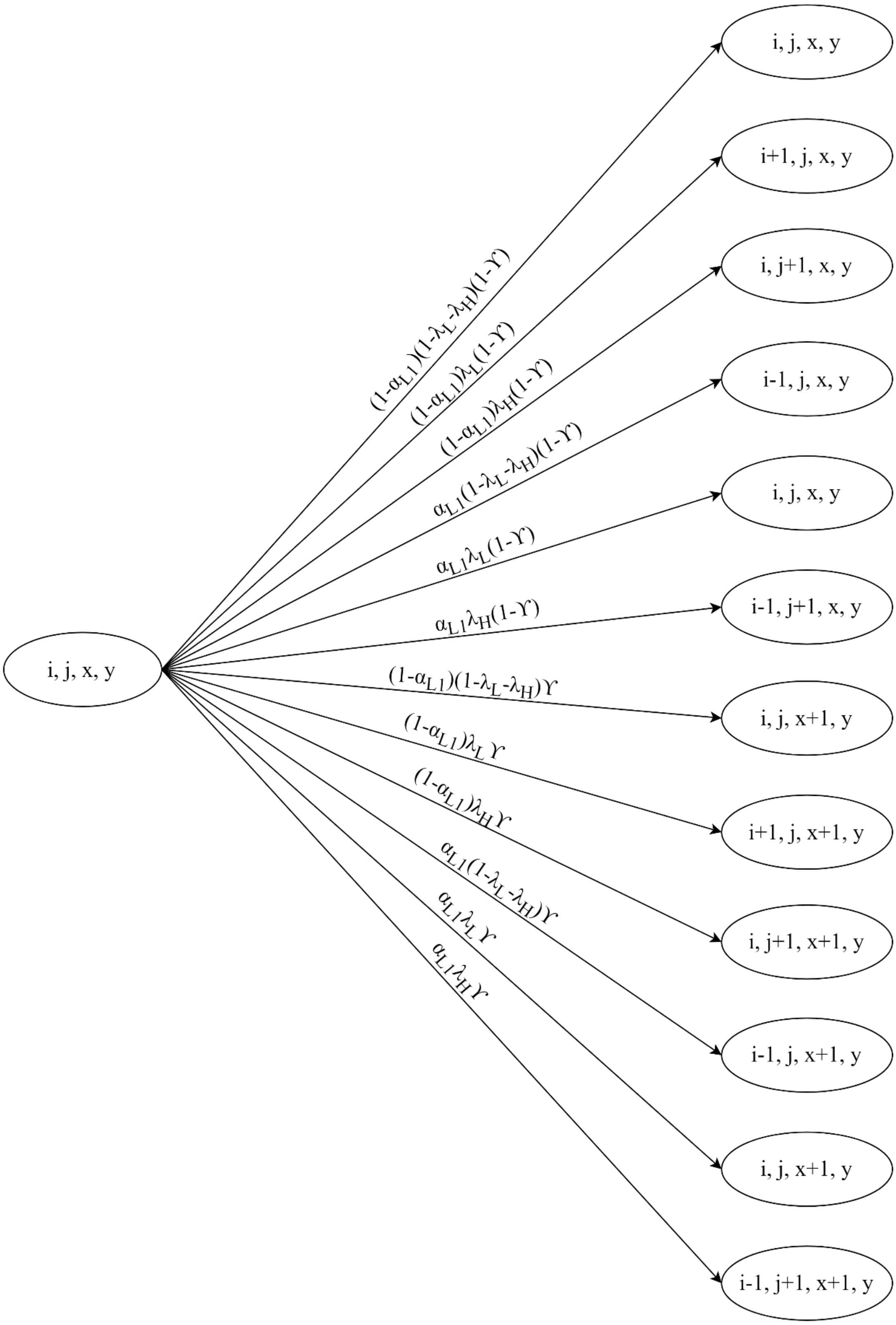


Fig 3. 81: The state diagram for $i = 0, \theta < j \leq K-2, x = 0, y = 2$

(8) $1 \leq i \leq \theta, j = 0, x = 0, y = 1$



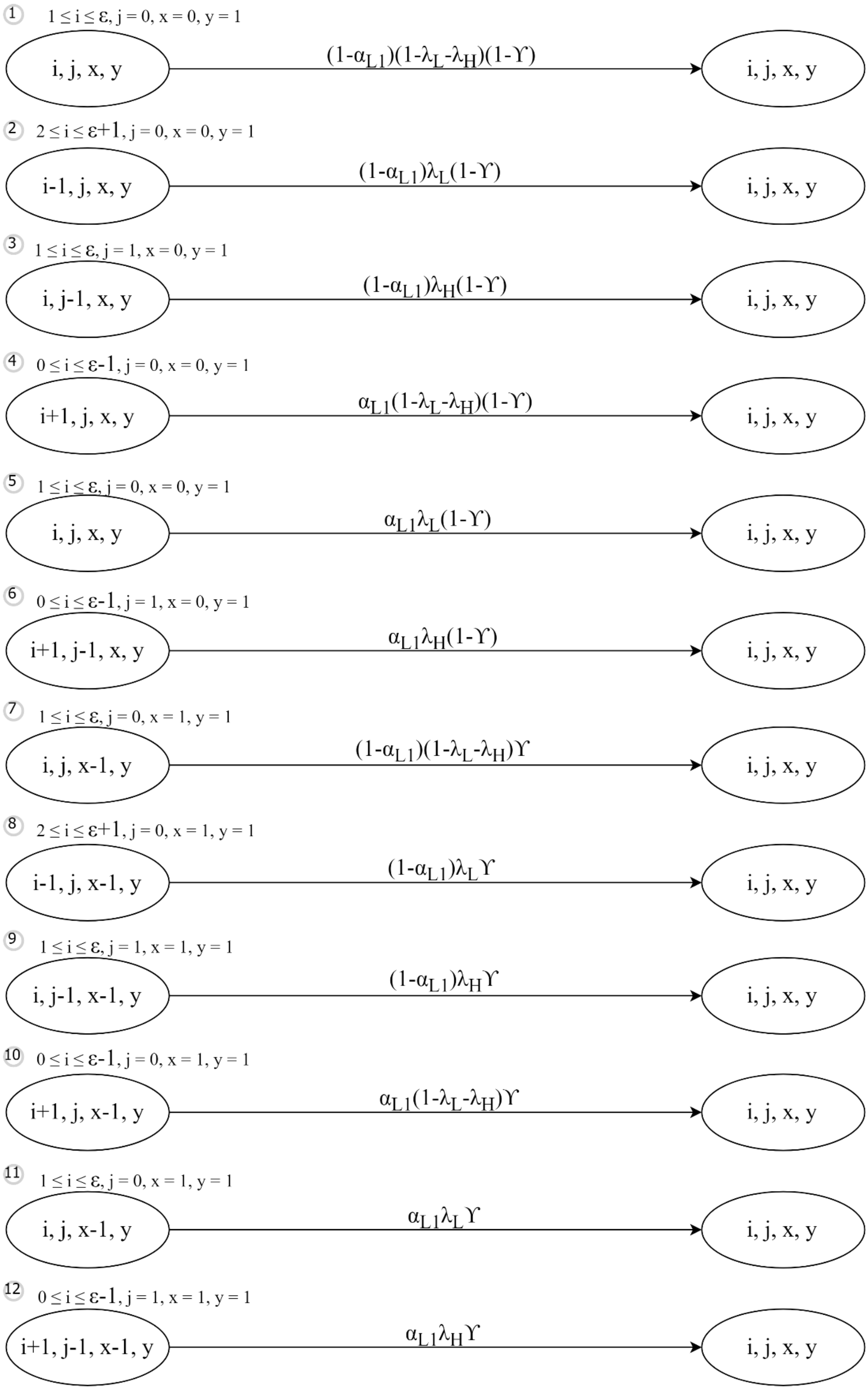
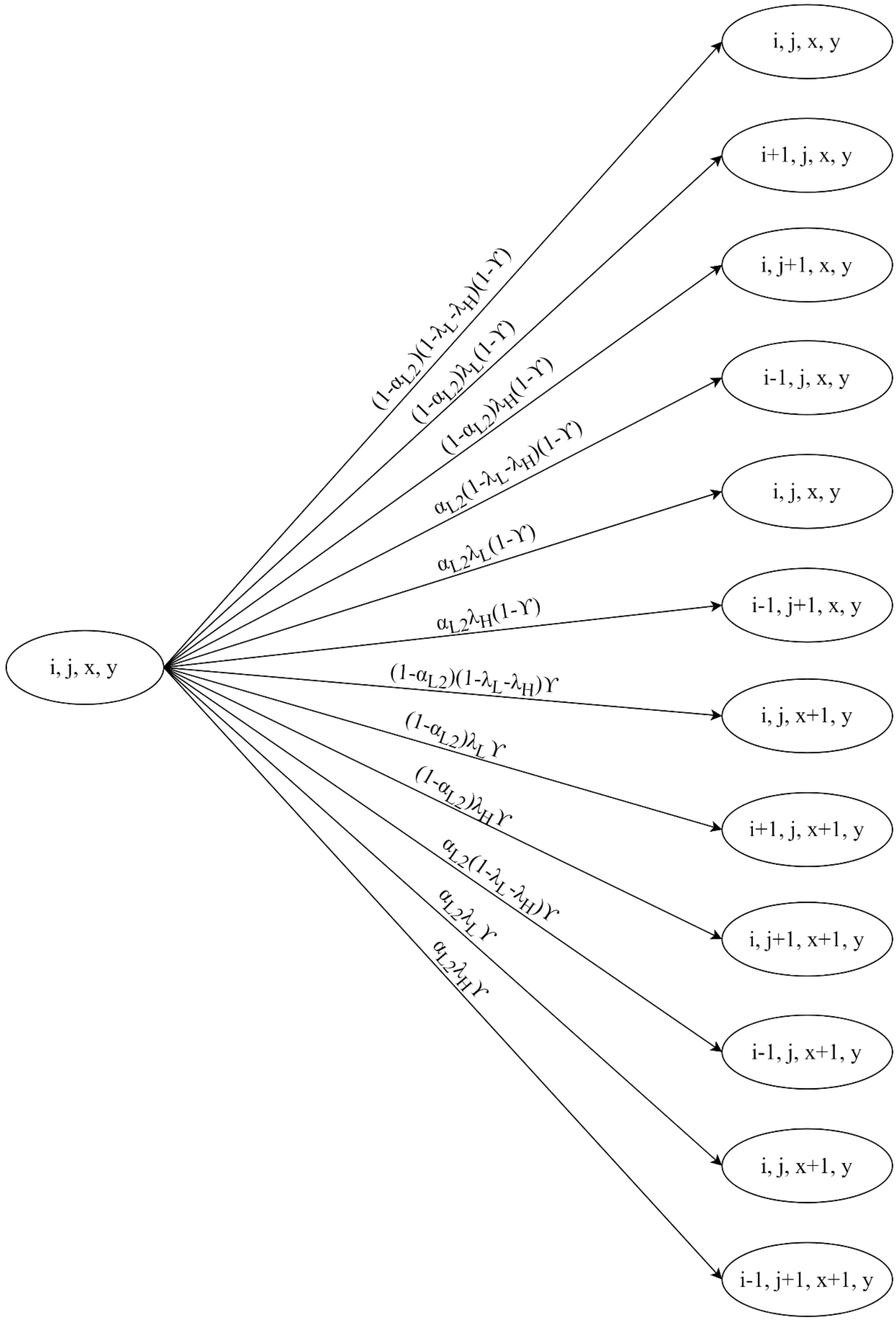


Fig 3. 82: The state diagram for $1 \le i \le \theta, j = 0, x = 0, y = 1$

(9) $\theta < i \leq K-2, j = 0, x = 0, y = 1$



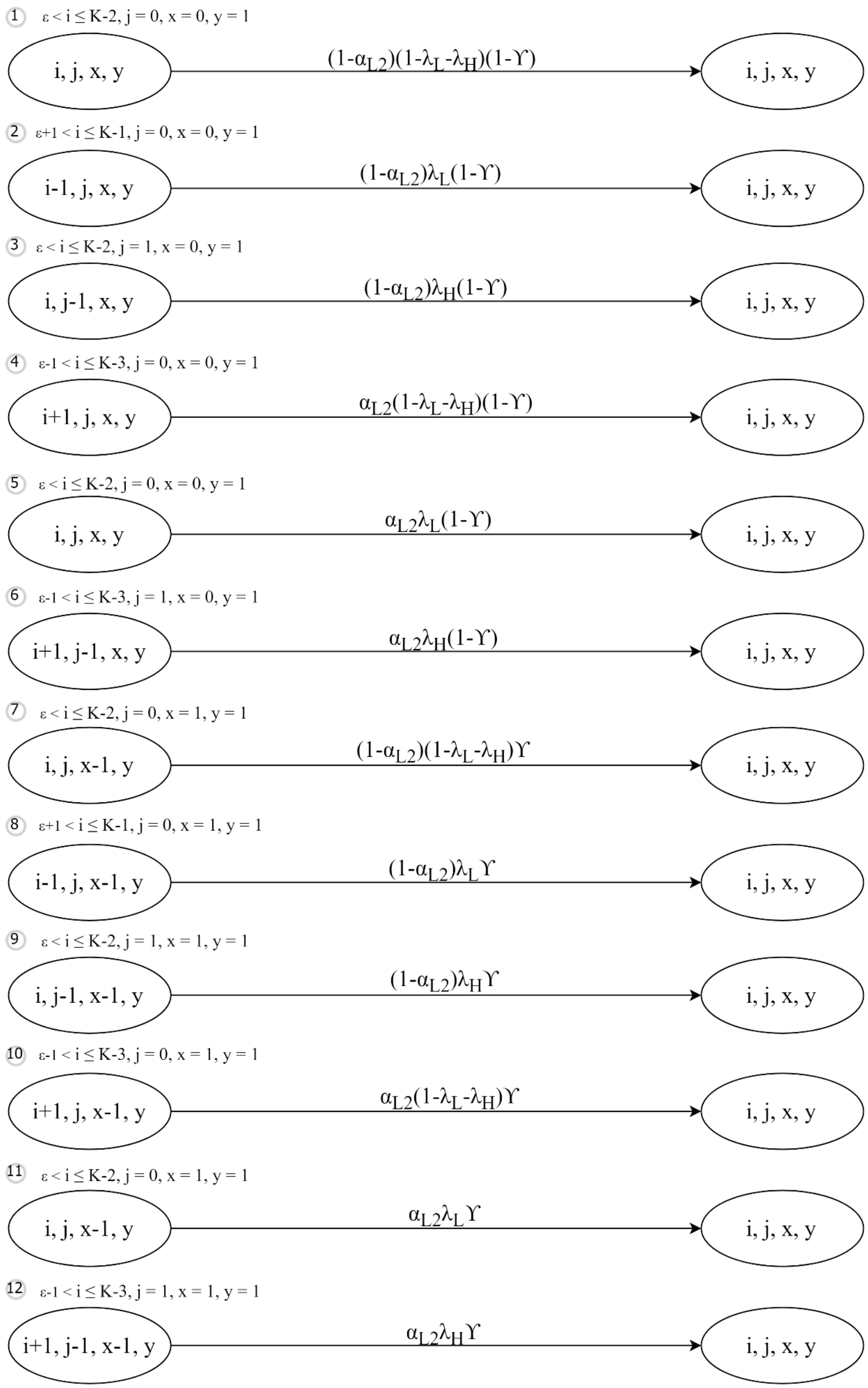
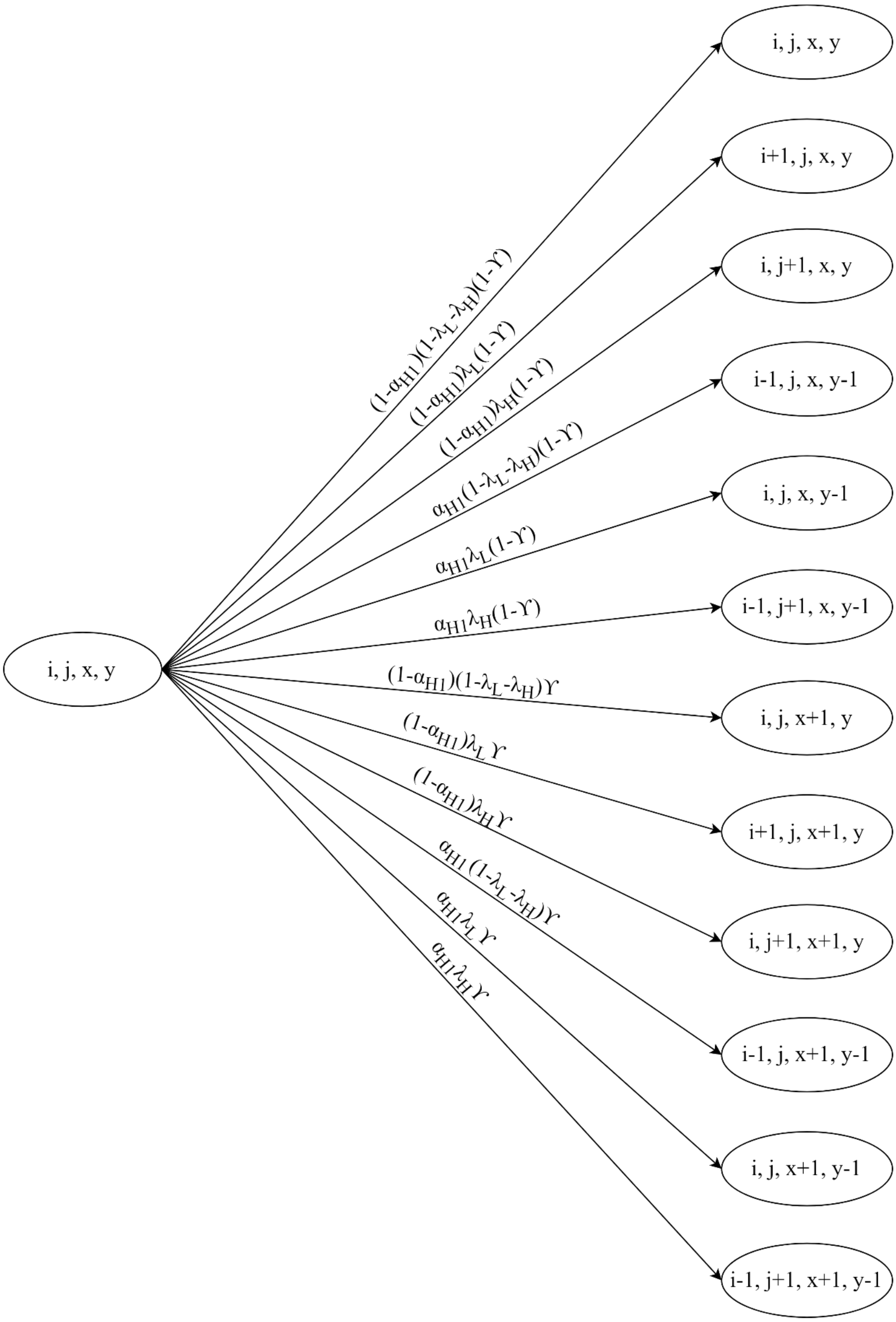


Fig 3. 83: The state diagram for $\theta < i \leq K-2, j = 0, x = 0, y = 1$

(10) $1 \leq i \leq \theta, j = 0, x = 0, y = 2$



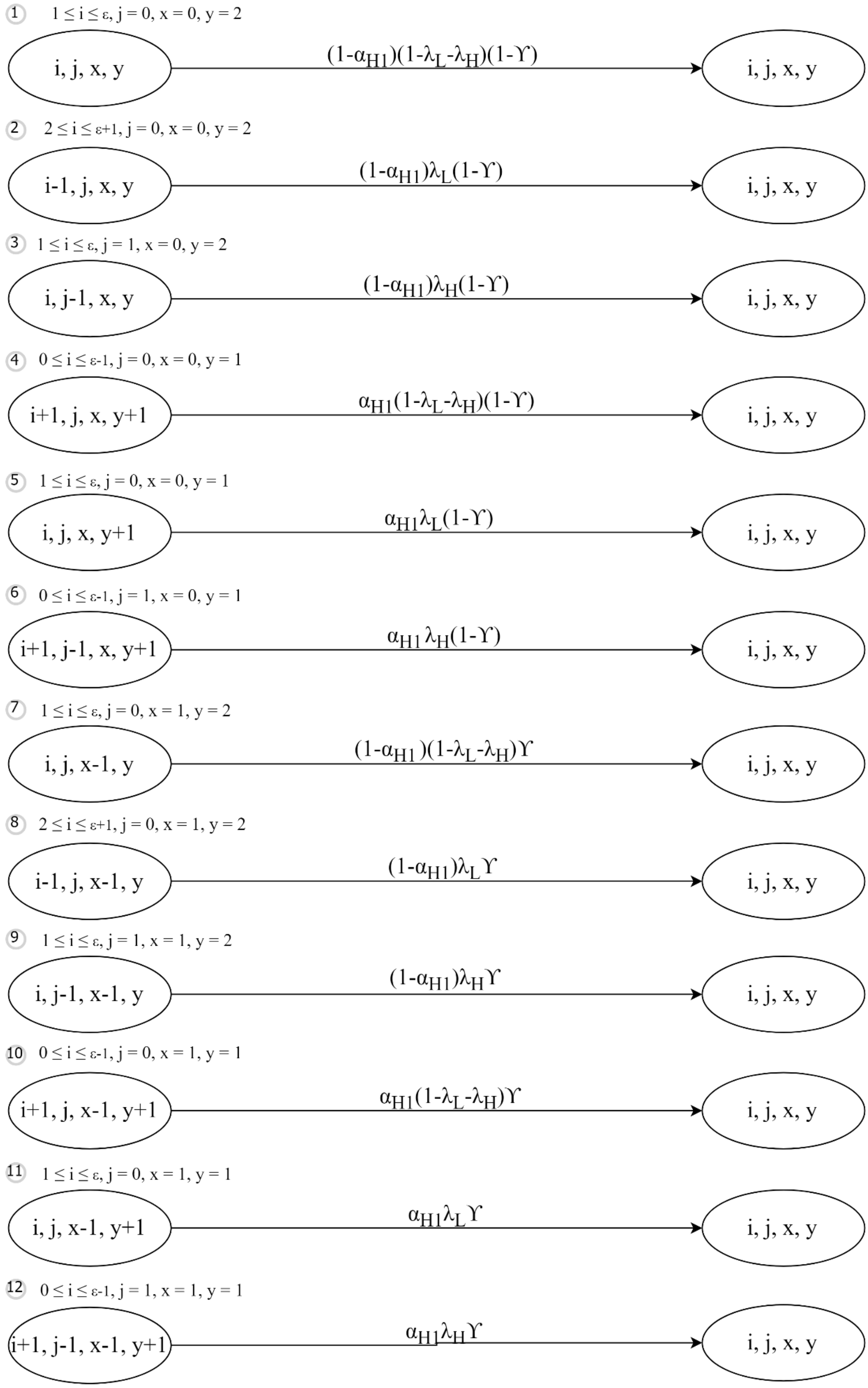
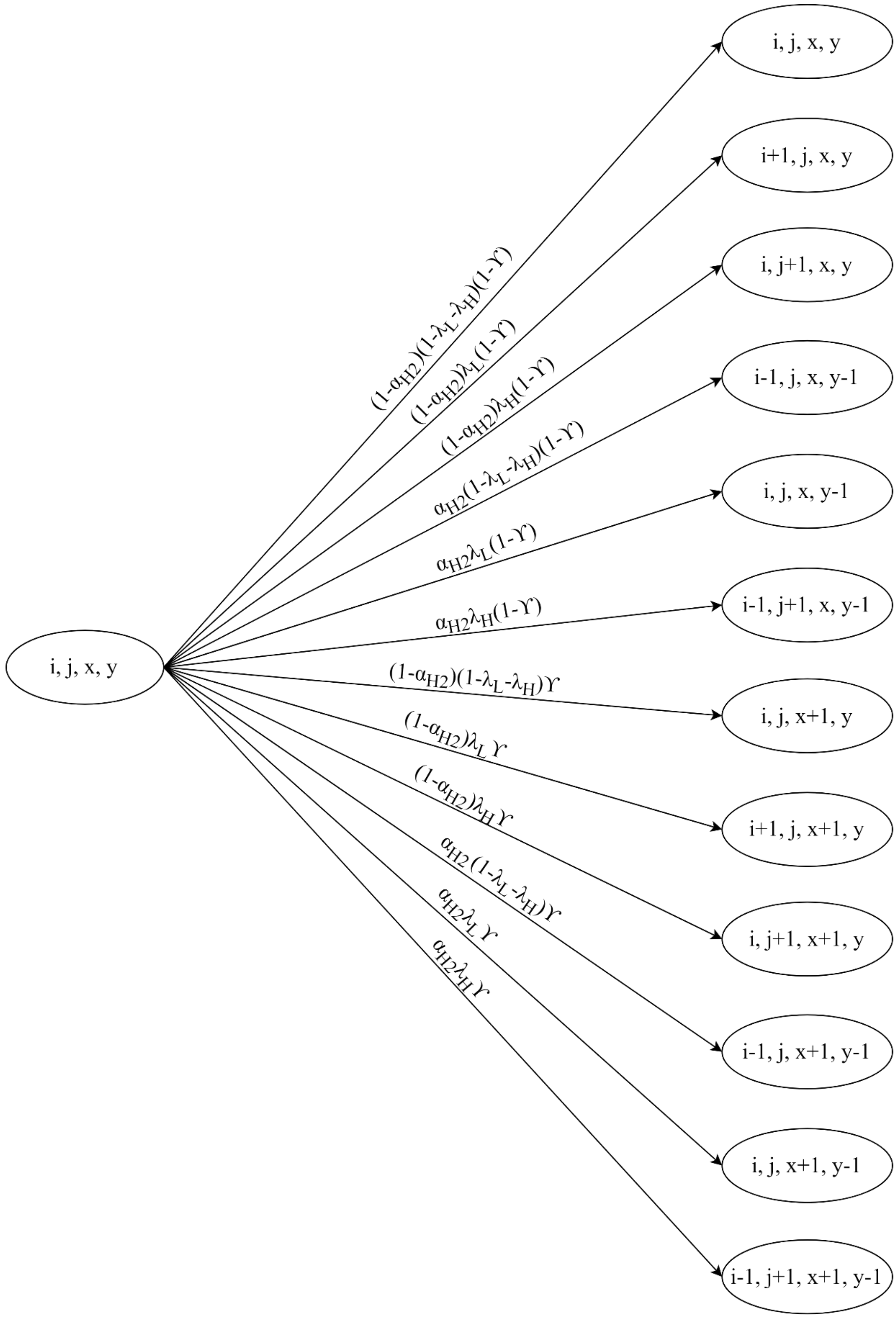


Fig 3. 84: The state diagram for $1 \le i \le \theta, j = 0, x = 0, y = 2$

(11) $\theta < i \leq K-2, j=0, x=0, y=2$



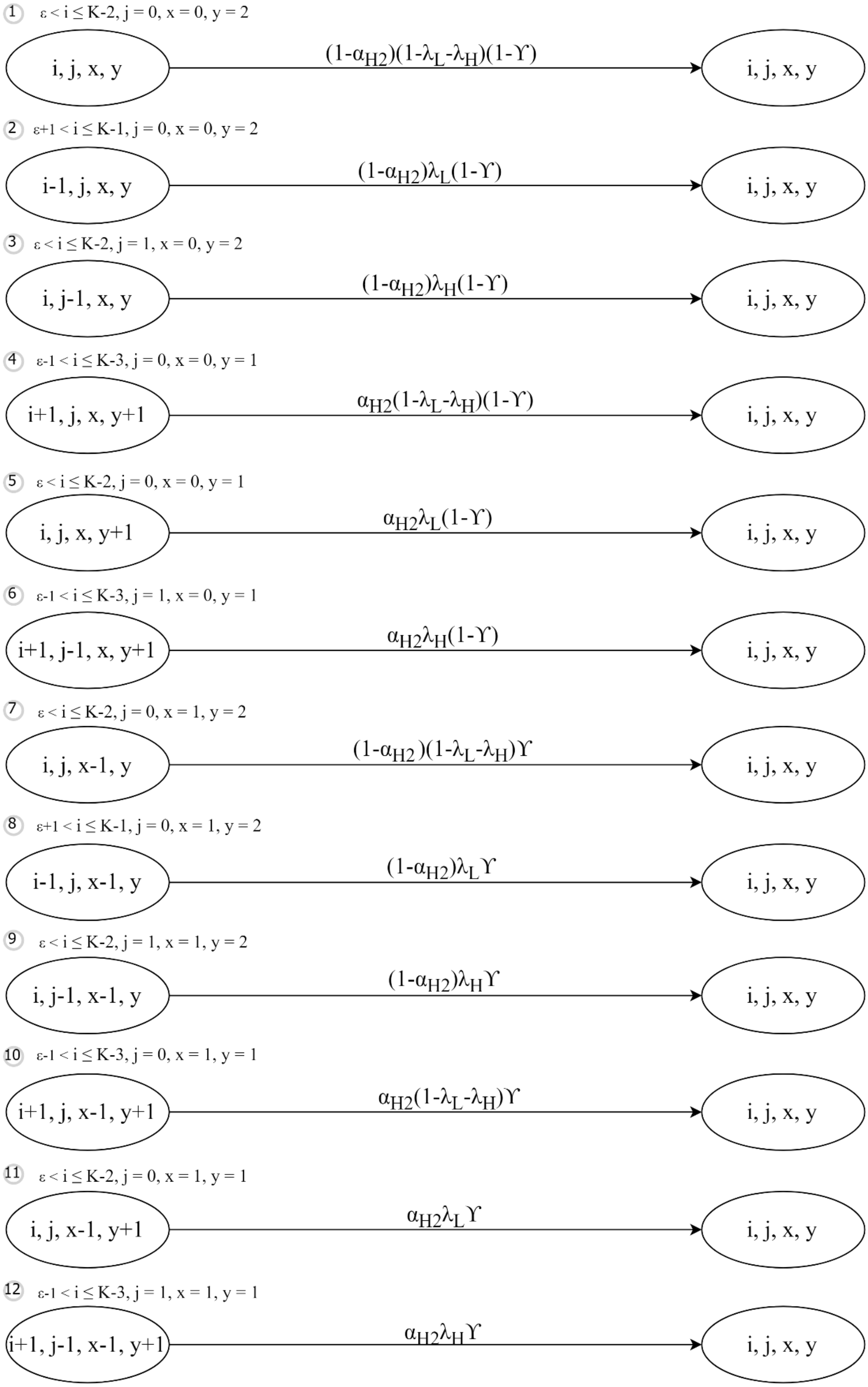
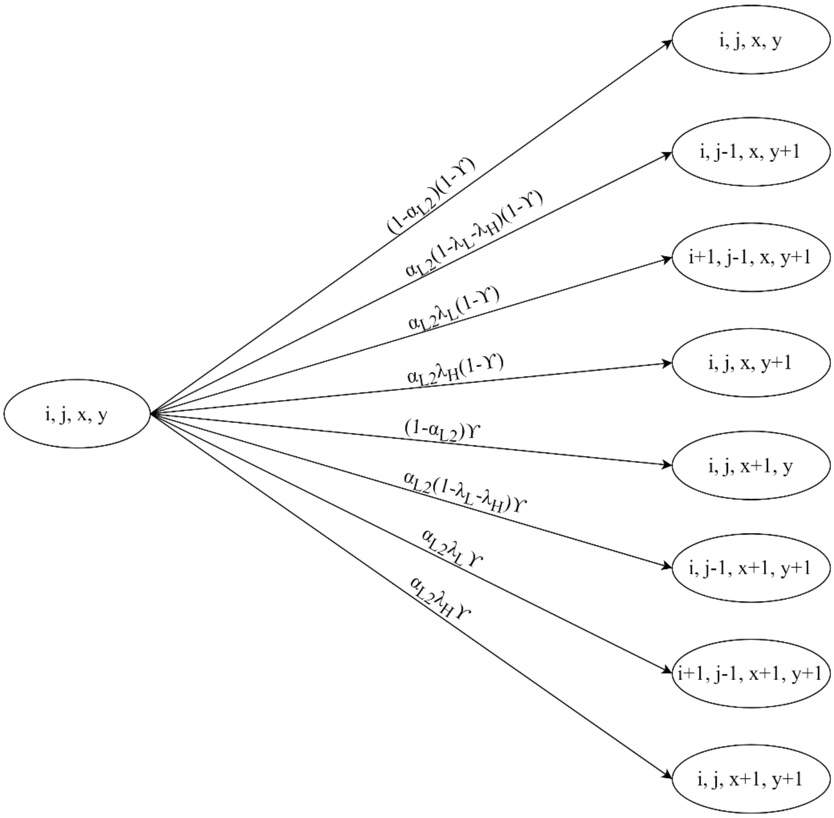


Fig 3. 85: The state diagram for $\varepsilon < i \leq K-2, j = 0, x = 0, y = 2$

(12) $i = 0, j = K-1, x = 0, y = 1$



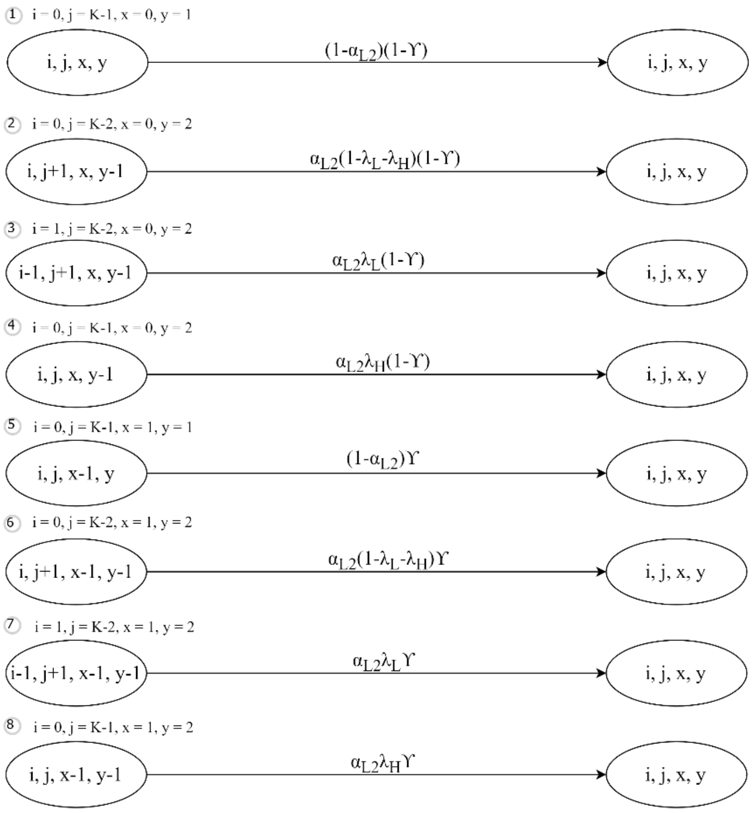


Fig 3. 86: The state diagram for $i = 0, j = K-1, x = 0, y = 1$

(13) $i = 0, j = K-1, x = 0, y = 2$

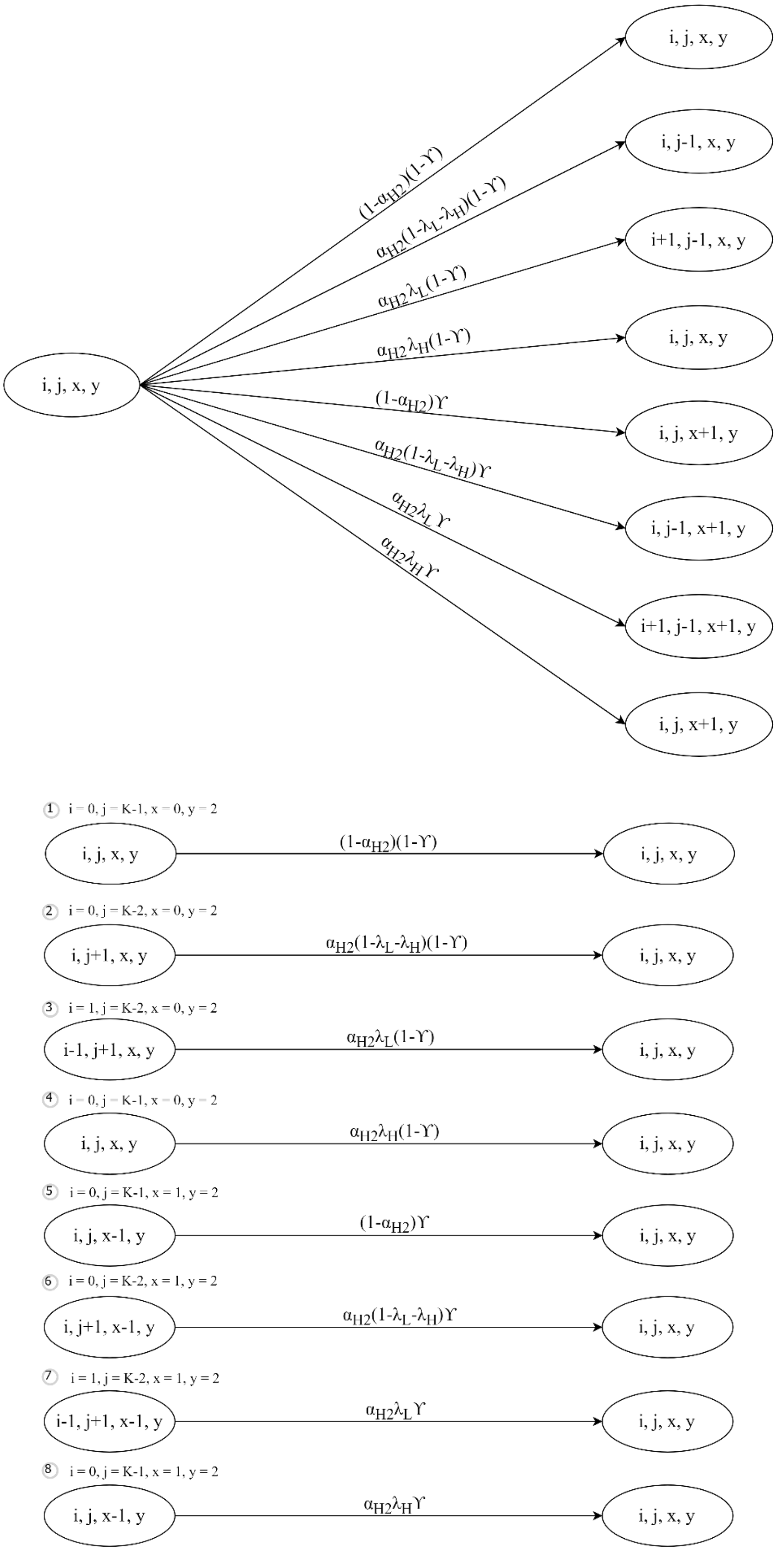
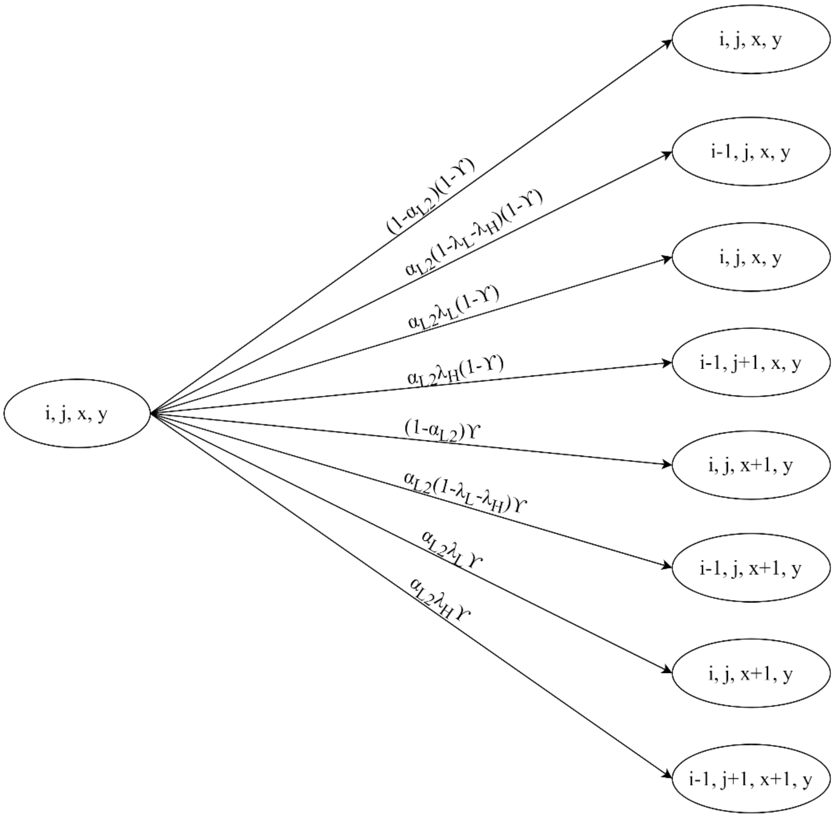


Fig 3. 87: The state diagram for $i = 0, j = K-1, x = 0, y = 2$

(14) $i = K - 1, j = 0, x = 0, y = 1$



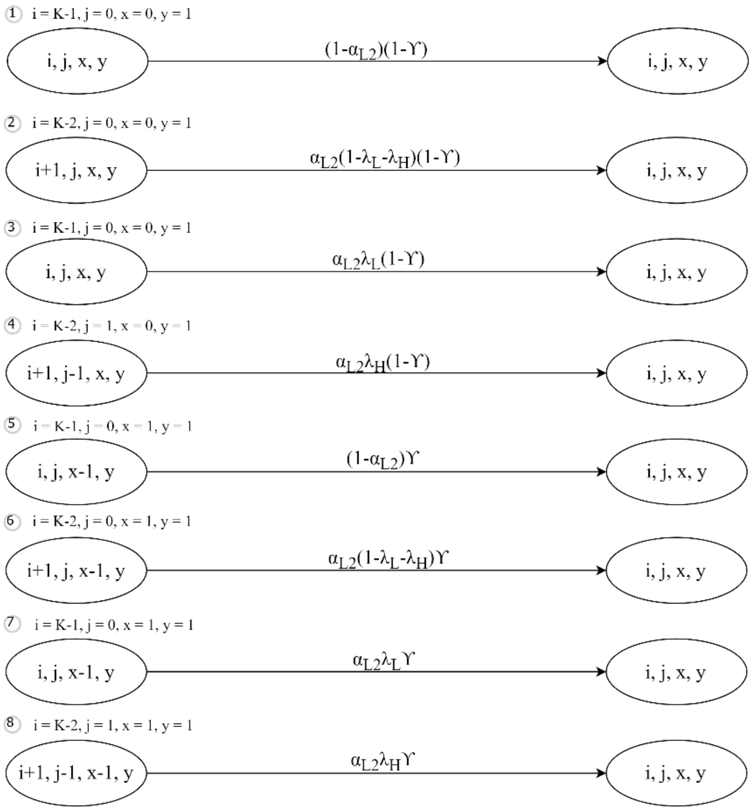
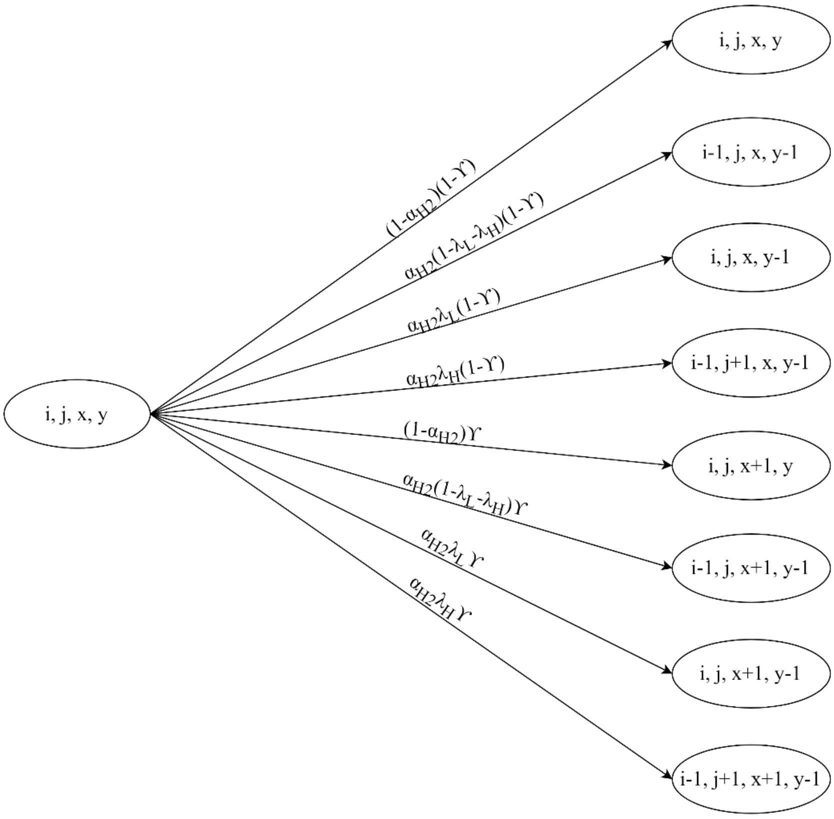


Fig 3. 88: The state diagram for $i = K - 1, j = 0, x = 0, y = 1$

(15) $i = K - 1, j = 0, x = 0, y = 2$



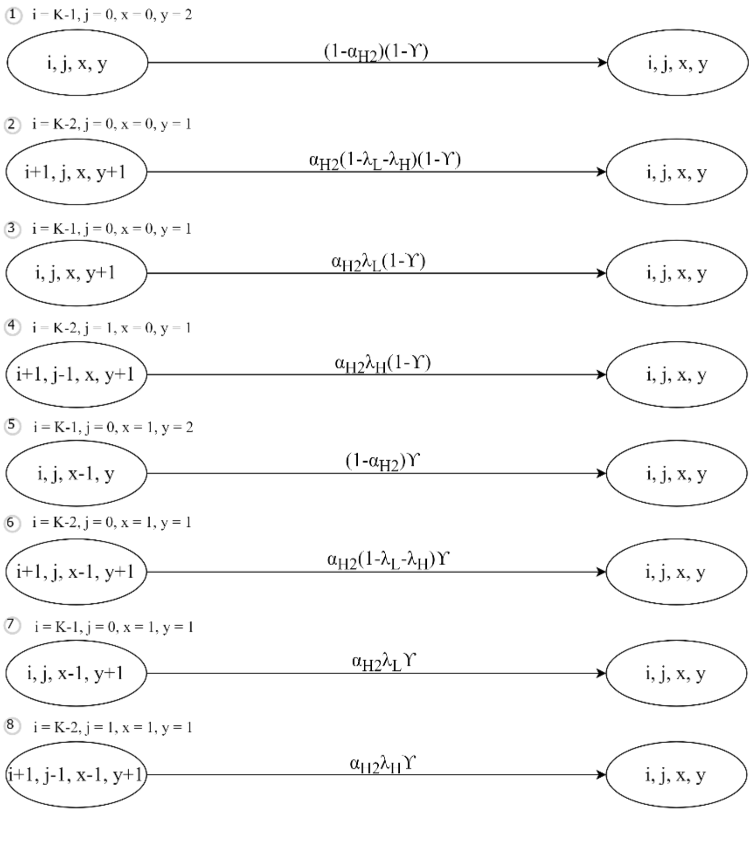
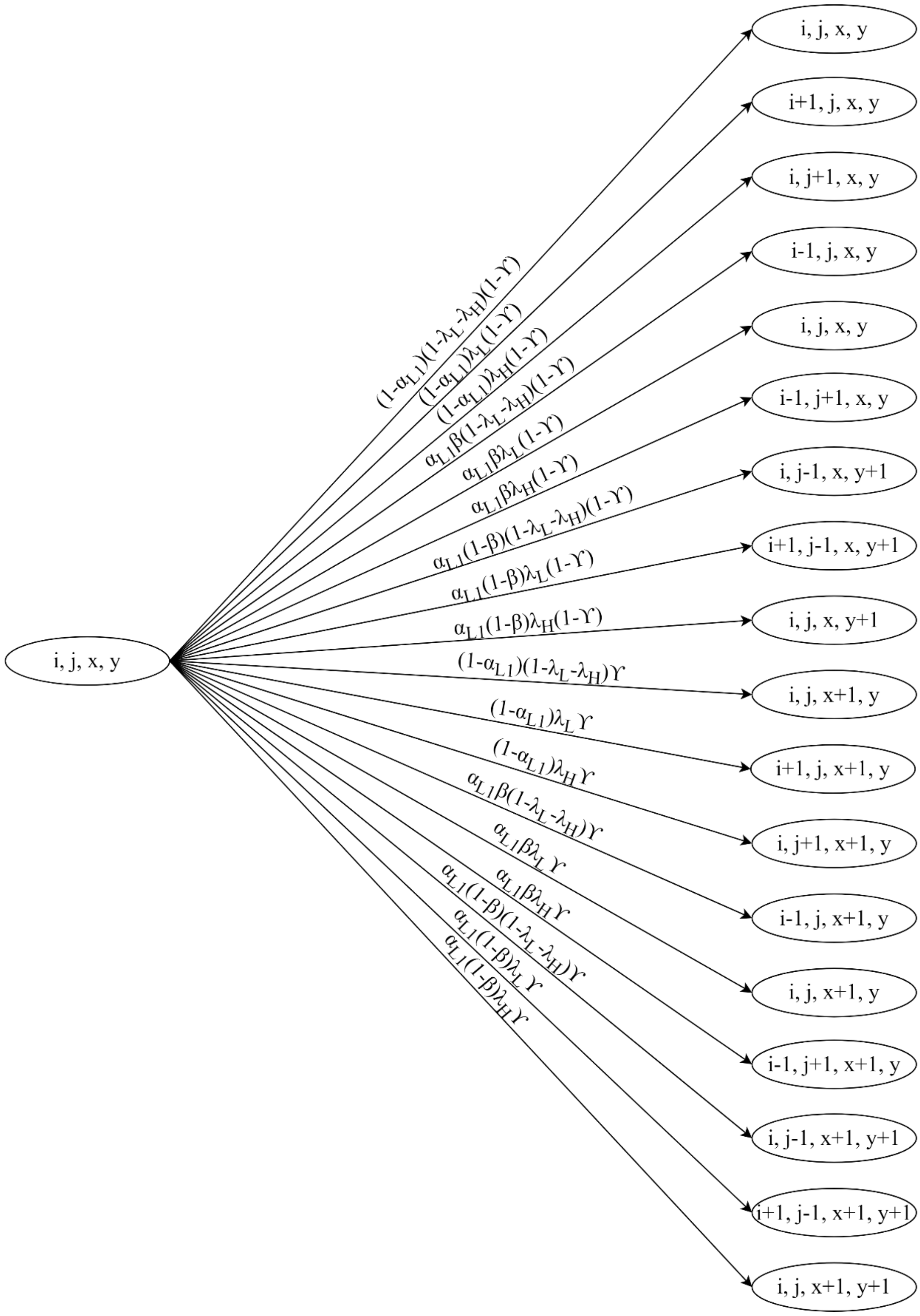


Fig 3. 89: The state diagram for $i = K - 1, j = 0, x = 0, y = 2$

(16) $1 \le i \le \theta, 1 \le j \le \theta - i, x = 0, y = 1$



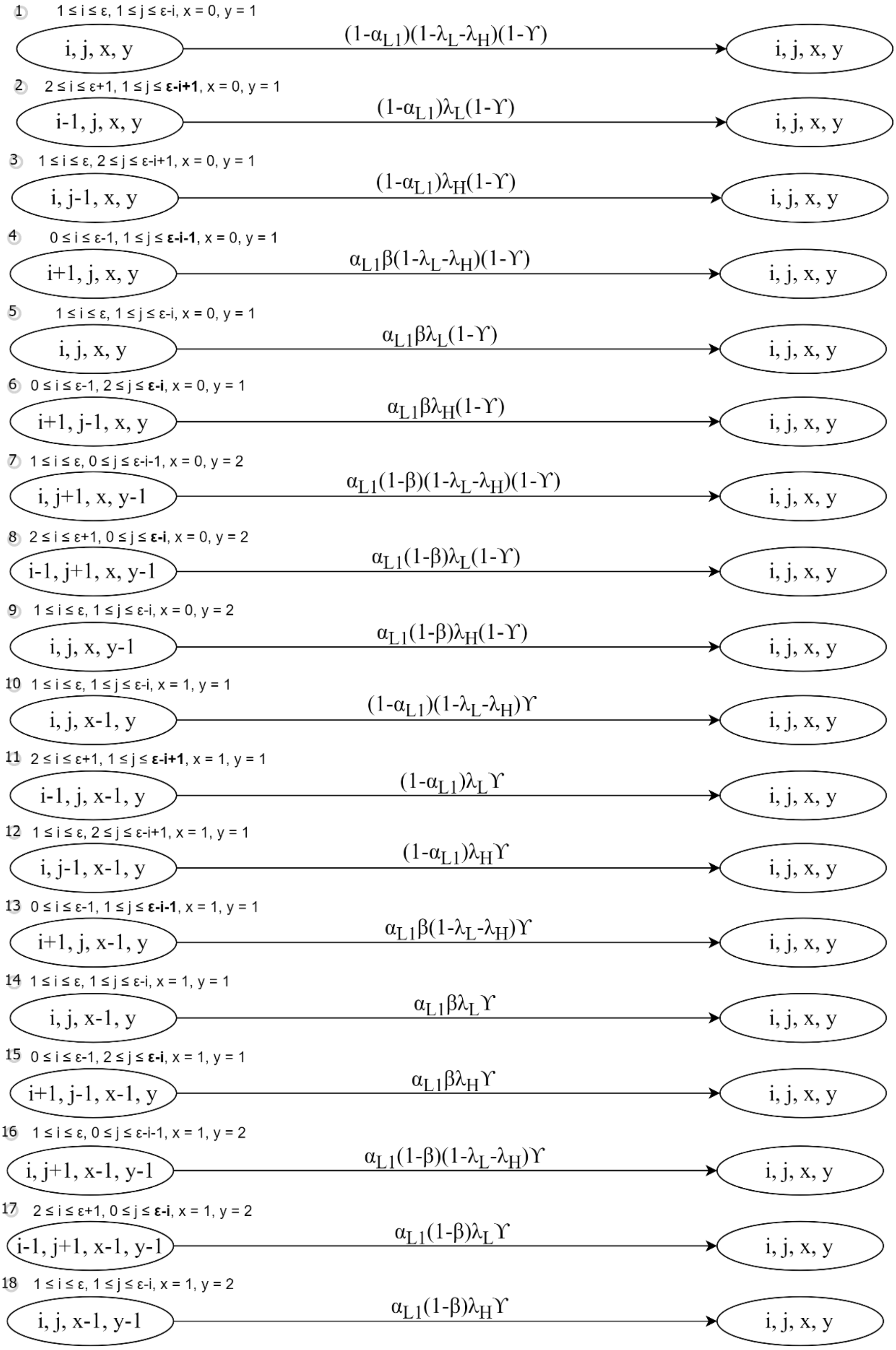
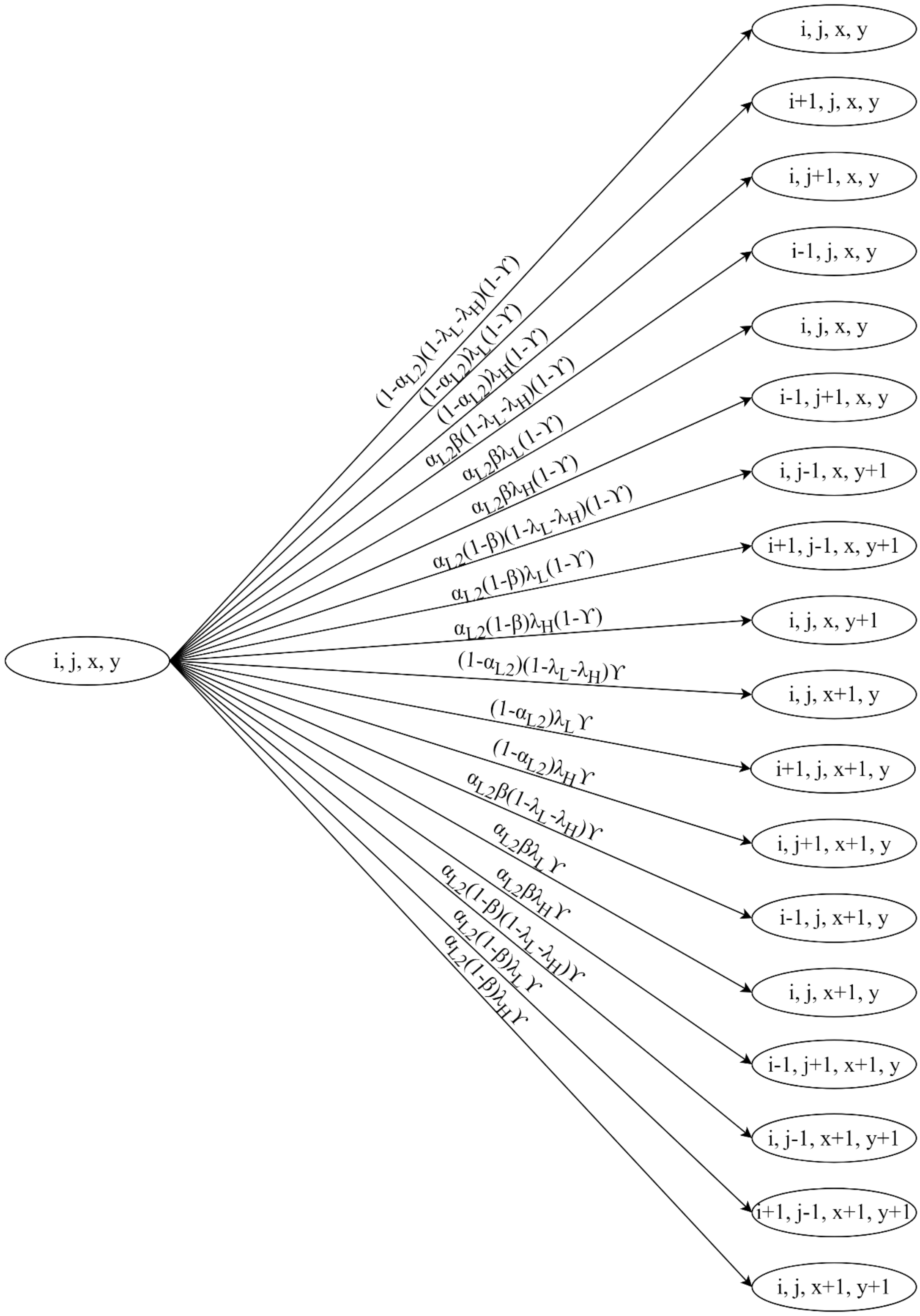


Fig 3. 90: The state diagram for $1 \leq i \leq \theta, 1 \leq j \leq \theta - i, x = 0, y = 1$

$(17) 1 \leq i \leq \theta, \theta - i < j < K - i - 1, x = 0, y = 1$



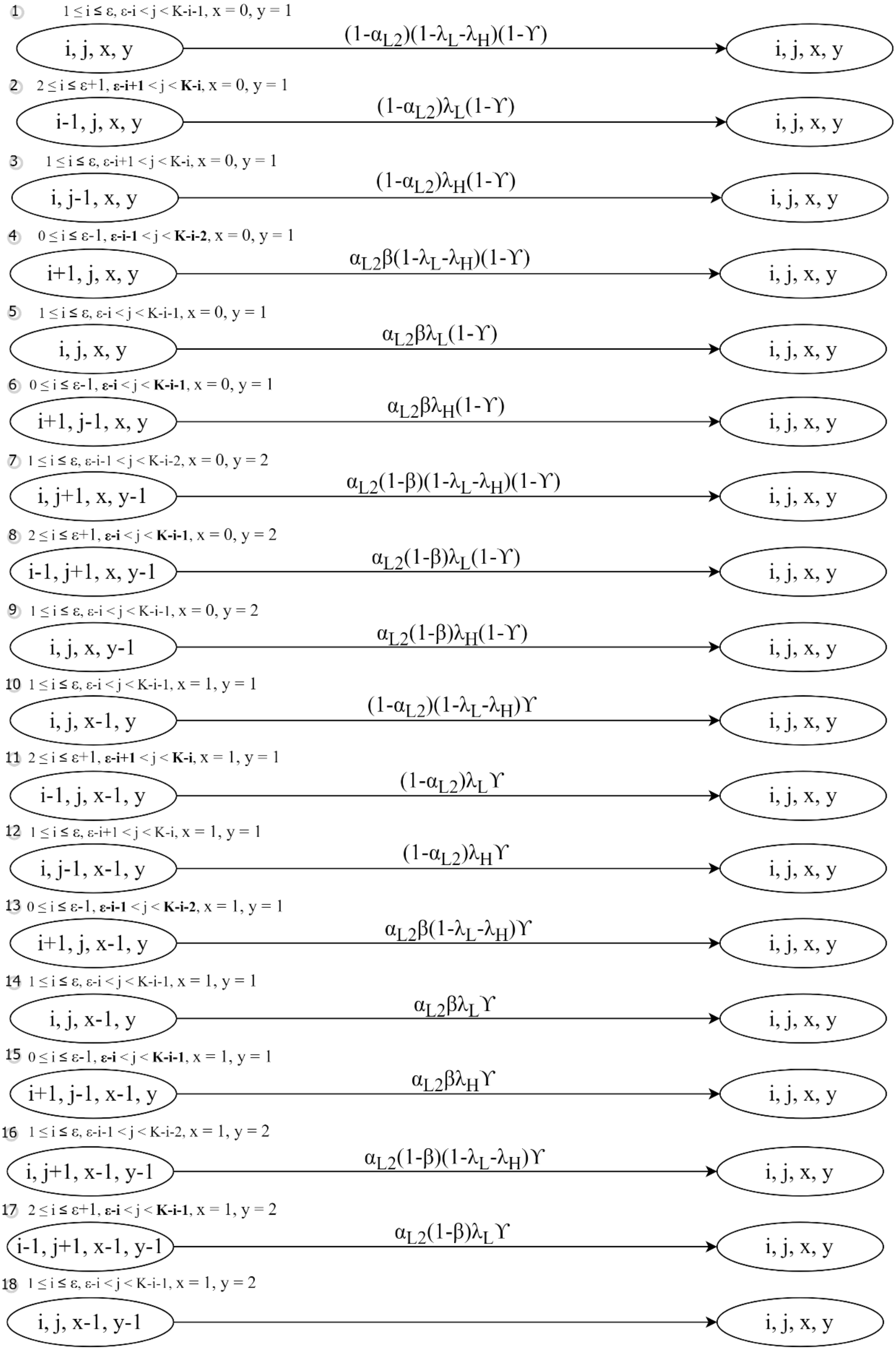
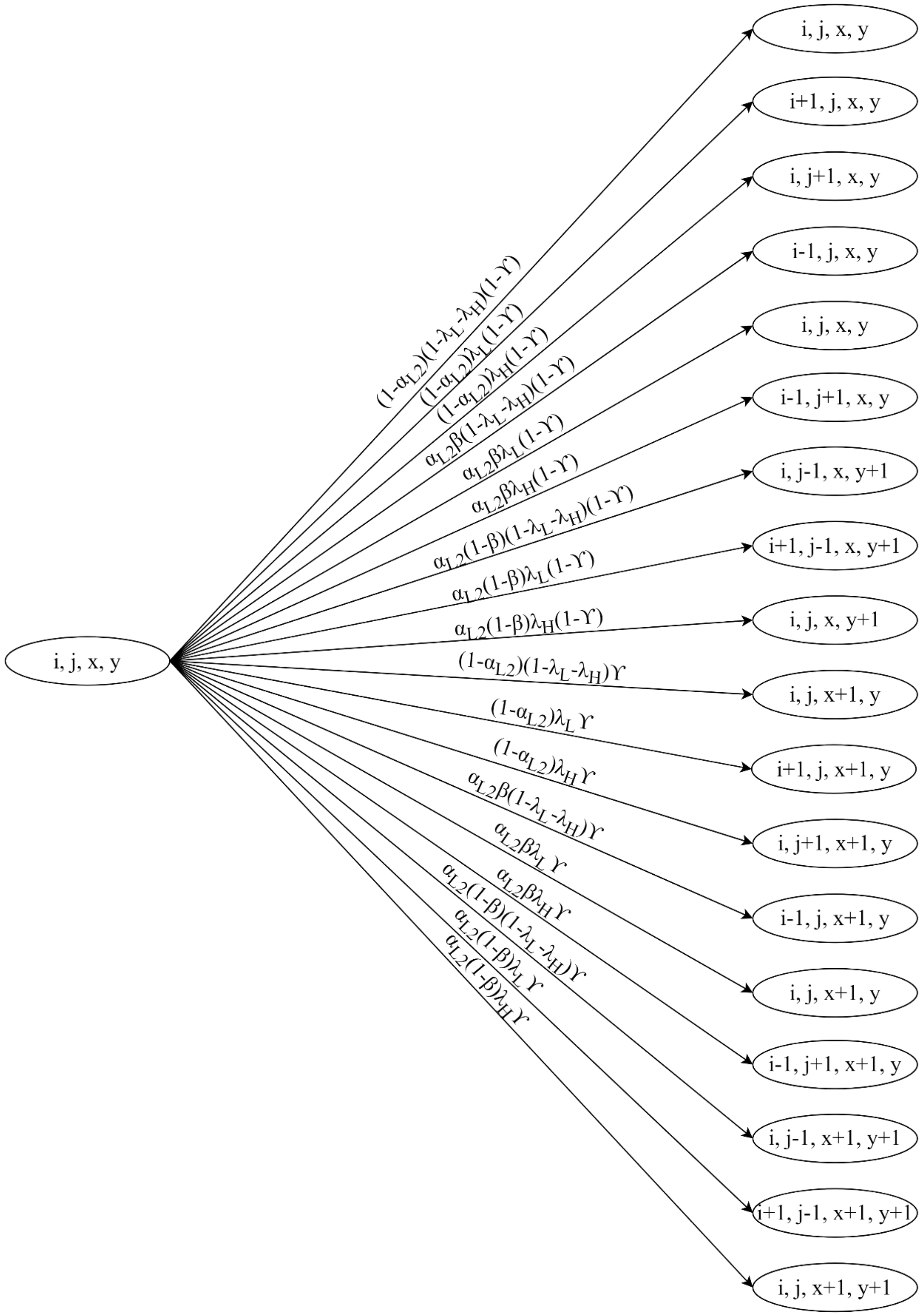


Fig 3. 91: The state diagram for $1 \leq i \leq \theta, \theta - i < j < K - i - 1, x = 0, y = 1$

(18) $\theta \leq i \leq K-2, 1 \leq j < K-i-1, x=0, y=1$



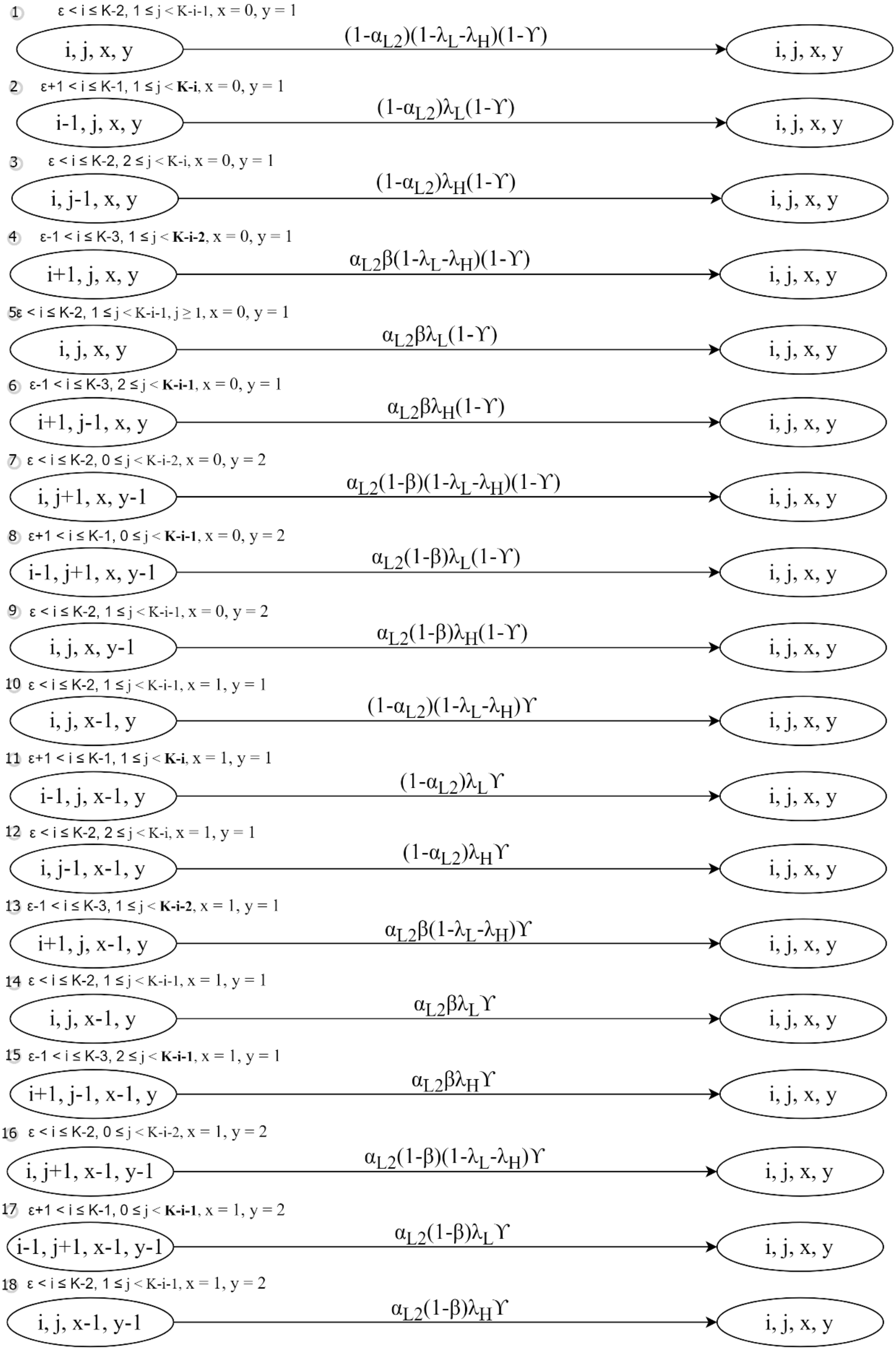
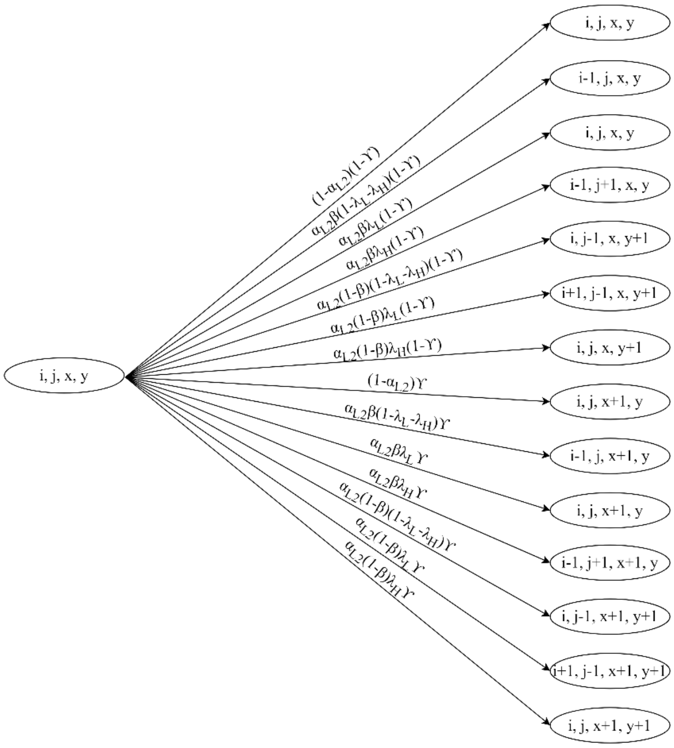


Fig 3. 92: The state diagram for $\theta \leq i \leq K-2, 1 \leq j < K-i-1, x=0, y=1$

(19) $1 \le i \le K-2, j = K-i-1, x = 0, y = 1$



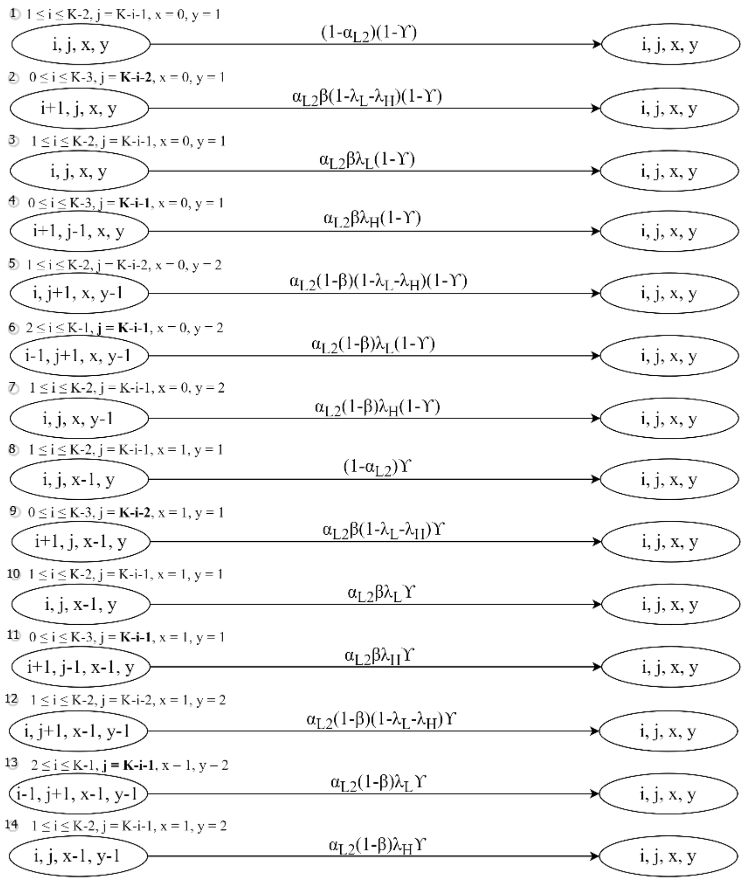
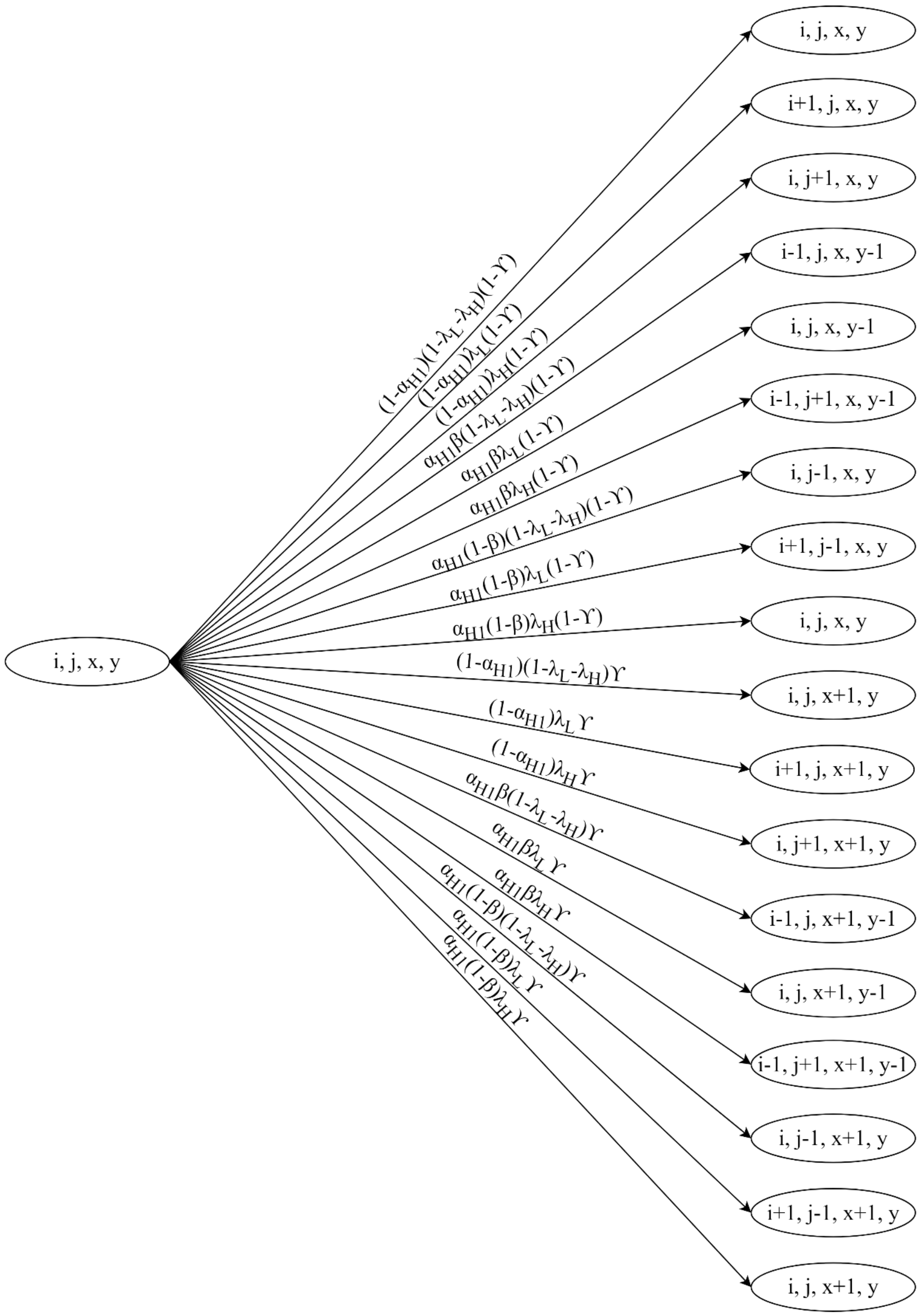


Fig 3. 93: The state diagram for $1 \le i \le K-2, j = K-i-1, x = 0, y = 1$

(20) $1 \le i \le \theta, 1 \le j \le \theta - i, x = 0, y = 2$



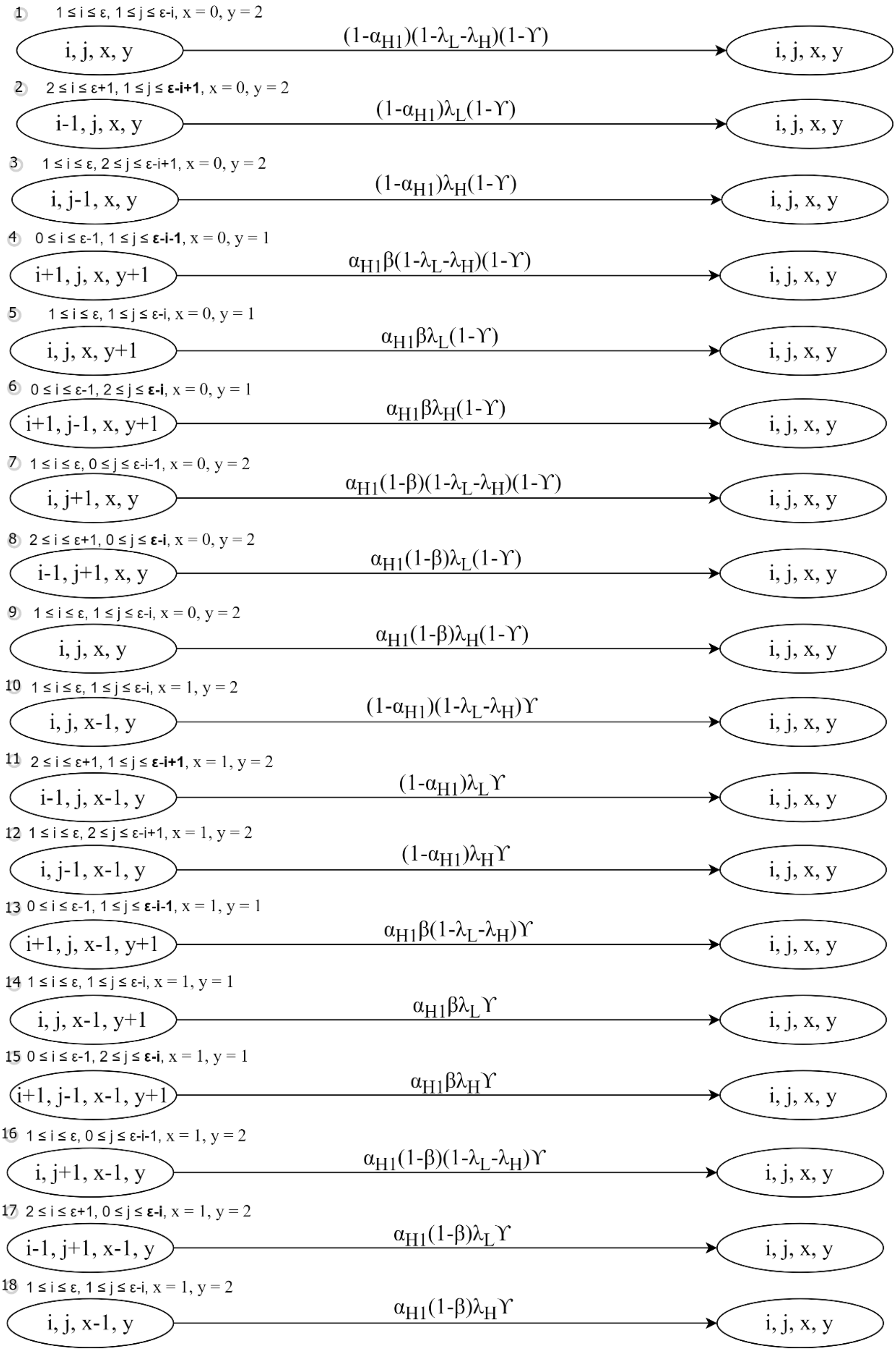
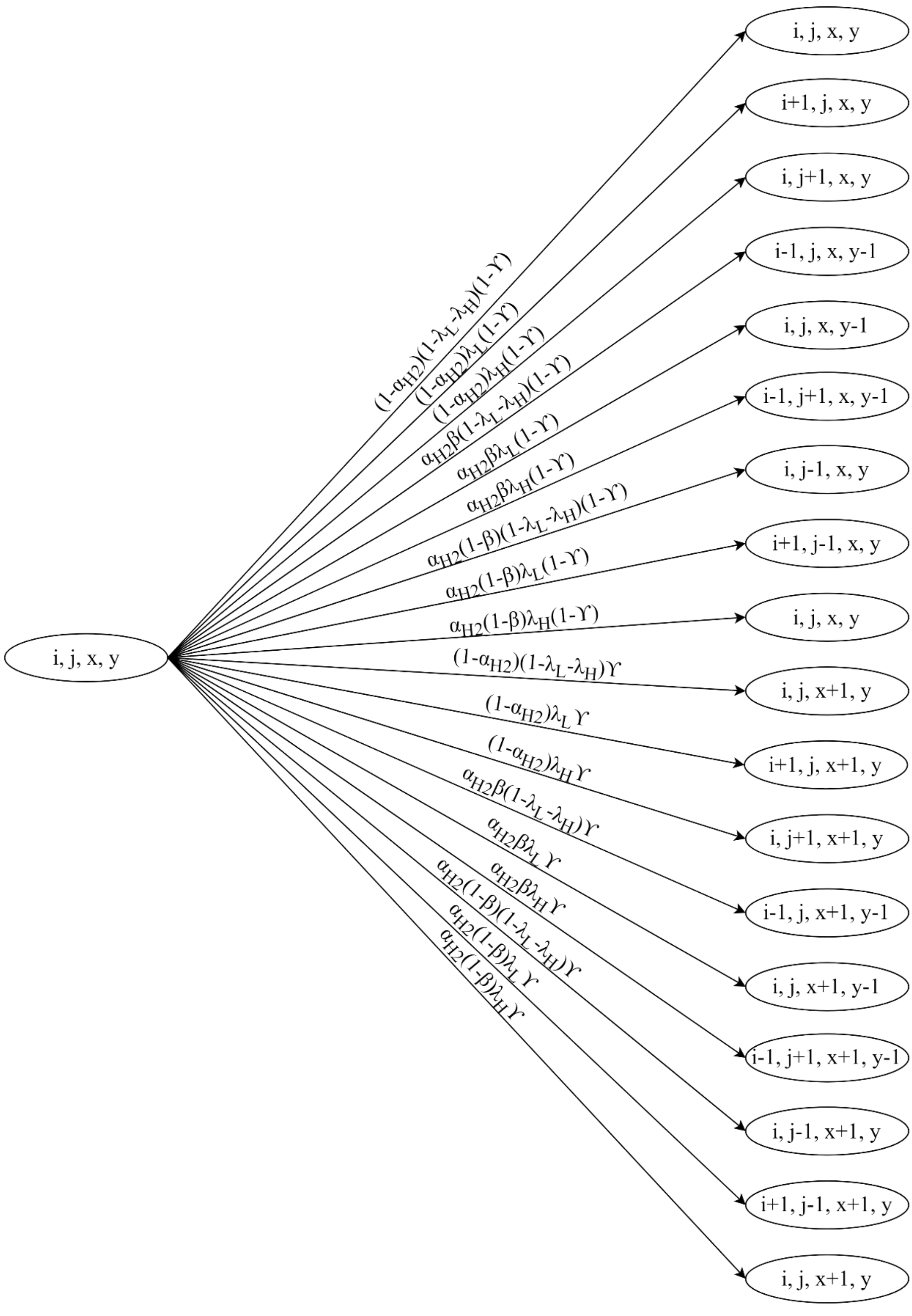


Fig 3. 94: The state diagram for $1 \leq i \leq \theta, 1 \leq j \leq \theta - i, x = 0, y = 2$

(21) $1 \leq i \leq \theta, \theta - i < j < K - i - 1, x = 0, y = 2$



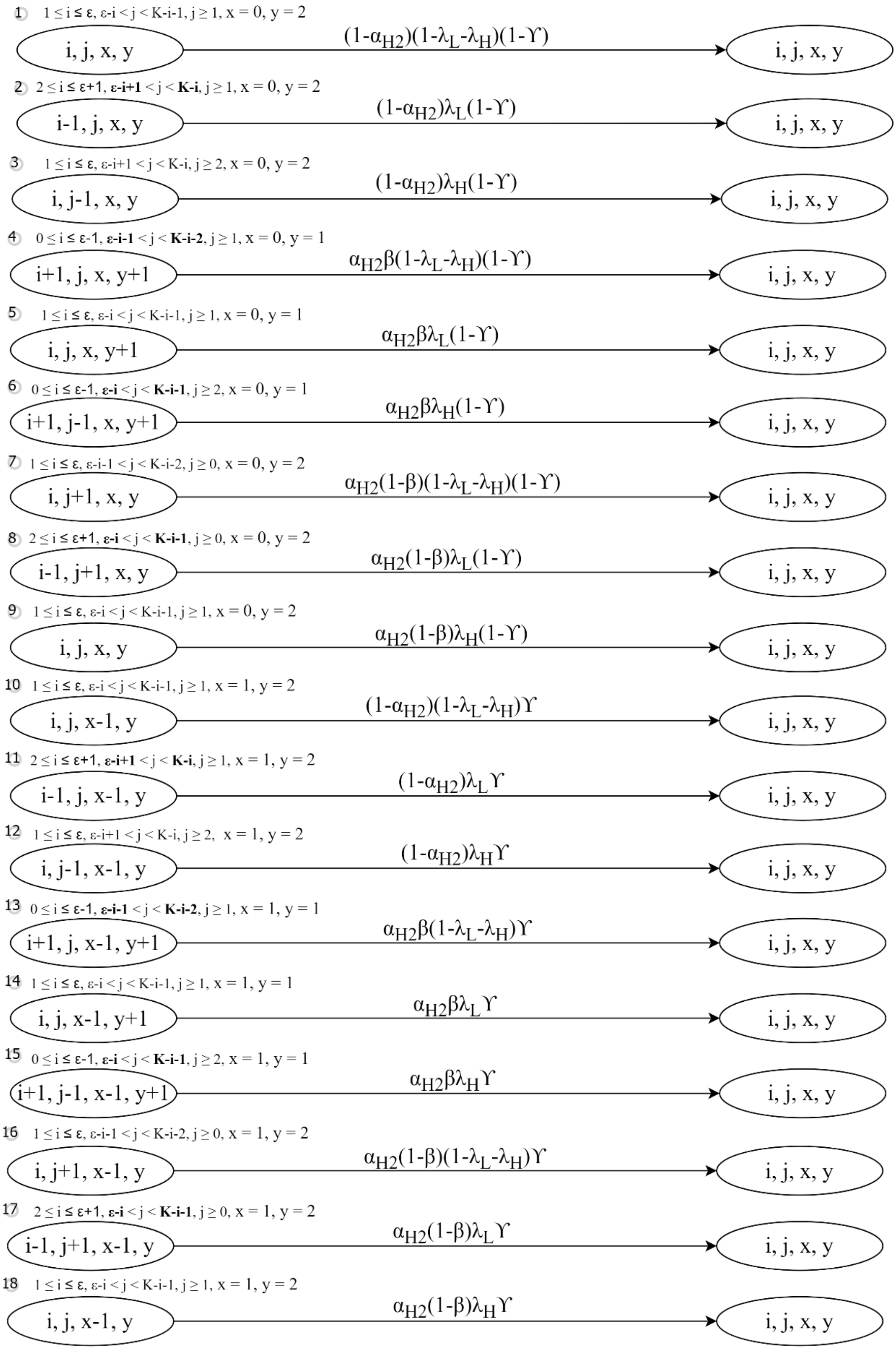
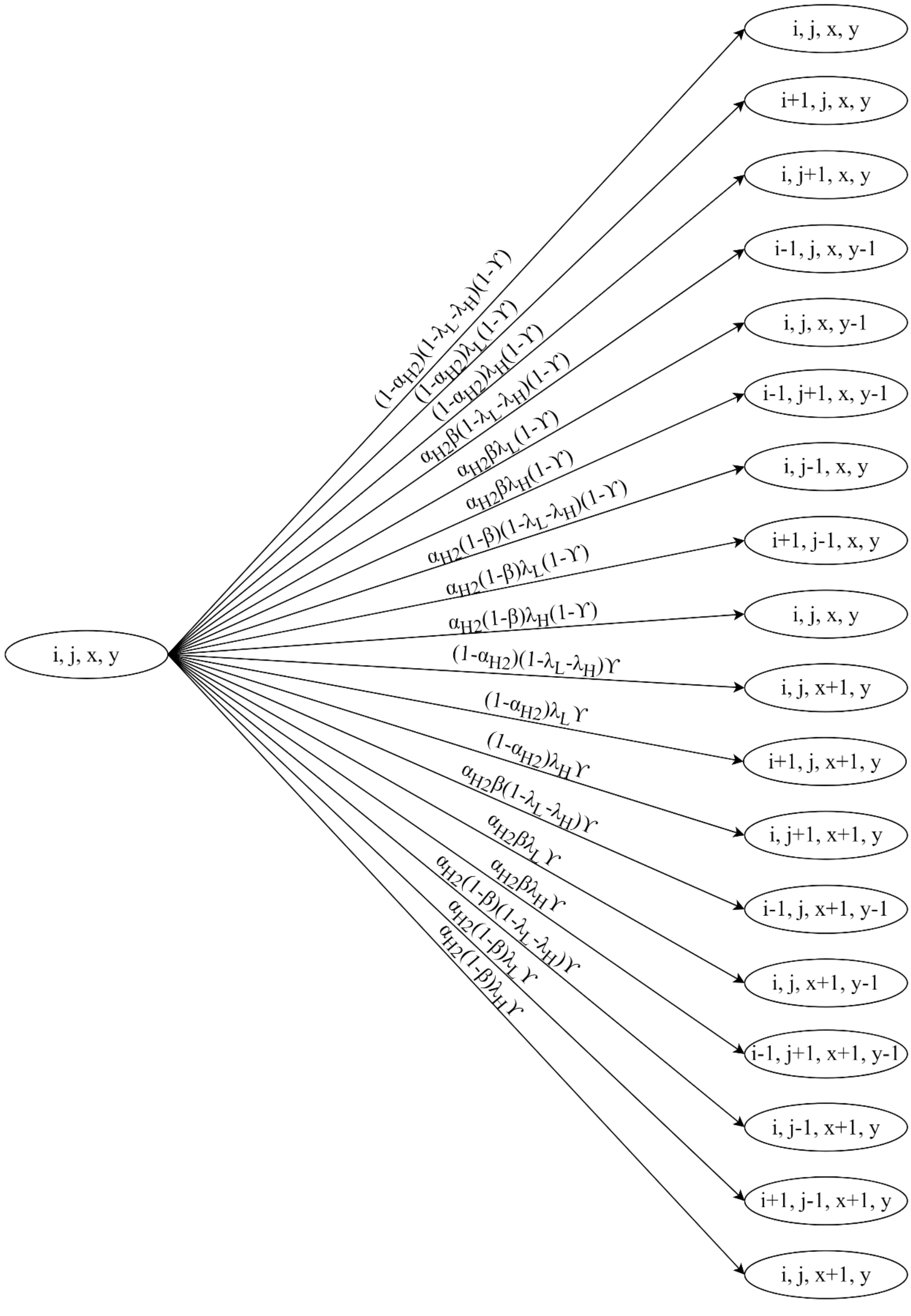


Fig 3. 95: The state diagram for $1 \le i \le \theta, \theta - i < j < K - i - 1, x = 0, y = 2$

(22) $\theta < i \leq K-2, 1 \leq j \leq K-i-2, x=0, y=2$



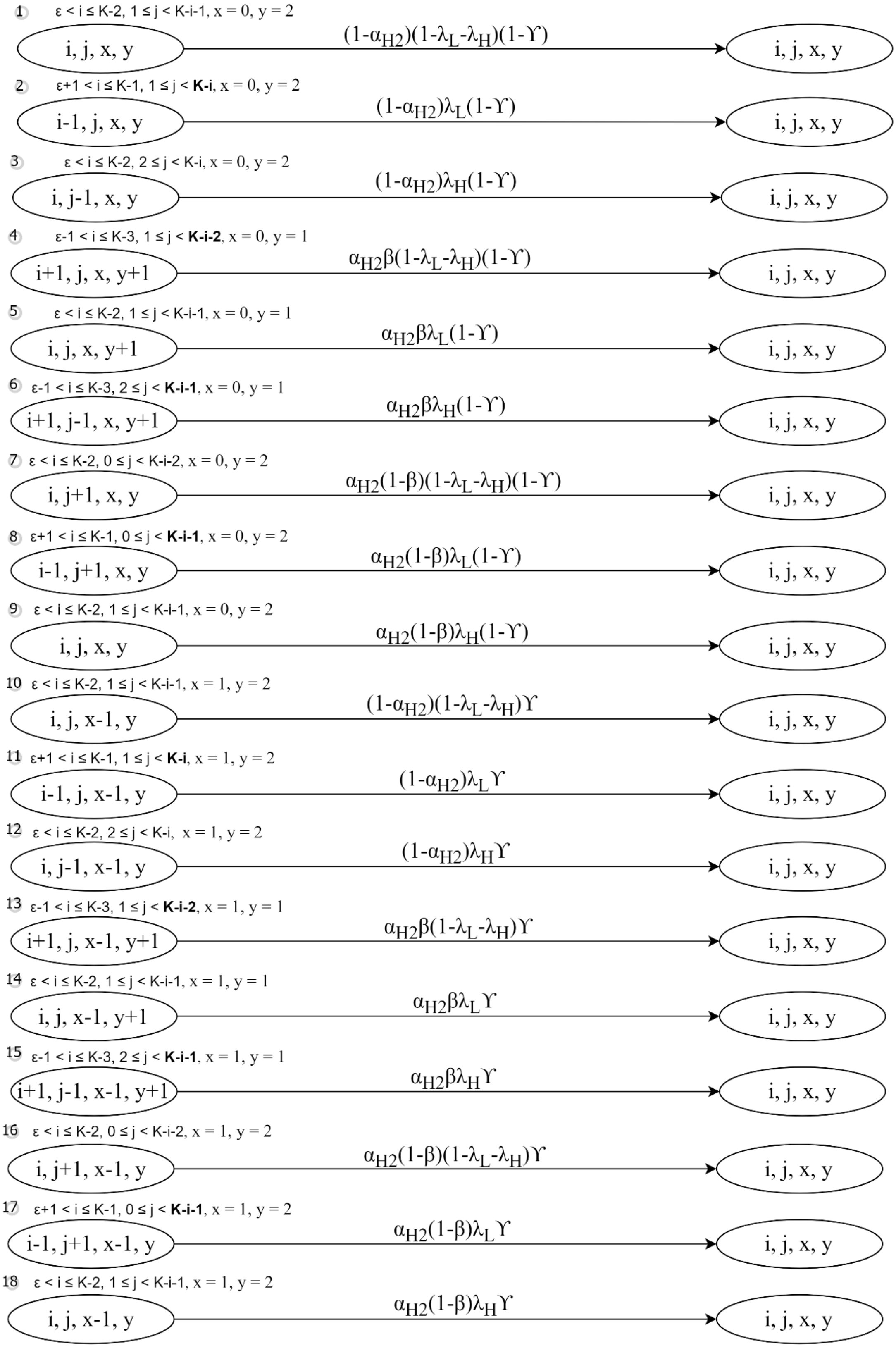
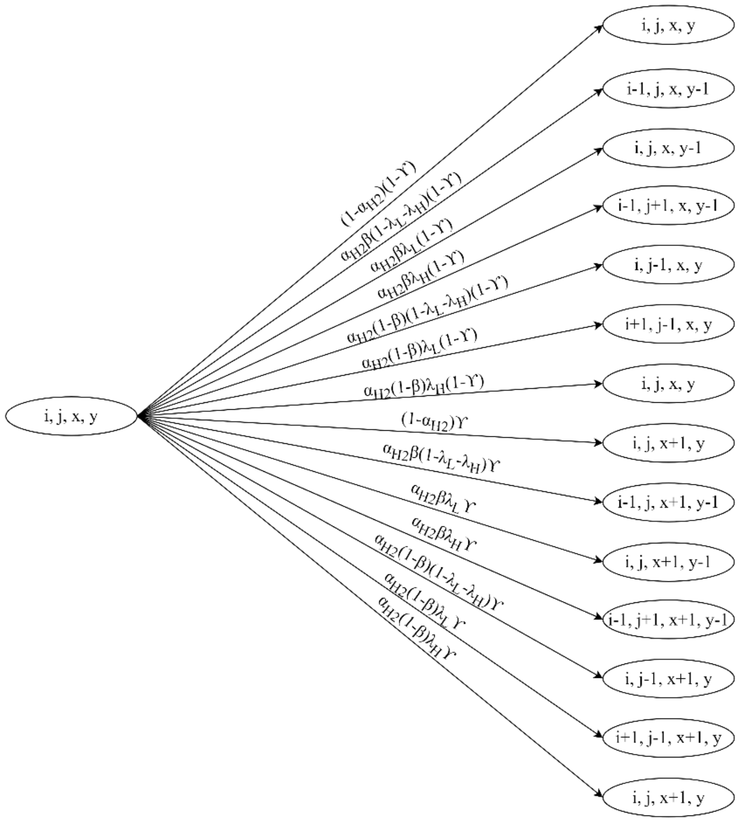


Fig 3. 96: The state diagram for $\theta < i \leq K-2, 1 \leq j \leq K-i-2, x=0, y=2$

(23) $1 \le i \le K-2, j = K-i-1, x = 0, y = 2$



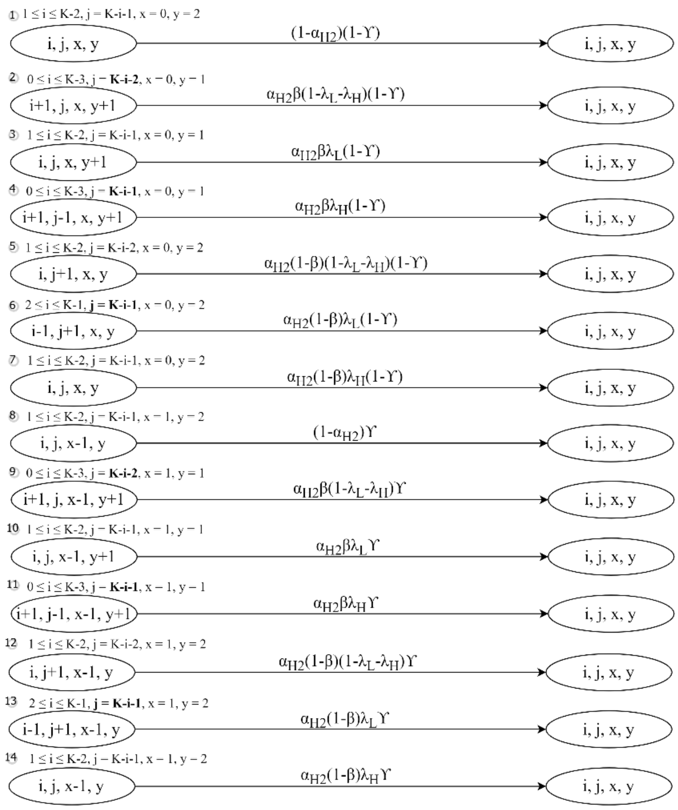


Fig 3. 97: The state diagram for $1 \le i \le K-2, j = K-i-1, x = 0, y = 2$

(24) $i = 0, j = 0, x = 1, y = 0$

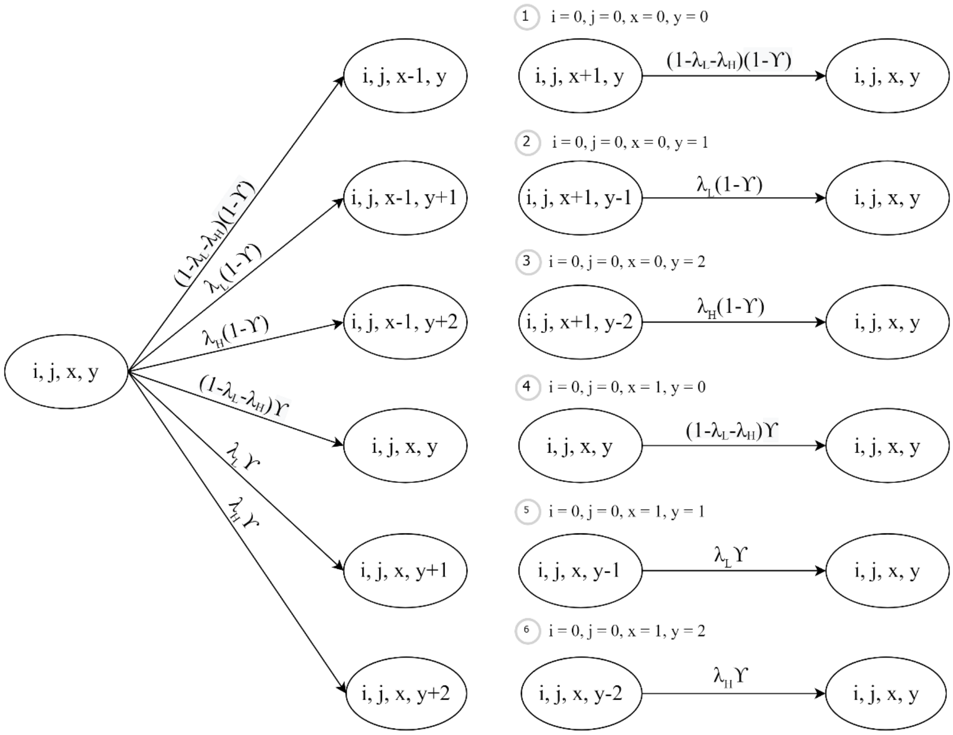


Fig 3. 98: The state diagram for $i = 0, j = 0, x = 1, y = 0$

(25) $i = 0, j = 0, x = 1, y = 1$

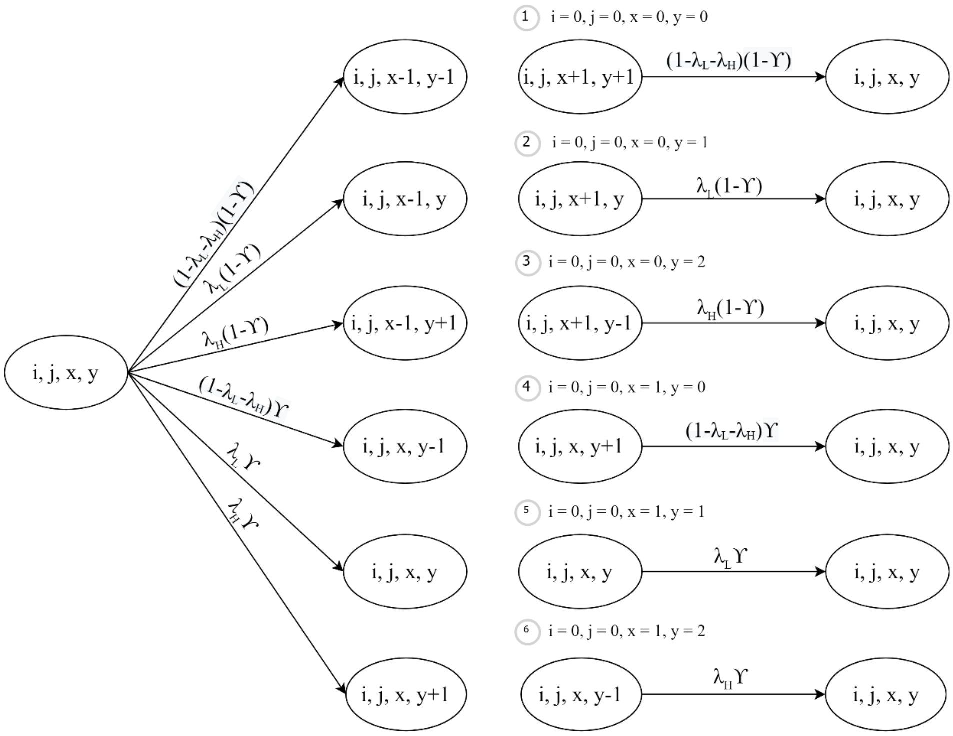


Fig 3. 99: The state diagram for $i = 0, j = 0, x = 1, y = 1$

(26) $i = 0, j = 0, x = 1, y = 2$

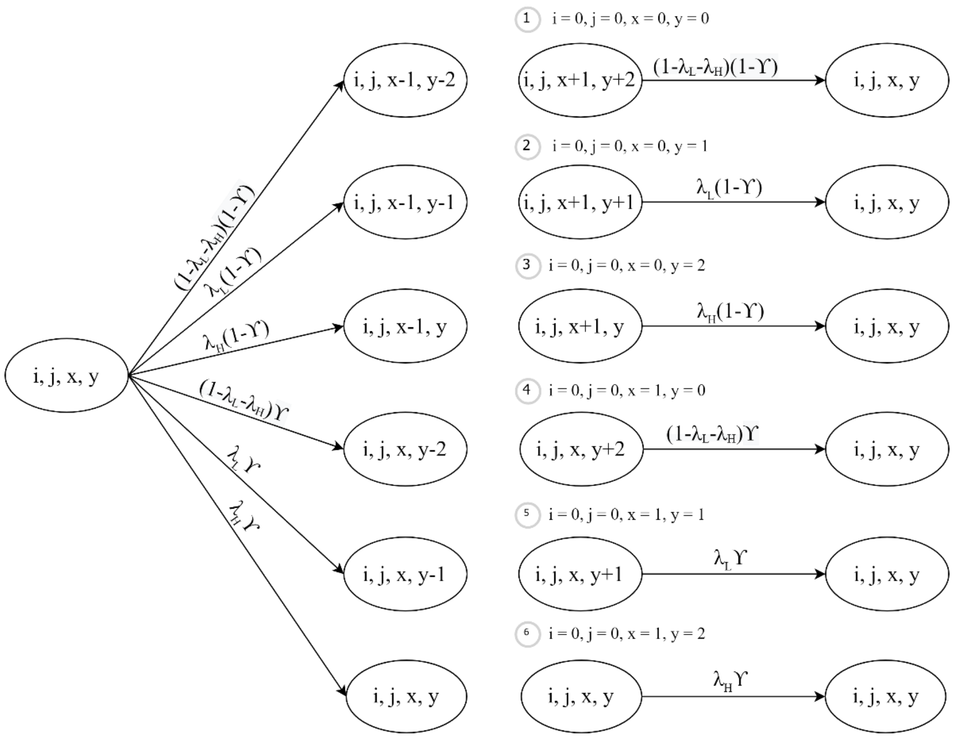


Fig 3. 100: The state diagram for $i = 0, j = 0, x = 1, y = 2$

(27) $i = 0, 1 \le j \le K - 1, x = 1, y = 1$

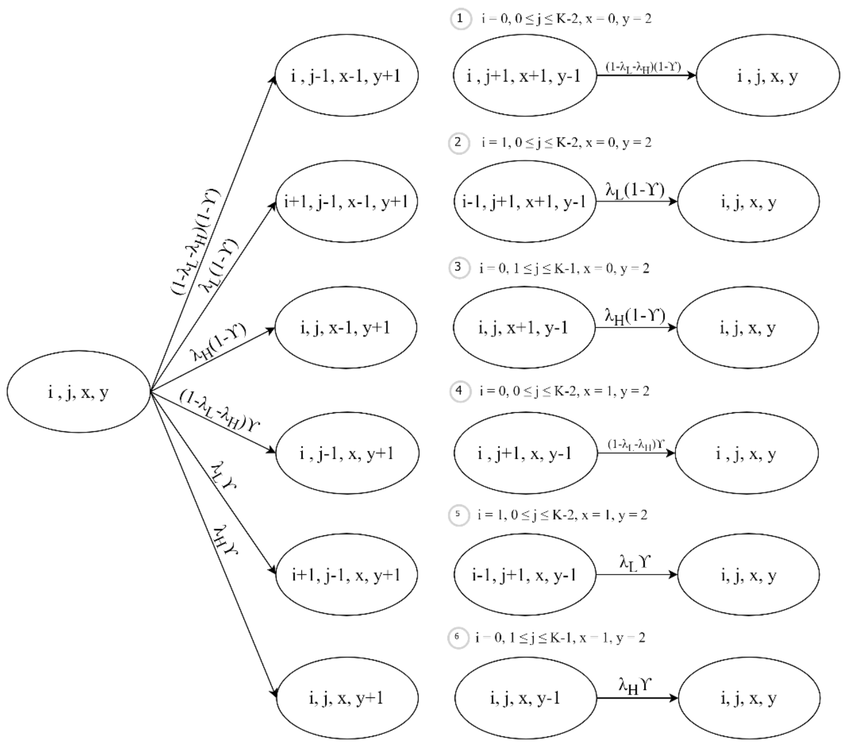


Fig 3. 101: The state diagram for $i = 0, 1 \le j \le K - 1, x = 1, y = 1$

(28) $i = 0, 1 \leq j \leq K-1, x = 1, y = 2$

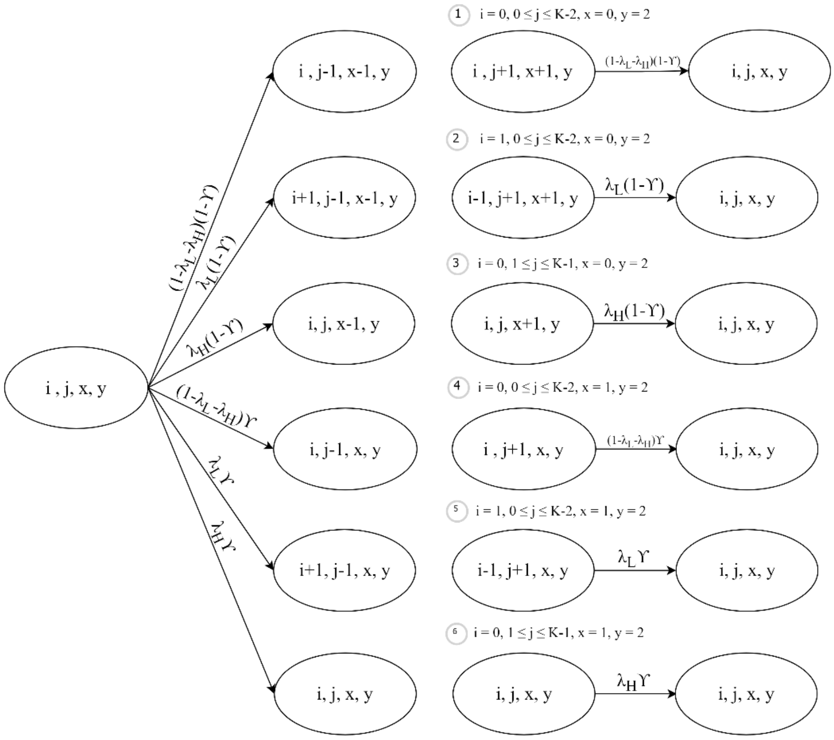


Fig 3. 102: The state diagram for $i = 0, 1 \leq j \leq K-1, x = 1, y = 2$

(29) $1 \leq i \leq K-1, j = 0, x = 1, y = 1$

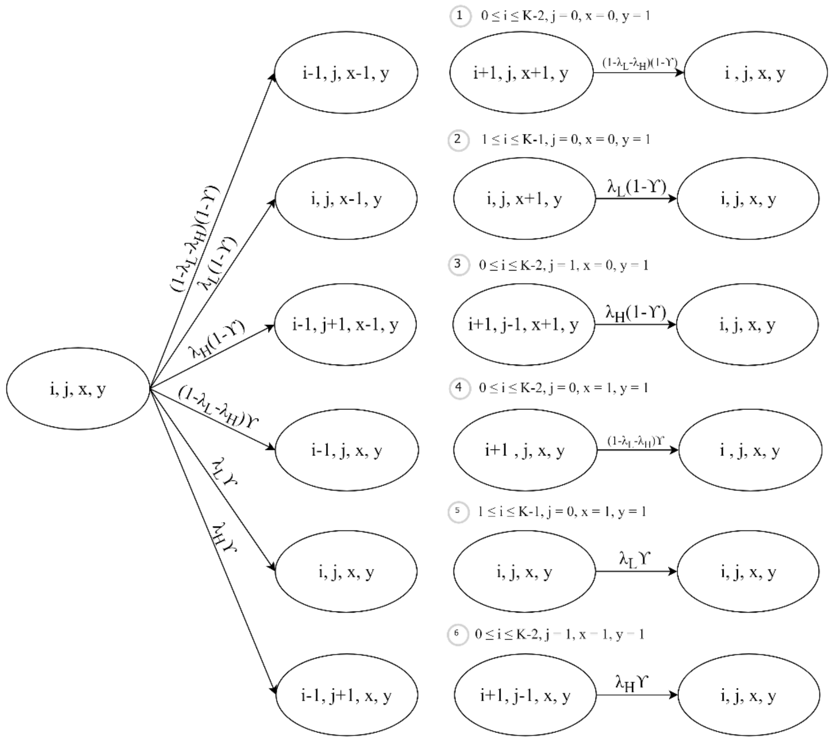


Fig 3. 103: The state diagram for $1 \leq i \leq K-1, j = 0, x = 1, y = 1$

(30) $1 \le i \le K-1, j = 0, x = 1, y = 2$

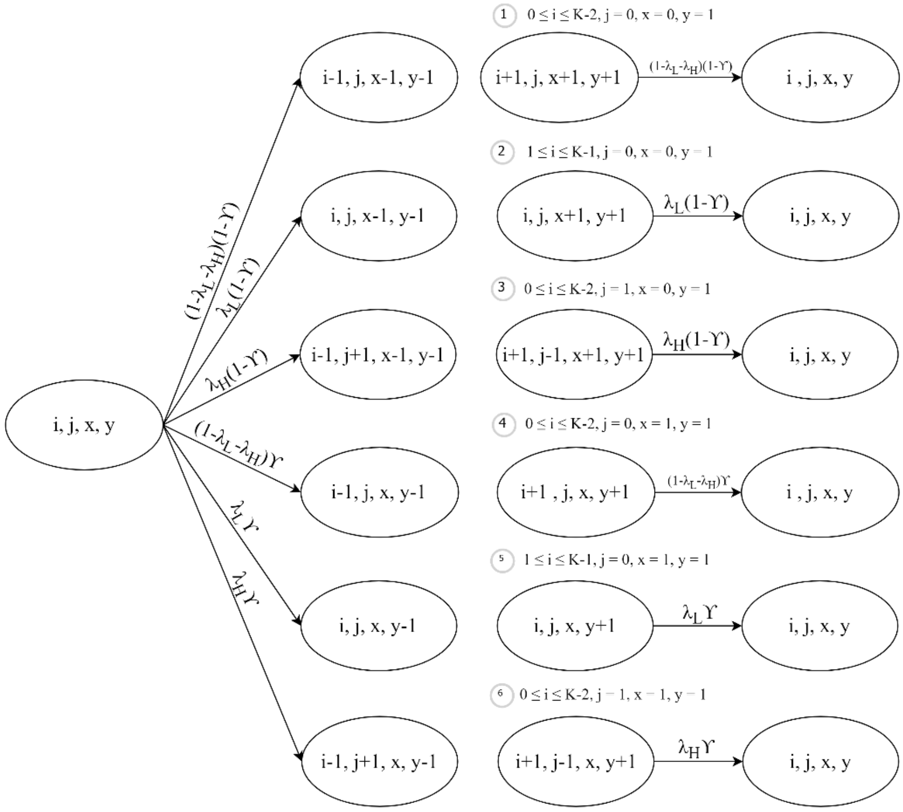
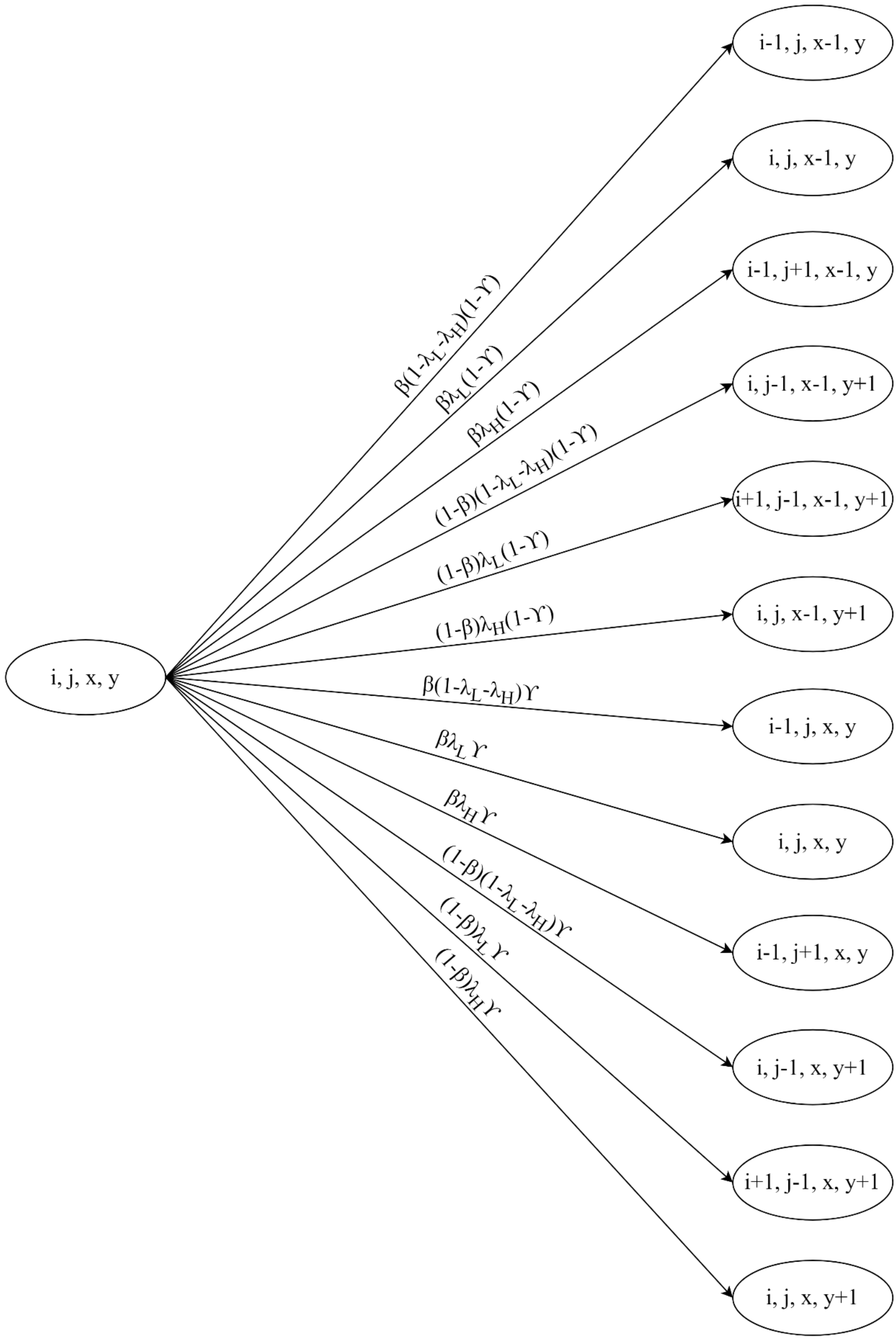


Fig 3. 104: The state diagram for $1 \le i \le K-1, j = 0, x = 1, y = 2$

(31) $1 \le i \le K-2, 1 \le j \le K-i-1, x=1, y=1$



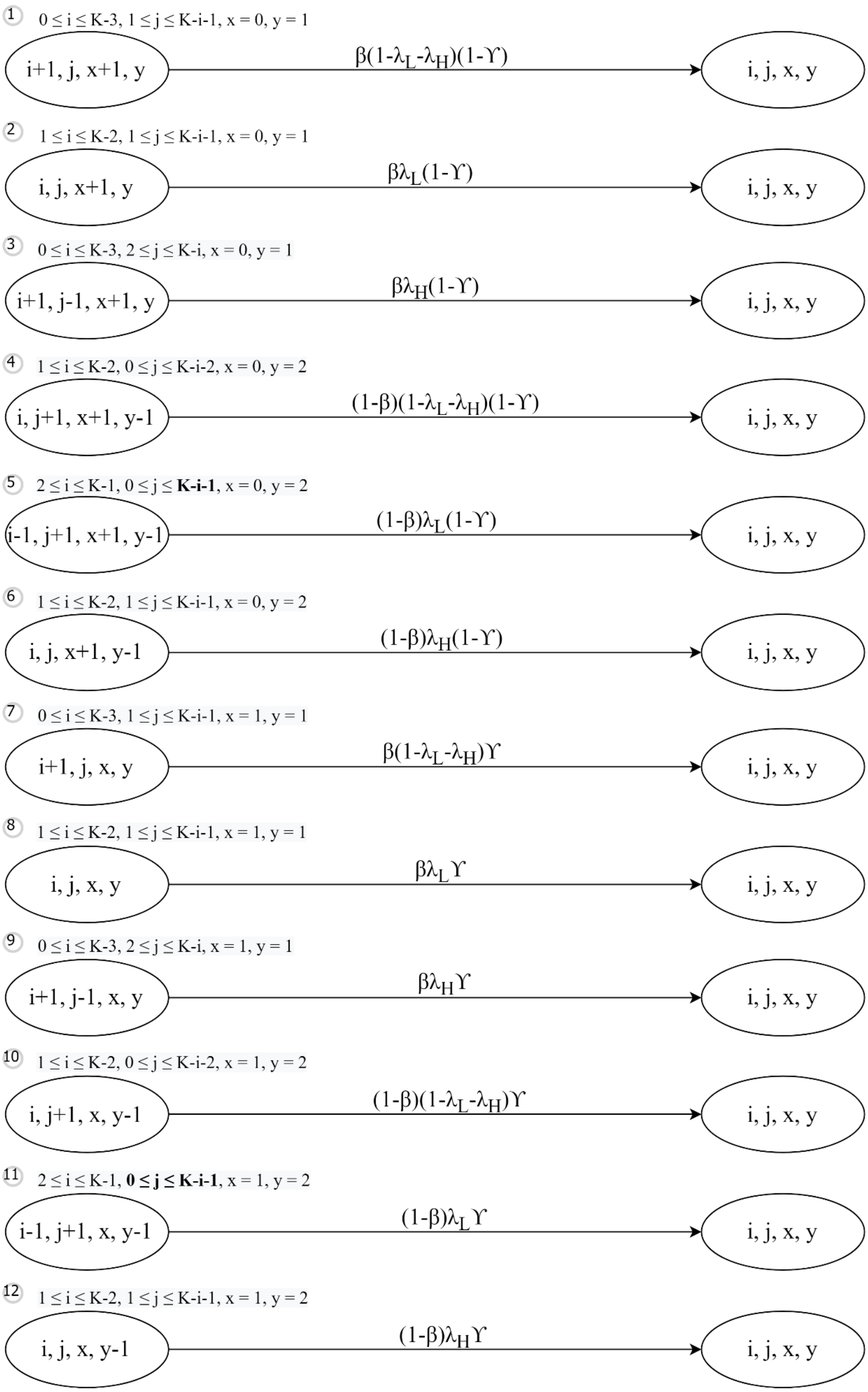
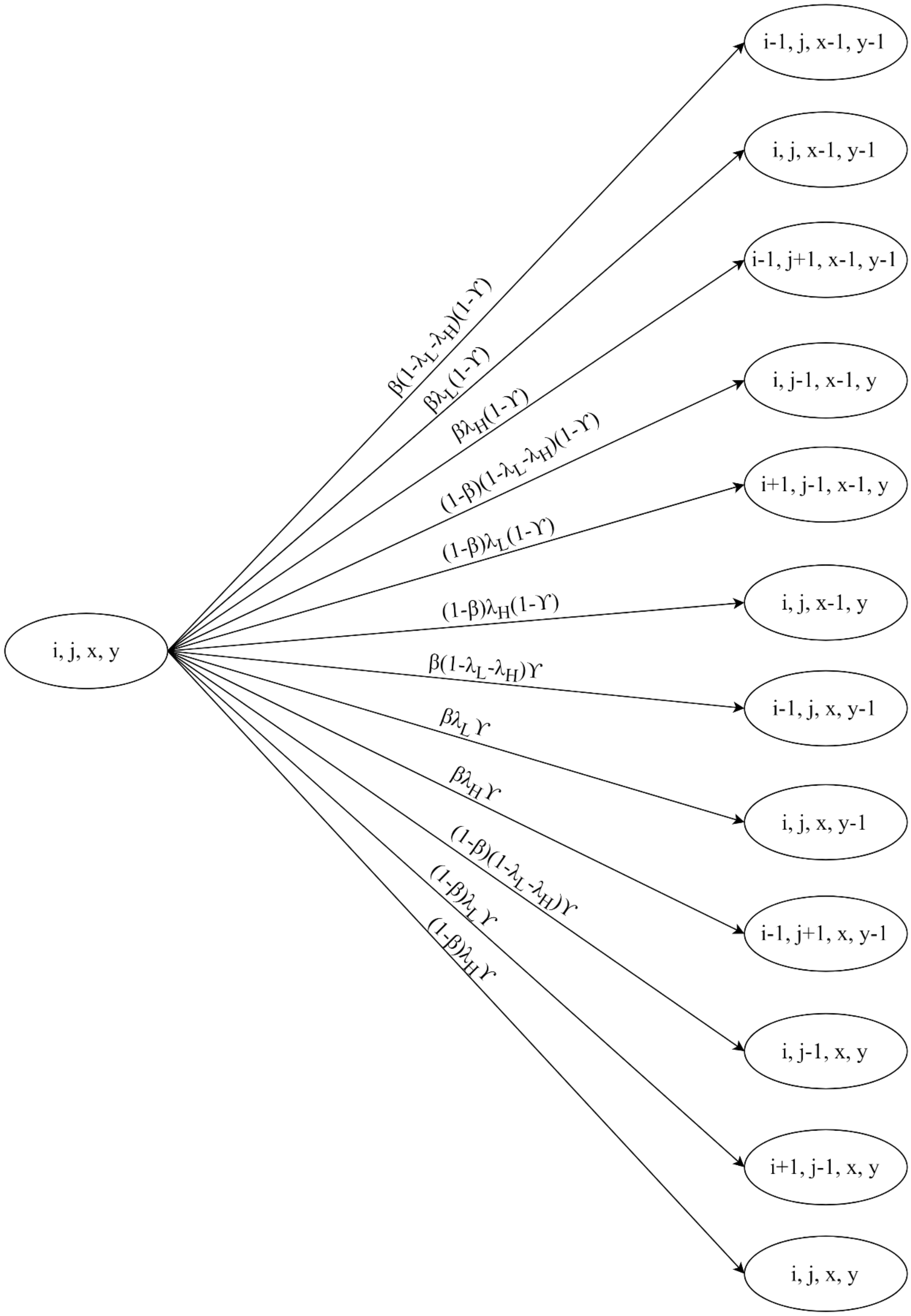


Fig 3. 105: The state diagram for $1 \leq i \leq K-2, 1 \leq j \leq K-i-1, x = 1, y = 1$

(32) $1 \le i \le K-2, 1 \le j \le K-i-1, x=1, y=2$



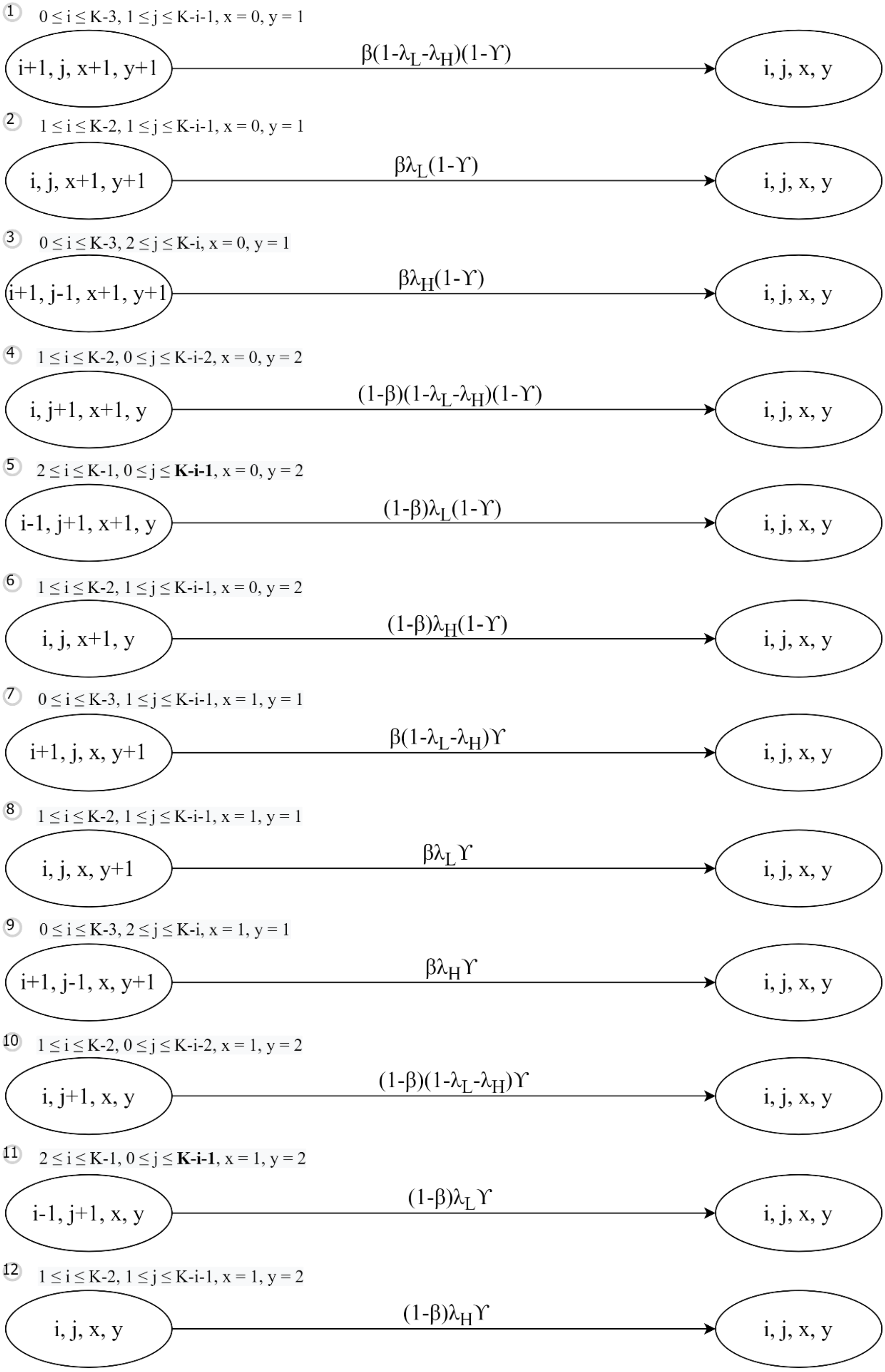


Fig 3. 106: The state diagram for $1 \leq i \leq K-2, 1 \leq j \leq K-i-1, x=1, y=2$

(b) Priority discipline

(1) $i = 0, j = 0, x = 0, y = 0$

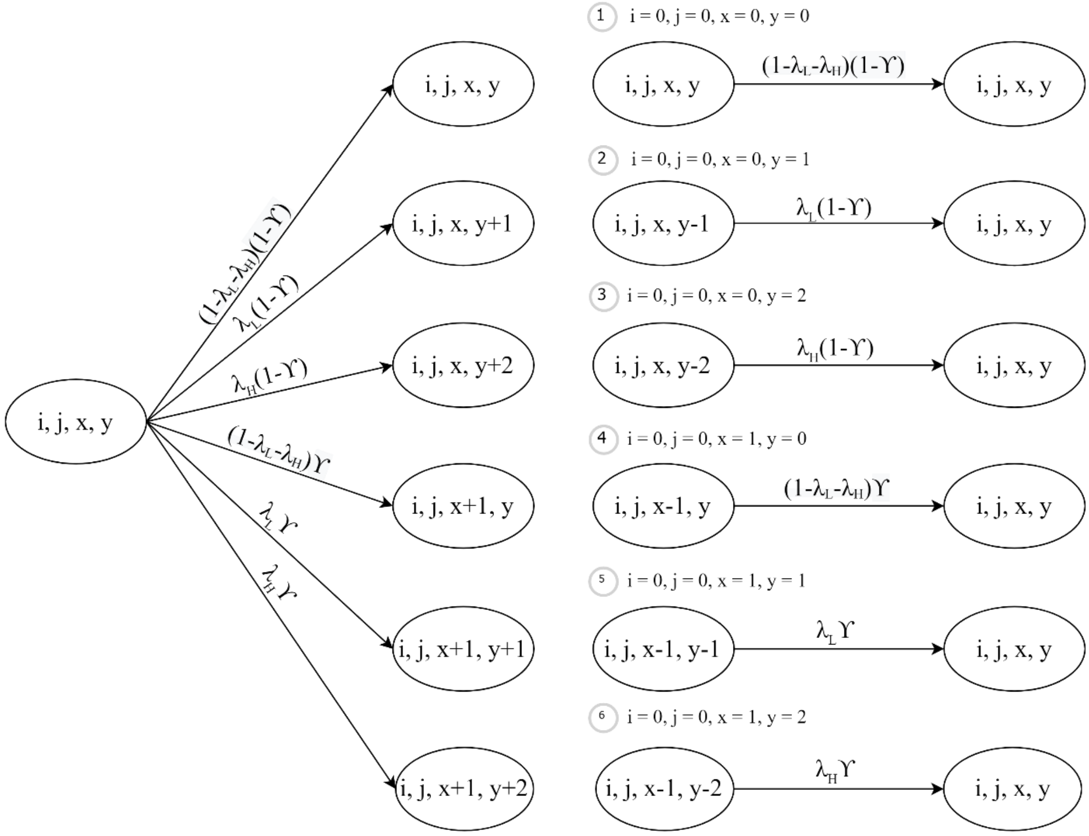
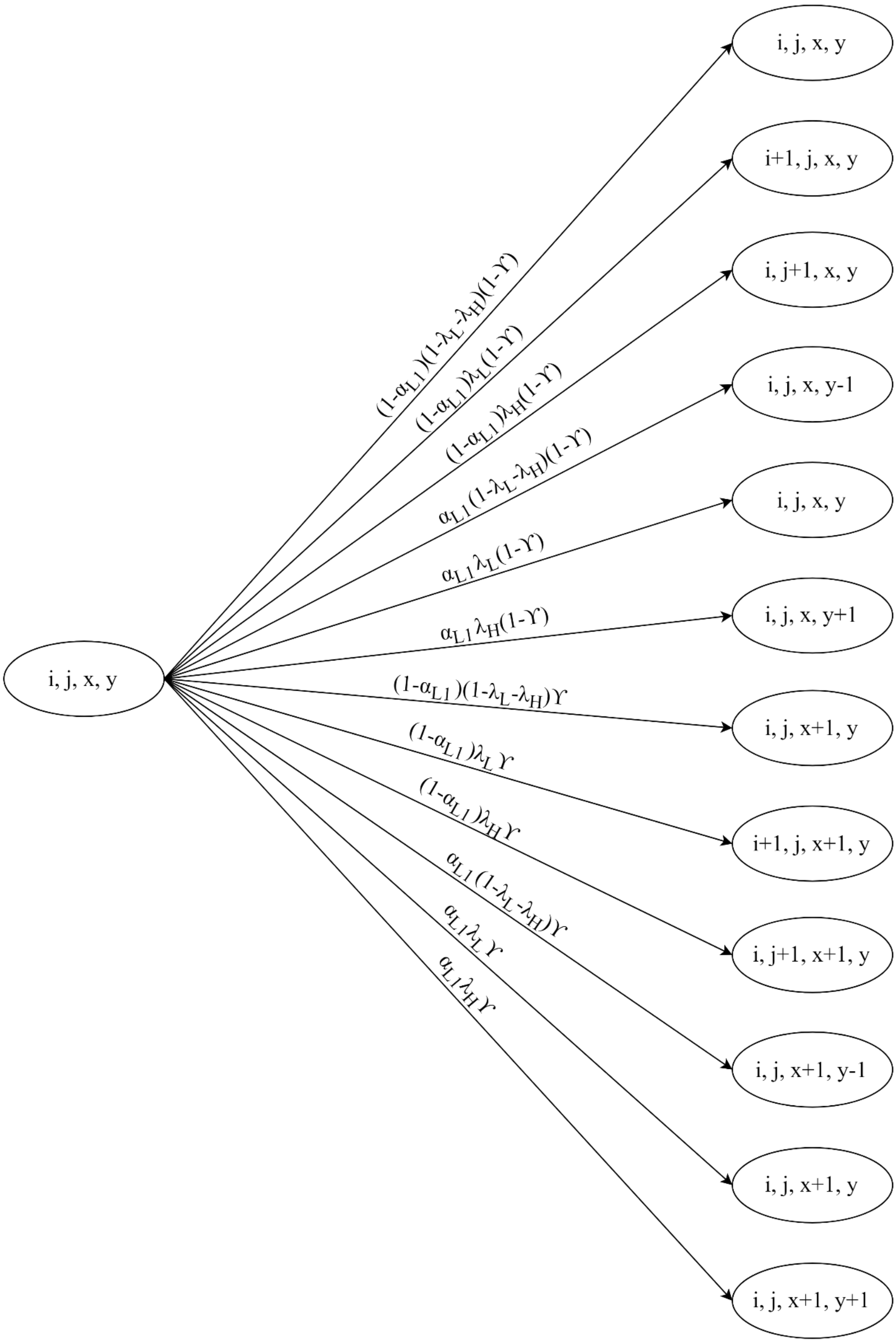


Fig 3. 107: The state diagram for $i = 0, j = 0, x = 0, y = 0$

(2) $i = 0, j = 0, x = 0, y = 1$


i, j, x, y
i, j, x, y
i+1, j, x, y
i, j+1, x, y
i, j, x, y-1
i, j, x, y
i, j, x, y+1
i, j, x+1, y
i+1, j, x+1, y
i, j+1, x+1, y
i, j, x+1, y-1
i, j, x+1, y
i, j, x+1, y+1
(1-αL1)(1-λL-λH)(1-ϒ)
(1-αL1)λL(1-ϒ)
(1-αL1)λH(1-ϒ)
αL1(1-λL-λH)(1-ϒ)
αL1λL(1-ϒ)
αL1λH(1-ϒ)
(1-αL1)(1-λL-λH)ϒ
(1-αL1)λLϒ
(1-αL1)λHϒ
αL1(1-λL-λH)ϒ
αL1λLϒ
αL1λHϒ

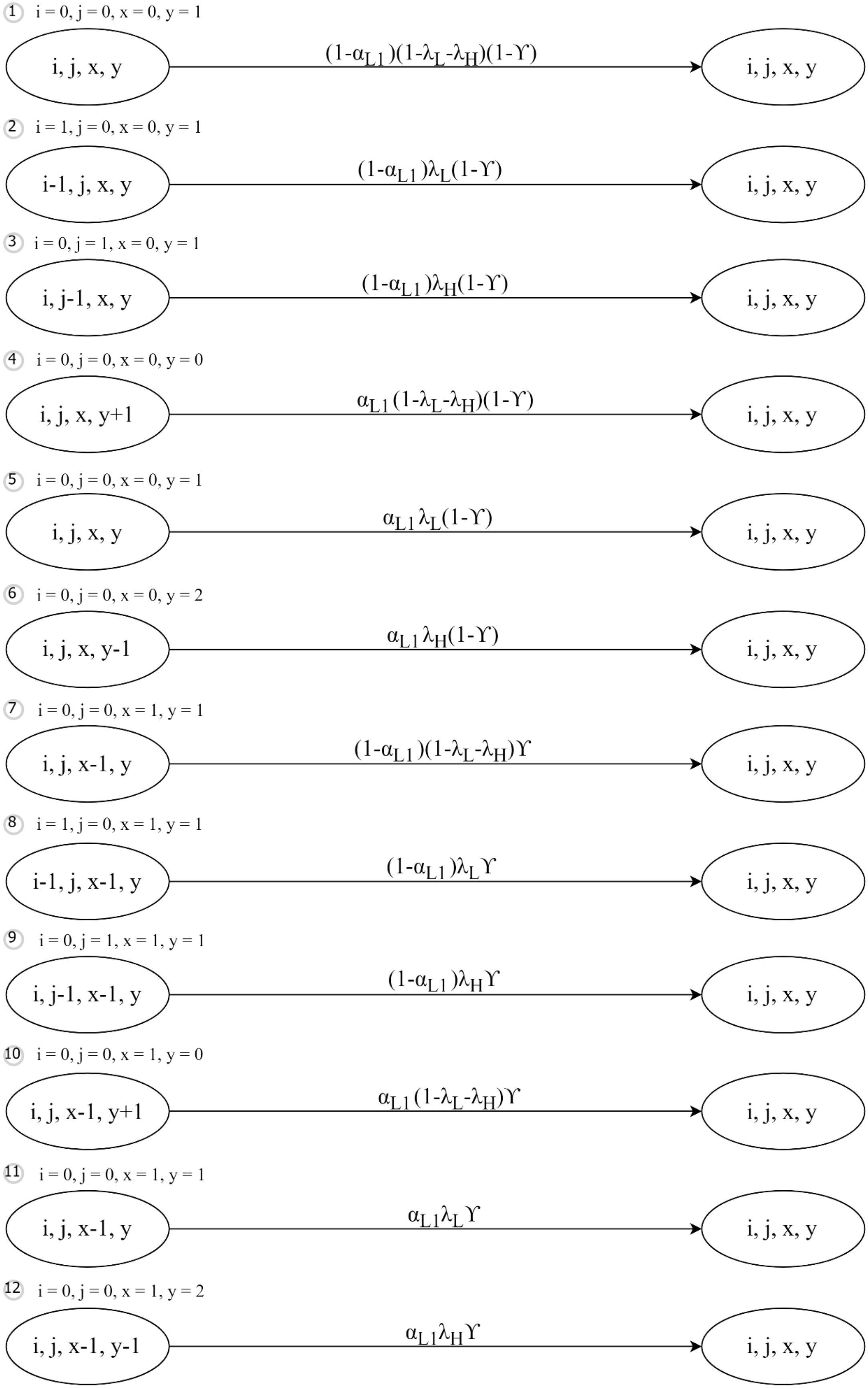
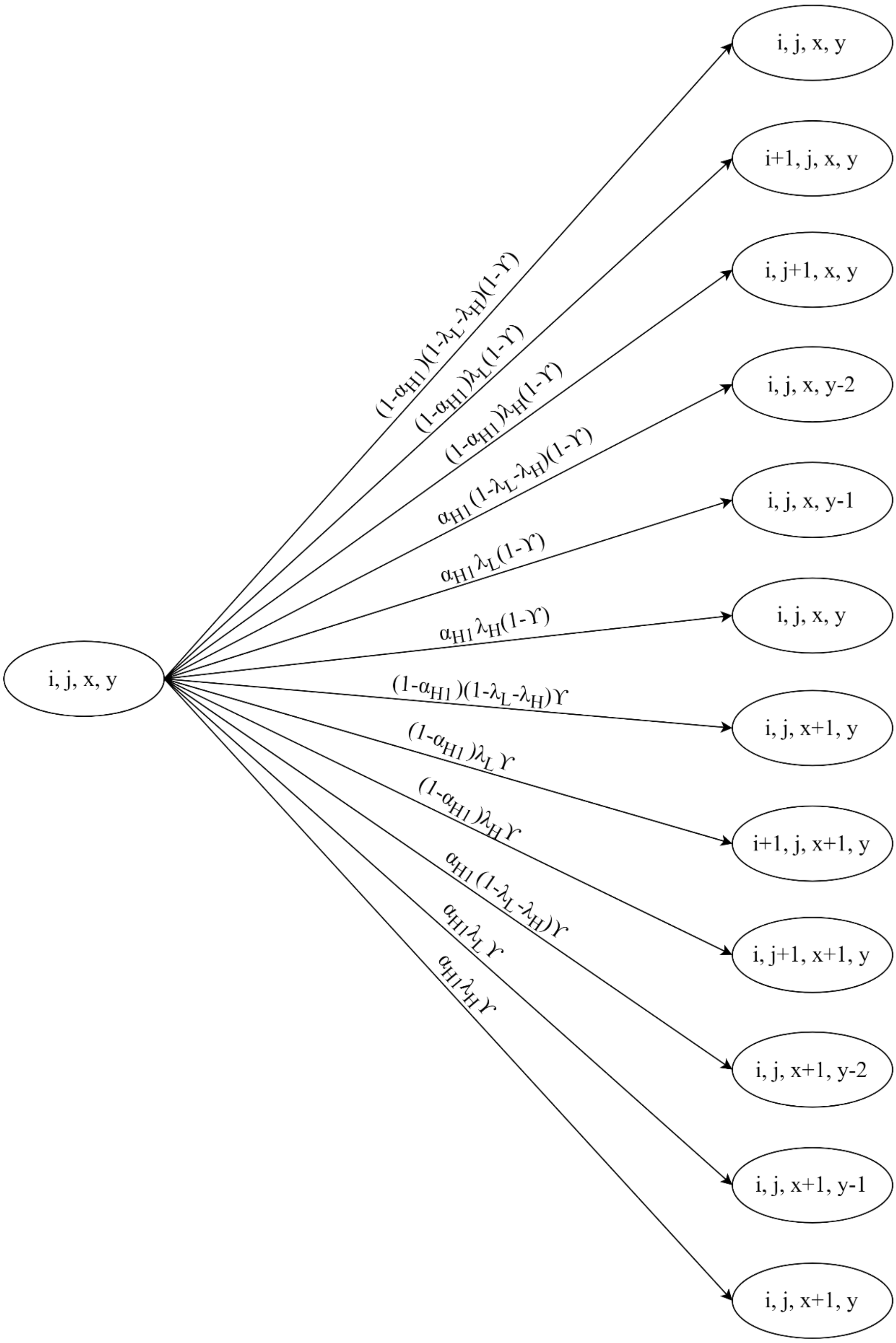


Fig 3. 108: The state diagram for $i = 0, j = 0, x = 0, y = 1$

(3) $i = 0, j = 0, x = 0, y = 2$


i, j, x, y
i, j, x, y
i+1, j, x, y
i, j+1, x, y
i, j, x, y-2
i, j, x, y-1
i, j, x, y
i, j, x+1, y
i+1, j, x+1, y
i, j+1, x+1, y
i, j, x+1, y-2
i, j, x+1, y-1
i, j, x+1, y
(1-αH1)(1-λL-λH)(1-ϒ)
(1-αH1)λL(1-ϒ)
(1-αH1)λH(1-ϒ)
αH1(1-λL-λH)(1-ϒ)
αH1λL(1-ϒ)
αH1λH(1-ϒ)
(1-αH1)(1-λL-λH)ϒ
(1-αH1)λL ϒ
(1-αH1)λH ϒ
αH1(1-λL-λH)ϒ
αH1λL ϒ
αH1λH ϒ

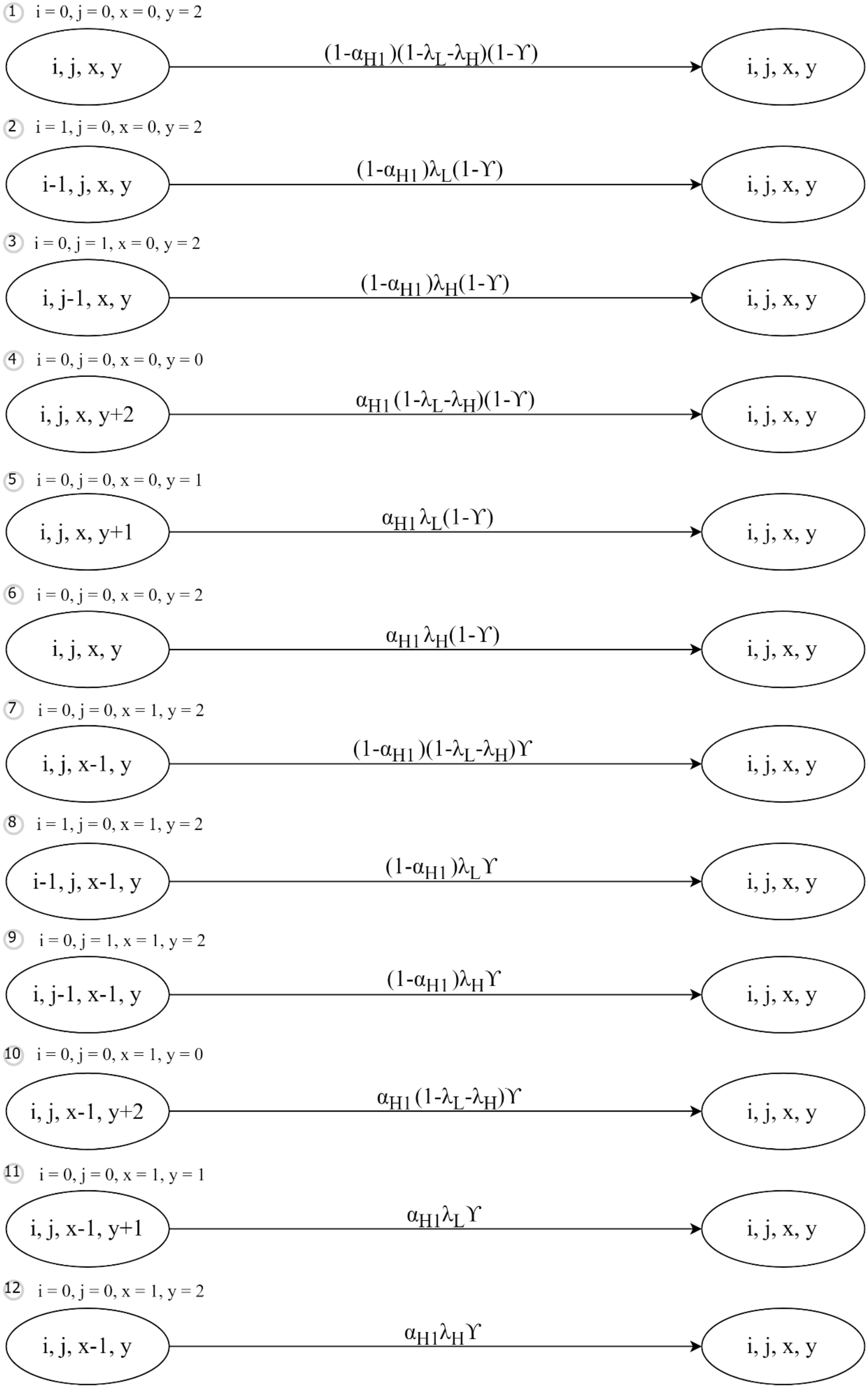
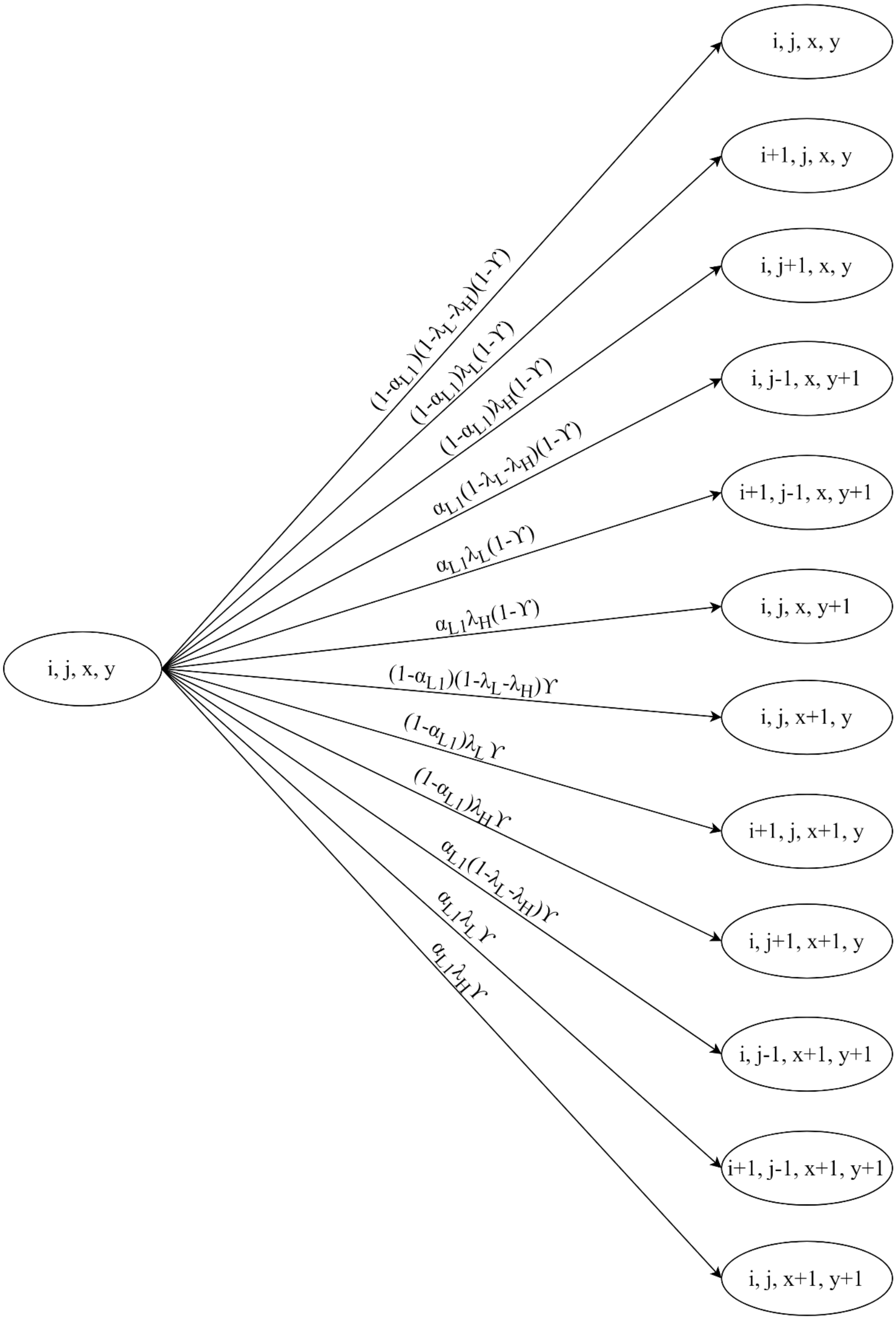


Fig 3. 109: The state diagram for $i = 0, j = 0, x = 0, y = 2$

(4) $i = 0, 1 \leq j \leq \theta, x = 0, y = 1$



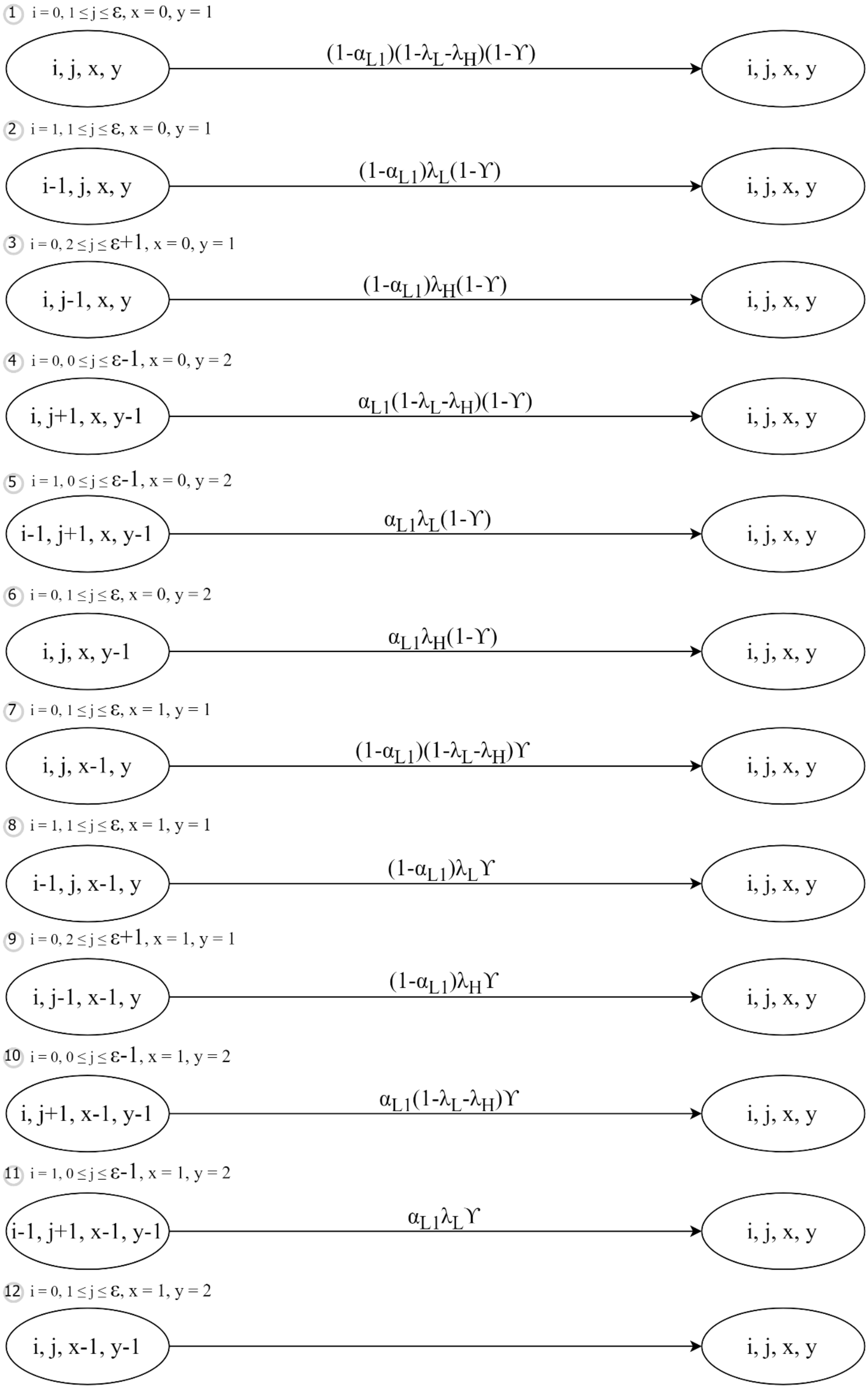
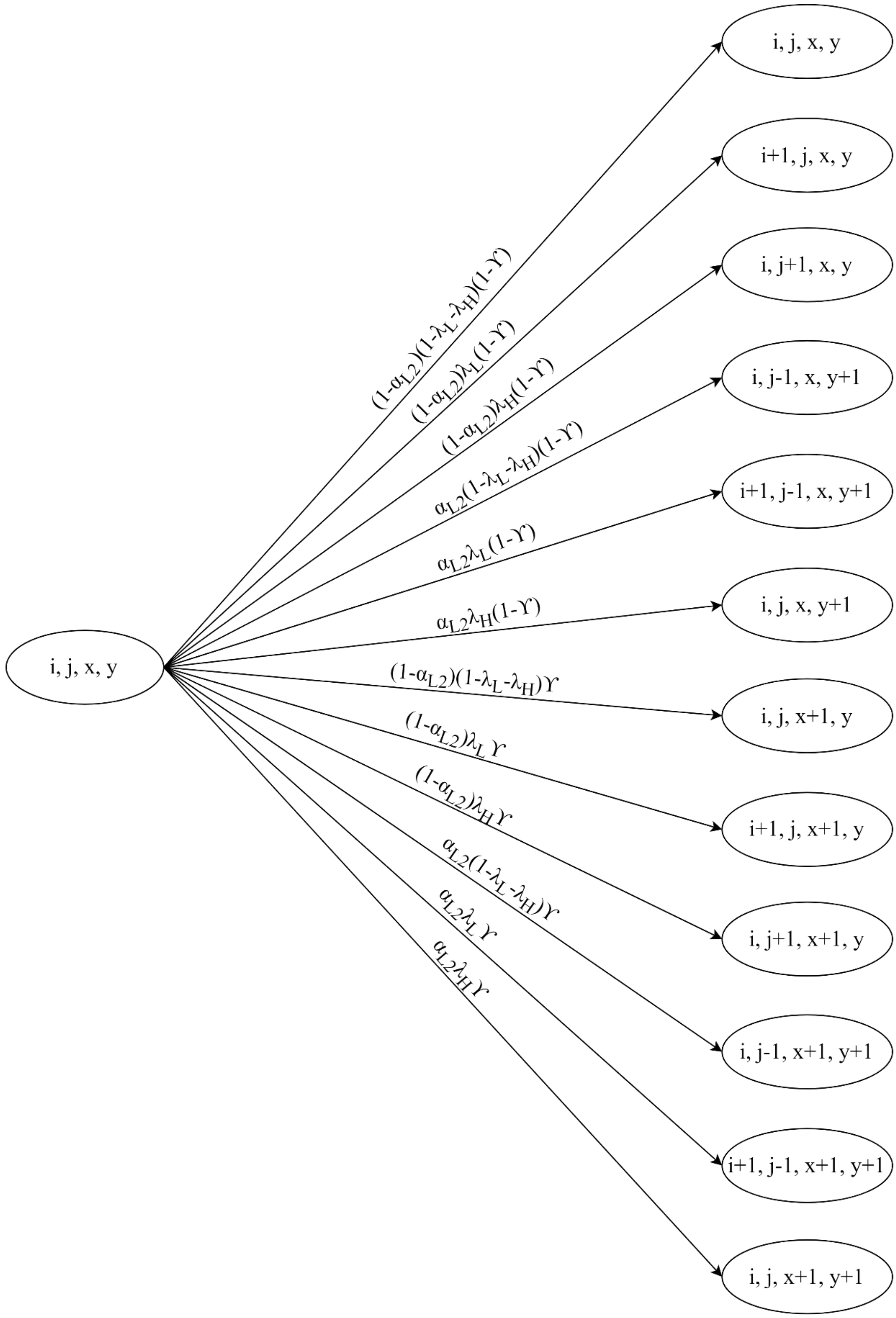


Fig 3. 110: The state diagram for $i = 0, 1 \leq j \leq \theta, x = 0, y = 1$

(5) $i = 0, \theta < j \leq K-2, x = 0, y = 1$



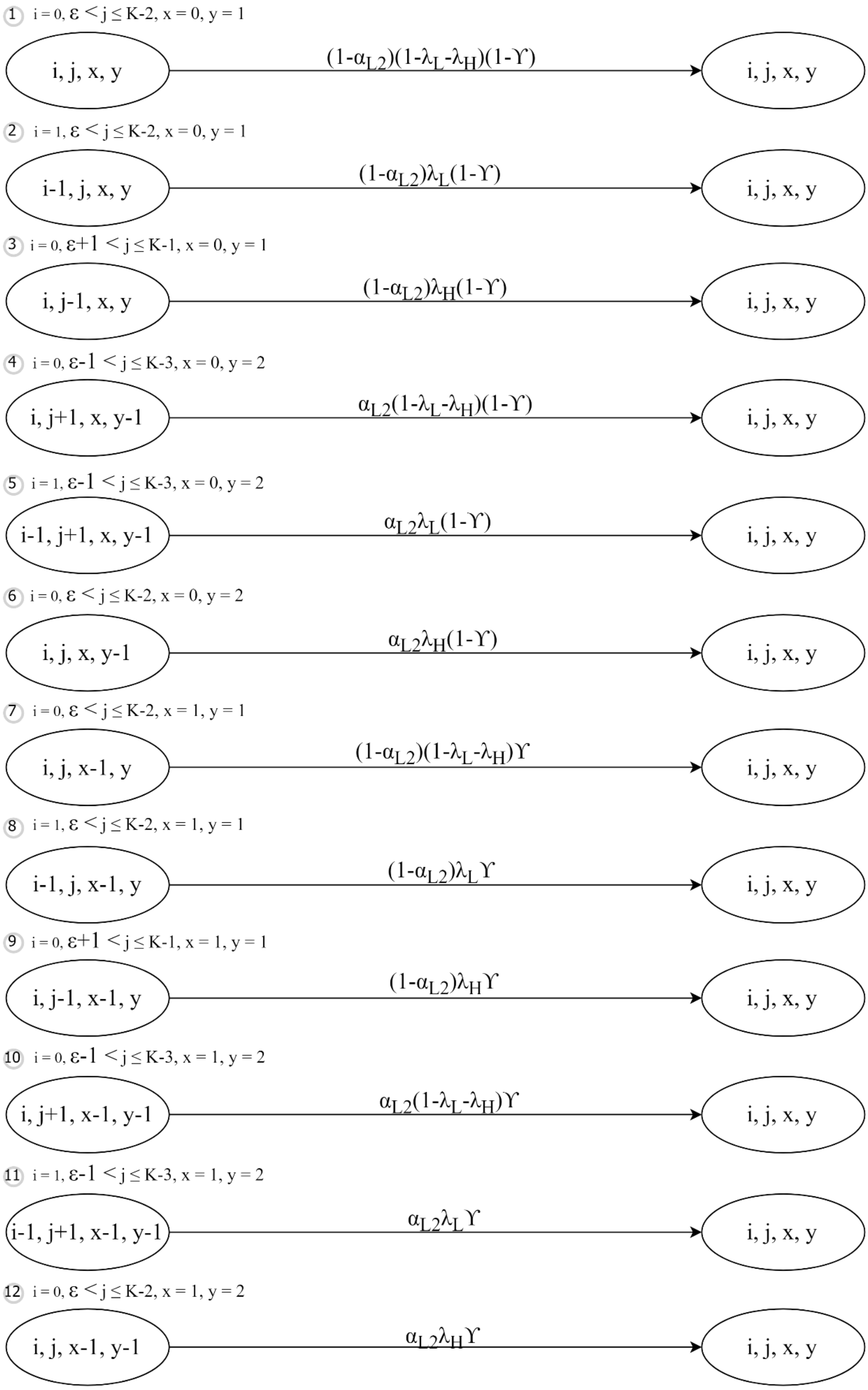
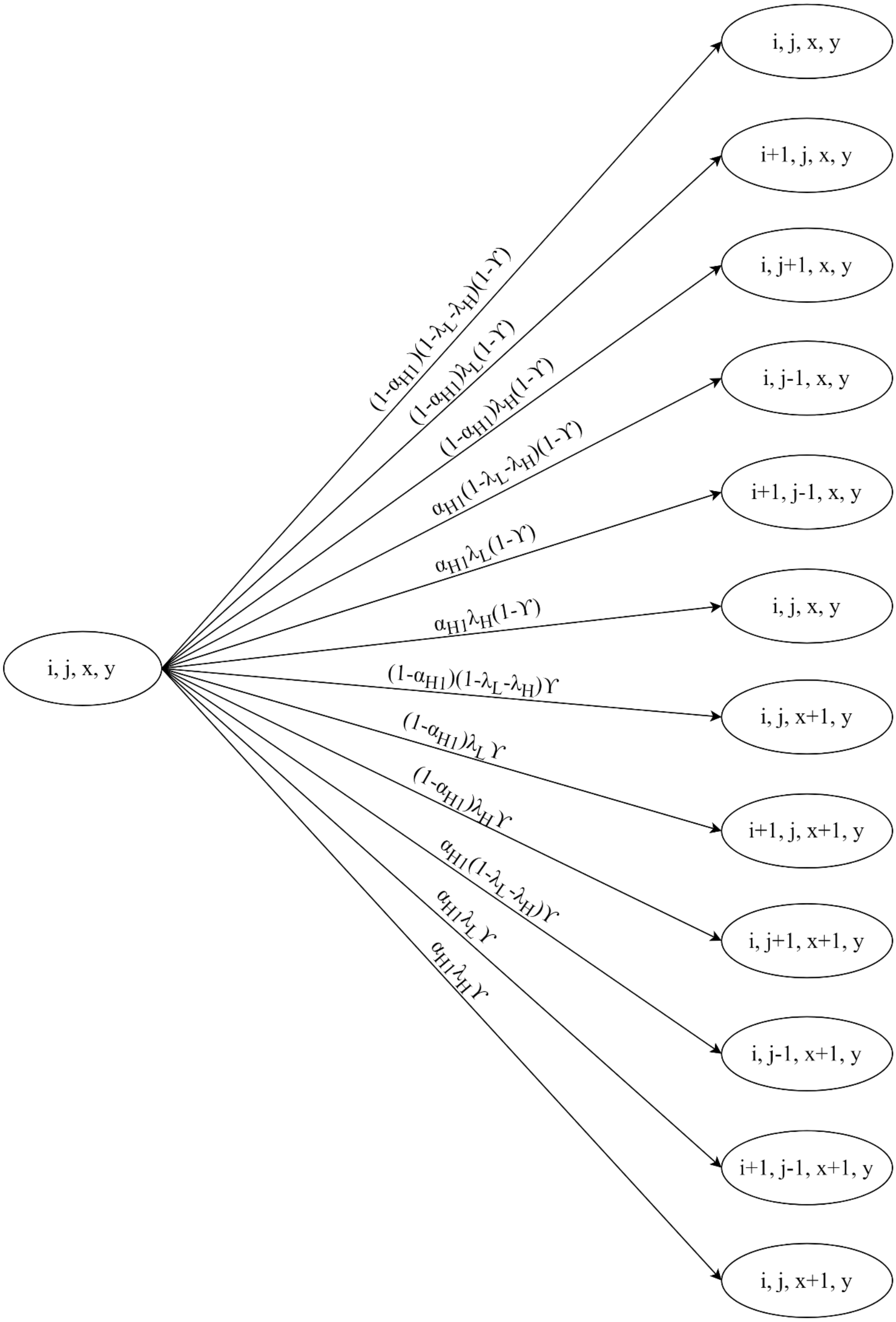


Fig 3. 111: The state diagram for $i = 0, \theta < j \leq K-2, x = 0, y = 1$

(6) $i = 0, 1 \leq j \leq \theta, x = 0, y = 2$



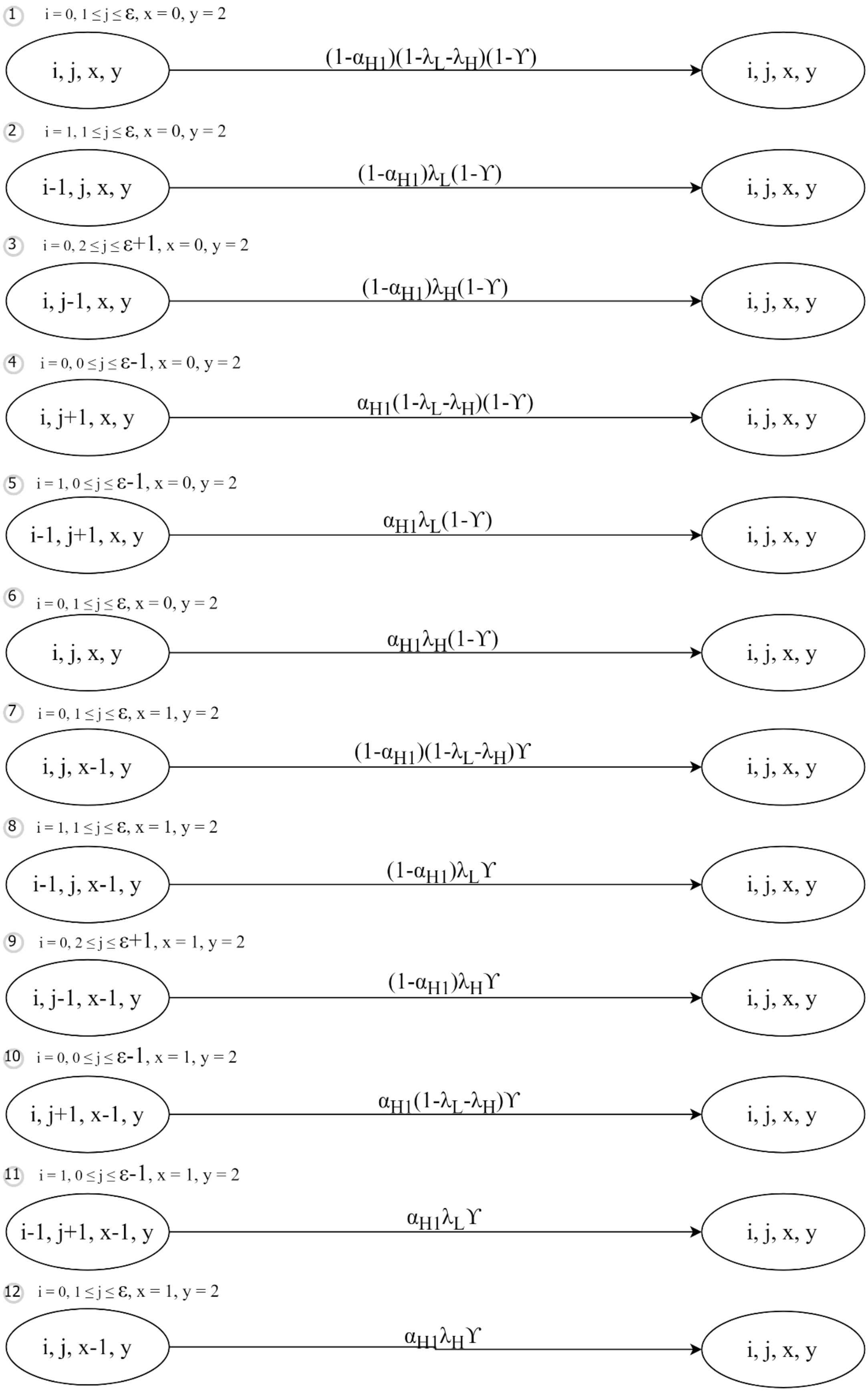
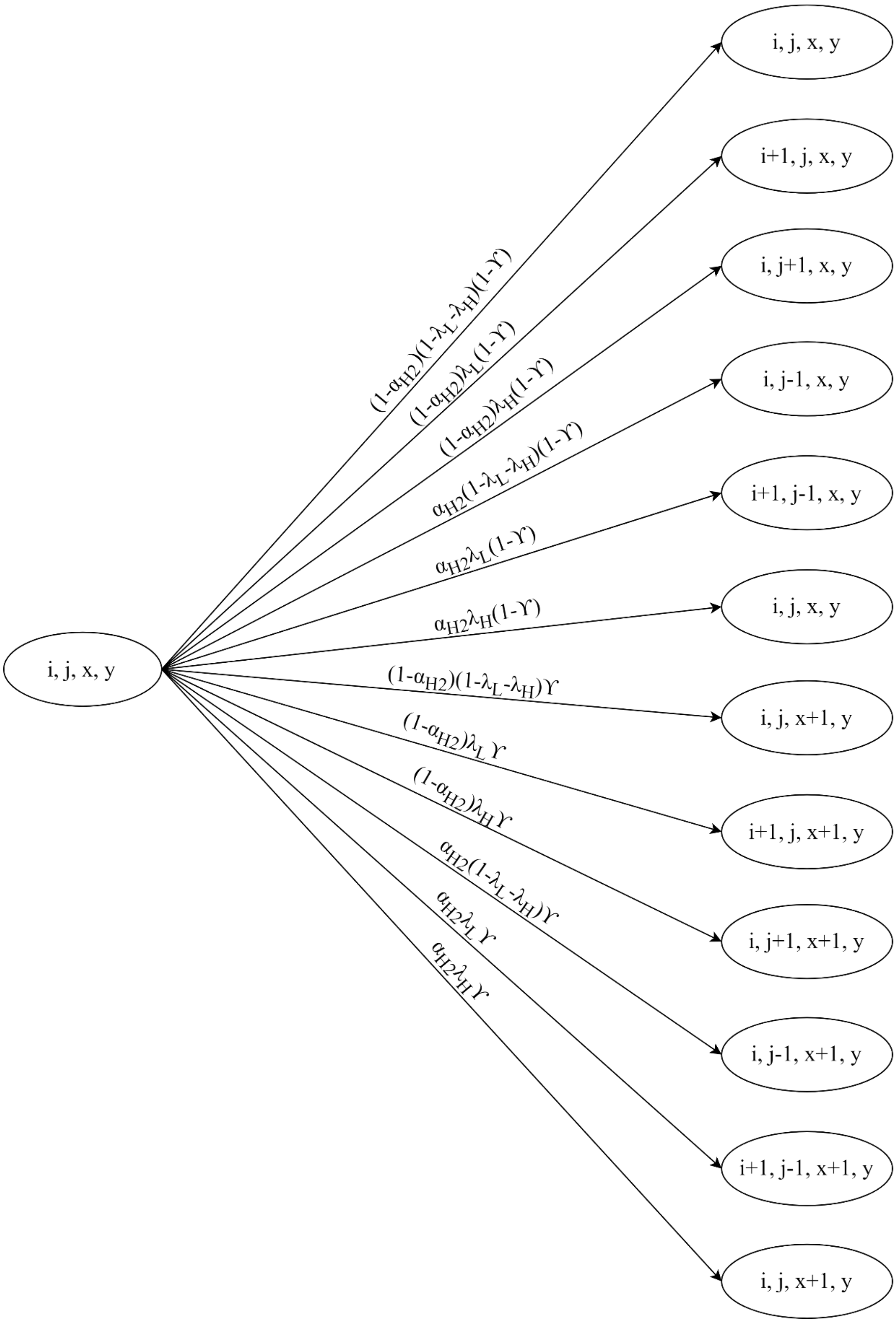


Fig 3. 112: The state diagram for $i = 0, 1 \leq j \leq \theta, x = 0, y = 2$

(7) $i = 0, \theta < j \leq K - 2, x = 0, y = 2$



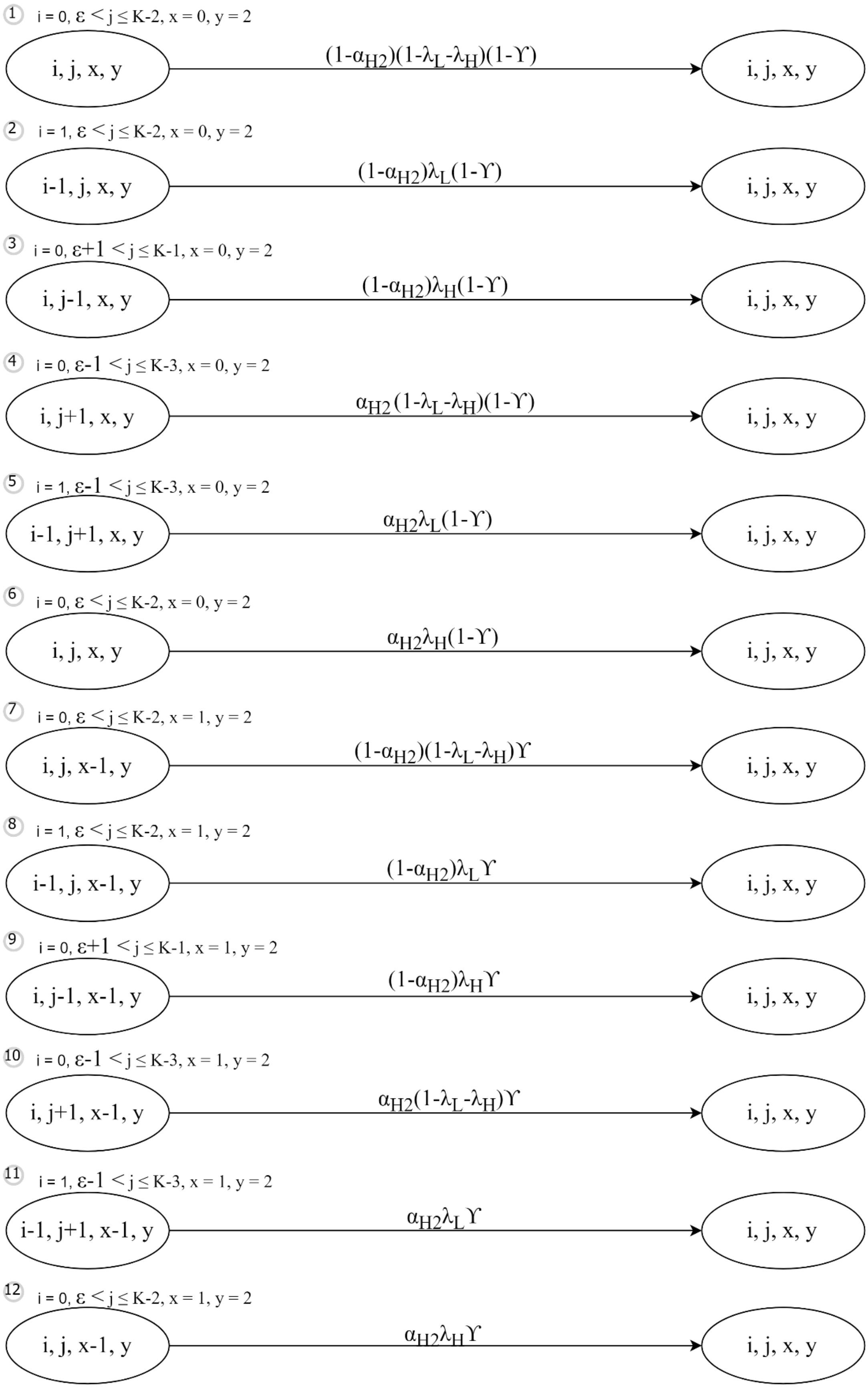
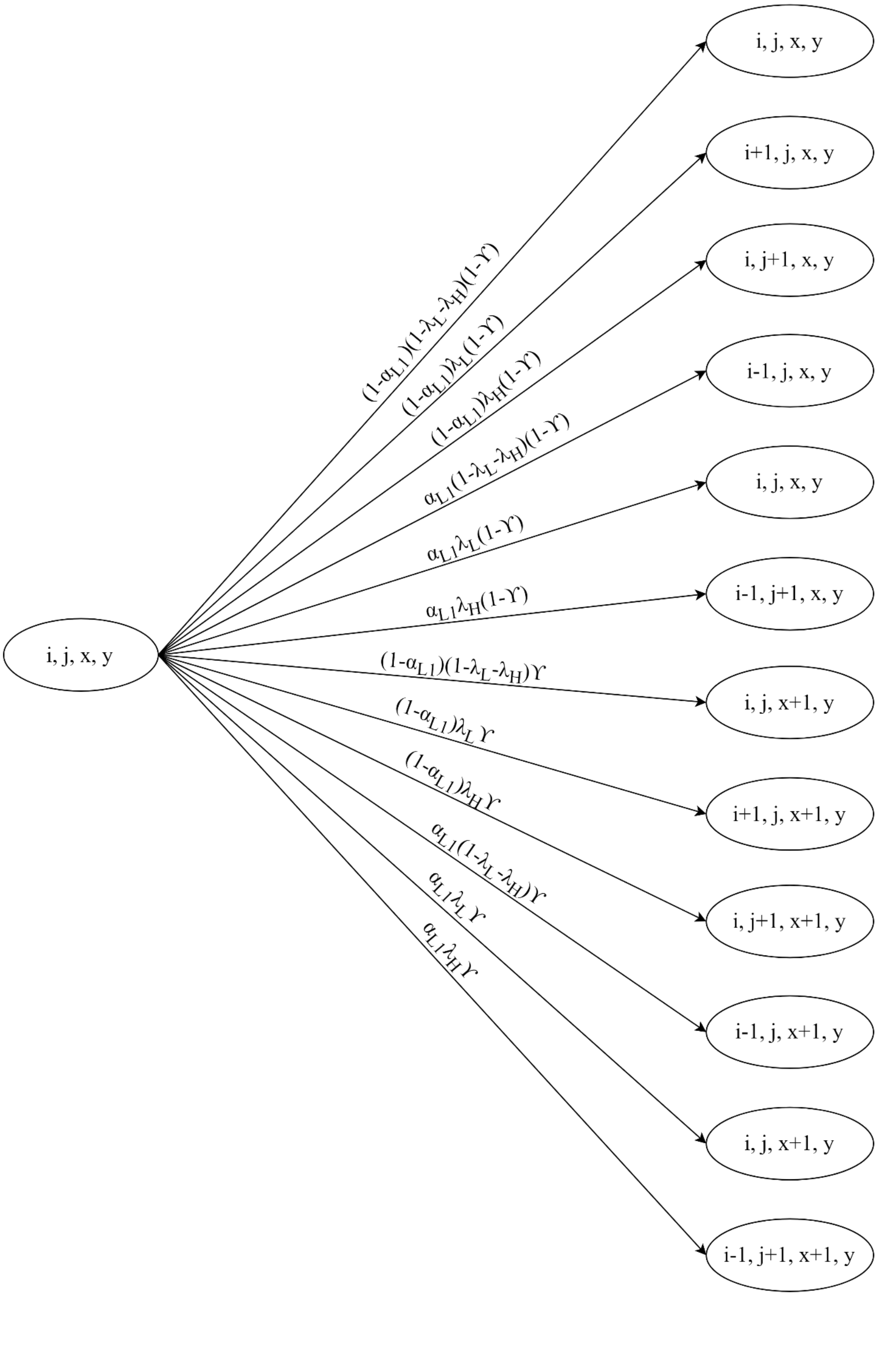


Fig 3. 113: The state diagram for $i = 0, \theta < j \leq K - 2, x = 0, y = 2$

(8) $1 \leq i \leq \theta, j = 0, x = 0, y = 1$



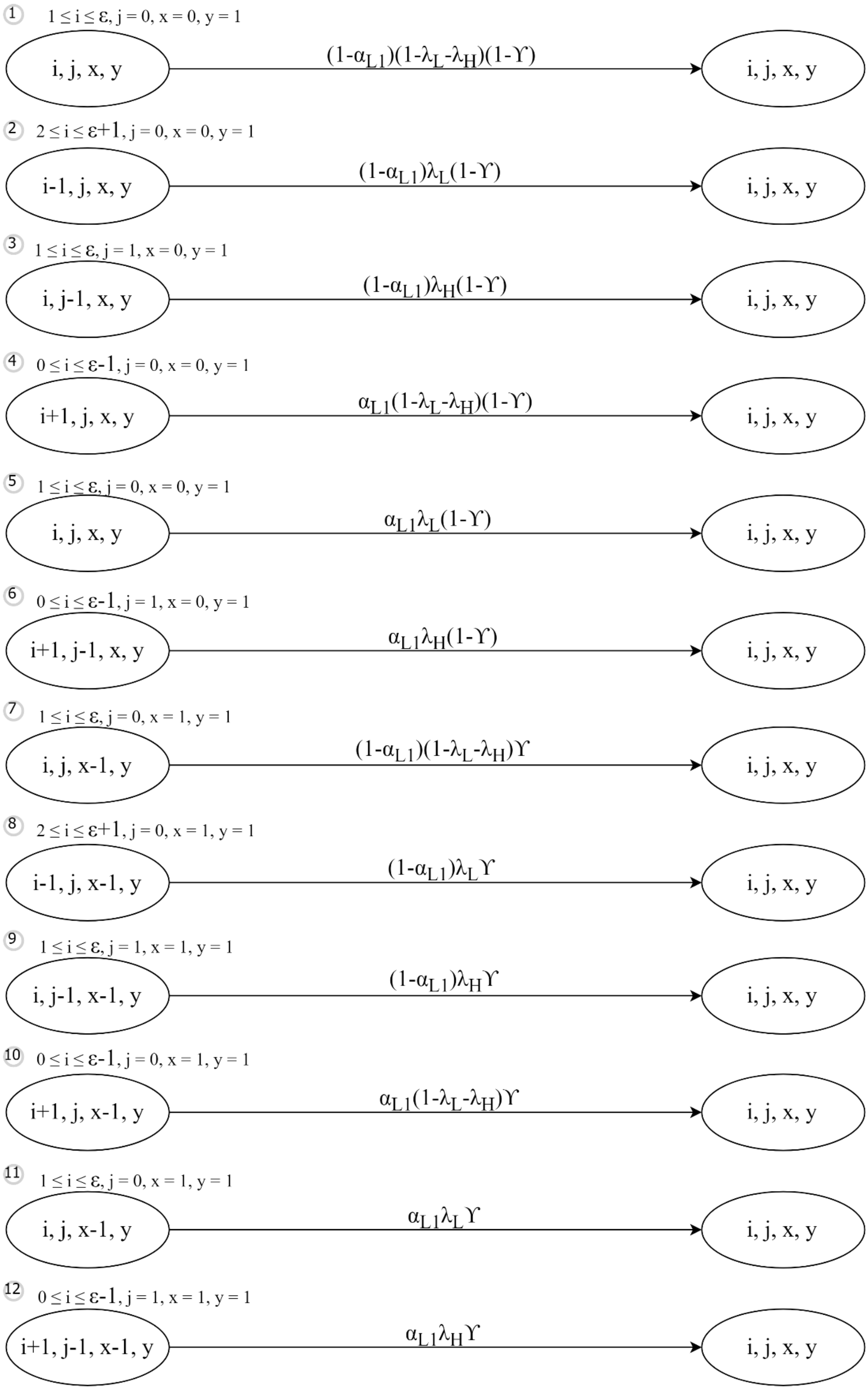
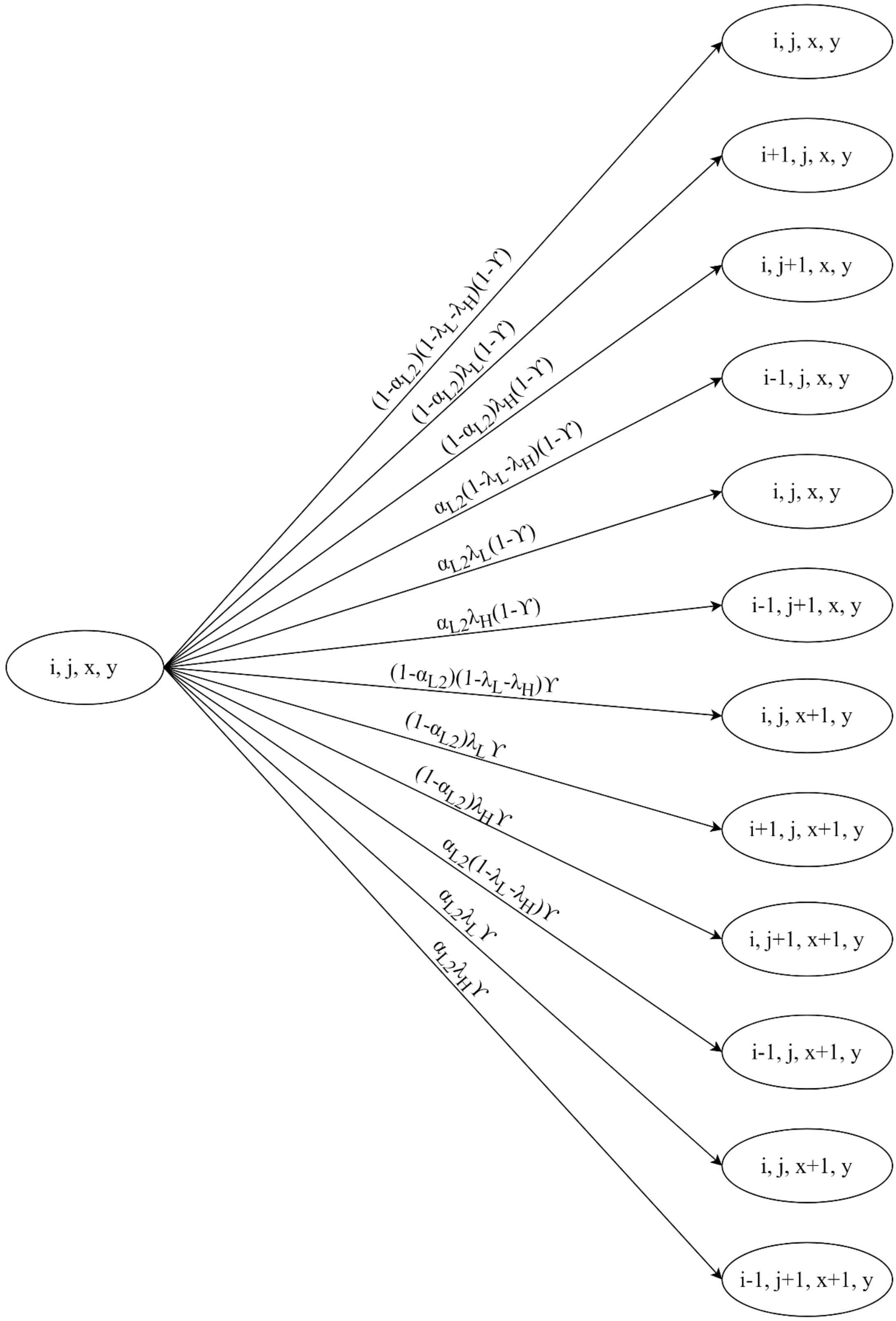


Fig 3. 114: The state diagram for $1 \leq i \leq \theta, j = 0, x = 0, y = 1$

(9) $\theta < i \leq K-2, j=0, x=0, y=1$



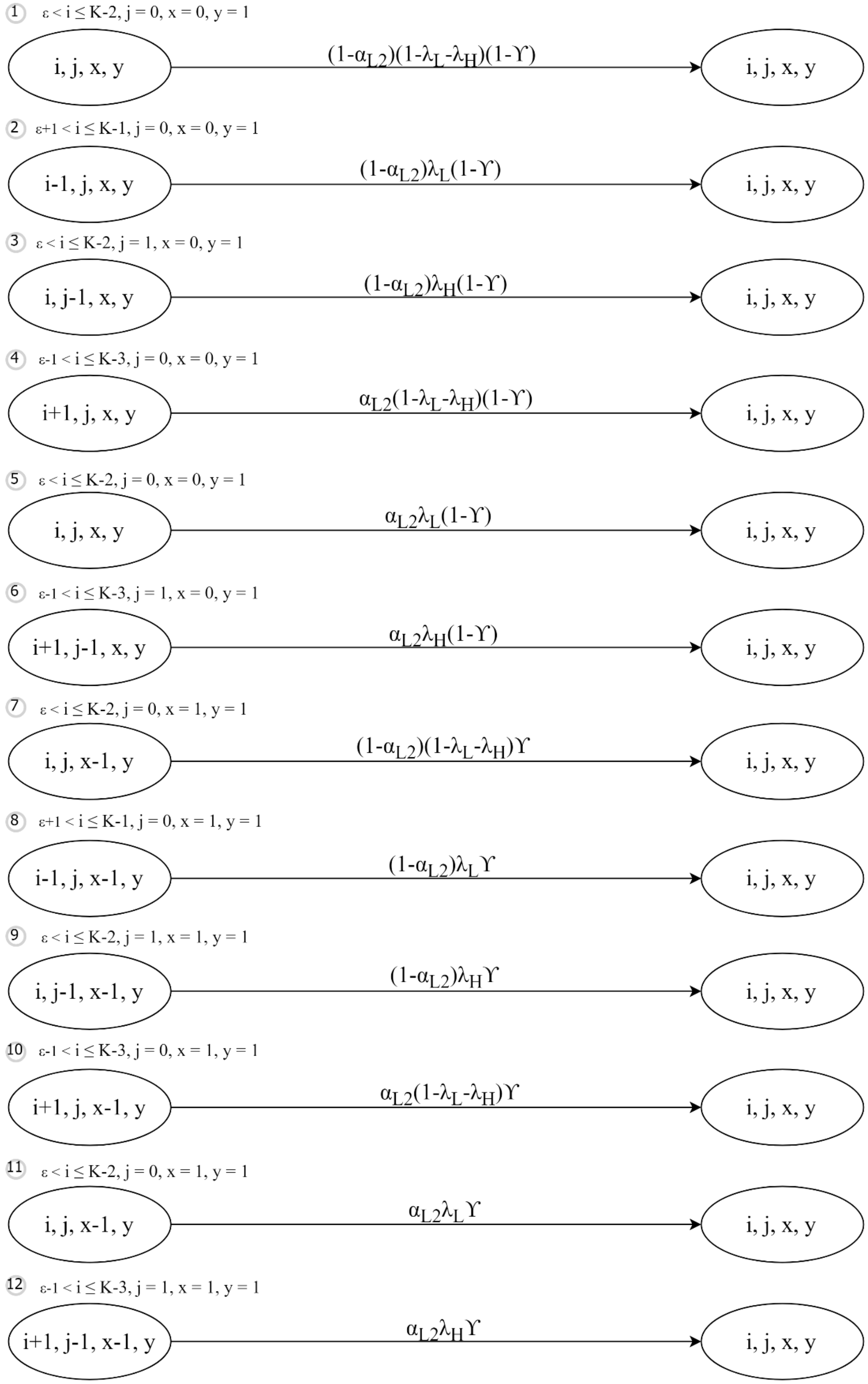
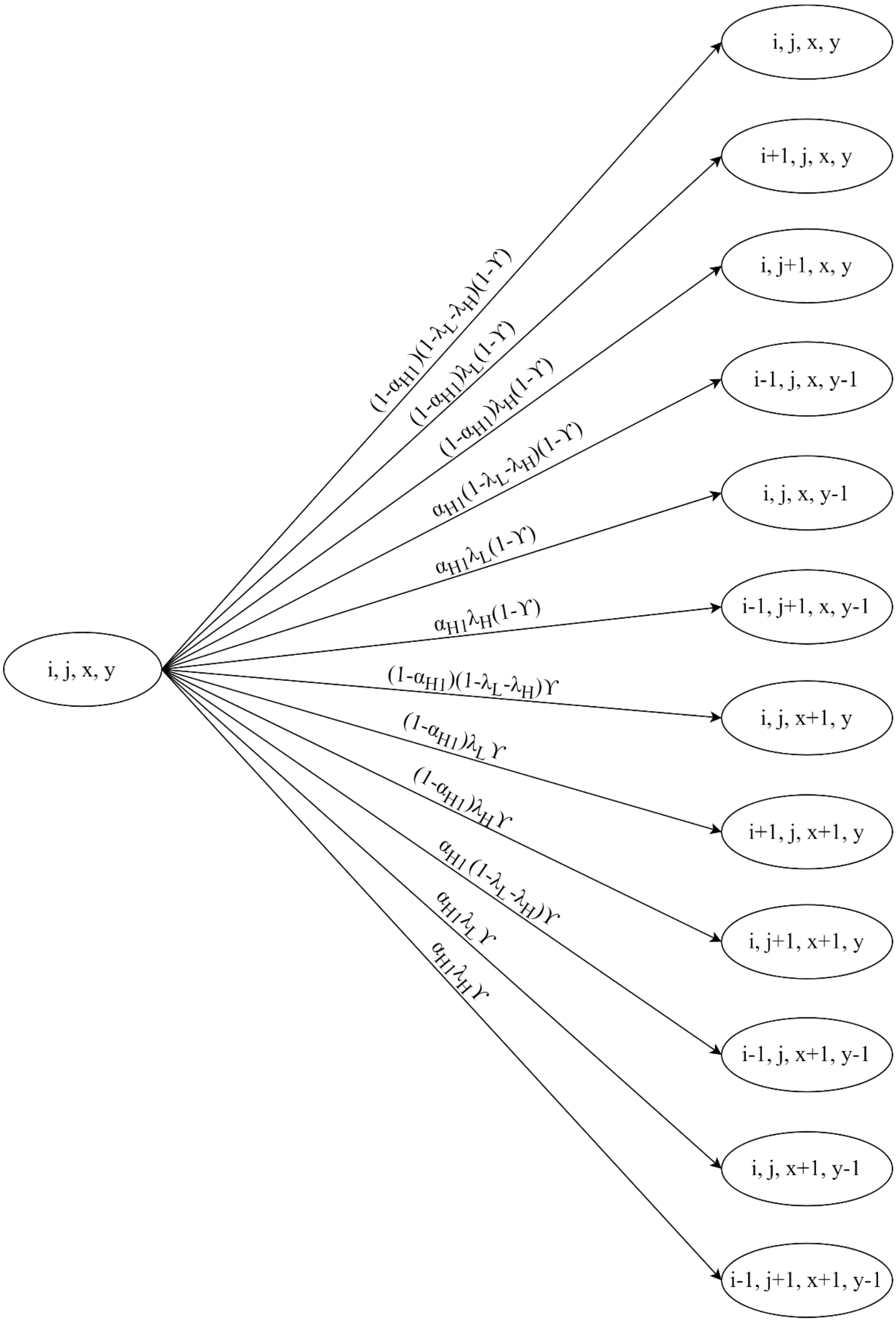


Fig 3. 115: The state diagram for $\theta < i \leq K-2, j = 0, x = 0, y = 1$

(10) $1 \leq i \leq \theta, j = 0, x = 0, y = 2$



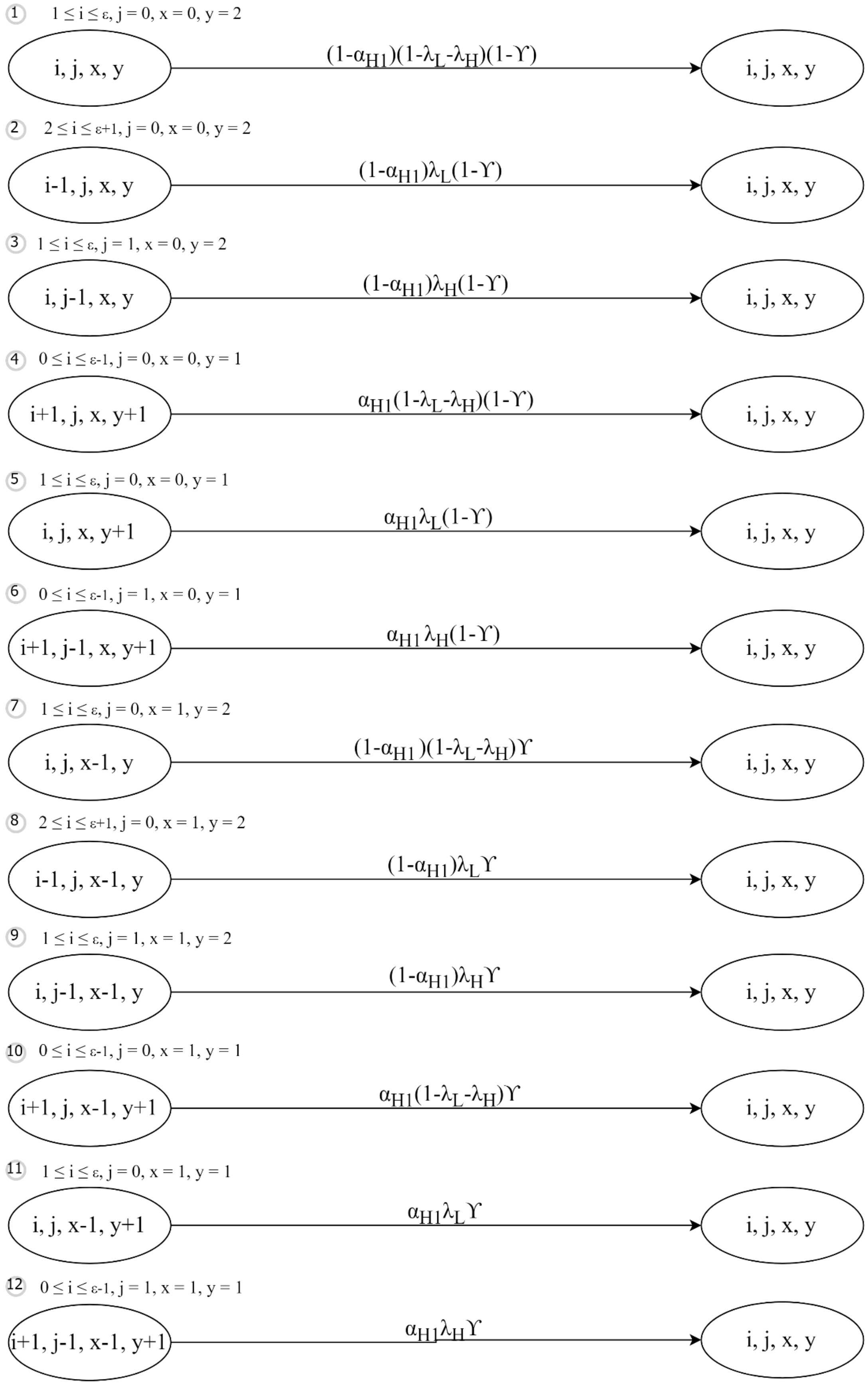
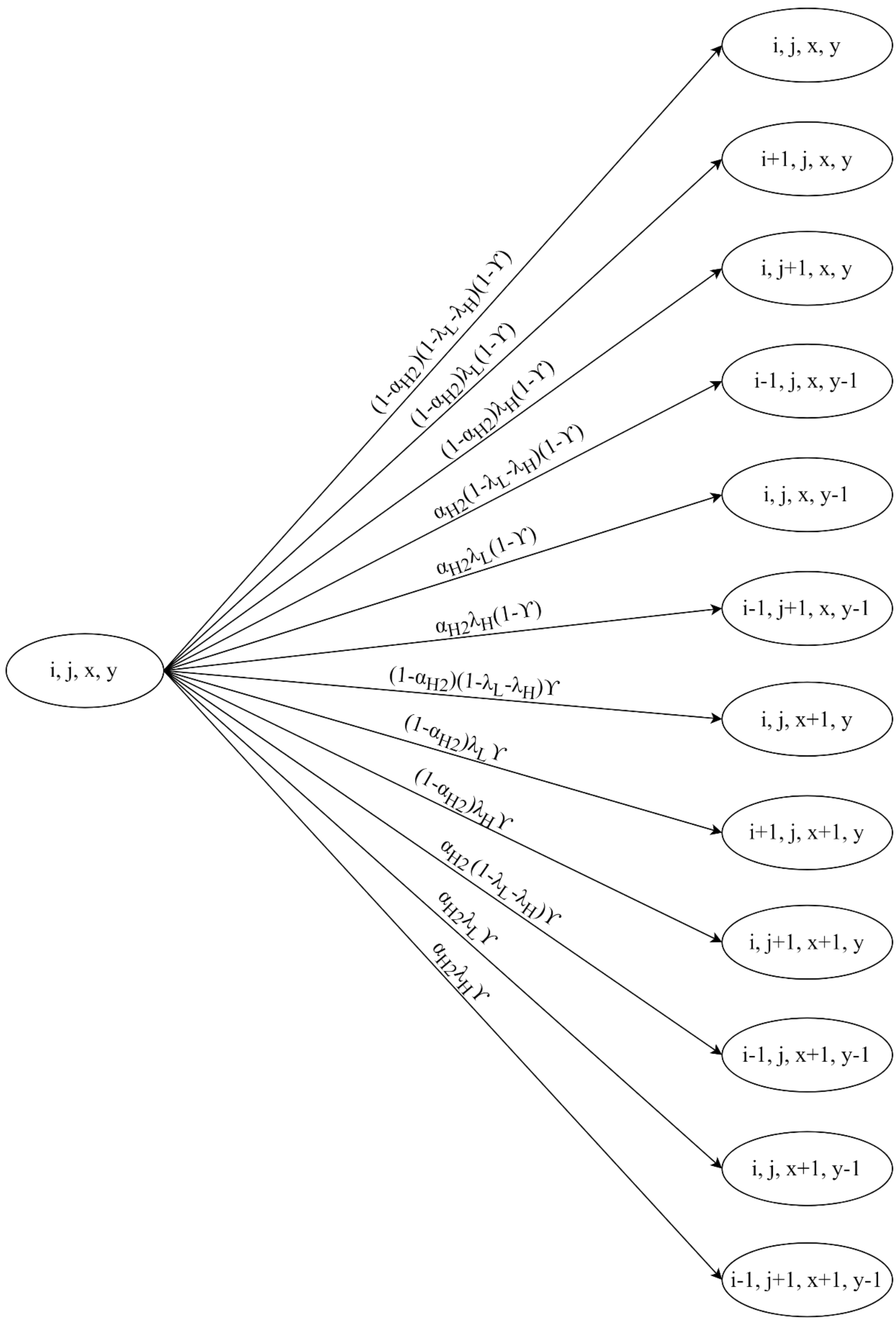


Fig 3. 116: The state diagram for $1 \le i \le \theta, j = 0, x = 0, y = 2$

(11) $\theta < i \leq K-2, j=0, x=0, y=2$



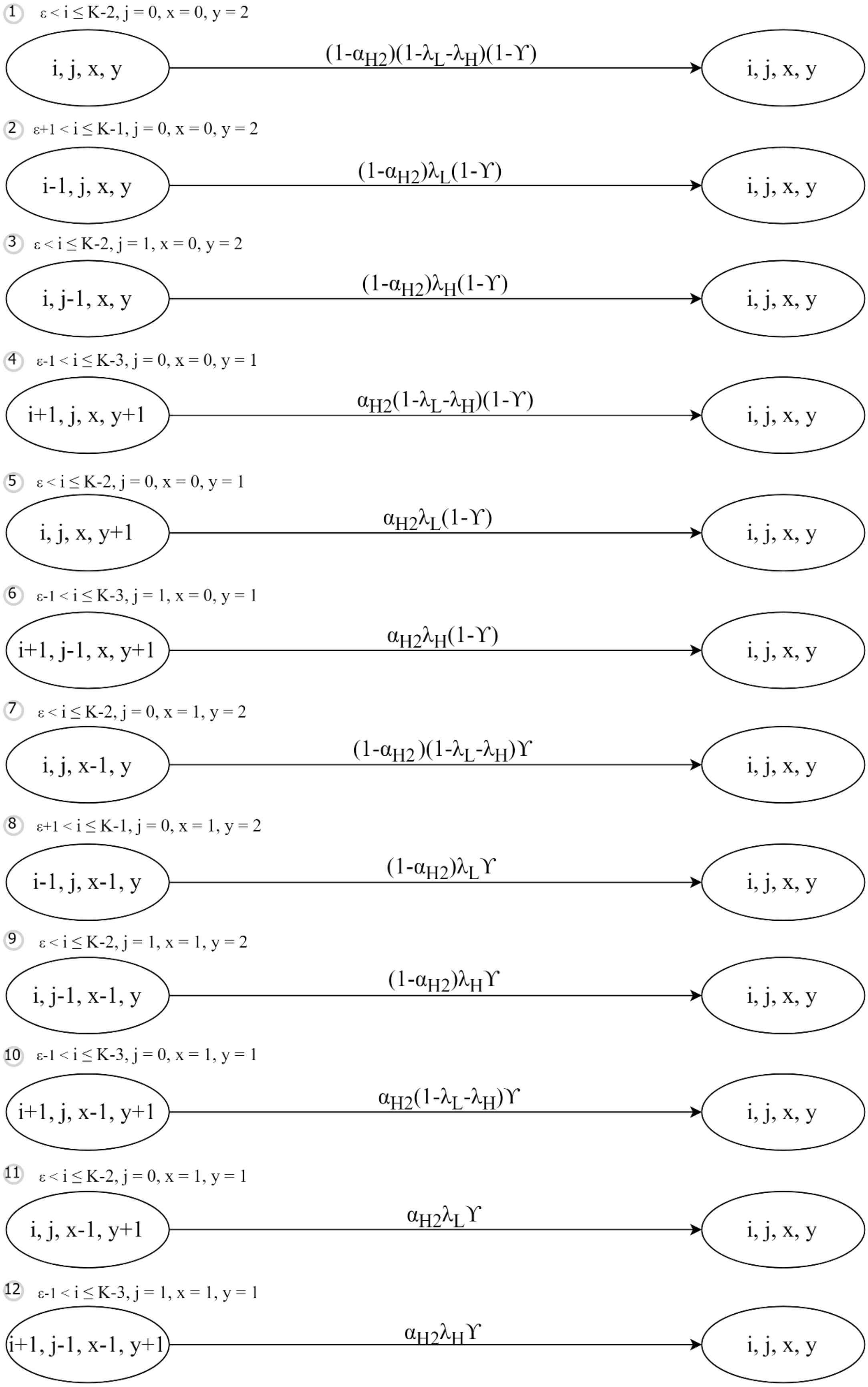
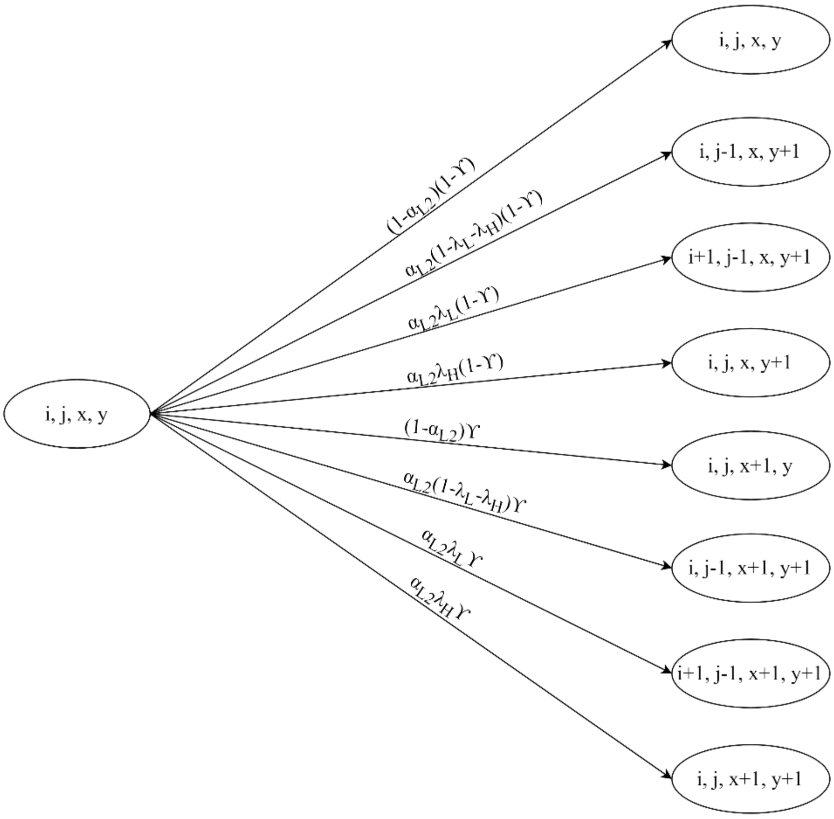


Fig 3. 117: The state diagram for $\theta < i \leq K-2, j = 0, x = 0, y = 2$

(12) $i = 0, j = K-1, x = 0, y = 1$



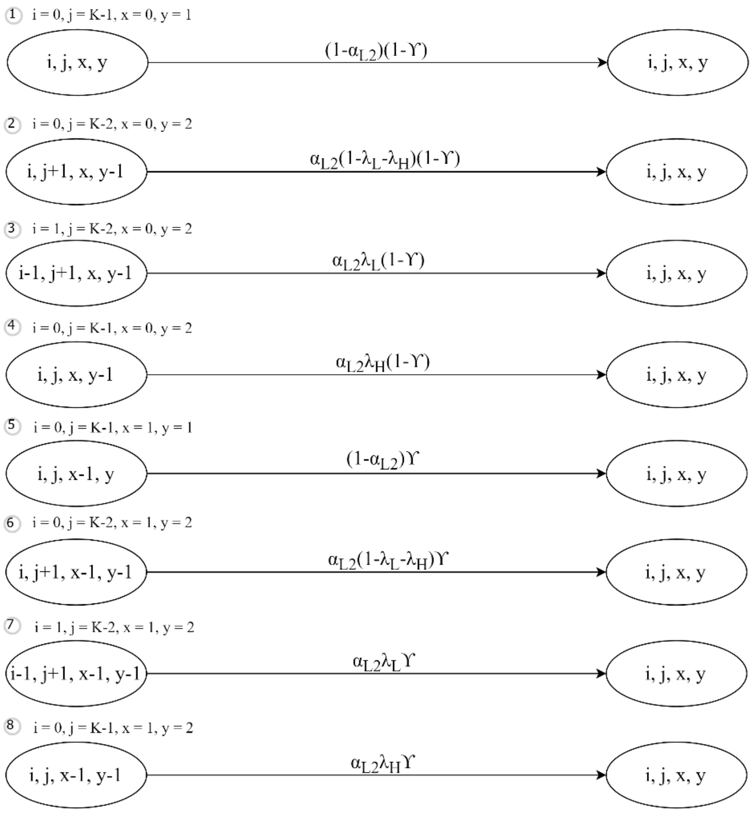


Fig 3. 118: The state diagram for $i = 0, j = K-1, x = 0, y = 1$

(13) $i = 0, j = K - 1, x = 0, y = 2$

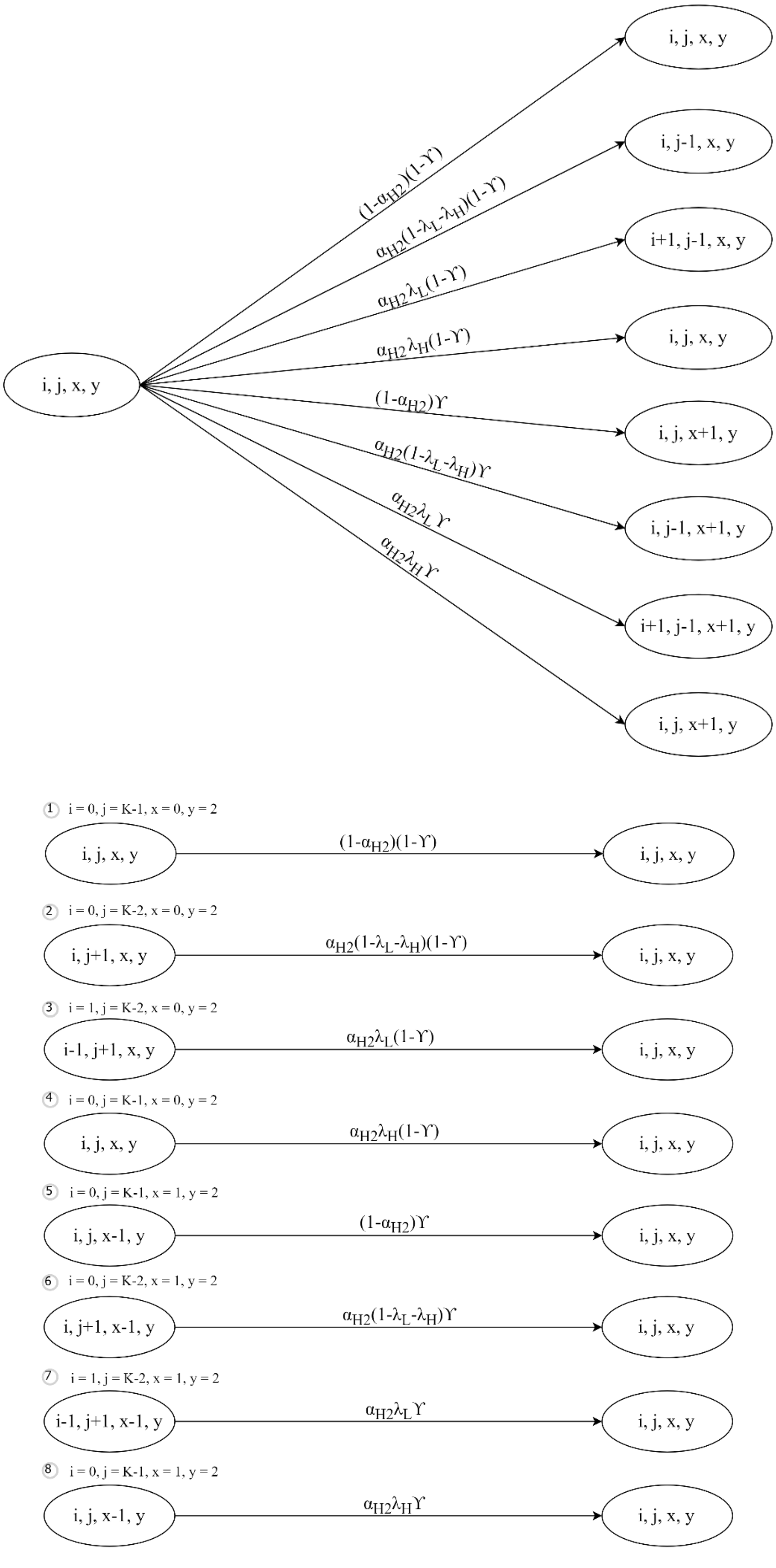


Fig 3. 119: The state diagram for $i = 0, j = K - 1, x = 0, y = 2$

(14) $i = K - 1, j = 0, x = 0, y = 1$

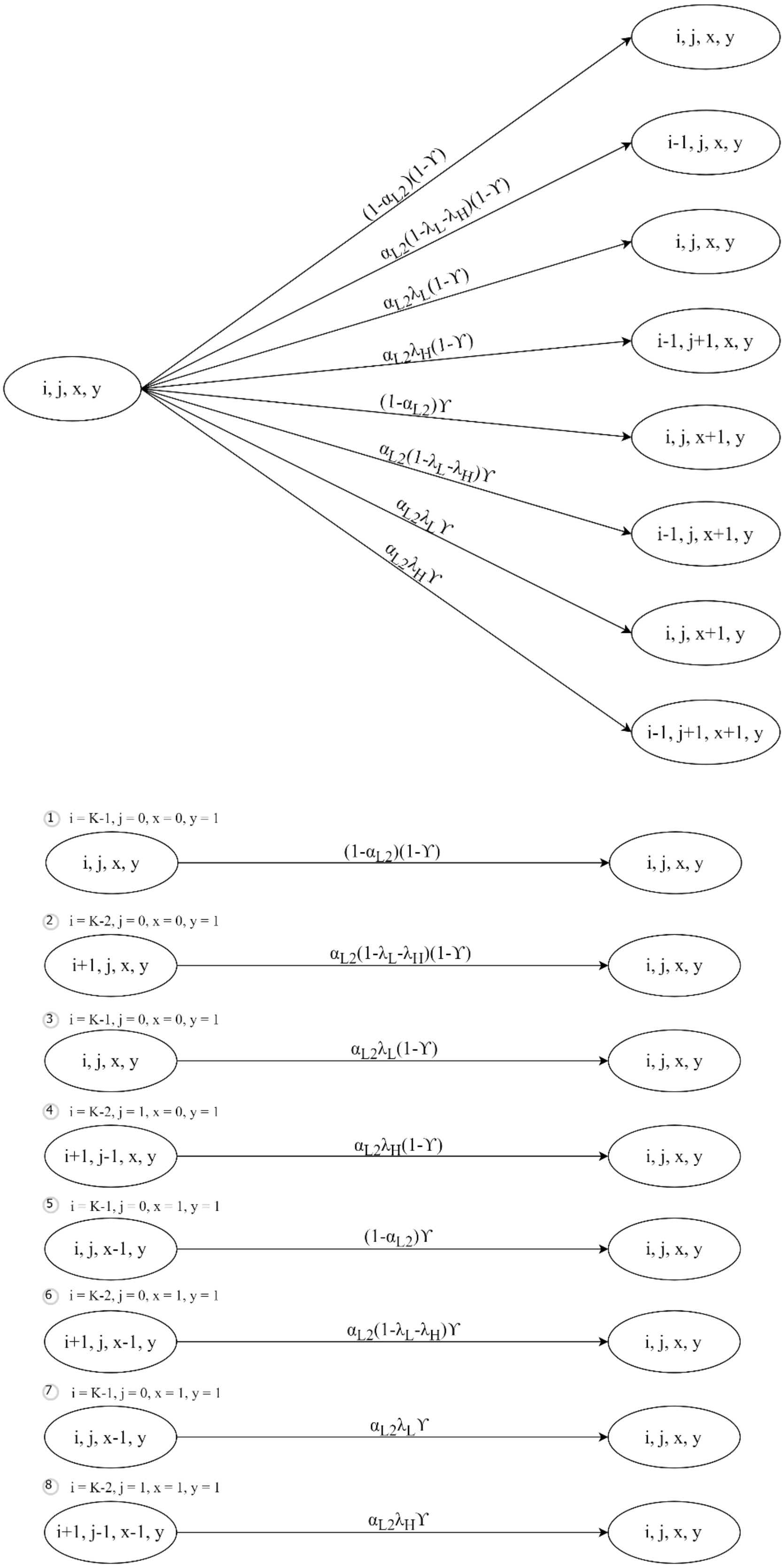


Fig 3. 120: The state diagram for $i = K - 1, j = 0, x = 0, y = 1$

(15) $i = K - 1, j = 0, x = 0, y = 2$

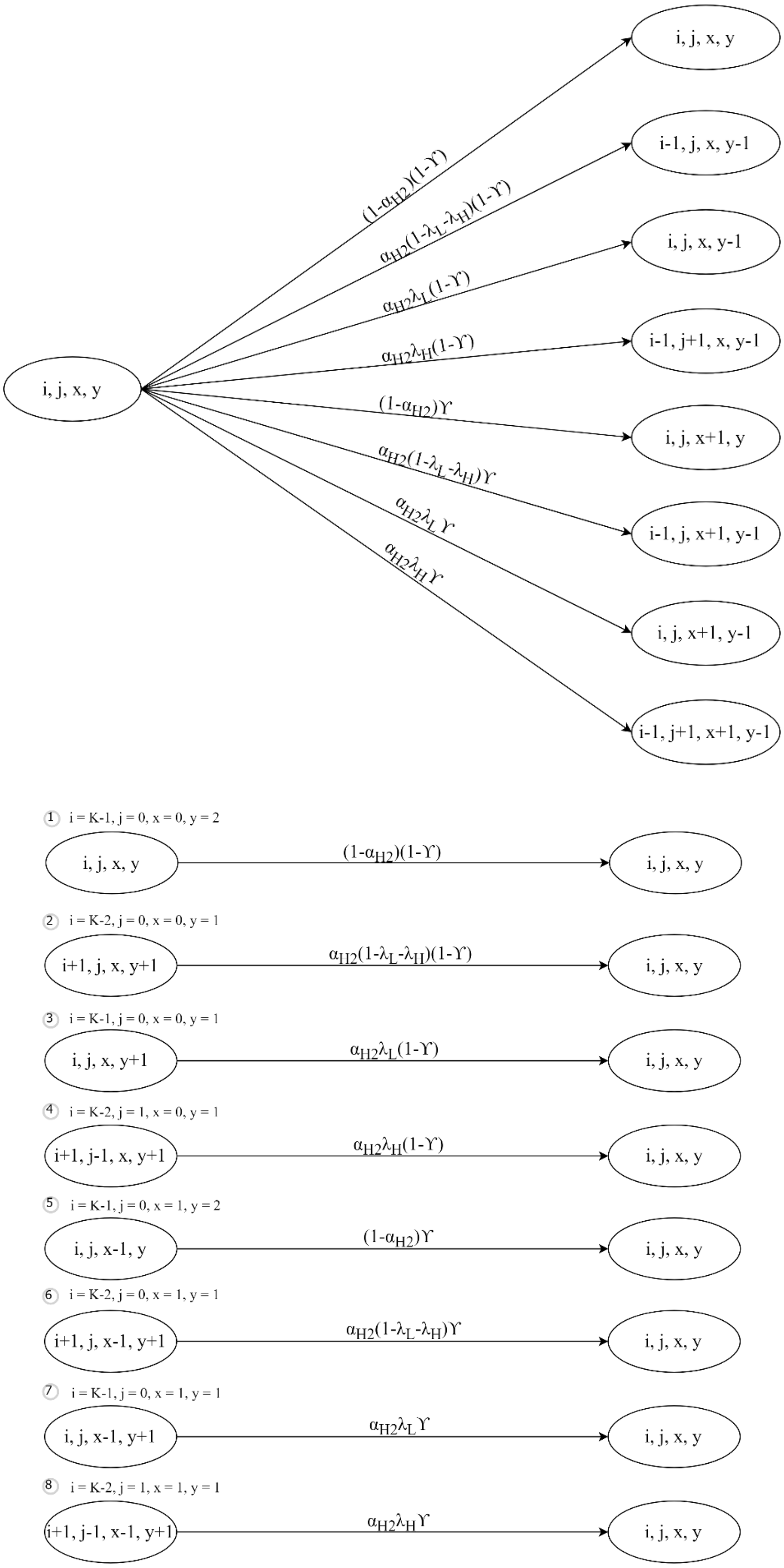


Fig 3. 121: The state diagram for $i = K - 1, j = 0, x = 0, y = 2$

(16) $1 \leq i \leq \theta, 1 \leq j \leq \theta - i, x = 0, y = 1$

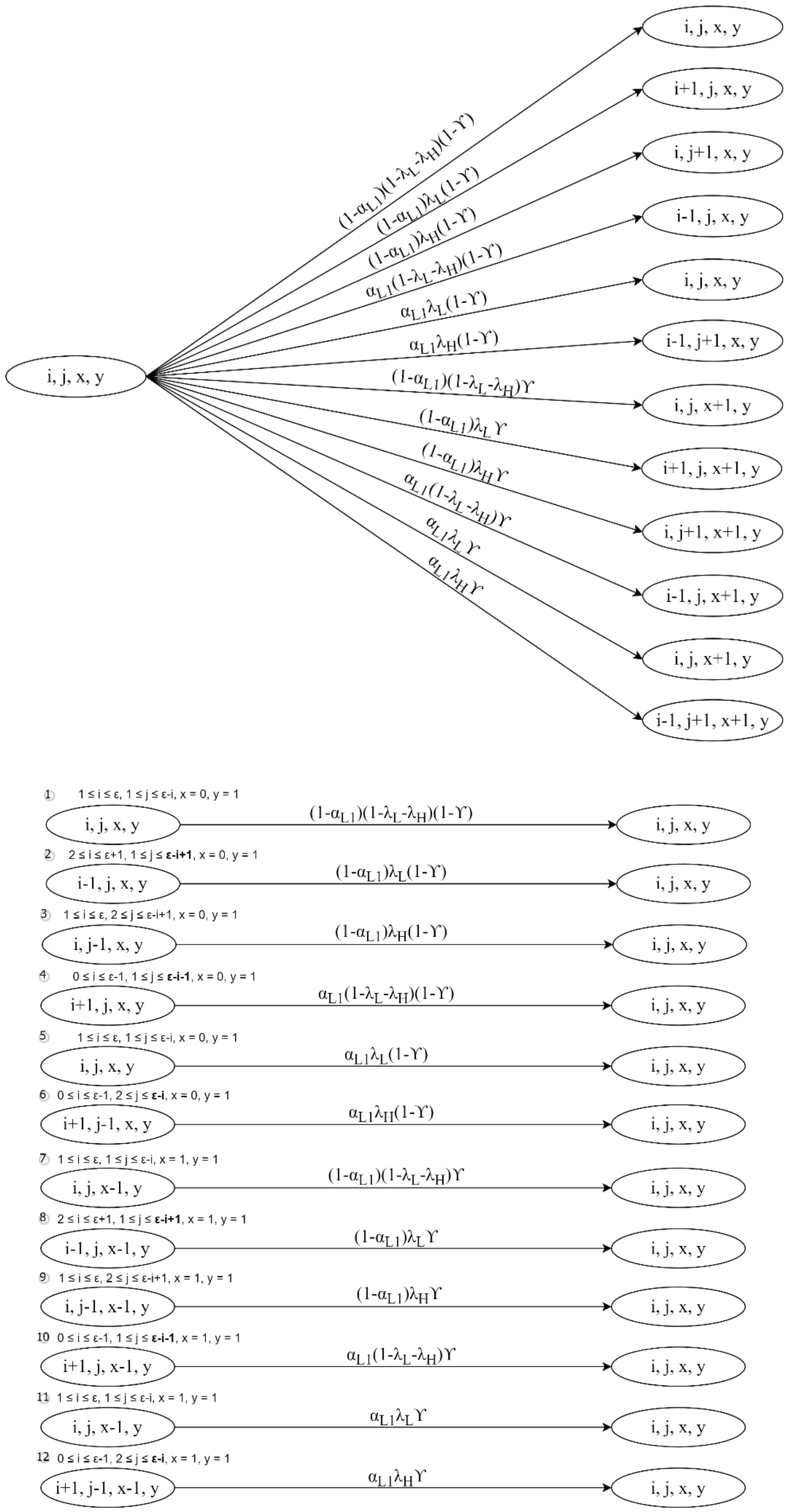


Fig 3. 122: The state diagram for $1 \leq i \leq \theta, 1 \leq j \leq \theta - i, x = 0, y = 1$

(17) $1 \leq i \leq \theta, \theta - i < j < K - i - 1, x = 0, y = 1$

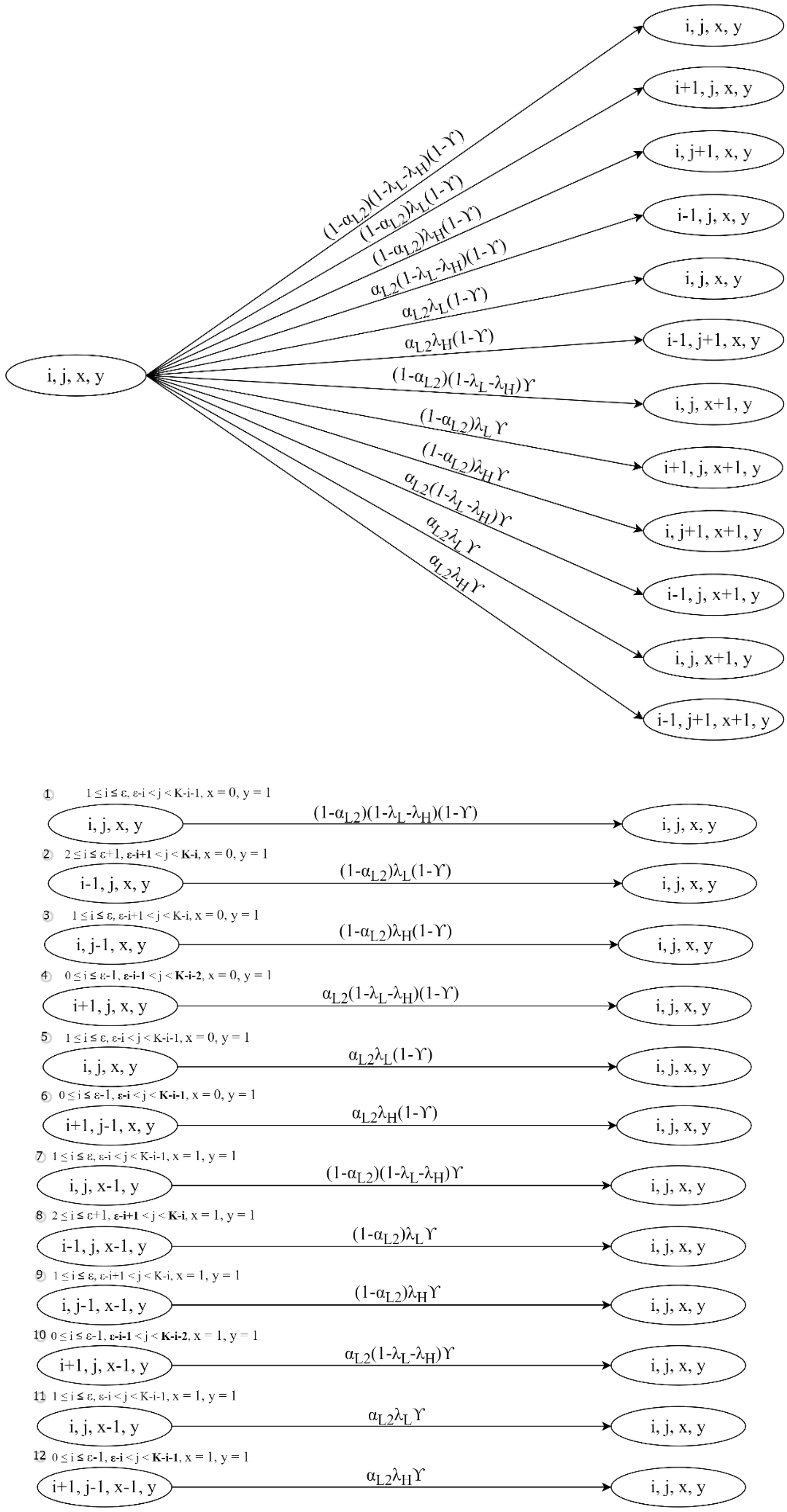
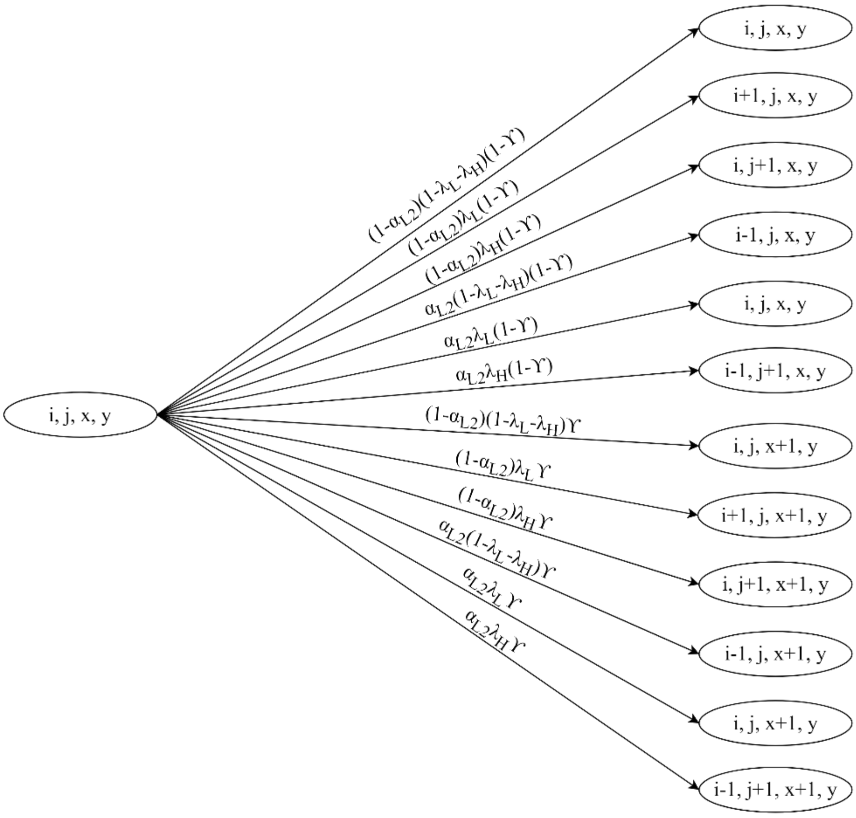


Fig 3. 123: The state diagram for $1 \leq i \leq \theta, \theta - i < j < K - i - 1, x = 0, y = 1$

(18) $\theta < i \leq K-2, 1 \leq j < K-i-1, x=0, y=1$



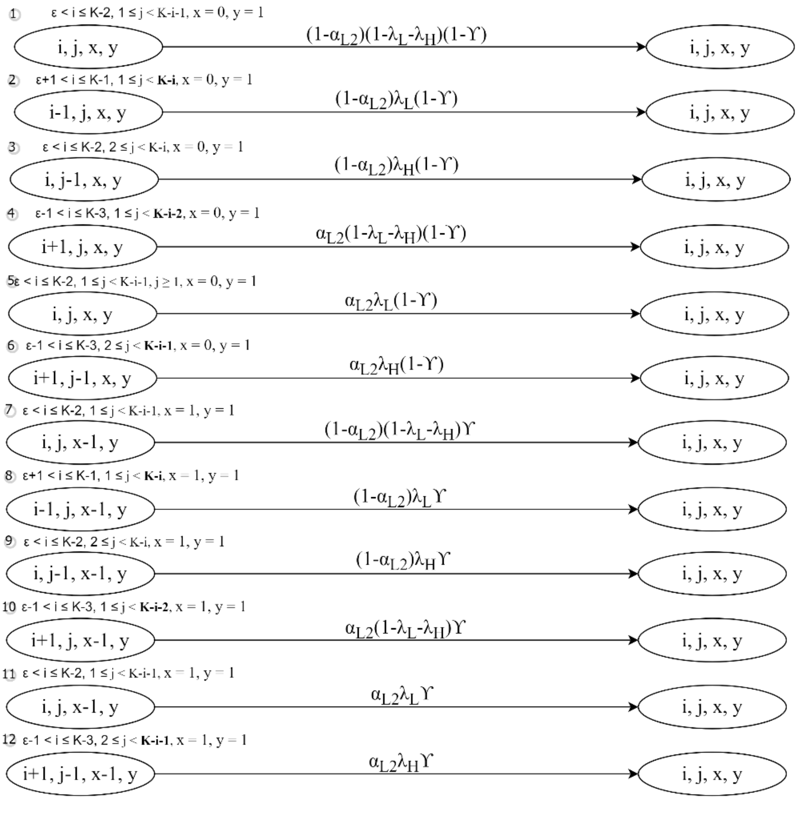
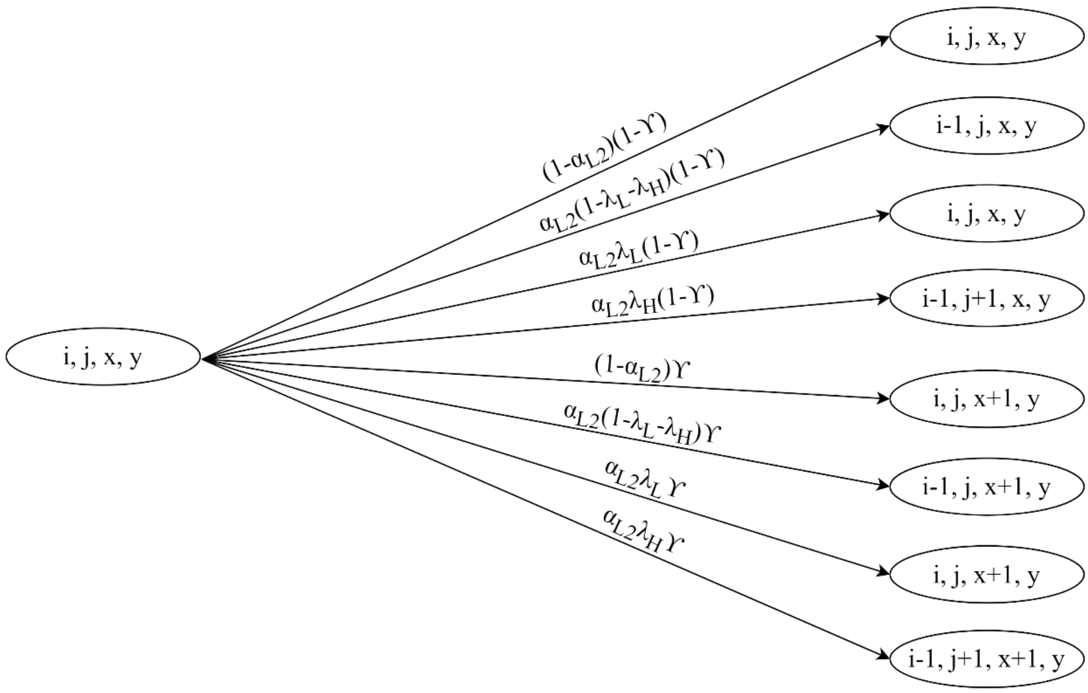


Fig 3. 124: The state diagram for $\theta < i \leq K-2, 1 \leq j < K-i-1, x=0, y=1$

(19) $1 \leq i \leq K-2, j = K-i-1, x = 0, y = 1$



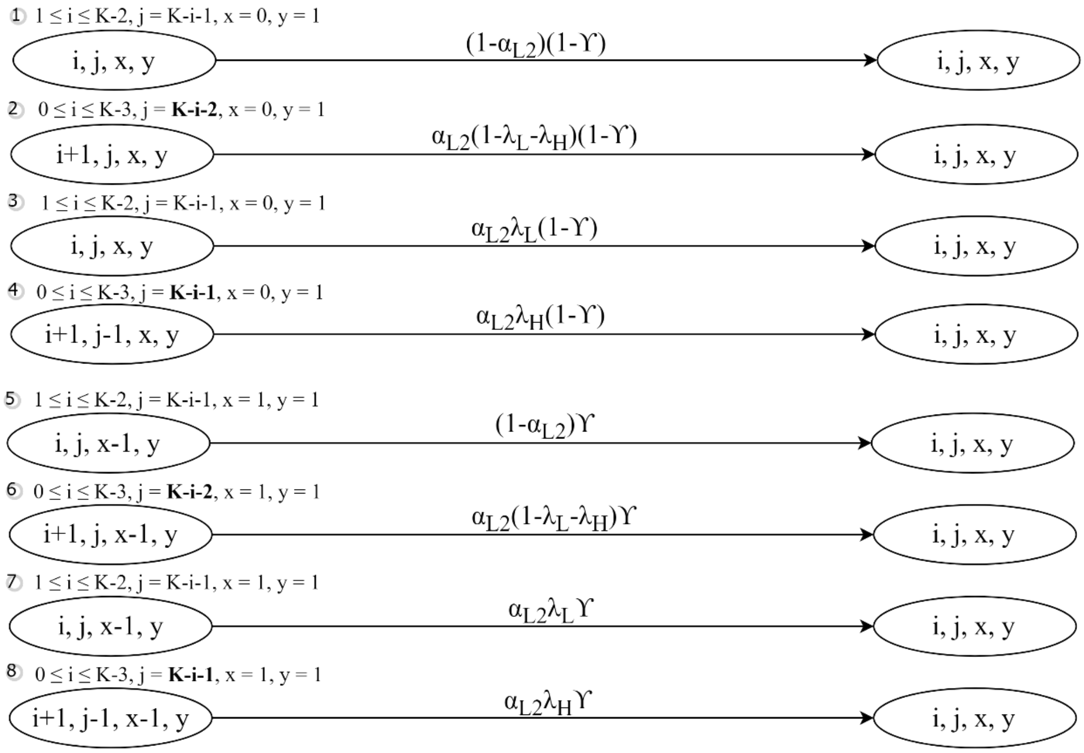
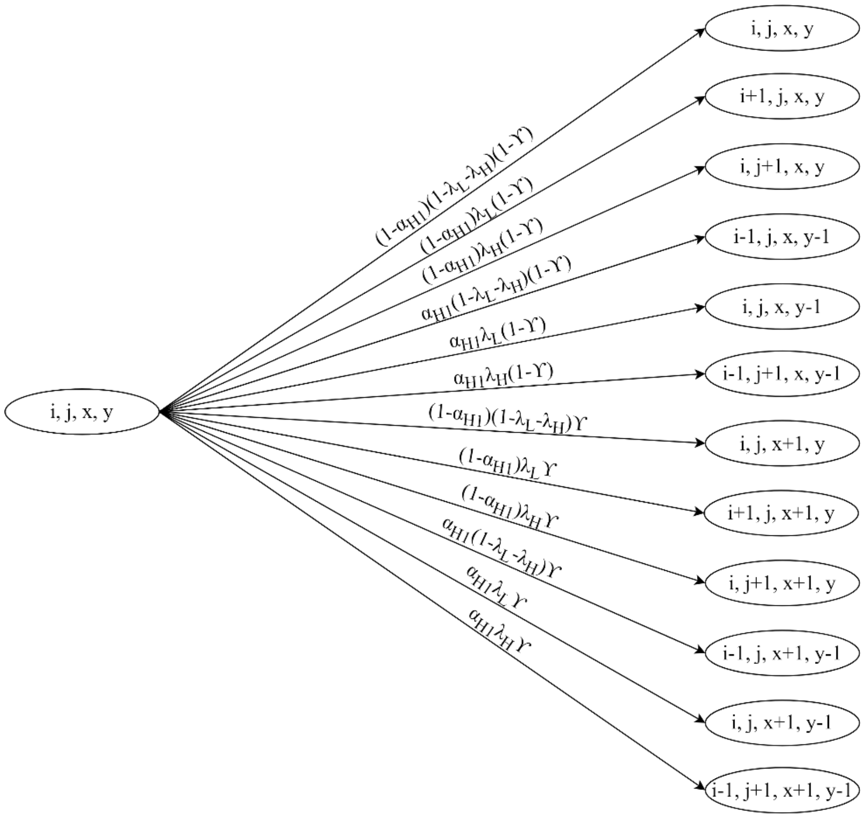


Fig 3. 125: The state diagram for $1 \leq i \leq K-2, j = K-i-1, x = 0, y = 1$

$(20)\ 1 \le i \le \theta, 1 \le j \le \theta - i, x = 0, y = 2$



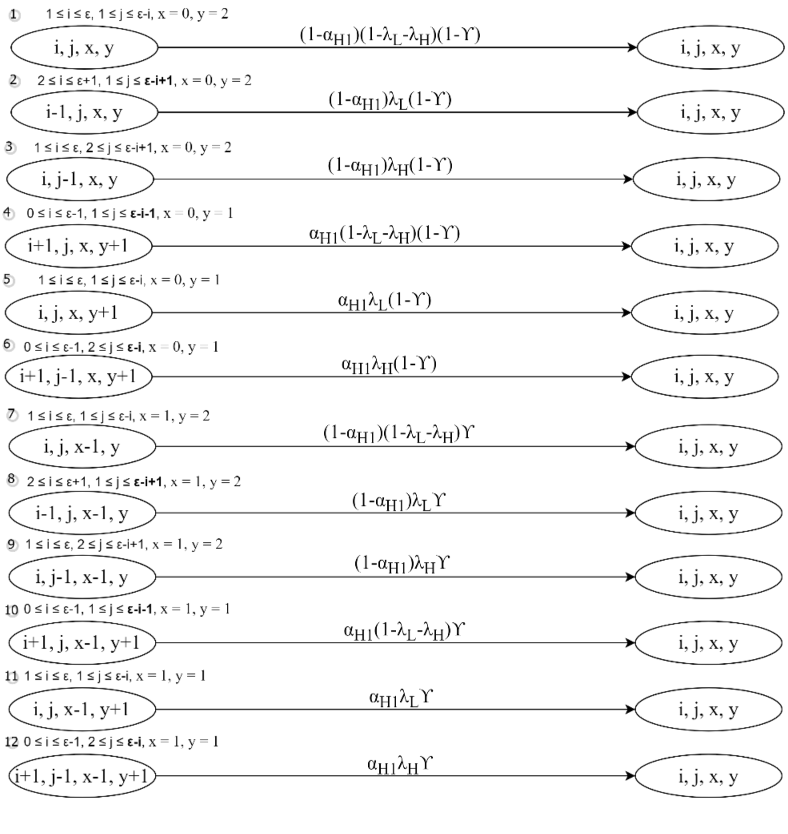


Fig 3. 126: The state diagram for $1 \le i \le \theta, 1 \le j \le \theta - i, x = 0, y = 2$

(21) $1 \leq i \leq \theta\ , \theta - i < j < K - i - 1, x = 0, y = 2$

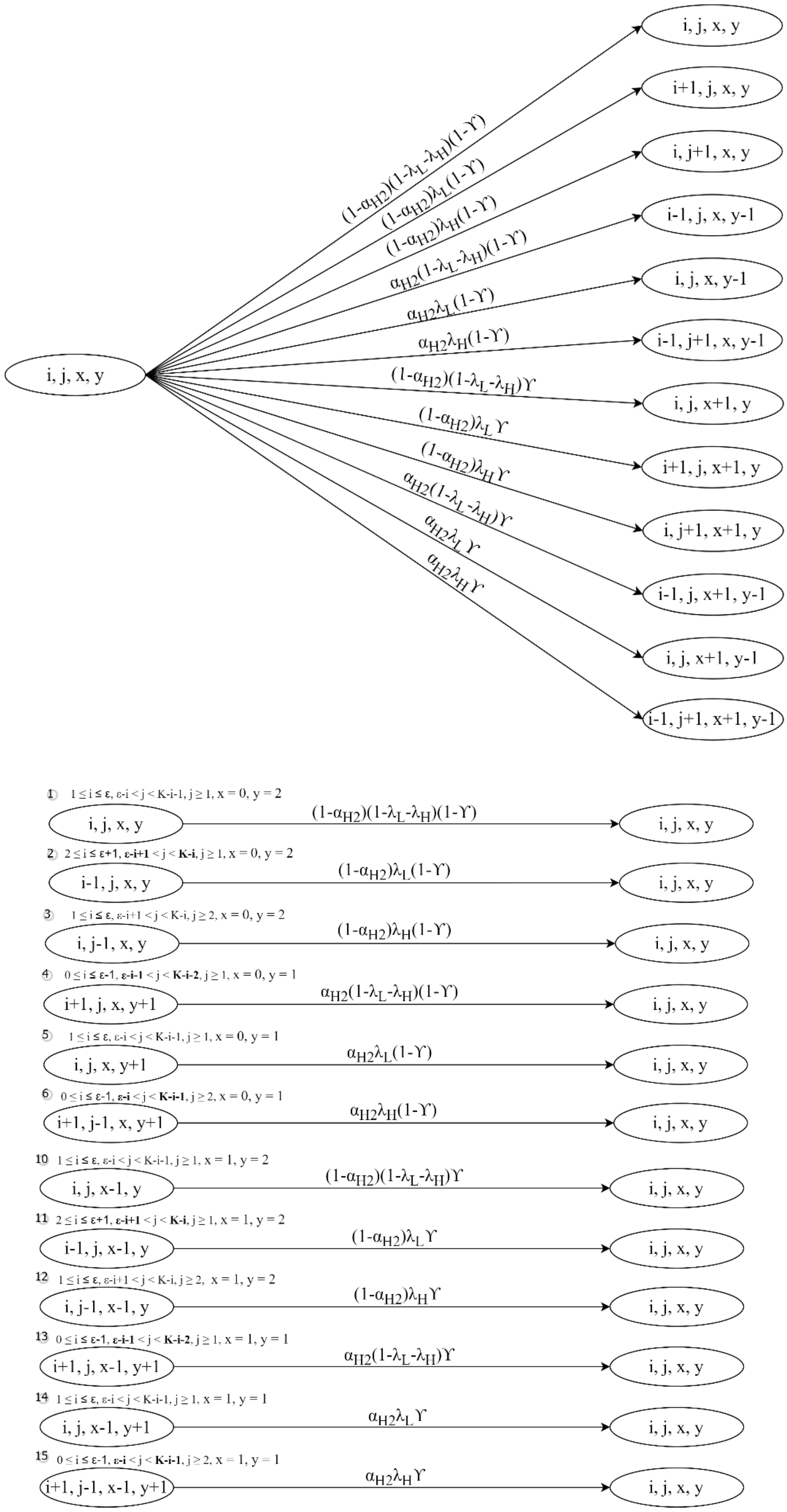
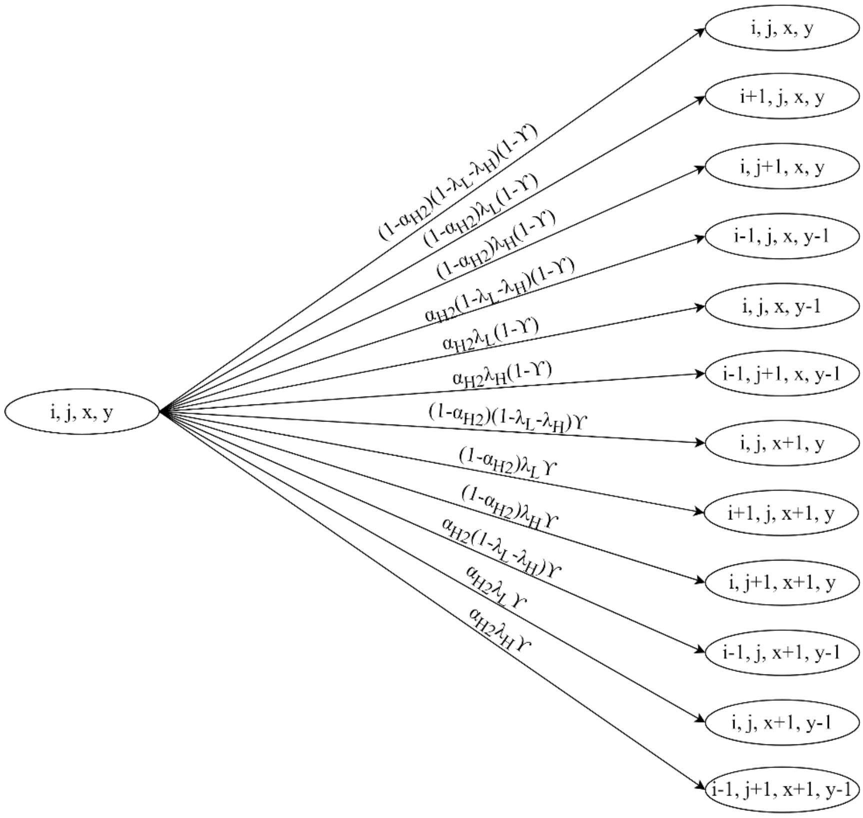


Fig 3. 127: The state diagram for $1 \leq i \leq \theta\ , \theta - i < j < K - i - 1, x = 0, y = 2$

(22) $\theta < i \leq K-2\,, 1 \leq j \leq K-i-1, x=0, y=2$



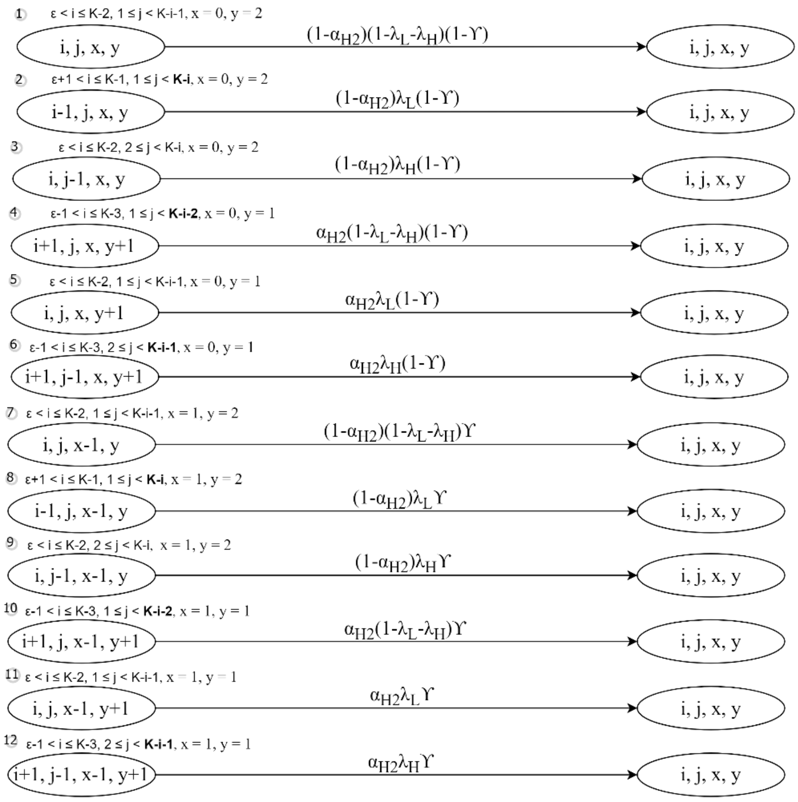
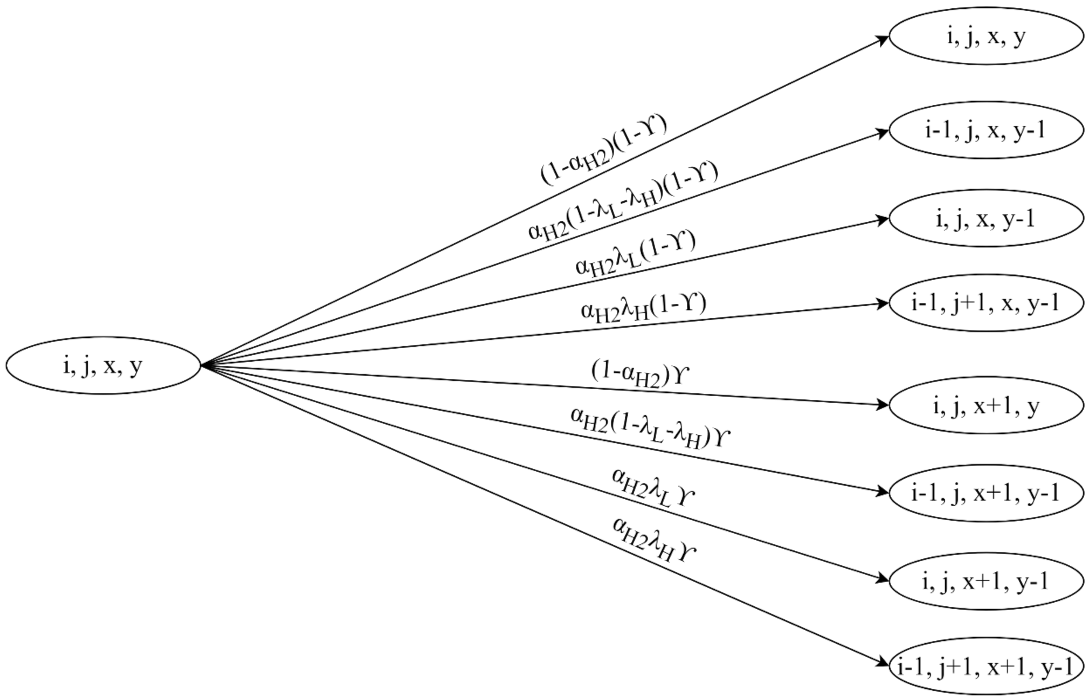


Fig 3. 128: The state diagram for $\theta < i \leq K-2\,, 1 \leq j \leq K-i-1, x=0, y=2$

(23) $1 \le i \le K-2, j = K-i-1, x = 0, y = 2$



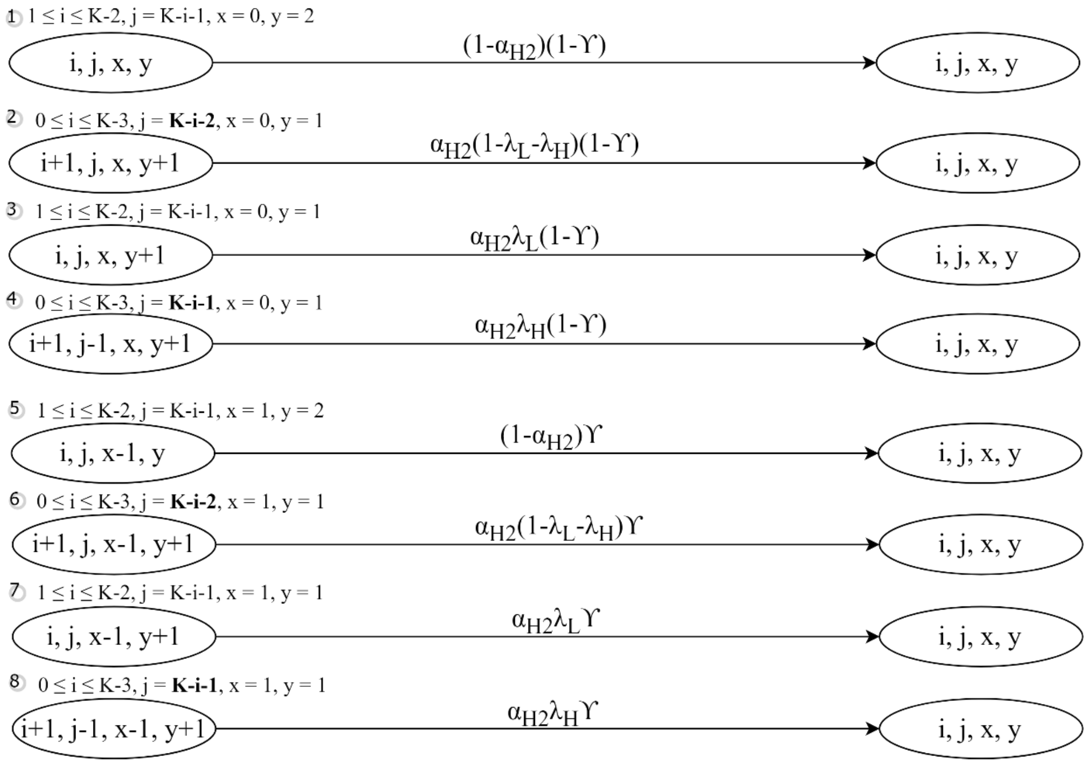


Fig 3. 129: The state diagram for $1 \le i \le K-2, j = K-i-1, x = 0, y = 2$

(24) $i = 0, j = 0, x = 1, y = 0$

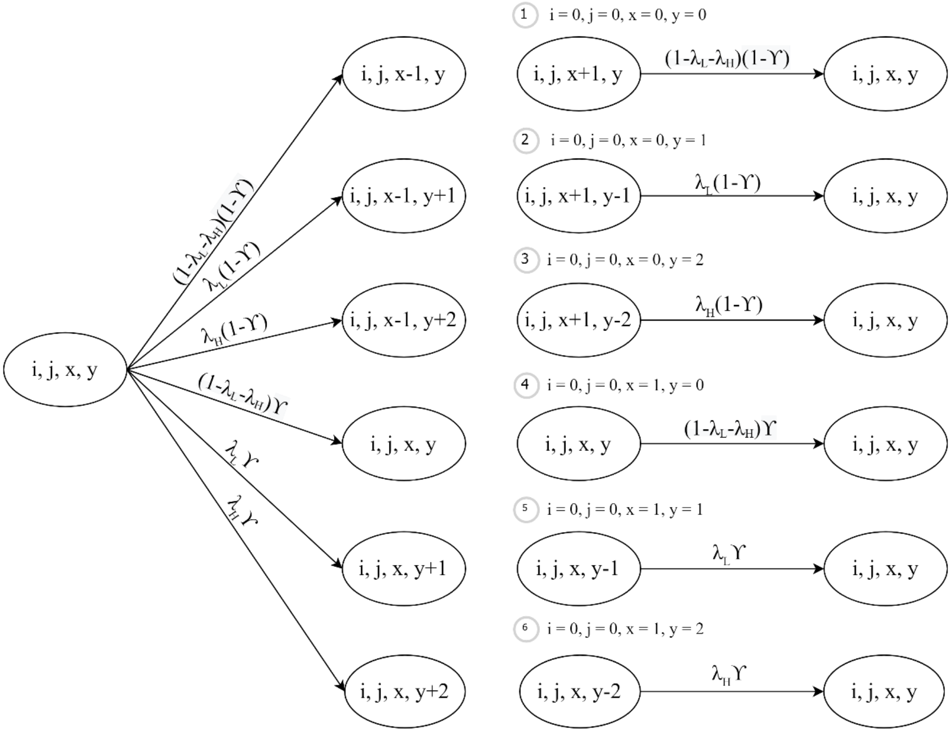


Fig 3. 130: The state diagram for $i = 0, j = 0, x = 1, y = 0$

(25) $i = 0, j = 0, x = 1, y = 1$

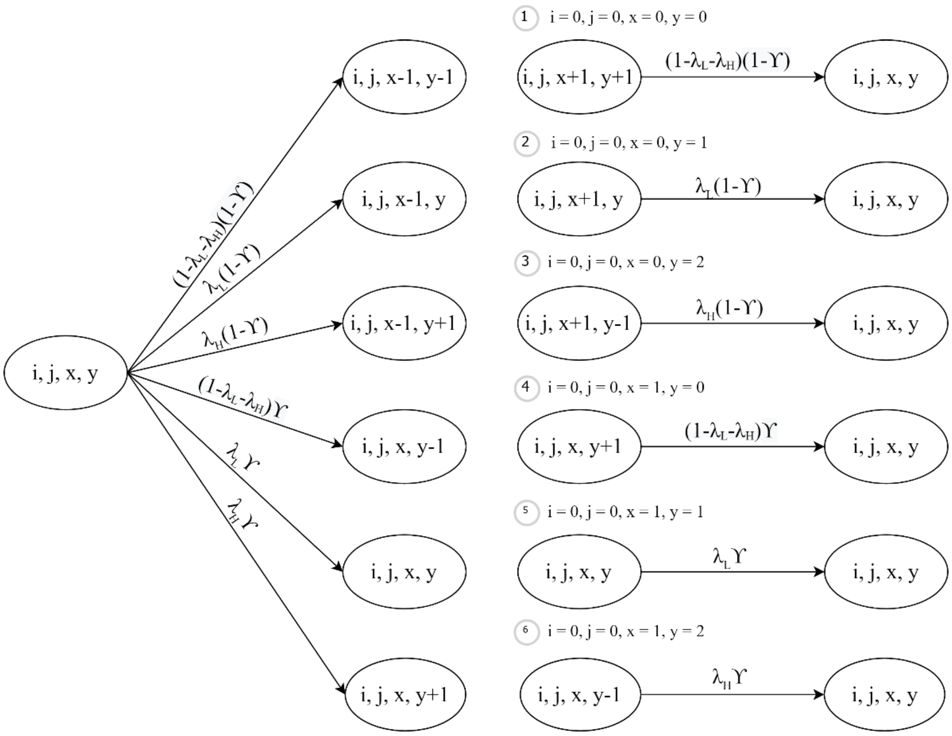


Fig 3. 131: The state diagram for $i = 0, j = 0, x = 1, y = 1$

(26) $i = 0, j = 0, x = 1, y = 2$

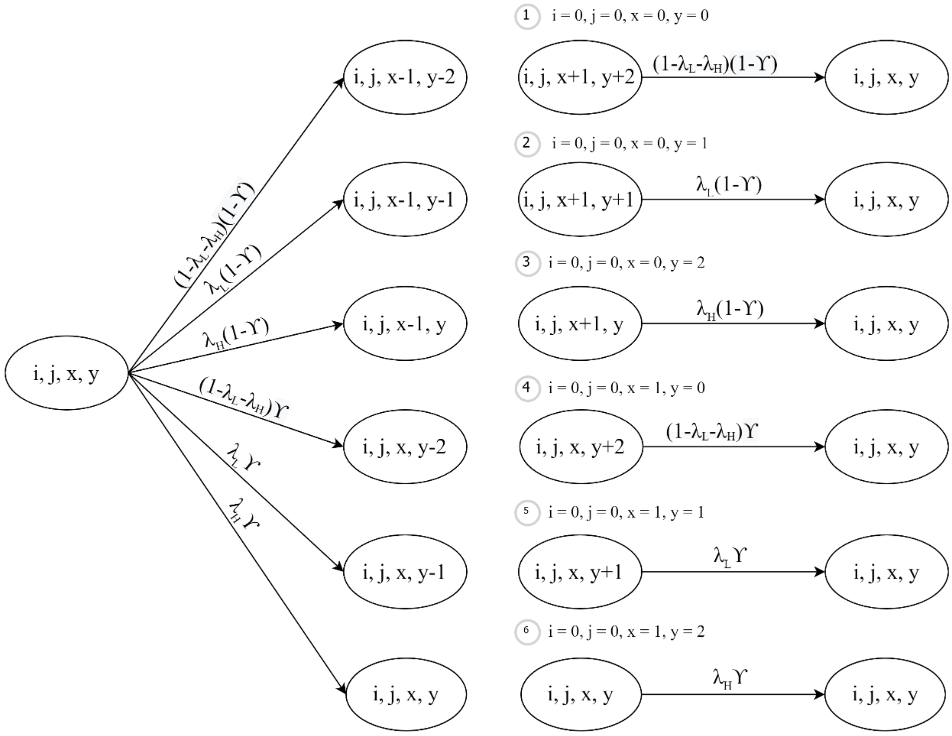


Fig 3. 132: The state diagram for $i = 0, j = 0, x = 1, y = 2$

(27) $i = 0, 1 \leq j \leq K - 1, x = 1, y = 1$

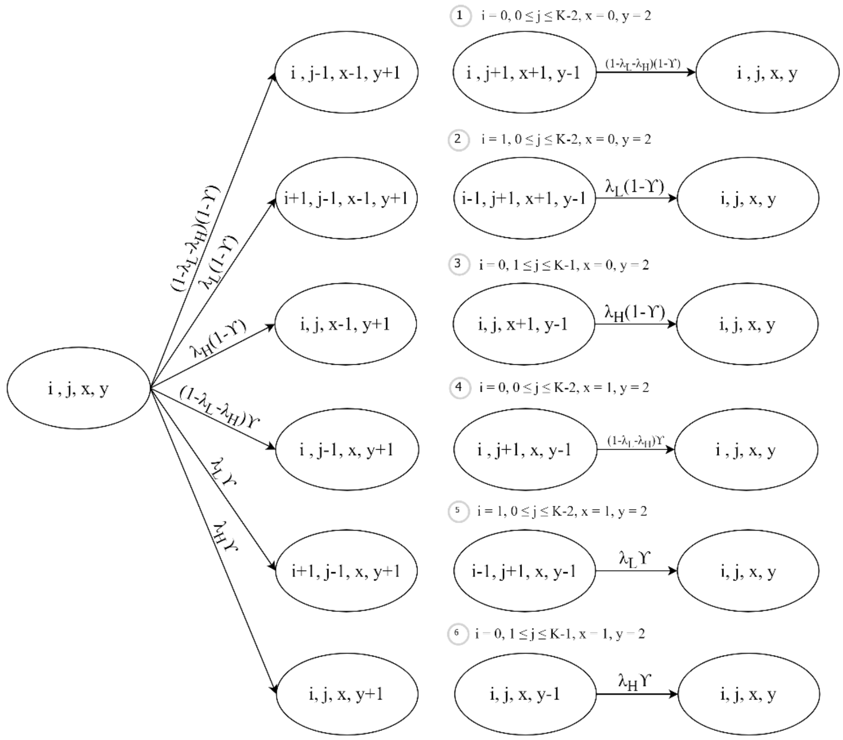


Fig 3. 133: The state diagram for $i = 0, 1 \leq j \leq K - 1, x = 1, y = 1$

(28) $i = 0, 1 \le j \le K-1, x = 1, y = 2$

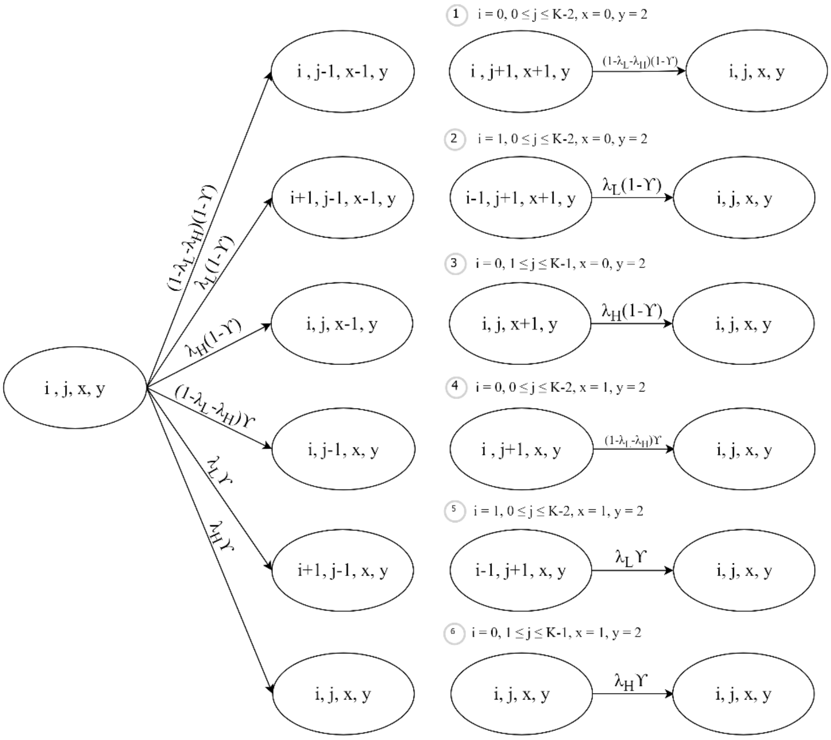


Fig 3. 134: The state diagram for $i = 0, j = 0, x = 1, y = 2$

(29) $1 \le i \le K-1, j = 0, x = 1, y = 1$

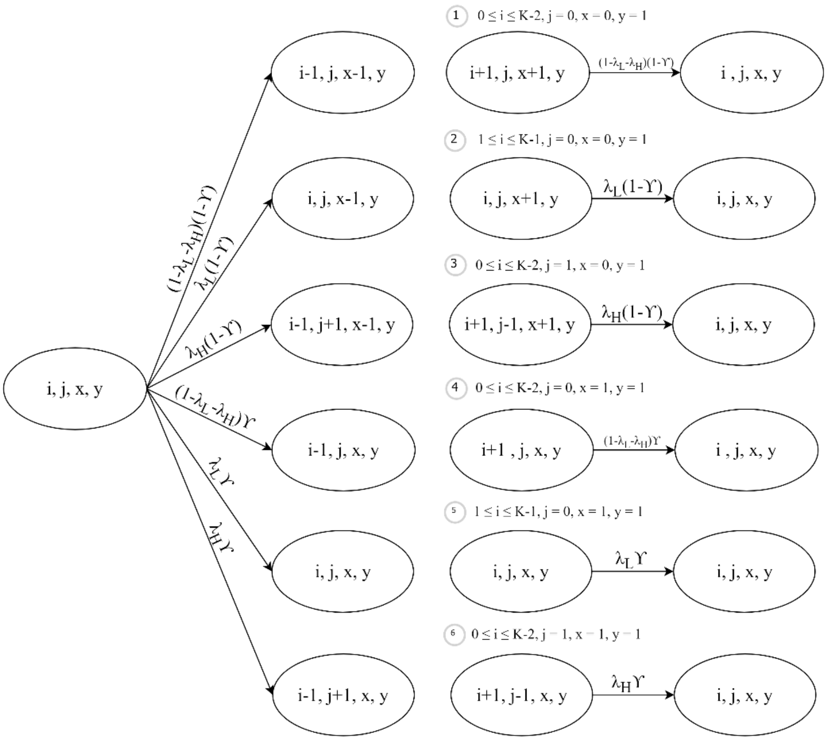


Fig 3. 135: The state diagram for $1 \le i \le K-1, j = 0, x = 1, y = 1$

(30) $1 \le i \le K-1, j = 0, x = 1, y = 2$

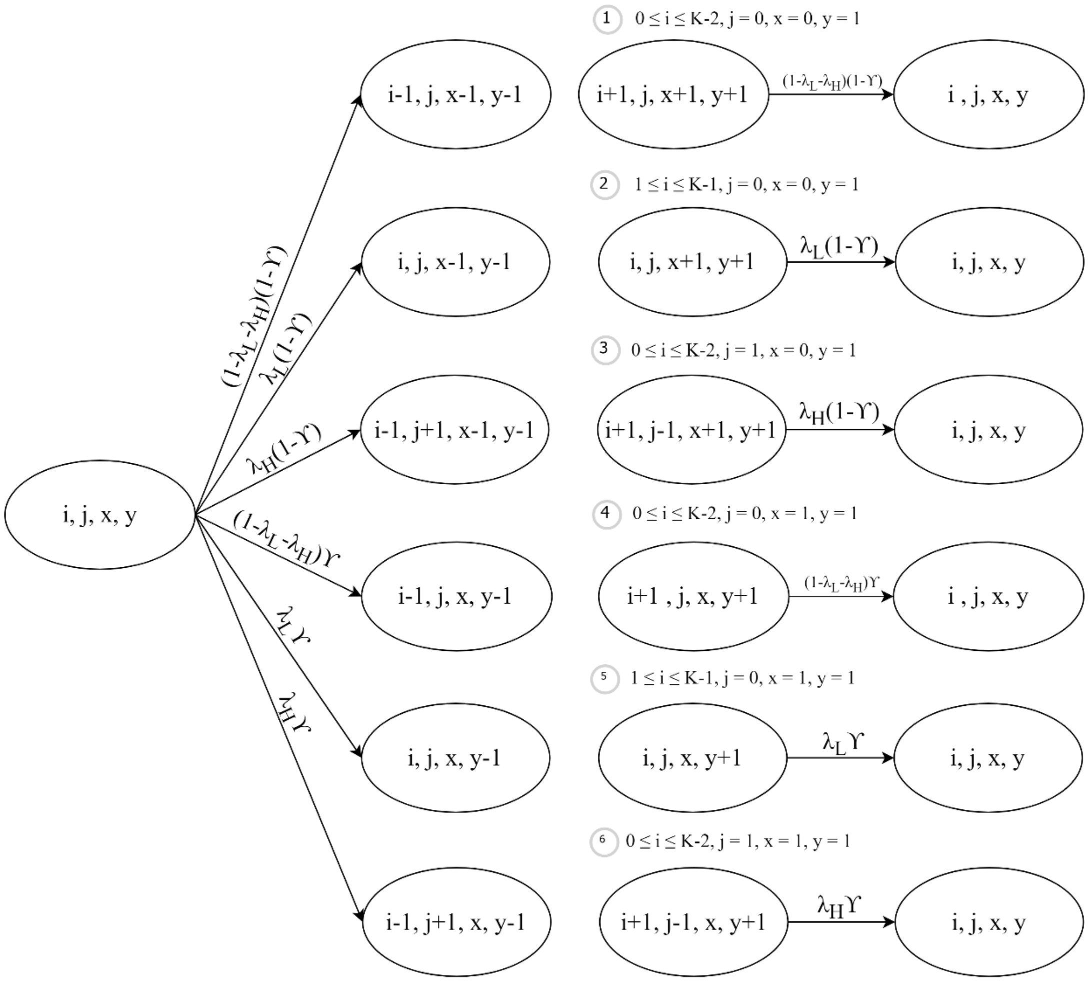
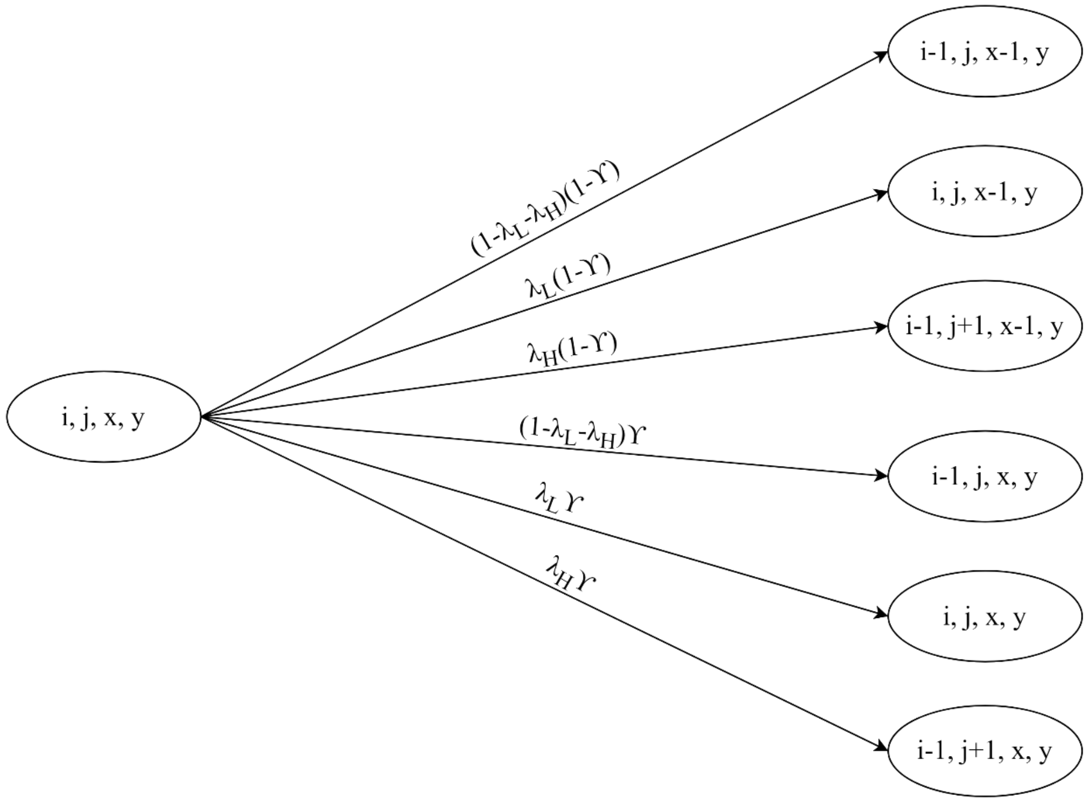


Fig 3. 136: The state diagram for $1 \le i \le K-1, j = 0, x = 1, y = 2$

(31) $1 \le i \le K-2, 1 \le j \le K-i-1, x=1, y=1$



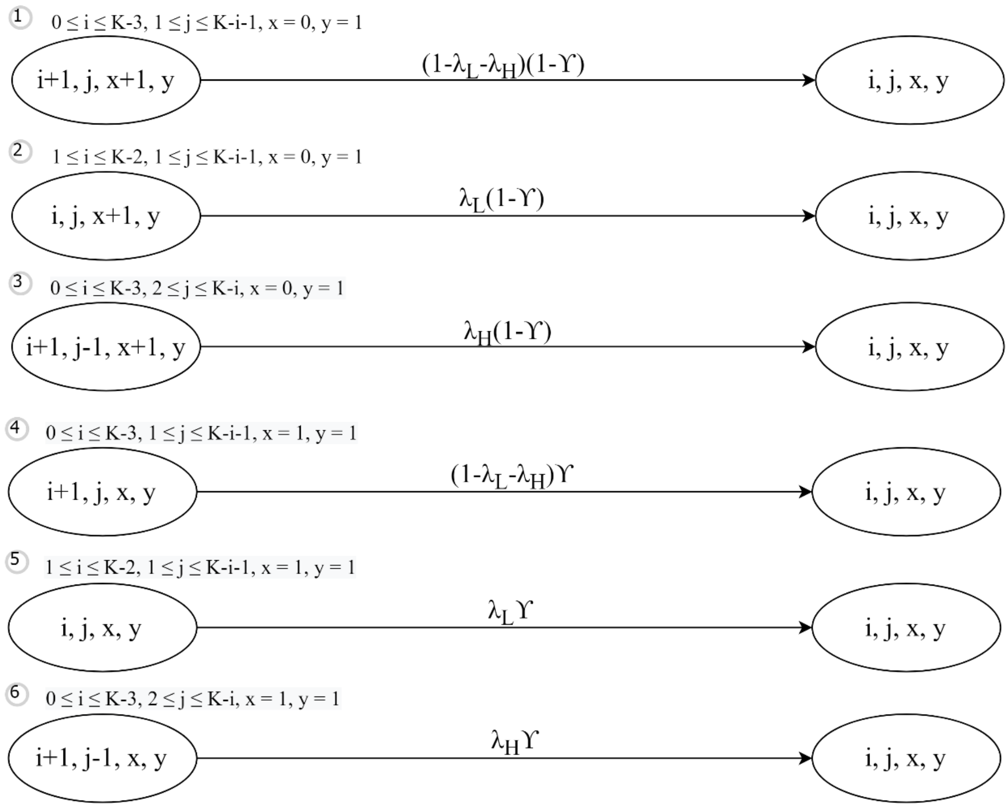


Fig 3. 137: The state diagram for $1 \le i \le K-2, 1 \le j \le K-i-1, x=1, y=1$

(32) $1 \leq i \leq K-2, 1 \leq j \leq K-i-1, x=1, y=2$

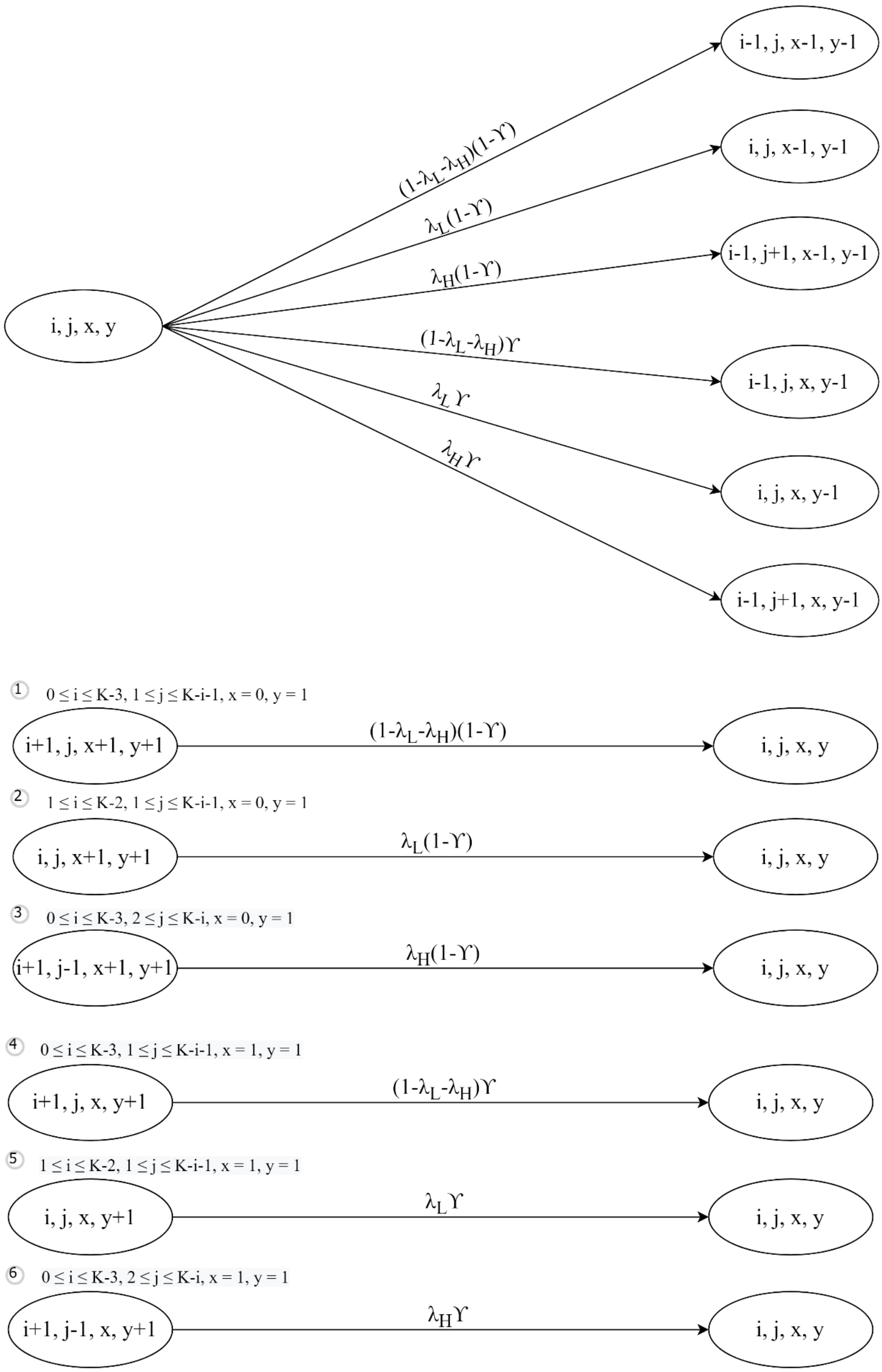


Fig 3. 138: The state diagram for $1 \leq i \leq K-2, 1 \leq j \leq K-i-1, x=1, y=2$

3.3.4 Iterative algorithm

In order to solve the state balance equations, we used the following iterative algorithm until the convergence is achieved. Consequently, we obtained the steady-state probability distribution of the system.

Iterative algorithm:

Step 1: Select the initial set of values for $\pi(i,j,x,y)^{old} = \frac{1}{|S|}$, $\forall i,j,x,y$, where $|S|$ is the total number of feasible states.

Step 2: Substitute $\pi(i,j,x,y)^{old}$ into Case 1 to Case 32 to find $\pi(i,j,x,y)^{new}$, $\forall i,j,x,y$.

Step 3: Normalize $\pi(i,j,x,y)^{new},\ \forall i,j,x,y$

Step 4: If $\sqrt{\sum\sum\sum\sum_{(i,j,x,y)\,\epsilon\, S}|\pi(i,j,x,y)^{old} - \pi(i,j,x,y)^{new}|^2} < \varepsilon$, stop the iteration, where ε is the stopping criterion. Otherwise, we set $\pi(i,j,x,y)^{old} = \pi(i,j,x,y)^{new}$ and return to step 2.

In our analytical analysis, the convergence criterion ε is set at $\varepsilon = 10^{-8}$, and the algorithm generally achieves convergence after about 350 iterations.

3.3.5 Performance index

In other words, to estimate the effectiveness of the system, we calculated various performance indices from the steady-state probability $\pi(i,j,x,y)$, which are summarized below.

First of all, the expected number of LBER (HBER) packets in the system, L_L (L_H), is given below.

$$L_L = \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}\sum_{y=0}^{2}[(i+1)\pi(i,j,x,1) + i\pi(i,j,x,2)] \qquad (3-52)$$

$$L_H = \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}\sum_{y=0}^{2}[j\pi(i,j,x,1) + (j+1)\pi(i,j,x,2)] \qquad (3-53)$$

The total number of packets in the system, L, is given below.

$$L = L_L + L_H \qquad (3-54)$$

Second, the expected number of LBER (HBER) packets in the queue L_{qL} (L_{qH}), is given below.

$$L_{qL} = \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}\sum_{y=0}^{2} i\pi(i,j,x,y) \qquad (3-55)$$

$$L_{qH} = \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}\sum_{y=0}^{2} j\pi(i,j,x,y) \qquad (3-56)$$

The summation of L_{qL} and L_{qH} will be the total number in queue L_q.

$$L_q = L_{qL} + L_{qH} \qquad (3-57)$$

Third, the blocking probability of LBER (HBER) packets, P_{bL} (P_{bH}), is given below.

$$P_{bL} = \lambda_L(1-\alpha_{L2})\sum_{i=0}^{Q}\pi(i,Q-i,0,1) + \lambda_L(1-\alpha_{H2})\sum_{i=0}^{Q}\pi(i,Q-i,0,2) \qquad (3-58)$$

$$P_{bH} = \lambda_H(1-\alpha_{L2})\sum_{i=0}^{Q}\pi(i,Q-i,0,1) + \lambda_H(1-\alpha_{H2})\sum_{i=0}^{Q}\pi(i,Q-i,0,2) \qquad (3-59)$$

The blocking probability of the system, P_b, is given below.

$$P_b = \lambda(1-\alpha_{L2})\sum_{i=0}^{Q}\pi(i,Q-i,0,1) + \lambda(1-\alpha_{H2})\sum_{i=0}^{Q}\pi(i,Q-i,0,2) \qquad (3-60)$$

Fourth, the throughput of LBER (HBER) packets, TH_L (TH_H), is given below.

$$TH_L = \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}\gamma\pi(i,j,x,1) + \sum_{i=0}^{\theta}\sum_{j=0}^{\theta-i}\sum_{x=0}^{1}(1-\gamma)\alpha_{L1}\pi(i,j,x,1) + \sum_{i=0}^{Q}\sum_{j=Q-i}^{Q}\sum_{x=0}^{1}(1-\gamma)\alpha_{L2}\pi(i,j,x,1) \qquad (3-61)$$

$$TH_H = \sum_{i=0}^{Q}\sum_{j=0}^{Q-i}\sum_{x=0}^{1}\gamma\pi(i,j,x,2) + \sum_{i=0}^{\theta}\sum_{j=0}^{\theta-i}\sum_{x=0}^{1}(1-\gamma)\alpha_{H1}\pi(i,j,x,2) + \sum_{i=0}^{Q}\sum_{j=Q-i}^{Q}\sum_{x=0}^{1}(1-\gamma)\alpha_{H2}\pi(i,j,x,2) \qquad (3-62)$$

Thus, the throughput of the system, TH, is given below.

$$TH = TH_L + TH_H \qquad (3-63)$$

Fifth, the average waiting time in the system, W, is given below.

$$W = \frac{L}{\lambda_{eff}} \qquad (3-64)$$

$$\text{with } \lambda_{eff} = (1 - P_b)\lambda \qquad (3-65)$$

Furthermore, the average waiting time of the LBER packets in the system, W_L, is given below.

$$W_L = \frac{L_L}{\lambda_{L\_eff}} \qquad (3-66)$$

$$\text{with } \lambda_{L\_eff} = (1 - P_{bL})\lambda_L \qquad (3-67)$$

On the other hand, the average waiting time of the HBER packets in the system, W_H, is given below.

$$W_H = \frac{L_H}{\lambda_{H\_eff}} \qquad (3-68)$$

$$\text{with } \lambda_{H\_eff} = (1 - P_{bH})\lambda_H \qquad (3-69)$$

Sixth, the average waiting time in queue, W_q, is given below.

$$W_q = \frac{L_q}{\lambda_{eff}} \qquad (3-70)$$

The average waiting time in queue for LBER (HBER) packets is given below.

$$W_{qL} = \frac{L_{qL}}{\lambda_{eff}} \qquad (3-71)$$

$$W_{qH} = \frac{L_{qH}}{\lambda_{eff}} \qquad (3-72)$$

4. Simulation model

In this chapter, we are going to present a comprehensive explanation of three kinds of simulation scenarios. Each of these scenarios includes both FIFO and Priority disciplines. The first simulation model will not transmit the packet in server while the channel is in state 0. The second simulation model will decide whether to transmit the packet in server in state 0 based on a predefined delivery probability. The final simulation model will set a transmission threshold and define two types of delivery probabilities for each kind of packets. While the channel is in state 0, the scheduler will check if the number of packets in queue exceeds the transmission threshold and switches between the delivery probabilities accordingly.

4.1. Scenario 1

When the channel is in state 0, transmitting packets requires higher energy consumption. Therefore, in the first simulation model, our goal is to reduce the system's power consumption. To achieve this, the scheduler will refrain from transmitting packets during state 0, opting to wait until the channel state improves. Both types of packets require energy for transmission; however, HBER (High Bit Error Rate) packets can tolerate a higher bit error rate and therefore can be transmitted using less energy. Conversely, LBER (Low Bit Error Rate) packets necessitate more energy for transmission due to their lower tolerance for bit errors. It is noted that the energy requirement of an LBER (HBER) packet in state 0 is higher than that of an LBER (HBER) packet in state 1. For clarity, our simulation framework consists of one main program and three subprograms to model the different scenarios.

4.1.1 Main program

The main program, illustrated in Fig. 4-1, follows a series of steps to simulate the system. Initially, all variables used in the simulation are initialized, including setting statistical parameters to zero and the server state to idle. The user is then prompted to input variables such as number of time slot required (T), system size (K), arrival probability for LBER and HBER (λ_L, λ_H), and the good channel rate (γ). The simulation uses a while loop to check if the current time slot exceeds the required number of time slots (T). If it does not, the time slot counter is incremented in each iteration, and the subprograms of the model are executed. At the start of each time slot, the channel state is updated, followed by the server handling departures and arrivals. The average performance metrics are also updated. Once the current time slot exceeds the required number (T), the while loop terminates, and the performance results are calculated and displayed.

4.1.2 Change channel state subprogram

Fig. 4-2 depicted the flow chart of the change channel state subprogram.

(1) The program generates a random number between 0 and 1, which is used for compare with the good channel rate (γ). If it is less than or equal to γ, the channel state is state 1. If it is greater than γ, the channel state is state 0.

4.1.3 Departure subprogram

Fig. 4-3 depicted the flow chart of the departure subprogram.

(1) Initially, the program first checks the server status. If the server is in the "IDLE" state, the program returns to the point A in main program. On the other hand, if the server is in the "BUSY" state, it proceeds to check the channel state.
(2) If the channel is in state 1, the packet in server will be transmitted. Subsequently, the relevant performance statistics will be updated, including number in system, number in queue, total of service time, total of delay time. If the head of queue is empty, the server status returns to IDLE. If the queue's head is not empty, the server processes the next packet in the queue.
(3) If the channel is in state 0, the packet remains in the server and wait until the channel changes to state 1.

4.1.4 Arrival subprogram

Fig. 4-3 illustrated the flow chart of the arrival subprogram. Either FIFO or priority queueing discipline can be adopted in this scenario. In this paragraph we will present two kinds of queueing disciplines separately in section (3).

(1) To begin with, the program will check the type of the arrived packet (LBER or HBER). The program generates a random value between 0 and 1, which is used for compare with

the arrival probability for LBER(HBER), $\lambda_L(\lambda_H)$. If it is less than or equal to λ_L, the type of arrived packet is LBER. If it is less than or equal to $\lambda_L + \lambda_H$ and greater than λ_L, the type of arrived packet is HBER. If it is greater than $\lambda_L + \lambda_H$, there is no packet arrives.

(2) If the queue is full, we will block the arrived packet, and the count of blocked packets is incremented.

(3)

(a) FIFO queue

Second, if the queue is not full, then the program will check the server state. If the server state is "BUSY", the arrived packet will be placed at the end of the queue, and the program returns to point B in main program.

(b) Priority queue

Second, if the queue is not full, then the program will check the server state. If the server state is "BUSY", the program checks the type of arrived packet. The LBER packet has higher priority, and it will be placed ahead of HBER packets in the queue. However, if there are already LBER packets in the queue, the new LBER packet will be placed after the existing LBER packets. On the other hand, the HBER packet has lower priority and it will be placed at the end of the queue. Then, the program returns to point B in main program.

(4) If the server state is "IDLE", the arrived packet enters the server but is not transmitted in the current time slot. Every packet must wait until the next time slot to be transmitted. Finally, the program returns to point B in main program.

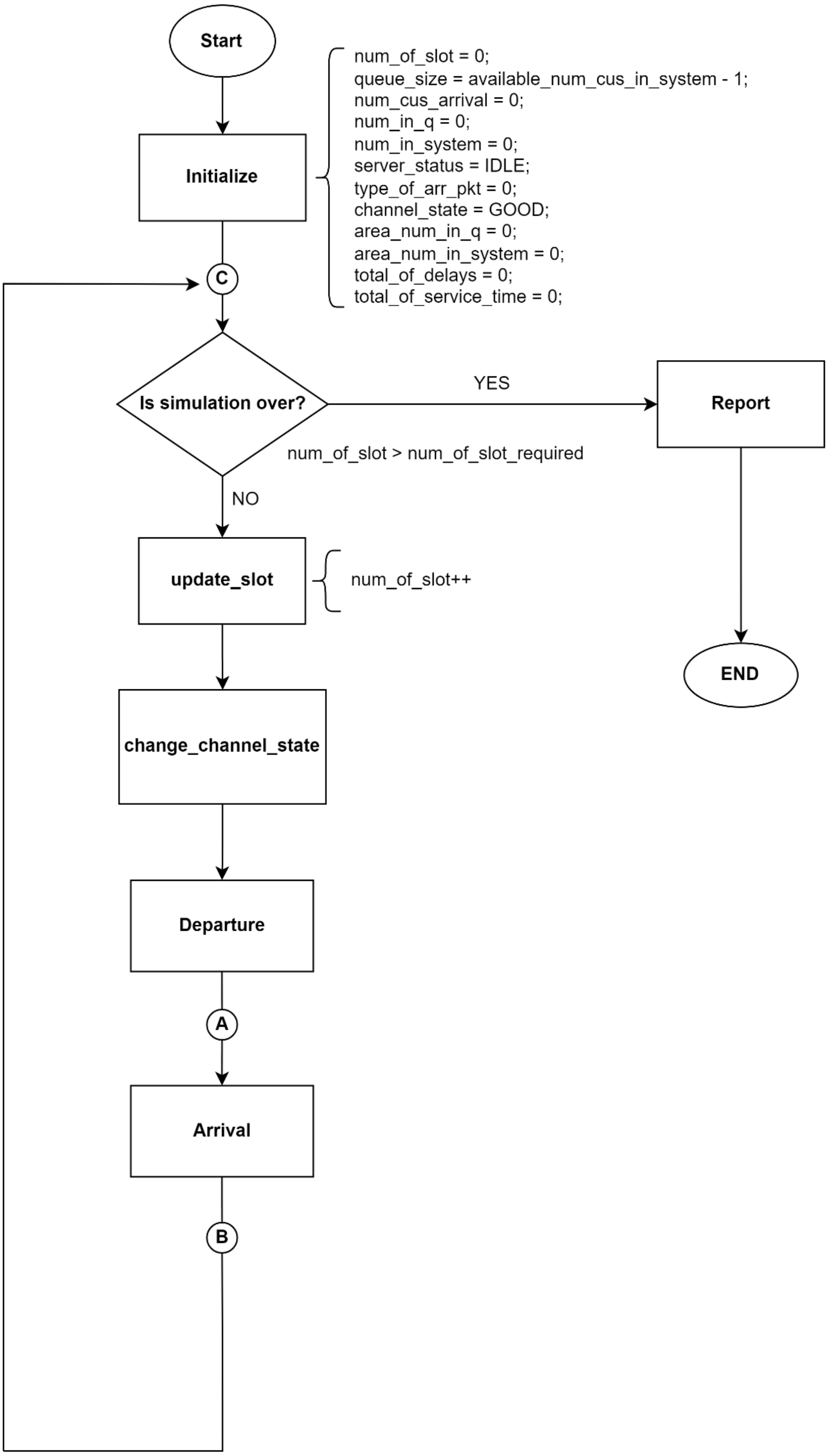


Fig 4. 1: Flow chart of main program in scenario 1

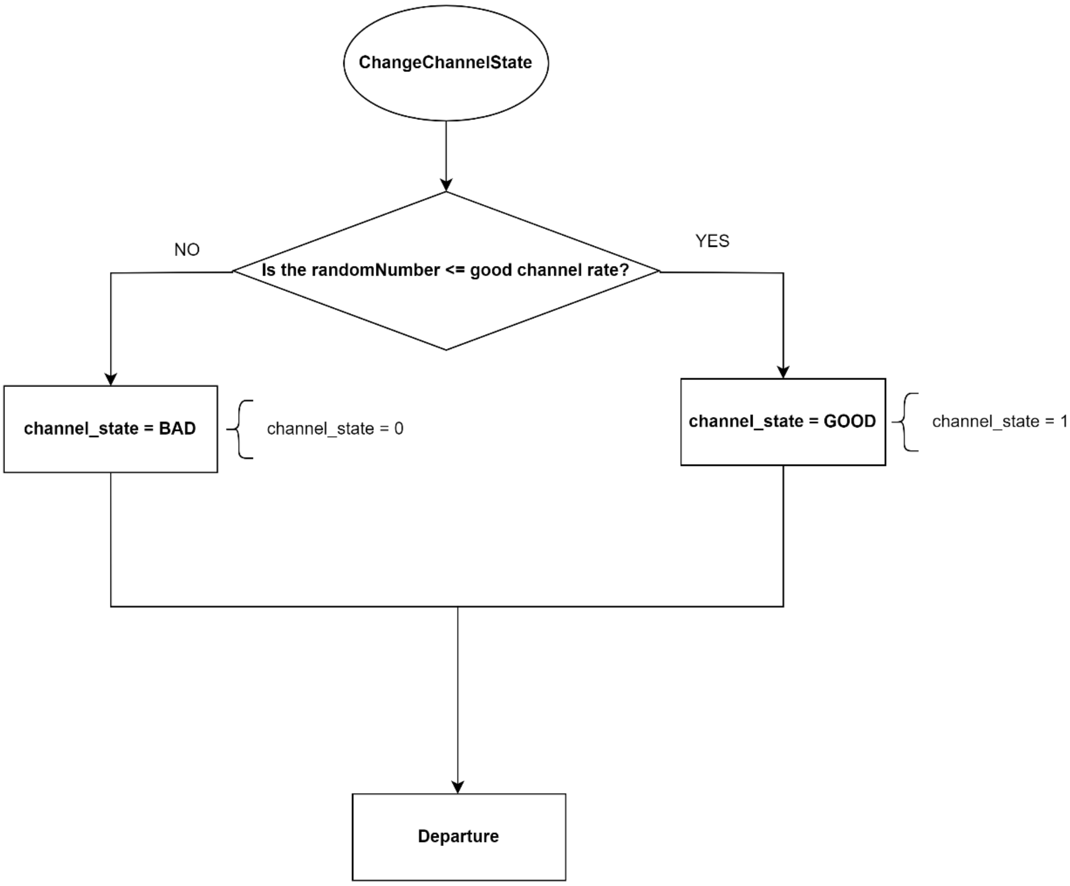


Fig 4. 2: Flow chart of change channel state subprogram in scenario 1

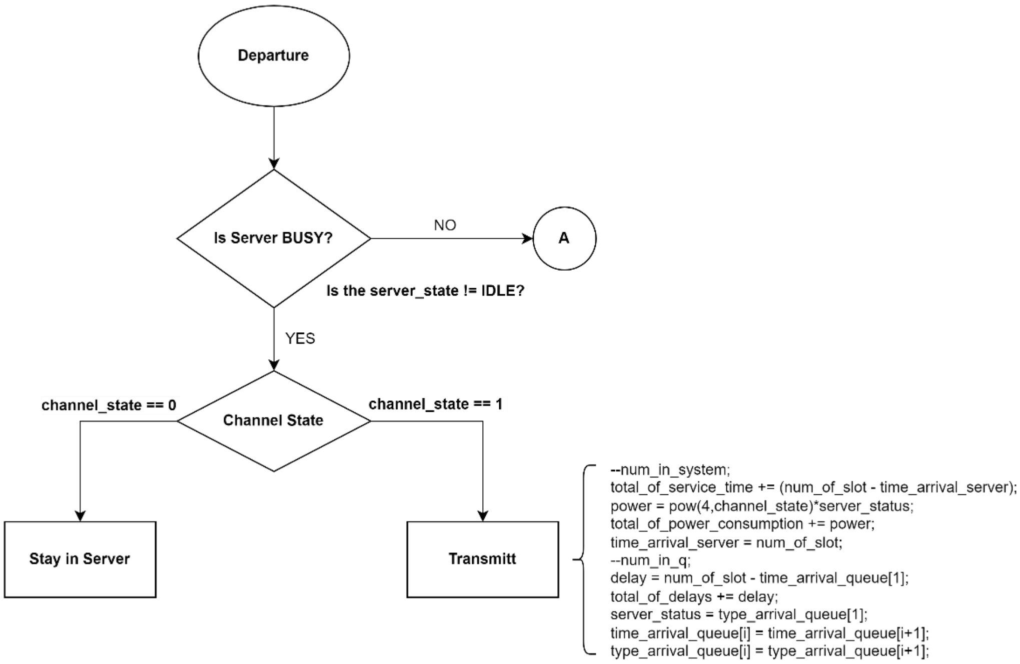


Fig 4. 3: Flow chart of departure subprogram in scenario 1

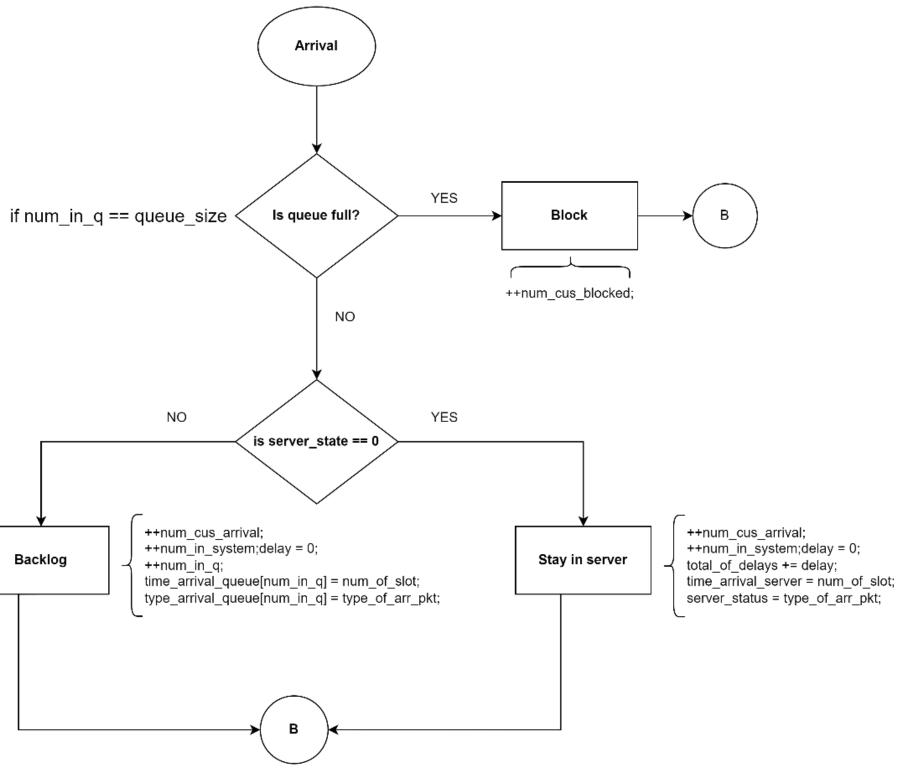


Fig 4. 4: Flow chart of arrival subprogram in scenario 1

4.1.5 Performance index

Based on the simulation results, we calculate several performance indices to evaluate the system model's performance. The following definitions describe these metrics:

(1) Average number of all (LBER, HBER) packets in the system, i.e., $L\ (L_L, L_H)$. This performance index represents the average number of all (LBER, HBER) packets in the system upon packet arrival. The formulas for these indices are given below:

$$L = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_system}{num\_of\_slot\_required}$$

$$L_L = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_system\_L}{num\_of\_slot\_required}$$

$$L_H = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_system\_H}{num\_of\_slot\_required}$$

(2) Average number of all (LBER, HBER) packets in the queue, i.e., $L_q\ (L_{qL}, L_{qH})$. This performance index represents the average number of all (LBER, HBER) packets in the queue upon packet arrival. The formulas for these indices are given below:

$$L_q = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_queue}{num\_of\_slot\_required}$$

$$L_{qL} = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_queue\_L}{num\_of\_slot\_required}$$

$$L_{qH} = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_queue\_H}{num\_of\_slot\_required}$$

(3) Mean waiting time of all (LBER, HBER) packets in the system, denoted as $W\ (W_L, W_H)$. This performance index represents the mean waiting time of all (LBER, HBER) packets in the system from arriving at the system to departing from the system. The formulas for these indices are given below:

$$W = \frac{total\_of\_delays + total\_of\_service\_time}{num\_cus\_arrival}$$

$$W_L = \frac{total\_of\_delays\_L + total\_of\_service\_time\_L}{num\_cus\_arrival\_L}$$

$$W_H = \frac{total\_of\_delays\_H + total\_of\_service\_time\_H}{num\_cus\_arrival\_H}$$

(4) Mean waiting time of all (LBER, HBER) packets in the queue, denoted as W_{qL} (W_{qL}, W_{qH}). This performance index represents the mean waiting time of all (LBER, HBER) packets in the queue from arriving at the queue to entering the server. The formulas for these indices are given below:

$$W = \frac{total\_of\_delays}{num\_cus\_arrival}$$

$$W_L = \frac{total\_of\_delays\_L}{num\_cus\_arrival\_L}$$

$$W_H = \frac{total\_of\_delays\_H}{num\_cus\_arrival\_H}$$

(5) Average throughput of all (LBER, HBER) packets of the system, denoted as TH (TH_L, TH_H). This performance index represents the average number of all (LBER, HBER) departed packets per time slot. The formulas for these indices are given below:

$$TH = \frac{num\_cus\_arrival}{num\_of\_slot\_required}$$

$$TH_L = \frac{num\_cus\_arrival\_L}{num\_of\_slot\_required}$$

$$TH_H = \frac{num\_cus\_arrival\_H}{num\_of\_slot\_required}$$

(6) Blocking rate of all (LBER, HBER) packets, denoted as Pb (Pb_L, Pb_H). This performance index represents the blocking probability of all (LBER, HBER) packets. The formulas for these indices are given below:

$$Pb = \frac{num\_cus\_blocked}{num\_cus\_arrival\ +\ num\_cus\_blocked}$$

$$Pb_L = \frac{num\_cus\_blocked\_L}{num\_cus\_arrival\_L\ +\ num\_cus\_blocked\_L}$$

$$Pb_H = \frac{num\_cus\_blocked\_H}{num\_cus\_arrival\_H\ +\ num\_cus\_blocked\_H}$$

4.2. Scenario 2

In scenario 2, in order to reduce the transmission waiting time, the delivery probability in state 0 for LBER (HBER) packet is proposed in the scheduling policy. Specifically, when the channel is in state 0, the scheduler will use the delivery probability to decide whether to transmit the packet in server or not. Both types of packets require energy for transmission; however, HBER (High Bit Error Rate) packets can tolerate a higher bit error rate and therefore can be transmitted using less energy. Conversely, LBER (Low Bit Error Rate) packets necessitate more energy for transmission due to their lower tolerance for bit errors. It is noted that the energy requirement of an LBER (HBER) packet in state 0 is higher than that of an LBER (HBER) packet in state 1. For clarity, our simulation framework consists of one main program and three subprograms to model the different scenarios.

4.2.1 Main program

The main program, illustrated in Fig. 4-5, follows a series of steps to simulate the system. Initially, all variables used in the simulation are initialized, including setting statistical parameters to zero and the server state to idle. The user is then prompted to input variables such as number of time slot required (T), system size (K), arrival probability for LBER and HBER (λ_L, λ_H), delivery probability for LBER and HBER (α_L, α_H), and the good channel rate (γ). The simulation uses a while loop to check if the current time slot exceeds the required number of time slots (T). If it does not, the time slot counter is incremented in each iteration, and the subprograms of the model are executed. At the start of each time slot, the channel state is updated, followed by the server handling departures and arrivals. The average performance metrics are also updated. Once the current time slot exceeds the required number (T), the while loop terminates, and the performance results are calculated and displayed.

4.2.2 Change channel state subprogram

Fig. 4-6 depicted the flow chart of the change channel state subprogram.

(1) The program generates a random number between 0 and 1, which is used for compare with the good channel rate (γ). If it is less than or equal to γ, the channel state is state 1. If it is greater than γ, the channel state is state 0.

4.2.3 Departure subprogram

Fig. 4-7 depicted the flow chart of the departure subprogram.

(1) Initially, the program first checks the server status. If the server is in the "IDLE" state, the program returns to the point A in main program. On the other hand, if the server is in the "BUSY" state, it proceeds to check the channel state.

(2) If the channel is in state 1, the packet in server will be transmitted. Subsequently, the relevant performance statistics will be updated, including number in system, number in queue, total of service time, total of delay time. If the head of queue is empty, the server status returns to IDLE. If the queue's head is not empty, the server processes the next packet in the queue.

(3) If the channel is in state 0, the scheduler will detect the type of packet in server, LBER or HBER. Consequently, the scheduler will use the corresponding delivery probability to decide whether to transmit the packet or not. The program generates a random number between 0 and 1, which is used for compare with the corresponding delivery probability $\alpha_L(\alpha_H)$. If it is less than or equal to $\alpha_L(\alpha_H)$, the scheduler will transmit the LBER (HBER) packet in server. If it is greater than $\alpha_L(\alpha_H)$, the LBER (HBER) packet will remain to stay in server.

4.2.4 Arrival subprogram

Fig. 4-8 illustrated the flow chart of the arrival subprogram. Either FIFO or priority queueing discipline can be adopted in this scenario. In this paragraph we will present two kinds of queueing disciplines separately in section (3).

(1) To begin with, the program will check the type of the arrived packet (LBER or HBER). The program generates a random value between 0 and 1, which is used for compare with the arrival probability for LBER (HBER), $\lambda_L(\lambda_H)$. If it is less than or equal to λ_L, the type of arrived packet is LBER. If it is less than or equal to $\lambda_L + \lambda_H$ and greater than λ_L, the type of arrived packet is HBER. If it is greater than $\lambda_L + \lambda_H$, there is no packet arrives.

(2) If the queue is full, we will block the arrived packet, and the count of blocked packets is incremented.

(3)

(a) FIFO queue

Second, if the queue is not full, then the program will check the server state. If the server state is “BUSY”, the arrived packet will be placed at the end of the queue, and the program returns to point B in main program.

(b) Priority queue

Second, if the queue is not full, then the program will check the server state. If the server state is “BUSY”, the program checks the type of arrived packet. The LBER packet has higher priority, and it will be placed ahead of HBER packets in the queue. However, if there are already LBER packets in the queue, the new LBER packet will be placed after the existing LBER packets. On the other hand, the HBER packet has lower priority and it will be placed at the end of the queue. Then, the program returns to point B in main program.

(4) If the server state is “IDLE”, the arrived packet enters the server but is not transmitted in the current time slot. Every packet must wait until the next time slot to be transmitted. Finally, the program returns to point B in main program.

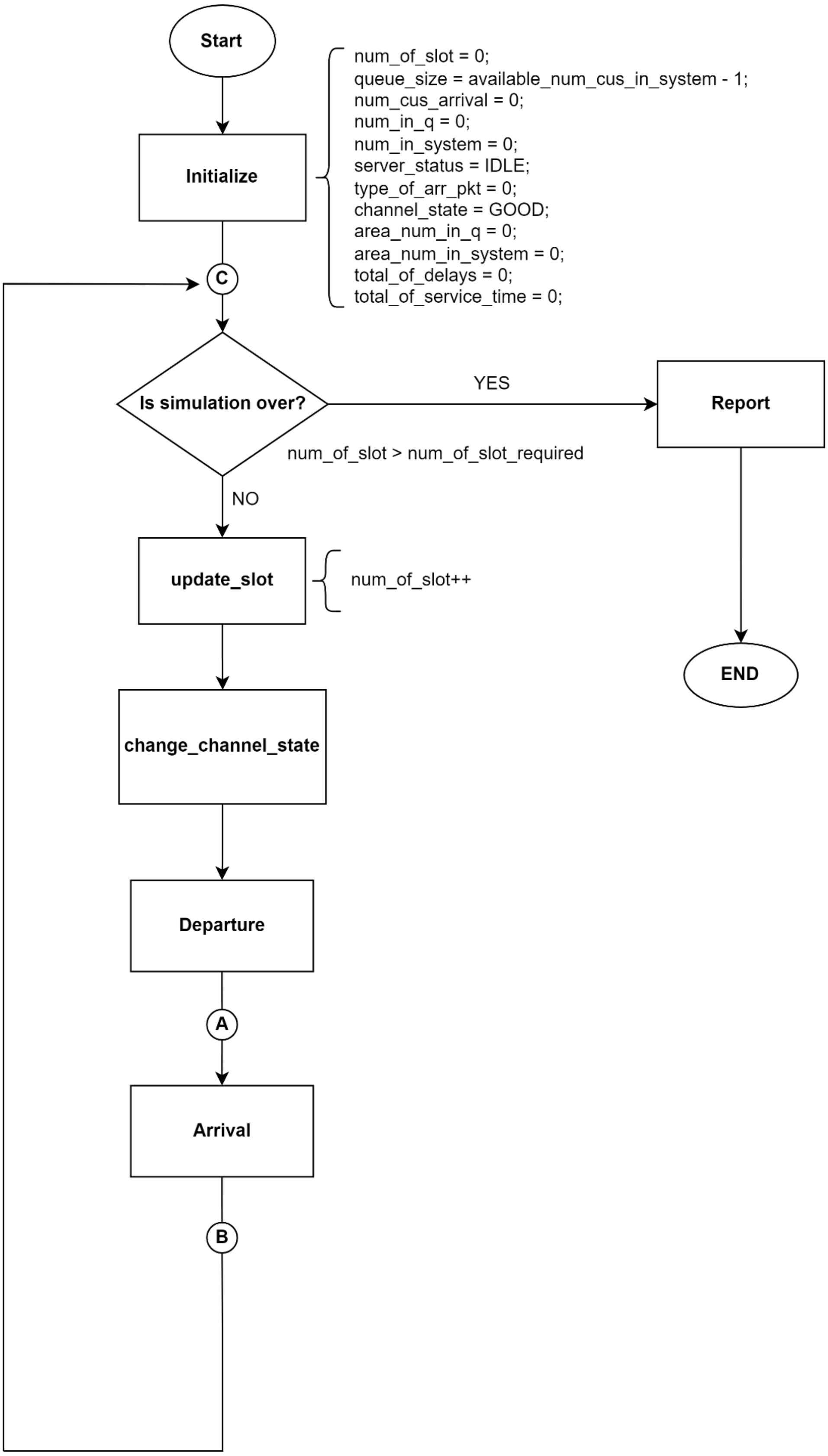


Fig 4. 5: Flow chart of main program in scenario 2

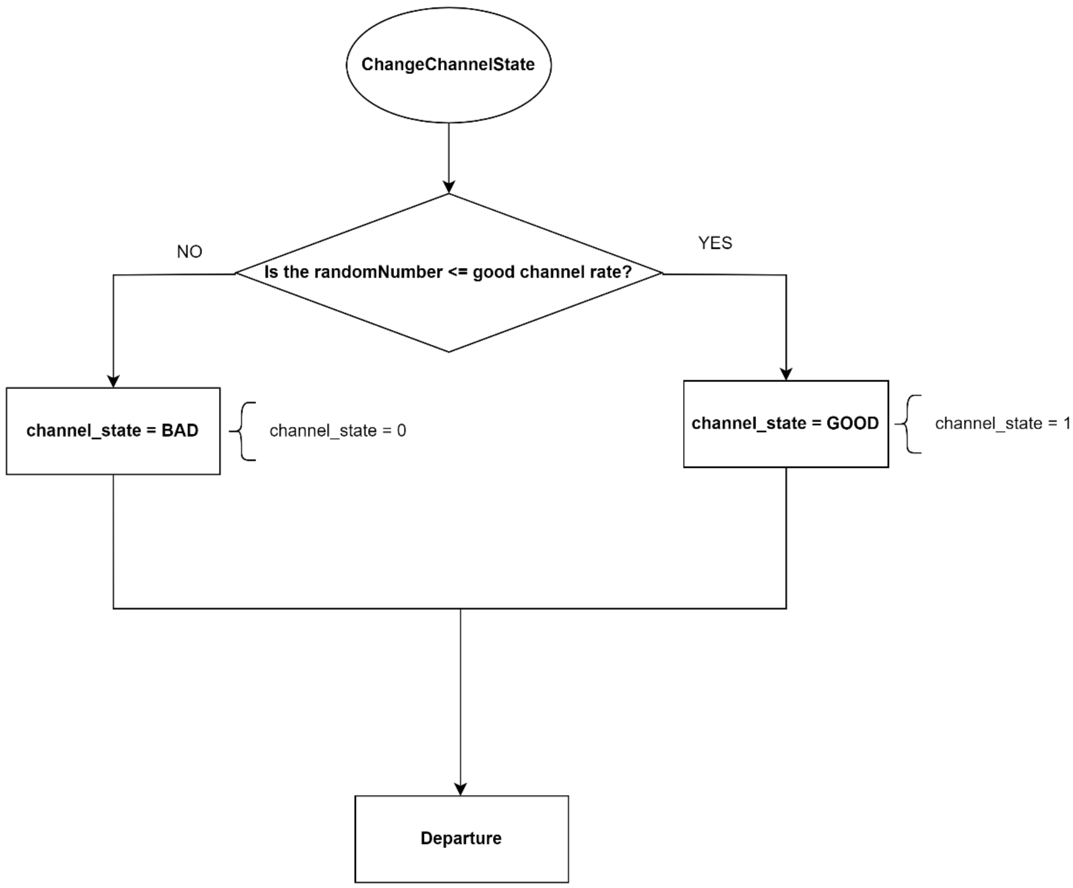


Fig 4. 6: Flow chart of change channel state subprogram in scenario 2

Fig 4. 7: Flow chart of departure subprogram in scenario 2

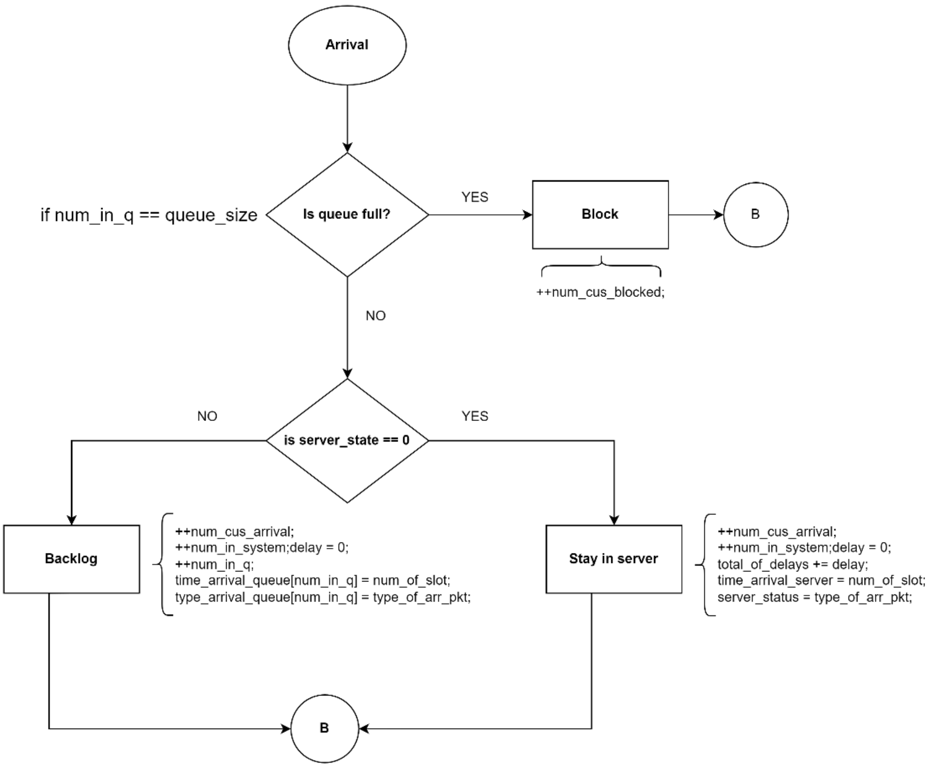


Fig 4. 8: Flow chart of arrival subprogram in scenario 2

4.2.5 Performance index

Based on the simulation results, we calculate several performance indices to evaluate the system model's performance. The following definitions describe these metrics:

(1) Average number of all (LBER, HBER) packets in the system, i.e., $L\ (L_L, L_H)$. This performance index represents the average number of all (LBER, HBER) packets in the system upon packet arrival. The formulas for these indices are given below:

$$L = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_system}{num\_of\_slot\_required}$$

$$L_L = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_system\_L}{num\_of\_slot\_required}$$

$$L_H = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_system\_H}{num\_of\_slot\_required}$$

(2) Average number of all (LBER, HBER) packets in the queue, i.e., $L_q\ (L_{qL}, L_{qH})$. This performance index represents the average number of all (LBER, HBER) packets in the queue upon packet arrival. The formulas for these indices are given below:

$$L_q = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_queue}{num\_of\_slot\_required}$$

$$L_{qL} = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_queue\_L}{num\_of\_slot\_required}$$

$$L_{qH} = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_queue\_H}{num\_of\_slot\_required}$$

(3) Mean waiting time of all (LBER, HBER) packets in the system, denoted as $W\ (W_L, W_H)$. This performance index represents the mean waiting time of all (LBER, HBER) packets in the system from arriving at the system to departing from the system. The formulas for these indices are given below:

$$W = \frac{total\_of\_delays + total\_of\_service\_time}{num\_cus\_arrival}$$

$$W_L = \frac{total\_of\_delays\_L + total\_of\_service\_time\_L}{num\_cus\_arrival\_L}$$

$$W_H = \frac{total\_of\_delays\_H + total\_of\_service\_time\_H}{num\_cus\_arrival\_H}$$

(4) Mean waiting time of all (LBER, HBER) packets in the queue, denoted as W_{qL} (W_{qL}, W_{qH}). This performance index represents the mean waiting time of all (LBER, HBER) packets in the queue from arriving at the queue to entering the server. The formulas for these indices are given below:

$$W = \frac{total\_of\_delays}{num\_cus\_arrival}$$

$$W_L = \frac{total\_of\_delays\_L}{num\_cus\_arrival\_L}$$

$$W_H = \frac{total\_of\_delays\_H}{num\_cus\_arrival\_H}$$

(5) Average throughput of all (LBER, HBER) packets of the system, denoted as TH (TH_L, TH_H). This performance index represents the average number of all (LBER, HBER) departed packets per time slot. The formulas for these indices are given below:

$$TH = \frac{num\_cus\_arrival}{num\_of\_slot\_required}$$

$$TH_L = \frac{num\_cus\_arrival\_L}{num\_of\_slot\_required}$$

$$TH_H = \frac{num\_cus\_arrival\_H}{num\_of\_slot\_required}$$

(6) Blocking rate of all (LBER, HBER) packets, denoted as Pb (Pb_L, Pb_H). This performance index represents the blocking probability of all (LBER, HBER) packets. The formulas for these indices are given below:

$$Pb = \frac{num\_cus\_blocked}{num\_cus\_arrival\ +\ num\_cus\_blocked}$$

$$Pb_L = \frac{num\_cus\_blocked\_L}{num\_cus\_arrival\_L\ +\ num\_cus\_blocked\_L}$$

$$Pb_H = \frac{num\_cus\_blocked\_H}{num\_cus\_arrival\_H\ +\ num\_cus\_blocked\_H}$$

4.3. Scenario 3

In scenario 3, we consider the trade-off between transmission waiting time and power consumption. To achieve this, we propose to adopt the transmission threshold θ and two kinds of delivery probability $\alpha_{L1}, \alpha_{L2}(\alpha_{H1}, \alpha_{H2})$ for LBER (HBER) packet in the scheduling policy. When the channel is in state 0, the scheduler will check if the number of packets in queue (n_q) exceeds the transmission threshold. If the number of packets in the queue is less than or equal to the transmission threshold, the delivery probability $\alpha_{L1}(\alpha_{H1})$ is used to determine whether to transmit the LBER (HBER) packet in the server. However, once the number of packets in the queue exceeds the transmission threshold, the scheduler switches to a different delivery probability $\alpha_{L2}(\alpha_{H2})$ to decide whether to transmit the LBER (HBER) packet in the server. Both types of packets require energy for transmission; however, HBER (High Bit Error Rate) packets can tolerate a higher bit error rate and therefore can be transmitted using less energy. Conversely, LBER (Low Bit Error Rate) packets necessitate more energy for transmission due to their lower tolerance for bit errors. It is noted that the energy requirement of an LBER (HBER) packet in state 0 is higher than that of an LBER (HBER) packet in state 1. For clarity, our simulation framework consists of one main program and three subprograms to model the different scenarios.

4.3.1 Main program

The main program, illustrated in Fig. 4-9, follows a series of steps to simulate the system. Initially, all variables used in the simulation are initialized, including setting statistical parameters to zero and the server state to idle. The user is then prompted to input variables such as number of time slot required (T), system size (K), arrival probability for LBER and HBER (λ_L, λ_H), delivery probability for LBER and HBER $(\alpha_{L2}, \alpha_{L2}, \alpha_{H1}, \alpha_{H2})$, and the good channel rate (γ). The simulation uses a while loop to check if the current time slot exceeds the required number of time slots (T). If it does not, the time slot counter is incremented in each iteration, and the subprograms of the model are executed. At the start of each time slot, the channel state is updated, followed by the server handling departures and arrivals. The average performance metrics are also updated. Once the current time slot exceeds the required number (T), the while loop terminates, and the performance results are calculated and displayed.

4.3.2 Change channel state subprogram

Fig. 4-10 depicted the flow chart of the change channel state subprogram.

(1) The program generates a random number between 0 and 1, which is used for compare with the good channel rate (γ). If it is less than or equal to γ, the channel state is state 1. If it is greater than γ, the channel state is state 0.

4.3.3 Departure subprogram

Fig. 4-11 depicted the flow chart of the departure subprogram.

(1) Initially, the program first checks the server status. If the server is in the "IDLE" state, the program returns to the point A in main program. On the other hand, if the server is in the "BUSY" state, it proceeds to check the channel state.

(2) If the channel is in state 1, the packet in server will be transmitted. Subsequently, the relevant performance statistics will be updated, including number in system, number in queue, total of service time, total of delay time. If the head of queue is empty, the server status returns to IDLE. If the queue's head is not empty, the server processes the next packet in the queue.

(3) If the channel is in state 0, the scheduler will detect the type of packet in server, LBER or HBER. Consequently, the scheduler will detect the number in queue (n_q). If $n_q \leq \theta$, the delivery probability $\alpha_L = \alpha_{L1}(\alpha_H = \alpha_{H1})$ is used to determine whether to transmit the LBER (HBER) packet in the server. However, once the $n_q > \theta$, the scheduler switches to a different delivery probability $\alpha_L = \alpha_{L2}(\alpha_H = \alpha_{H2})$. The program generates a random number between 0 and 1, which is used for compare with the corresponding delivery probability. If it is less than or equal to $\alpha_L(\alpha_H)$, the scheduler will transmit the LBER (HBER) packet in server. If it is greater than $\alpha_L(\alpha_H)$, the LBER (HBER) packet will remain to stay in server.

4.3.4 Arrival subprogram

Fig. 4-12 illustrated the flow chart of the arrival subprogram. Either FIFO or priority queueing discipline can be adopted in this scenario. In this paragraph we will present two kinds of queueing disciplines separately in section (3).

(1) To begin with, the program will check the type of the arrived packet (LBER or HBER). The program generates a random value between 0 and 1, which is used for compare with the arrival probability for LBER (HBER), $\lambda_L(\lambda_H)$. If it is less than or equal to λ_L, the type of arrived packet is LBER. If it is less than or equal to $\lambda_L + \lambda_H$ and greater than λ_L, the type of arrived packet is HBER. If it is greater than $\lambda_L + \lambda_H$, there is no packet arrives.

(2) If the queue is full, we will block the arrived packet, and the count of blocked packets is incremented.

(3)

(a) FIFO queue

Second, if the queue is not full, then the program will check the server state. If the server state is "BUSY", the arrived packet will be placed at the end of the queue, and the program returns to point B in main program.

(b) Priority queue

Second, if the queue is not full, then the program will check the server state. If the server state is "BUSY", the program checks the type of arrived packet. The LBER packet has higher priority, and it will be placed ahead of HBER packets in the queue. However, if there are already LBER packets in the queue, the new LBER packet will be placed after the existing LBER packets. On the other hand, the HBER packet has lower priority and it will be placed at the end of the queue. Then, the program returns to point B in main program.

(4) If the server state is "IDLE", the arrived packet enters the server but is not transmitted in the current time slot. Every packet must wait until the next time slot to be transmitted. Finally, the program returns to point B in main program.

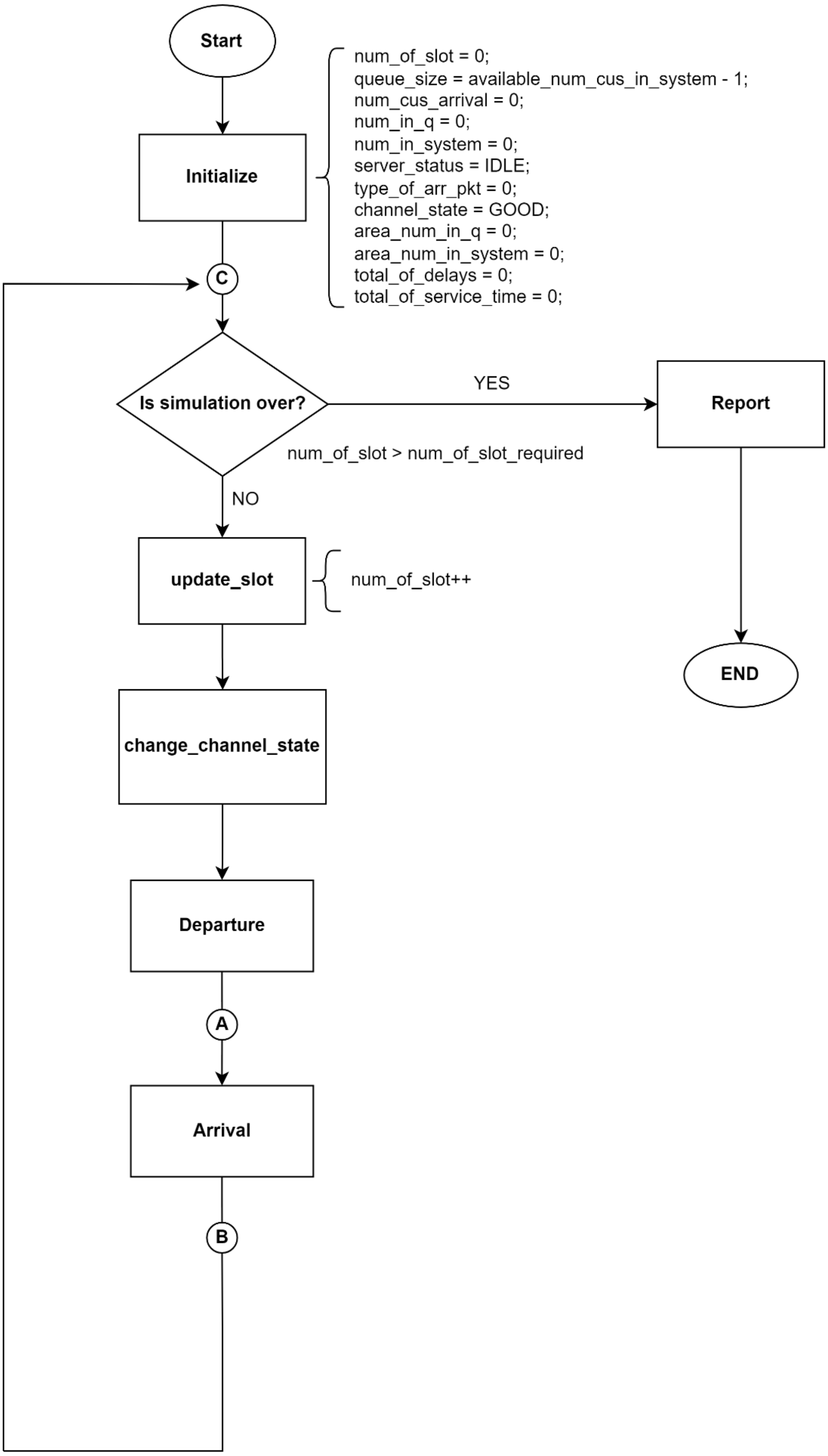


Fig 4. 9: Flow chart of main program in scenario 3

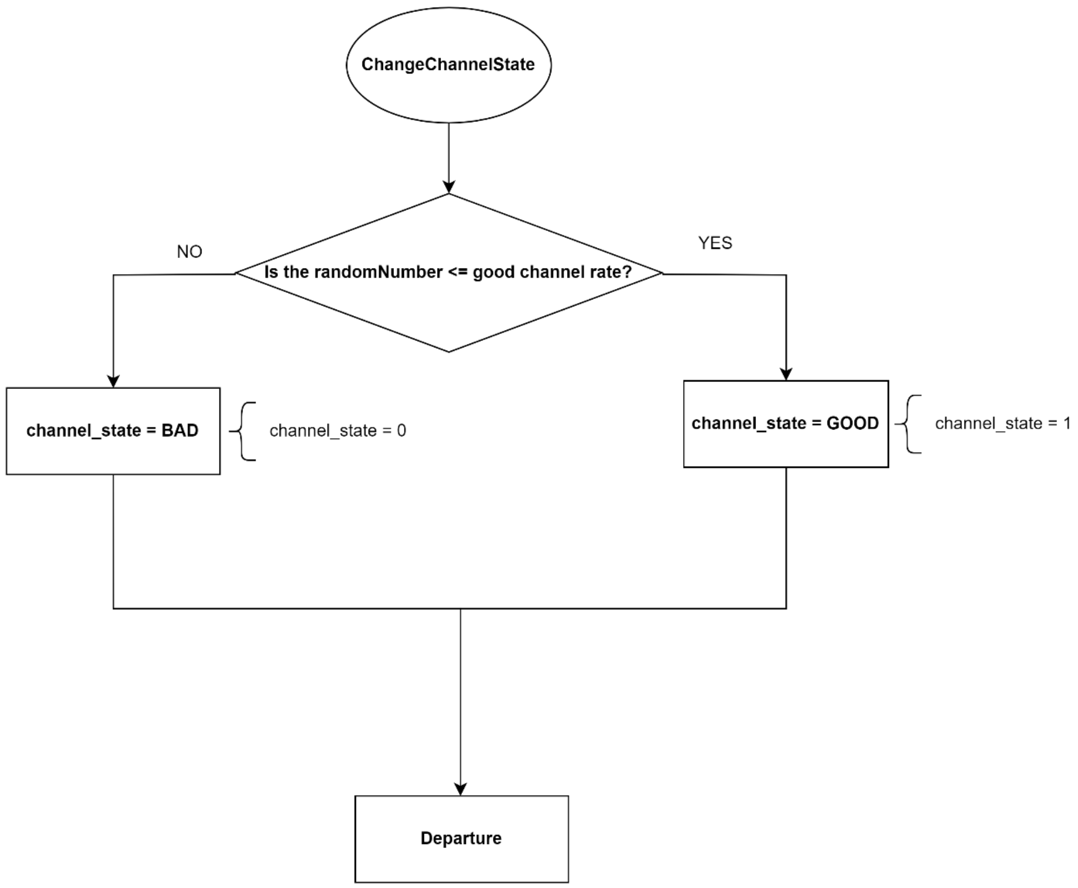


Fig 4. 10: Flow chart of change channel state subprogram in scenario 3

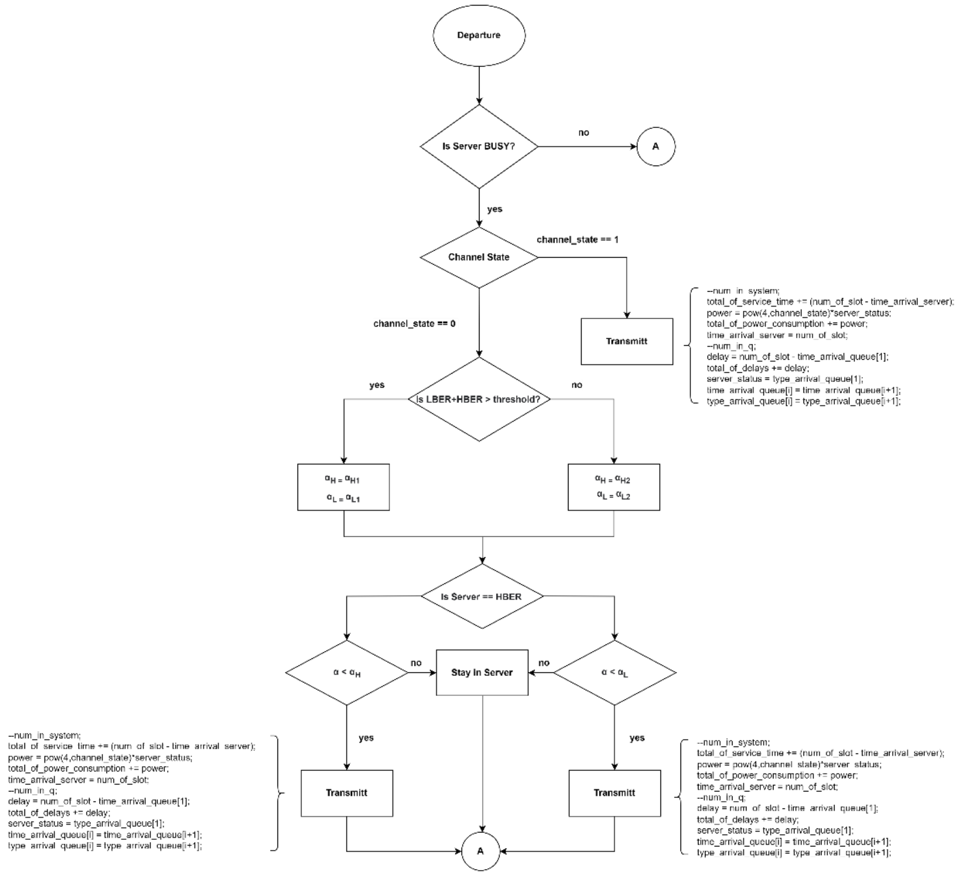


Fig 4. 11: Flow chart of departure subprogram in scenario 3

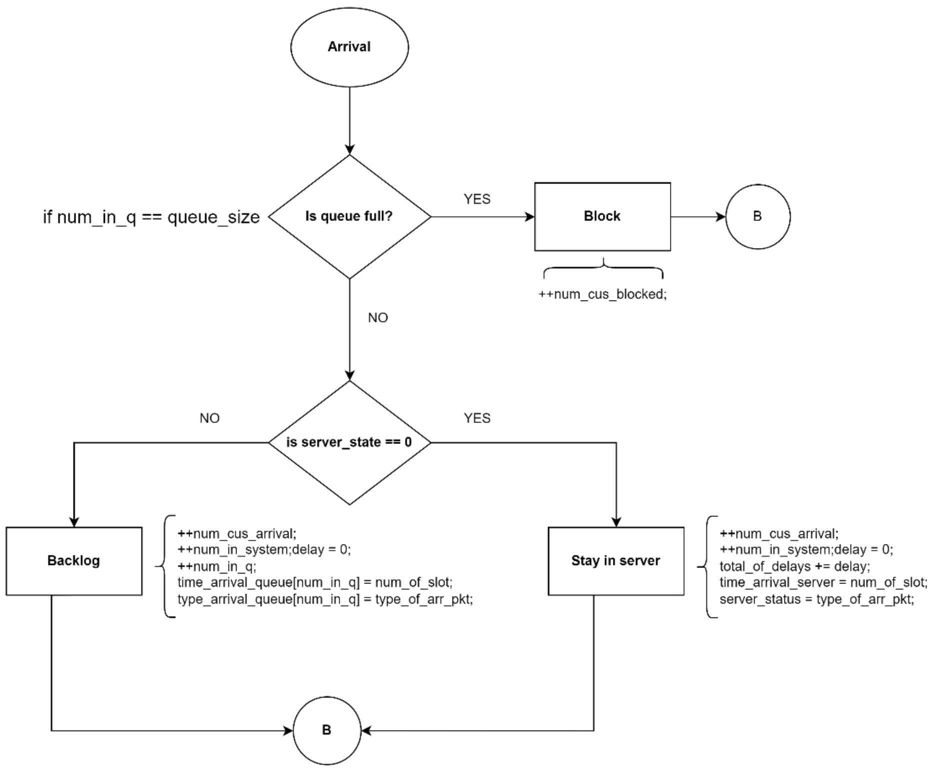


Fig 4. 12: Flow chart of arrival subprogram in scenario 3

4.3.5 Performance index

Based on the simulation results, we calculate several performance indices to evaluate the system model's performance. The following definitions describe these metrics:

(1) Average number of all (LBER, HBER) packets in the system, i.e., $L\ (L_L, L_H)$. This performance index represents the average number of all (LBER, HBER) packets in the system upon packet arrival. The formulas for these indices are given below:

$$L = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_system}{num\_of\_slot\_required}$$

$$L_L = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_system\_L}{num\_of\_slot\_required}$$

$$L_H = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_system\_H}{num\_of\_slot\_required}$$

(2) Average number of all (LBER, HBER) packets in the queue, i.e., $L_q\ (L_{qL}, L_{qH})$. This performance index represents the average number of all (LBER, HBER) packets in the queue upon packet arrival. The formulas for these indices are given below:

$$L_q = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_queue}{num\_of\_slot\_required}$$

$$L_{qL} = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_queue\_L}{num\_of\_slot\_required}$$

$$L_{qH} = \frac{\sum_0^{num\_of\_slot\_required} total\_num\_in\_queue\_H}{num\_of\_slot\_required}$$

(3) Mean waiting time of all (LBER, HBER) packets in the system, denoted as $W\ (W_L, W_H)$. This performance index represents the mean waiting time of all (LBER, HBER) packets in the system from arriving at the system to departing from the system. The formulas for these indices are given below:

$$W = \frac{total\_of\_delays + total\_of\_service\_time}{num\_cus\_arrival}$$

$$W_L = \frac{total\_of\_delays\_L + total\_of\_service\_time\_L}{num\_cus\_arrival\_L}$$

$$W_H = \frac{total\_of\_delays\_H + total\_of\_service\_time\_H}{num\_cus\_arrival\_H}$$

(4) Mean waiting time of all (LBER, HBER) packets in the queue, denoted as W_{qL} (W_{qL}, W_{qH}). This performance index represents the mean waiting time of all (LBER, HBER) packets in the queue from arriving at the queue to entering the server. The formulas for these indices are given below:

$$W = \frac{total\_of\_delays}{num\_cus\_arrival}$$
$$W_L = \frac{total\_of\_delays\_L}{num\_cus\_arrival\_L}$$
$$W_H = \frac{total\_of\_delays\_H}{num\_cus\_arrival\_H}$$

(5) Average throughput of all (LBER, HBER) packets of the system, denoted as TH (TH_L, TH_H). This performance index represents the average number of all (LBER, HBER) departed packets per time slot. The formulas for these indices are given below:

$$TH = \frac{num\_cus\_arrival}{num\_of\_slot\_required}$$
$$TH_L = \frac{num\_cus\_arrival\_L}{num\_of\_slot\_required}$$
$$TH_H = \frac{num\_cus\_arrival\_H}{num\_of\_slot\_required}$$

(6) Blocking rate of all (LBER, HBER) packets, denoted as Pb (Pb_L, Pb_H). This performance index represents the blocking probability of all (LBER, HBER) packets. The formulas for these indices are given below:

$$Pb = \frac{num\_cus\_blocked}{num\_cus\_arrival\ +\ num\_cus\_blocked}$$
$$Pb_L = \frac{num\_cus\_blocked\_L}{num\_cus\_arrival\_L\ +\ num\_cus\_blocked\_L}$$
$$Pb_H = \frac{num\_cus\_blocked\_H}{num\_cus\_arrival\_H\ +\ num\_cus\_blocked\_H}$$

5. Numerical results

In this section, we present the numerical results of both simulation and analytical models for three distinct scheduling policies, each employing two types of queuing disciplines. The first policy, the Power Consumption Control Policy (PCCP), focuses on minimizing the system's power consumption. The second policy, the Adaptive Delivery Policy (ADP), adapts based on the delivery probability when the channel is in state 0. The third policy, the Threshold-based Transmission Policy (TTP), sets a transmission threshold and alternates between different delivery probabilities based on this threshold. Furthermore, various input parameters are utilized to evaluate their impact on the system's performance.

5.1 Scenario 1

The input parameters in model 1, applicable to both FIFO and priority queuing disciplines, are as provided below: $K, \lambda_L, \lambda_H, \gamma$. To assess their impact on the system, we will adjust only one parameter at a time. Additionally, the system size (K) is set to 10. The default values are provided below: $\lambda_L = 0.3,\ \lambda_H = 0.3,\ \gamma = 0.5$.

5.1.1 LBER packet arrival rate

We increment the LBER packet arrival rate by 0.1 and compare it against several performance indices such as: $L, L_q, Pb, Power, TH, W, Wq$.

Fig. 5-1 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the system $L\ (L_L, L_H)$ and LBER packet arrival rate λ_L under a FIFO queueing discipline. As λ_L increases, the number of LBER packets in the system rises correspondingly. Consequently, as the system approaches full system size, the number of HBER packets decreases due to the growing presence of LBER packets in the system. Furthermore, as λ_L increases, more packets enter the system per time slot and L increases. Lastly, the analytical results match well with the simulation results.

Fig. 5-2 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the system $L\ (L_L, L_H)$ and LBER packet arrival rate λ_L under a priority queueing discipline. As λ_L increases, the number of LBER packets in the system rises correspondingly. Furthermore, since the LBER packets have higher priority, they will enter the server before HBER packets. Consequently, the number of LBER packets will be lower compared to that of Fig. 5-1 under the same condition. As a result, due to the higher priority of LBER packets, the number of HBER packets increases because HBER packets will be placed behind LBER packets when there are LBER packets in the queue. Furthermore, as λ_L increases, more packets enter the system per time slot and L increases. Lastly, the analytical results match well with the simulation results.

Fig. 5-3 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the queue L_q $\left(L_{qL}, L_{qH}\right)$ and LBER packet arrival rate λ_L under a FIFO queueing discipline. As λ_L increases, the number of LBER packets in the queue rises correspondingly. Consequently, as the queue approaches full system size, the number of HBER packets in queue decreases due to the growing presence of LBER packets in the system. Furthermore, as λ_L increases, more packets enter the system per time slot and L_q increases. Lastly, the analytical results match well with the simulation results.

Fig. 5-4 illustrates the relationship between the number all $(LBER, HBER)$ packets in the queue L_q $\left(L_{qL}, L_{qH}\right)$ and LBER packet arrival rate λ_L under a priority, they will enter the server before HBER packets. Consequently, the number of LBER packets will be lower compared to that of Fig. 5-3 under the same condition. As a result, due to the higher priority of LBER packets, the number of HBER packets increases because HBER packets will be placed behind LBER packets when there are LBER packets in the queue. Furthermore, as λ_L increases, more packets enter the system per time slot and L_q increases. Lastly, the analytical results match well with the simulation results.

Fig. 5-5 illustrates the relationship between the system's waiting time for all $(LBER, HBER)$ packets W (W_L, W_H) and LBER packet arrival rate λ_L under a FIFO queueing discipline. As λ_L increases, the waiting time in the system rises correspondingly. Since the queue is a FIFO system, the waiting time of LBER and HBER packets will be identical. Furthermore, as λ_L increases, more packets enter the system per time slot, each packet needs to wait for more packets finishing service in the queue, and thus W increases. Lastly, the analytical results match well with the simulation results.

Fig. 5-6 illustrates the relationship between the system's waiting time for all $(LBER, HBER)$ packets, denoted as W (W_L, W_H), and the arrival rate of LBER packets, λ_L, under a priority queuing discipline. As λ_L increases, the waiting time in the system correspondingly rises. In a priority system, LBER packets have higher priority, resulting in lower waiting times compared to those shown in Fig. 5-5. Additionally, LBER packets will experience lower waiting times than HBER packets since LBER packets are placed in front of all HBER packets in the queue. Lastly, the analytical results match well with the simulation results.

Fig. 5-7 illustrates the relationship between the waiting time in queue for all $(LBER, HBER)$ packets W_q $\left(W_{qL}, W_{qH}\right)$ and LBER packet arrival rate λ_L under a FIFO queueing discipline. As λ_L increases, the waiting time in the queue rises correspondingly. Since the queue is a FIFO system, the waiting time in queue of LBER and HBER packets will be identical. Furthermore, as λ_L increases, more packets enter the system per time slot, each packet needs to wait for more packets finishing service in the queue, and thus W_q W increases. Lastly, the analytical results match well with the simulation results.

Fig. 5-8 illustrates the relationship between the waiting time in queue for all $(LBER, HBER)$ packets, denoted as W_q $\left(W_{qL}, W_{qH}\right)$, and the arrival rate of LBER packets, λ_L, under a priority queuing discipline. As λ_L increases, the waiting time in the queue correspondingly rises. In a priority system, LBER packets have higher priority, resulting in lower waiting times compared to those shown in Fig. 5-7. Additionally, LBER packets will experience lower waiting times than HBER packets since LBER packets are placed in front of all HBER packets in the queue. Lastly, the analytical results match well with the simulation results.

Fig. 5-9 illustrates the relationship between the blocking probability for all $(LBER, HBER)$ packets Pb (Pb_L, Pb_H) and LBER packet arrival rate λ_L under a FIFO queueing discipline. As λ_L increases, the blocking probability rises because there are more packets enter the system. Furthermore, the blocking probability of LBER packet and HBER packet will be identical. Lastly, the analytical results match well with the simulation results.

Fig. 5-10 illustrates the relationship between the blocking probability for all $(LBER, HBER)$ packets Pb (Pb_L, Pb_H) and LBER packet arrival rate λ_L under a priority queueing discipline. As λ_L increases, the blocking probability rises because there are more packets enter the system. Furthermore, the blocking probability of LBER packet and HBER packet will be identical. Lastly, the analytical results match well with the simulation results.

Fig. 5-11 illustrates the relationship between the throughput for all $(LBER, HBER)$ packets TH (TH_L, TH_H) and LBER packet arrival rate λ_L under a FIFO queueing discipline. As λ_L increases, the throughput rises but eventually reaches γ because packets can only be transmitted in state 1. The throughput of LBER packet rises as the λ_L increases, but throughput of HBER decreases since the HBER packet arrival rate is fixed, more LBER packets enter the system and less HBER packets can be served per time slot. Lastly, the analytical results match well with the simulation results.

Fig. 5-12 illustrates the relationship between the throughput for all $(LBER, HBER)$ packets TH (TH_L, TH_H) and LBER packet arrival rate λ_L under a priority queueing discipline. As λ_L increases, the throughput rises but eventually reaches γ because packets can only be transmitted in state 1. The throughput of LBER packet rises as the λ_L increases, but throughput of HBER decreases since the more LBER packets enter the system, the less HBER packets behind the LBER packets in the queue can be served. Lastly, the analytical results match well with the simulation results.

Fig. 5-13 illustrates the relationship between the power consumption for all $(LBER, HBER)$ packets P (P_L, P_H) and LBER packet arrival rate λ_L under a FIFO queueing discipline. As λ_L increases, the power consumption rises because there are more packets enter the system. Furthermore, as λ_L increases, more packets enter the system per time slot and P_L increases. The P_H decreases since there are more LBER packets in the system. Moreover, since LBER packets require higher energy to transmit, when $\lambda_L = \lambda_H = 0.3$, the power consumption $P_L > P_H$ under the same condition. Lastly, the analytical results match well with the simulation results.

Fig. 5-14 illustrates the relationship between the power consumption for all $(LBER, HBER)$ packets P (P_L, P_H) and LBER packet arrival rate λ_L under a priority queueing discipline. As λ_L increases, the power consumption rises because there are more packets enter the system. Furthermore, as λ_L increases, more packets enter the system per time slot and P_L increases. The P_H decreases since there are more LBER packets in the system. Moreover, since LBER packets require higher energy to transmit, when $\lambda_L = \lambda_H = 0.3$, the power consumption $P_L > P_H$ under the same condition. Lastly, the analytical results match well with the simulation results.

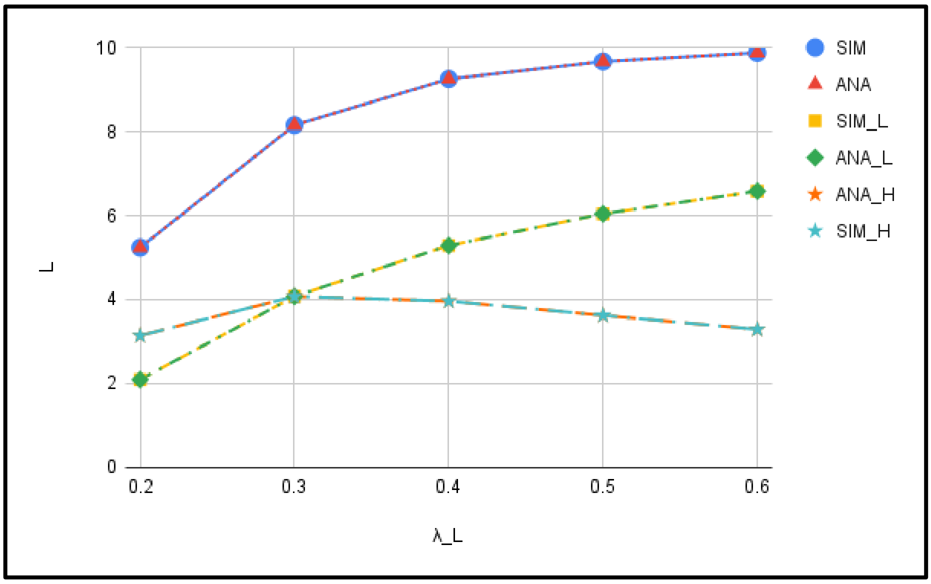


Fig 5. 1: The number of all $(LBER, HBER)$ packets in the system and LBER packet arrival rate under a FIFO queueing discipline

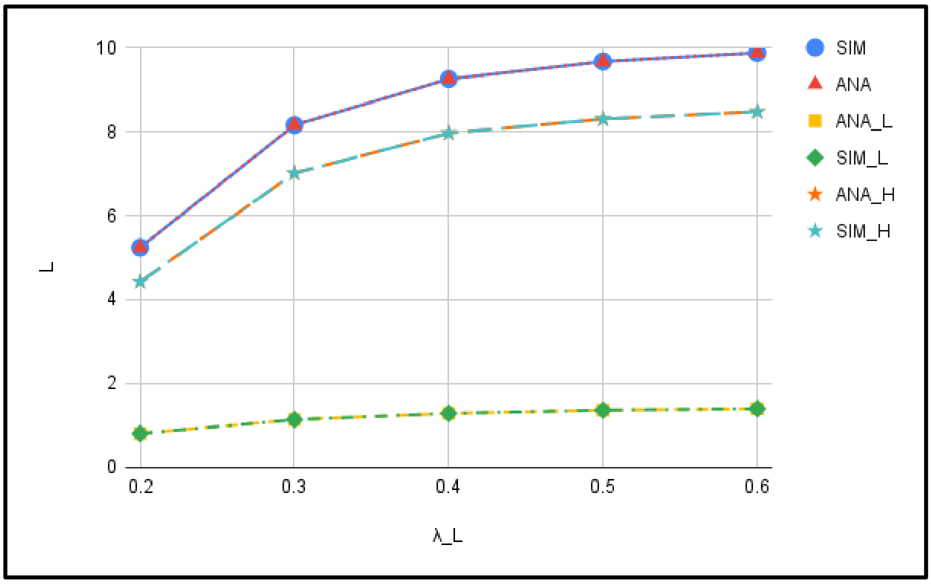


Fig 5. 2: The number of all $(LBER, HBER)$ packets in the system and LBER packet arrival rate under a priority queueing discipline

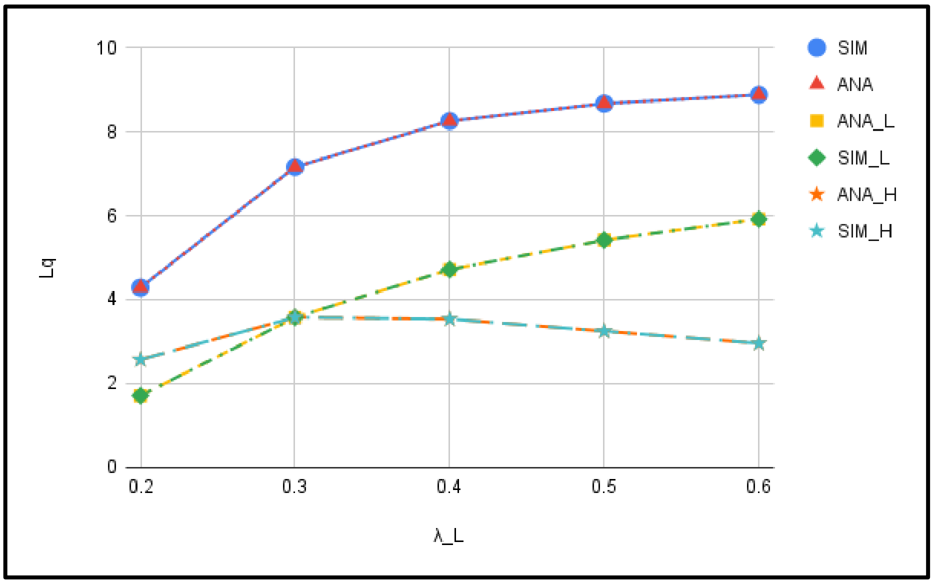


Fig 5. 3: The number of all $(LBER, HBER)$ packets in the queue and LBER packet arrival rate under a FIFO queueing discipline

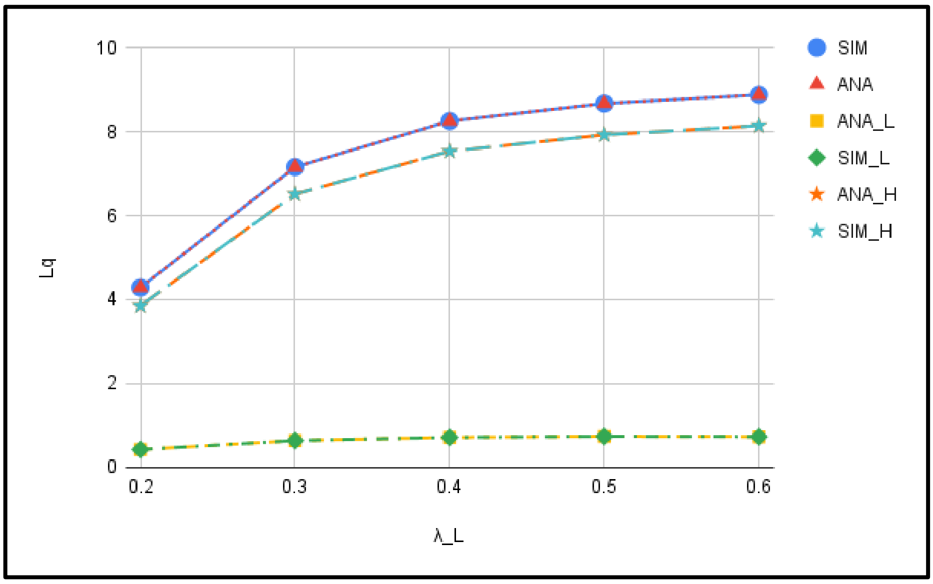


Fig 5. 4: The number of all $(LBER, HBER)$ packets in the queue and LBER packet arrival rate under a priority queueing discipline

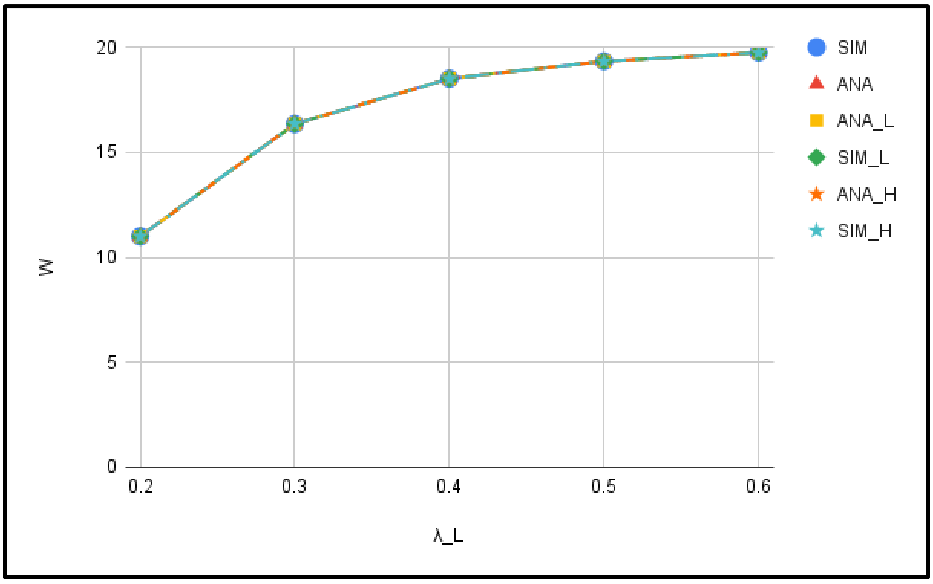


Fig 5. 5: The waiting time of all $(LBER, HBER)$ packets in the system and LBER packet arrival rate under a FIFO queueing discipline

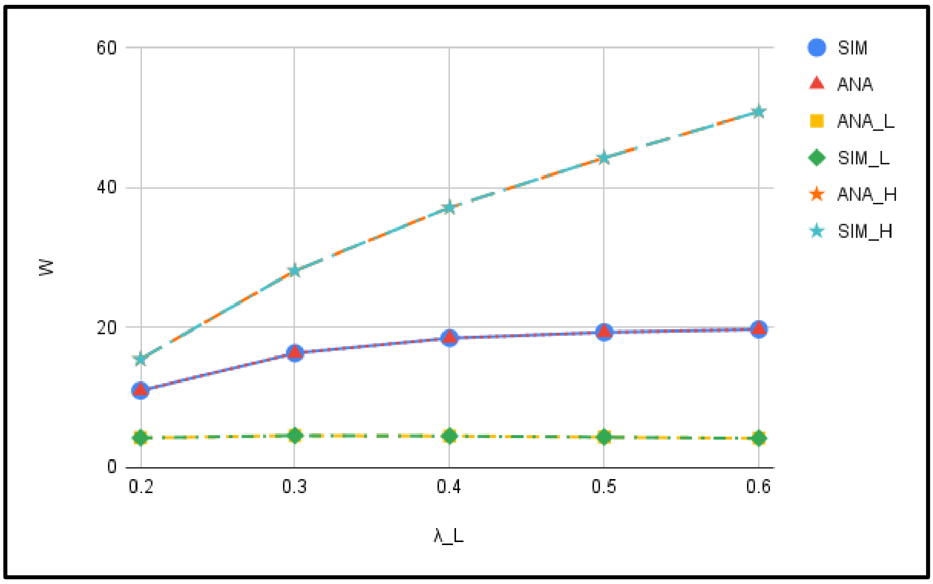


Fig 5. 6: The waiting time of all $(LBER, HBER)$ packets in the system and LBER packet arrival rate under a priority queueing discipline

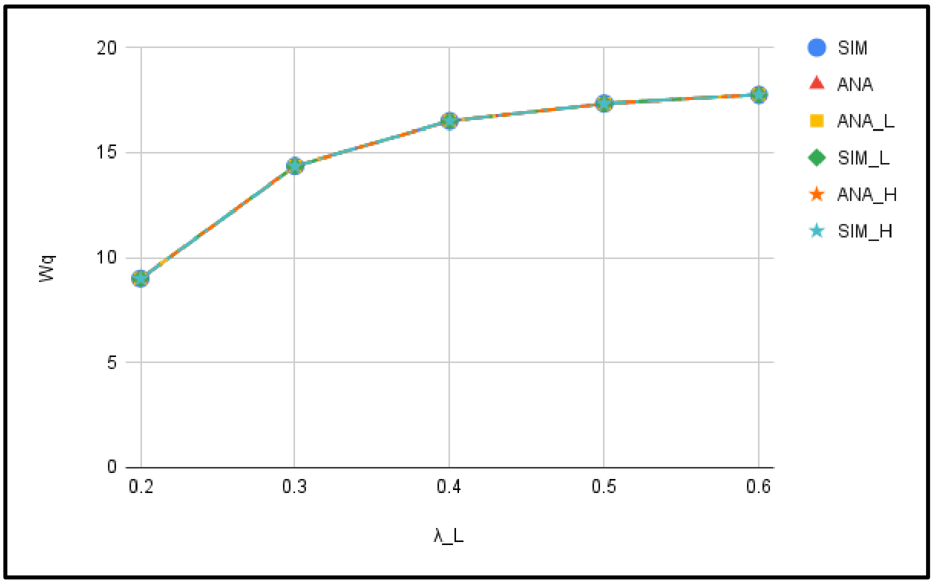


Fig 5. 7: The waiting time of all $(LBER, HBER)$ packets in the queue and LBER packet arrival rate under a FIFO queueing discipline

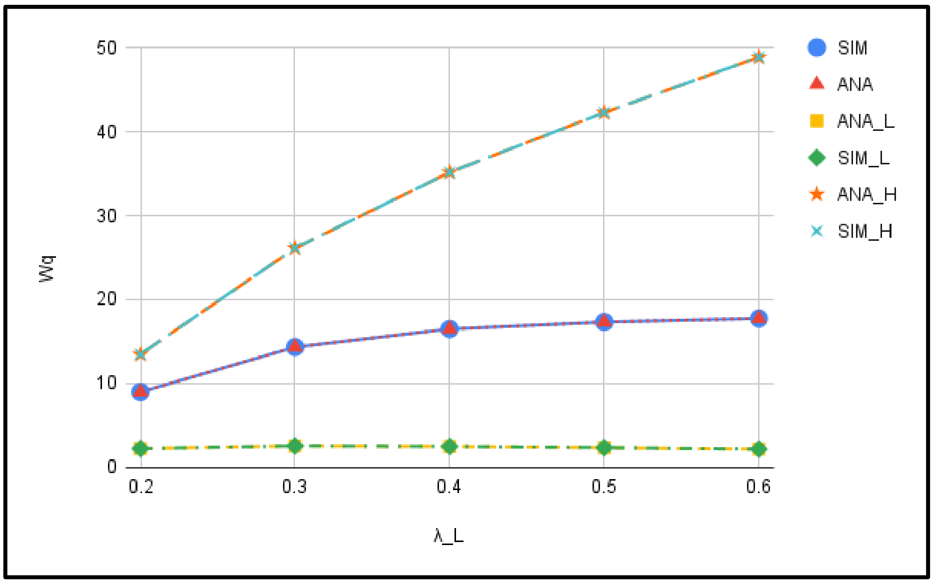


Fig 5. 8: The waiting time of all $(LBER, HBER)$ packets in the queue and LBER packet arrival rate under a priority queueing discipline

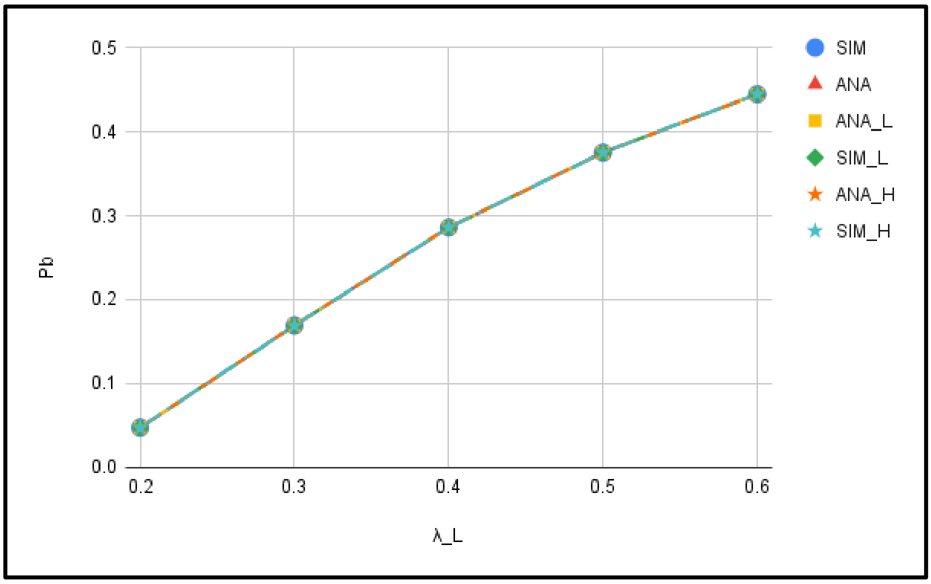


Fig 5. 9: The blocking probability of all $(LBER, HBER)$ packets and LBER packet arrival rate under a FIFO queueing discipline

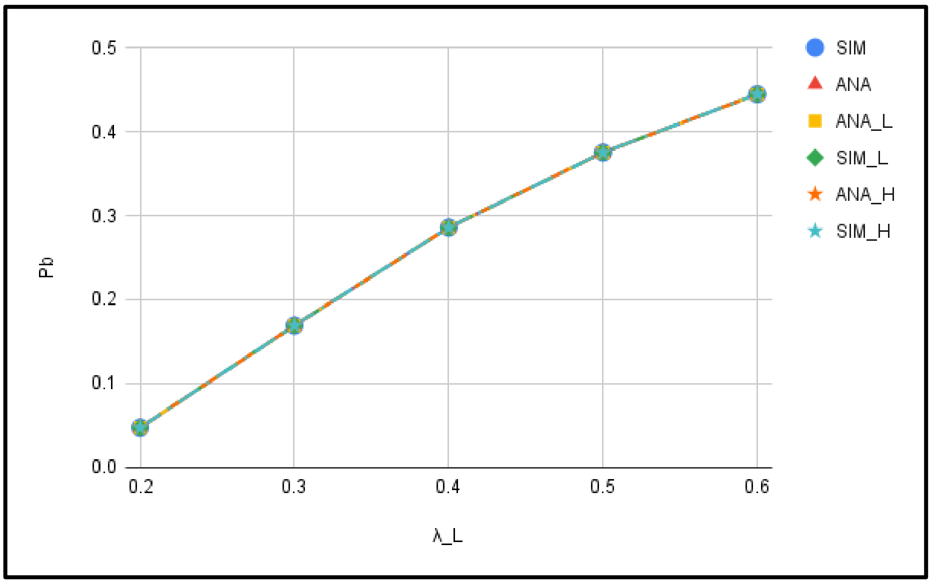


Fig 5. 10: The blocking probability of all $(LBER, HBER)$ packets and LBER packet arrival rate under a priority queueing discipline

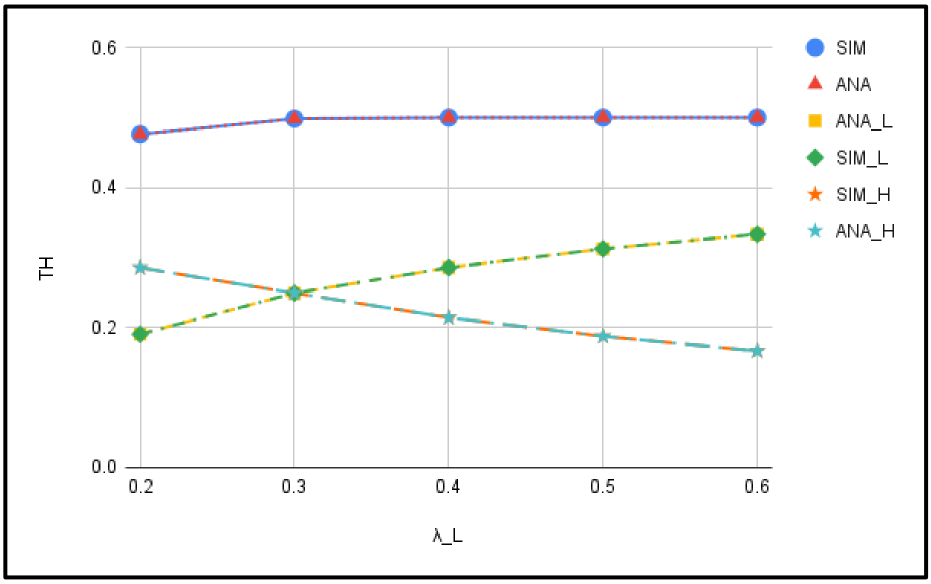


Fig 5. 11: The throughput of all $(LBER, HBER)$ packets and LBER packet arrival rate under a FIFO queueing discipline

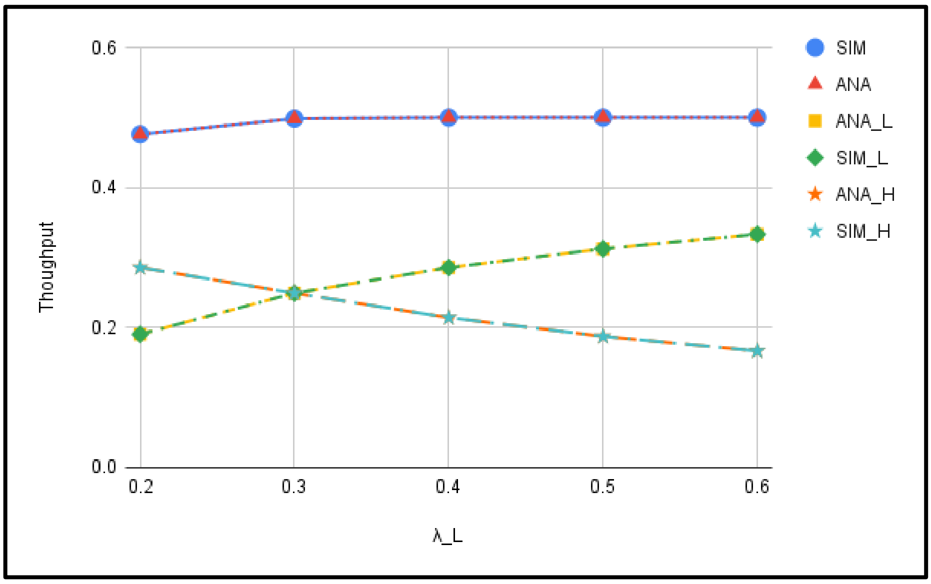


Fig 5. 12: The throughput of all $(LBER, HBER)$ packets and LBER packet arrival rate under a priority queueing discipline

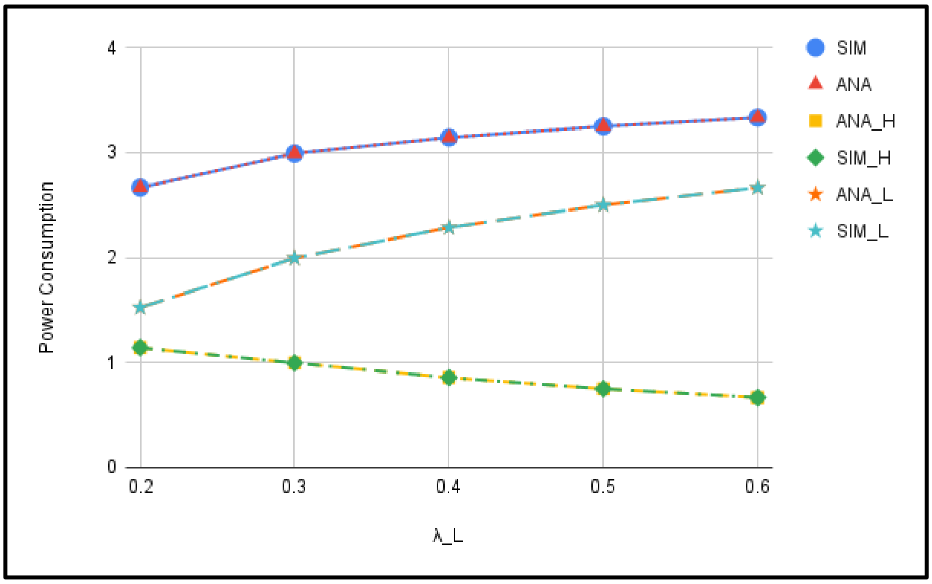


Fig 5. 13: The power consumption of all $(LBER, HBER)$ packets and LBER packet arrival rate under a FIFO queueing discipline

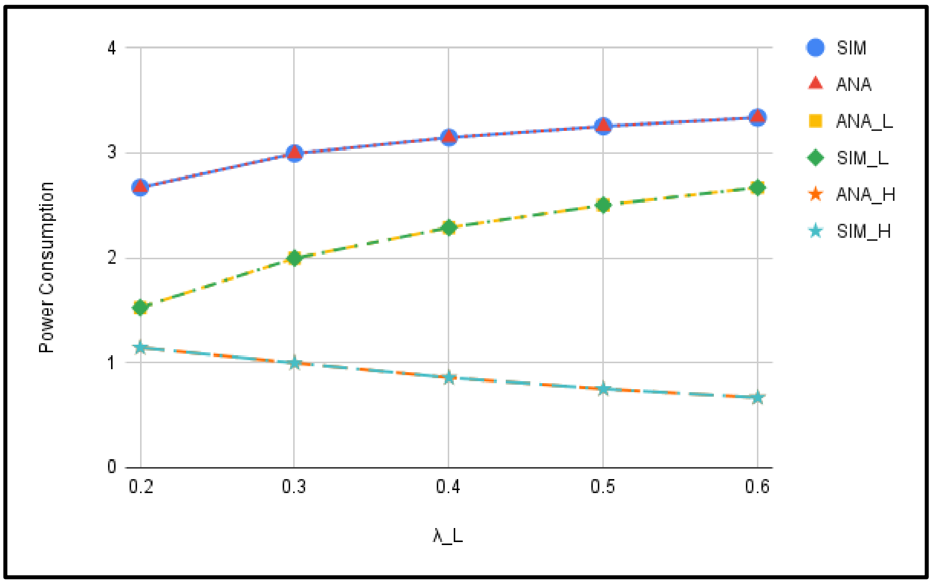


Fig 5. 14: The power consumption of all $(LBER, HBER)$ packets and LBER packet arrival rate under a priority queueing discipline

5.2 Scenario 2

The input parameters in model 2, applicable to both FIFO and priority queuing disciplines, are as provided below: $K, \lambda_L, \lambda_H, \alpha_L, \alpha_H, \gamma$. To assess their impact on the system, we will adjust only one parameter at a time. Additionally, the system size (K) is set to 10. The default values are provided below: $\lambda_L = 0.3,\ \lambda_H = 0.3,\ \alpha_L = 0.5,\ \alpha_H = 0.5, \gamma = 0.5$.

5.2.1 LBER packet arrival rate

We increment the LBER packet arrival rate by 0.1 and compare it against several performance indices such as: $L, L_q, Pb, Power, TH, W, Wq$.

Fig. 5-15 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the system $L\ (L_L, L_H)$ and LBER packet arrival rate λ_L under a FIFO queueing discipline. As λ_L increases, the number of LBER packets in the system rises correspondingly. At $\lambda_L = 0.3$, the numbers of LBER and HBER packets in the system become identical since $\lambda_H = 0.3$. However, the number of HBER packets in the system continues to increase since the system is not yet full. Moreover, as λ_L increases, more packets enter the system per time slot, causing L to increase. Lastly, the analytical results align well with the simulation results.

Fig. 5-16 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the system $L\ (L_L, L_H)$ and LBER packet arrival rate λ_L under a priority queueing discipline. As λ_L increases, the number of LBER packets in the system rises correspondingly. However, compared to Fig. 5-15, L_L rises more slowly since LBER packets are given higher priority. Conversely, the number of HBER packets continues to increase significantly since they are placed after LBER packets in the queue. Moreover, as λ_L increases, more packets enter the system per time slot, causing L to increase. More importantly, as λ_L increases, L_L is always lower than L_H since LBER packets are given higher priority over HBER packets. Lastly, the analytical results align well with the simulation results.

Fig. 5-17 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the queue $L_q\ (L_{qL}, L_{qH})$ and LBER packet arrival rate λ_L under a FIFO queueing discipline. As λ_L increases, the number of LBER packets in the queue rises correspondingly. At $\lambda_L = 0.3$, the numbers of LBER and HBER packets in the queue become identical since $\lambda_H = 0.3$. However, the number of HBER packets in the queue continues to increase since the system is not yet full.

Moreover, as λ_L increases, more packets enter the queue per time slot, causing L_q to increase. Lastly, the analytical results align well with the simulation results.

Fig. 5-18 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the queue L_{qL} $\left(L_{qL}, L_{qH}\right)$ and LBER packet arrival rate λ_L under a priority queueing discipline. As λ_L increases, the number of LBER packets in the queue rises correspondingly. However, compared to Fig. 5-17, L_{qL} rises more slowly since LBER packets are given higher priority. Conversely, the number of HBER packets continues to increase significantly since they are placed after LBER packets in the queue. Moreover, as λ_L increases, more packets enter the queue per time slot, causing L_q to increase. More importantly, as λ_L increases, L_{qL} is always lower than L_{qH} since LBER packets are given higher priority over HBER packets. Lastly, the analytical results align well with the simulation results.

Fig. 5-19 illustrates the relationship between the system's waiting time for all $(LBER, HBER)$ packets W (W_L, W_H) and LBER packet arrival rate λ_L under a FIFO queueing discipline. As λ_L increases, the waiting time in the system rises correspondingly. Since the queue is a FIFO system, the waiting time of LBER and HBER packets will be identical. Furthermore, as λ_L increases, more packets enter the system per time slot, each packet needs to wait for more packets finishing service in the queue, and thus W increases. However, compared to Fig. 5-5, the system's waiting time decreases since packets can still be transmitted based on the associated delivery probability even when the channel is in state 0. Lastly, the analytical results match well with the simulation results.

Fig. 5-20 illustrates the relationship between the system's waiting time for all $(LBER, HBER)$ packets, denoted as W (W_L, W_H), and the arrival rate of LBER packets, λ_L, under a priority queuing discipline. As λ_L increases, the waiting time in the system correspondingly rises. In a priority system, LBER packets have higher priority, resulting in lower waiting times compared to those shown in Fig. 5-19. Additionally, LBER packets will experience lower waiting times than HBER packets since LBER packets are placed in front of all HBER packets in the queue. Moreover, compared to Fig. 5-6, the system's waiting time decreases since packets can still be transmitted based on the associated delivery probability even when the channel is in state 0. Lastly, the analytical results match well with the simulation results.

Fig. 5-21 illustrates the relationship between the waiting time in queue for all $(LBER, HBER)$ packets W_q $\left(W_{qL}, W_{qH}\right)$ and LBER packet arrival rate λ_L under a FIFO queueing discipline. As λ_L increases, the waiting time in the queue rises correspondingly. Since the queue is a FIFO system, the waiting time of LBER and HBER packets in the queue will be identical. Furthermore, as λ_L increases, more packets enter the system per time slot, each packet needs to wait for more packets finishing service in the queue, and thus W_q increases. However, compared to Fig. 5-7, the waiting time in queue decreases since packets can still be transmitted based on the associated delivery probability even when the channel is in state 0. Lastly, the analytical results match well with the simulation results.

Fig. 5-22 illustrates the relationship between the waiting time in queue for all $(LBER, HBER)$ packets, denoted as W_q $\left(W_{qL}, W_{qH}\right)$, and the arrival rate of LBER packets, λ_L, under a priority queuing discipline. As λ_L increases, the waiting time in the queue correspondingly rises. In a priority system, LBER packets have higher priority, resulting in lower waiting times compared to those shown in Fig. 5-21. Additionally, LBER packets will experience lower waiting times than HBER packets since LBER packets are placed in front of all HBER packets in the queue. Moreover, compared to Fig. 5-8, the system's waiting time decreases since packets can still be transmitted based on the associated delivery probability even when the channel is in state 0. Lastly, the analytical results match well with the simulation results.

Fig. 5-23 illustrates the relationship between the blocking probability for all $(LBER, HBER)$ packets Pb (Pb_L, Pb_H) and LBER packet arrival rate λ_L under a FIFO queueing discipline. As λ_L increases, the blocking probability rises because more packets enter the system and the system mis more likely to be full. However, compared to Fig. 5-11, the blocking probability is lower since packets can still be transmitted based on the associated delivery probability even when the channel is in state 0. Furthermore, the blocking probabilities of LBER packet and HBER packet will be identical since all packets are blocked upon arrival if the system is full. Lastly, the analytical results match well with the simulation results.

Fig. 5-24 illustrates the relationship between the blocking probability for all $(LBER, HBER)$ packets Pb (Pb_L, Pb_H) and LBER packet arrival rate λ_L under a priority queueing discipline. As λ_L increases, the blocking probability rises because more packets enter the system and the system mis more likely to be full. However, compared to Fig. 5-12, the blocking probability is lower since packets can still be transmitted based on the associated delivery probability even when the channel is in state 0. Furthermore, the blocking probabilities of LBER packet and HBER packet will be identical since all packets are blocked upon arrival if the system is full. Lastly, the analytical results match well with the simulation results.

Fig. 5-25 illustrates the relationship between the throughput for all $(LBER, HBER)$ packets TH (TH_L, TH_H) and LBER packet arrival rate λ_L under a FIFO queueing discipline. As λ_L increases, the throughput rises correspondingly, and it achieves higher throughput compared to Fig. 5-9 since packets can still be transmitted based on the associated delivery probability even when the channel is in state 0. Furthermore, the throughput of LBER packet rises as the λ_L increases, but throughput of HBER decreases since the HBER packet arrival rate is fixed, more LBER packets enter the system and less HBER packets can be served per time slot. Lastly, the analytical results match well with the simulation results.

Fig. 5-26 illustrates the relationship between the throughput for all $(LBER, HBER)$ packets TH (TH_L, TH_H) and LBER packet arrival rate λ_L under a priority queueing discipline. As λ_L increases, the throughput rises correspondingly, and it achieves higher throughput compared to Fig. 5-10 since packets can still be transmitted based on the associated delivery probability even when the channel is in state 0. Furthermore, the throughput of LBER packet rises as the λ_L increases, but throughput of HBER decreases since the more LBER packets enter the system, the less HBER packets behind the LBER packets in the queue can be served. Lastly, the analytical results match well with the simulation results.

Fig. 5-27 illustrates the relationship between the power consumption for all $(LBER, HBER)$ packets P (P_L, P_H) and LBER packet arrival rate λ_L under a FIFO queueing discipline. As λ_L increases, the power consumption rises because more packets enter the system and more packets are likely to be transmitted in state 0 with a higher power consumption. Furthermore, as λ_L increases, more LBER packets enter the system per time slot, more LBER packets are likely to be transmitted in state 0 with a higher power consumption and P_L increases. P_H decreases since the more LBER packets are in the system, the less HBER packets are in the system and can be transmitted. Moreover, since LBER packets require higher energy to transmit, when $\lambda_L = \lambda_H = 0.3$, the power consumption $P_L > P_H$ under the same condition. However, compared to Fig. 5-13, the power consumption is higher since packets require higher energy to transmit in state 0. Lastly, the analytical results match well with the simulation results.

Fig. 5-28 illustrates the relationship between the power consumption for all $(LBER, HBER)$ packets P (P_L, P_H) and LBER packet arrival rate λ_L under a priority queueing discipline. As λ_L increases, the power consumption rises because more packets enter the system and more packets are likely to be transmitted in state 0 with a higher power consumption. Furthermore, as λ_L increases, more LBER packets enter the system per time slot, more LBER packets are likely to be transmitted in state 0 with a higher power consumption and P_L increases.

P_H decreases since the more LBER packets are in the system, the less HBER packets are in the system and can be transmitted. Moreover, since LBER packets require higher energy to transmit, when $\lambda_L = \lambda_H = 0.3$, the power consumption $P_L > P_H$ under the same condition. However, compared to Fig. 5-14, the power consumption is higher since packets require higher energy to transmit in state 0. Lastly, the analytical results match well with the simulation results.

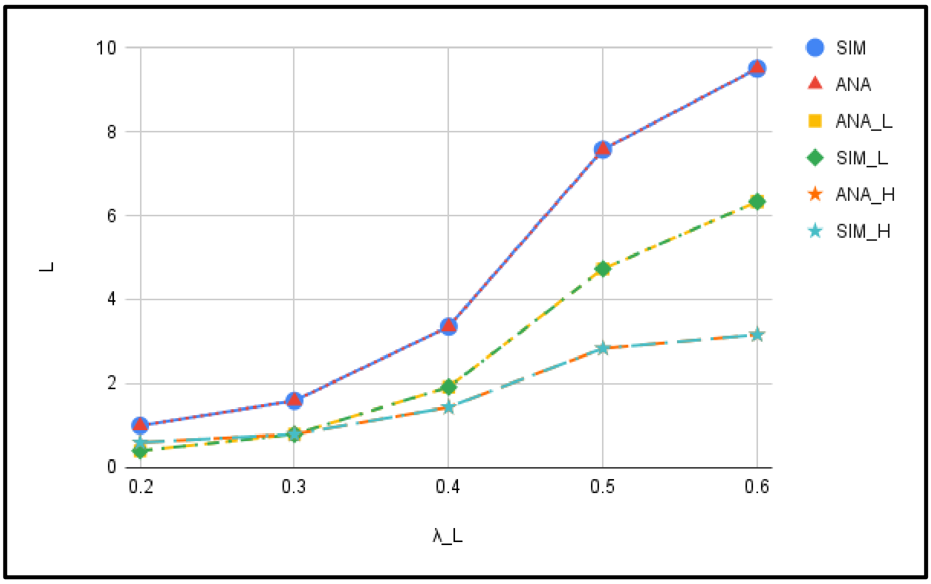


Fig 5. 15: The number of all $(LBER, HBER)$ packets in the system and LBER packet arrival rate under a FIFO queueing discipline

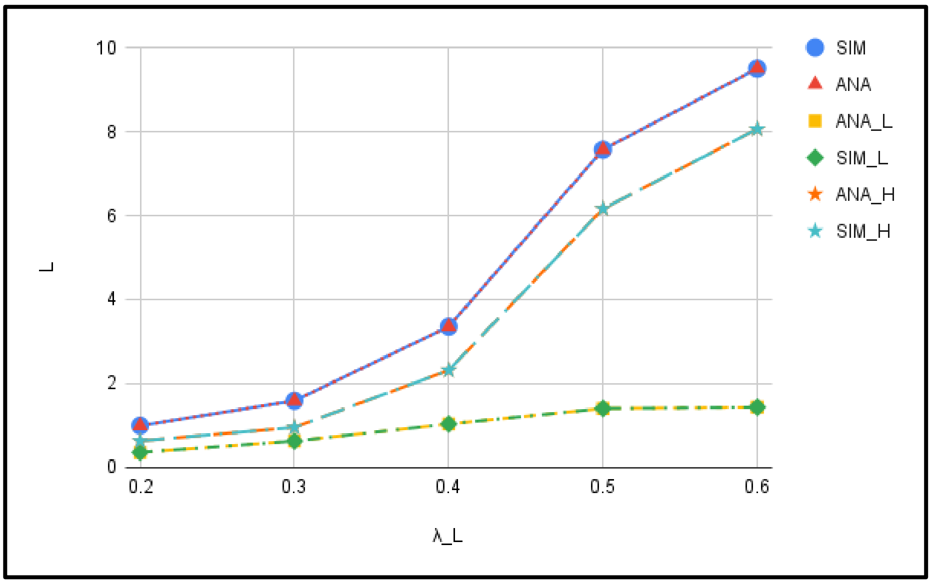


Fig 5. 16: The number of all $(LBER, HBER)$ packets in the system and LBER packet arrival rate under a priority queueing discipline

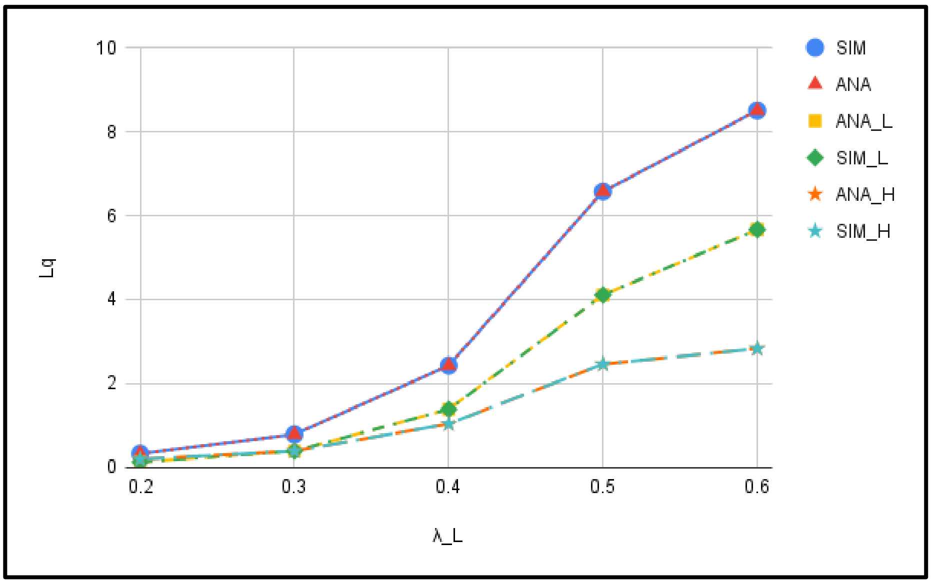


Fig 5. 17: The number of all $(LBER, HBER)$ packets in the queue and LBER packet arrival rate under a FIFO queueing discipline

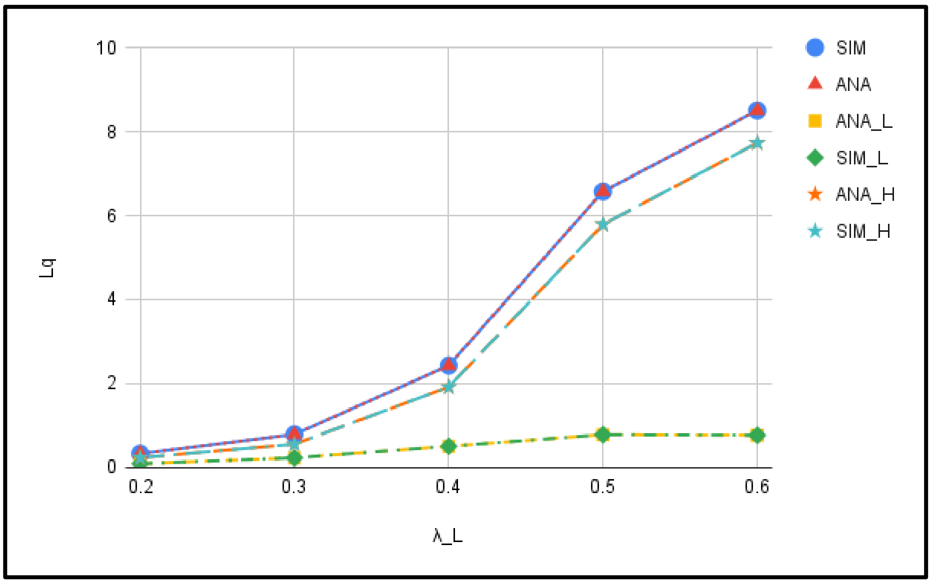


Fig 5. 18: The number of all $(LBER, HBER)$ packets in the queue and LBER packet arrival rate under a priority queueing discipline

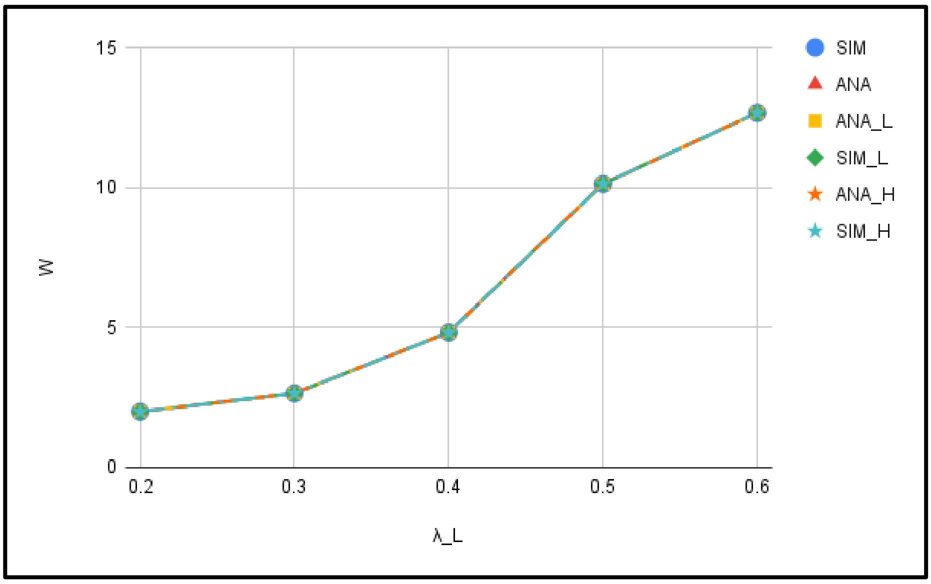


Fig 5. 19: The waiting time of all $(LBER, HBER)$ packets in the system and LBER packet arrival rate under a FIFO queueing discipline

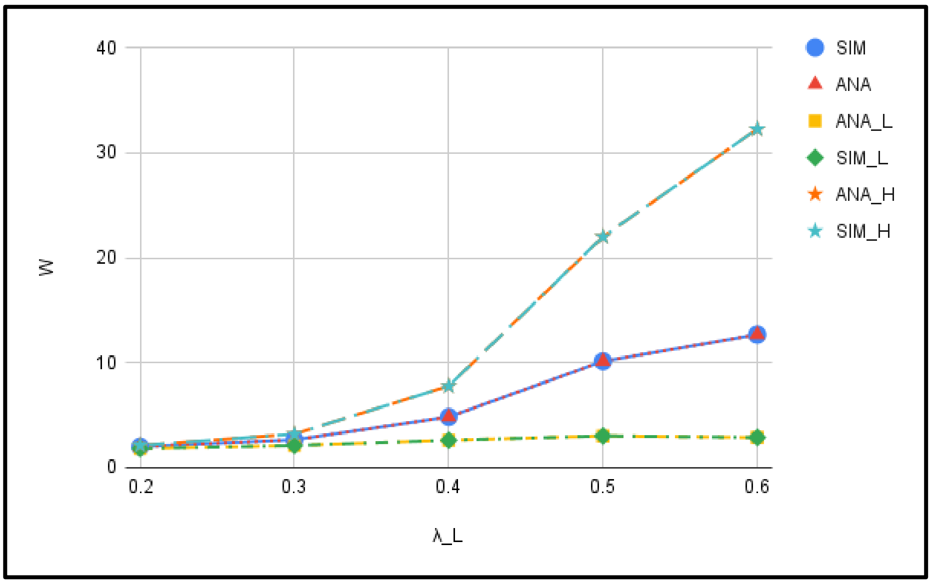


Fig 5. 20: The waiting time of all $(LBER, HBER)$ packets in the system and LBER packet arrival rate under a priority queueing discipline

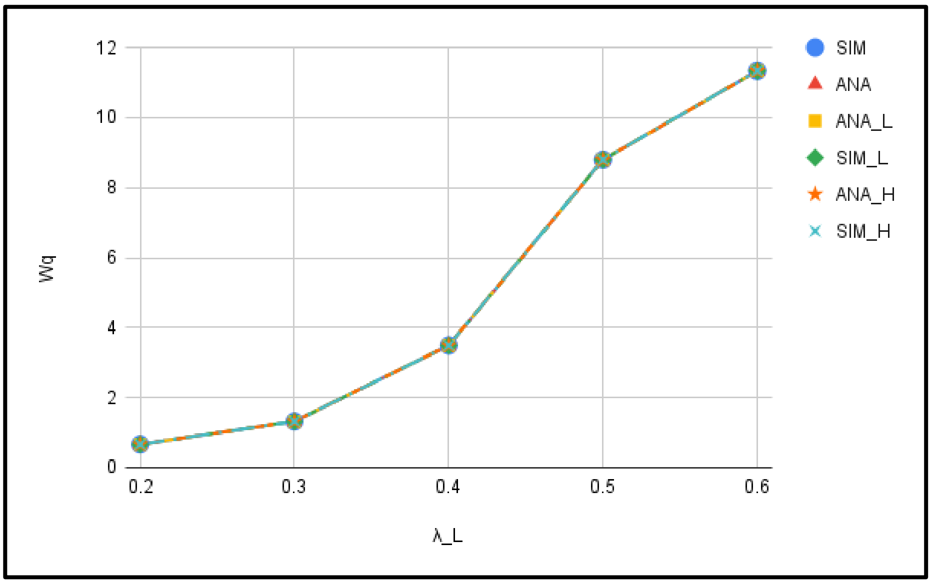


Fig 5. 21: The waiting time of all $(LBER, HBER)$ packets in the queue and LBER packet arrival rate under a FIFO queueing discipline

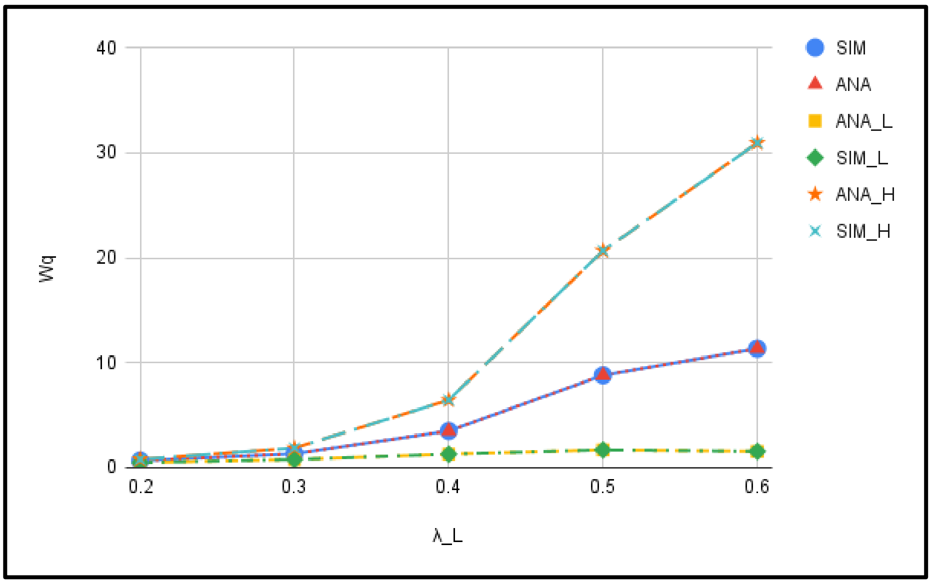


Fig 5. 22: The waiting time of all $(LBER, HBER)$ packets in the queue and LBER packet arrival rate under a priority queueing discipline

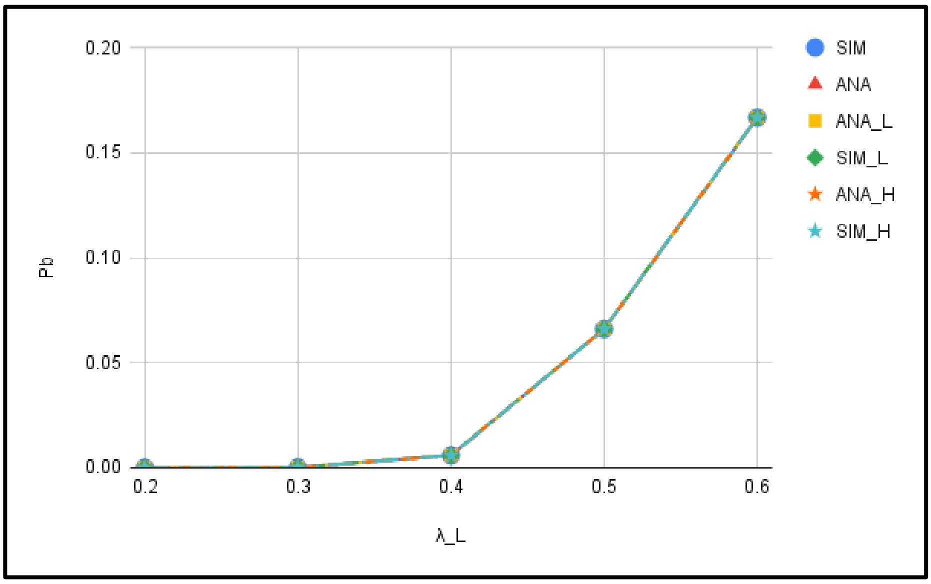


Fig 5. 23: The blocking probability of all $(LBER, HBER)$ packets and LBER packet arrival rate under a FIFO queueing discipline

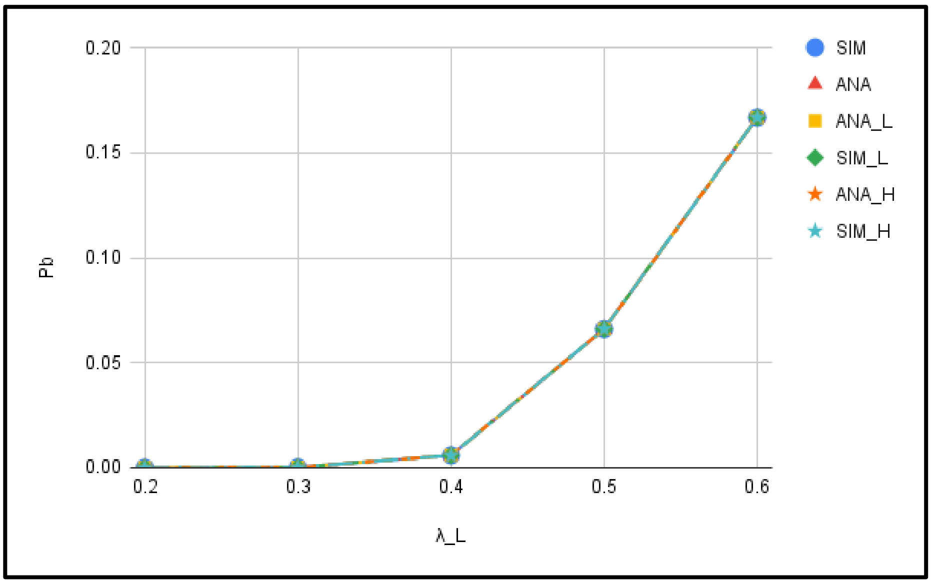


Fig 5. 24: The blocking probability of all $(LBER, HBER)$ packets and LBER packet arrival rate under a priority queueing discipline

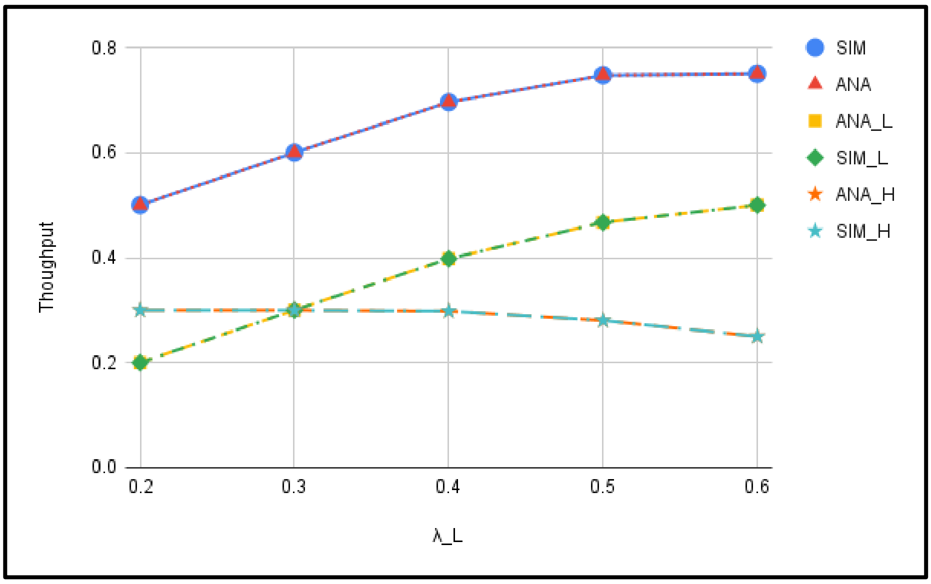


Fig 5. 25: The throughput of all $(LBER, HBER)$ packets and LBER packet arrival rate under a FIFO queueing discipline

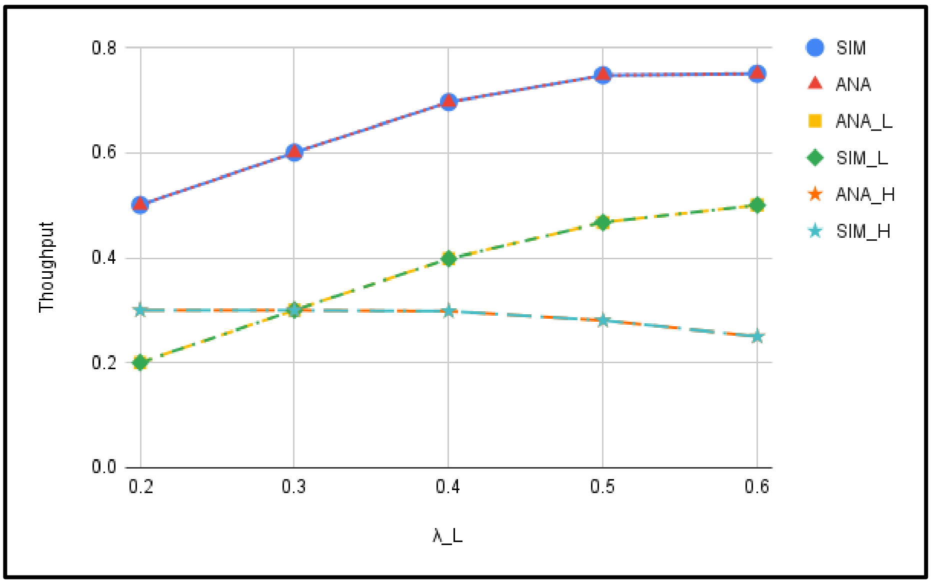


Fig 5. 26: The throughput of all $(LBER, HBER)$ packets and LBER packet arrival rate under a priority queueing discipline

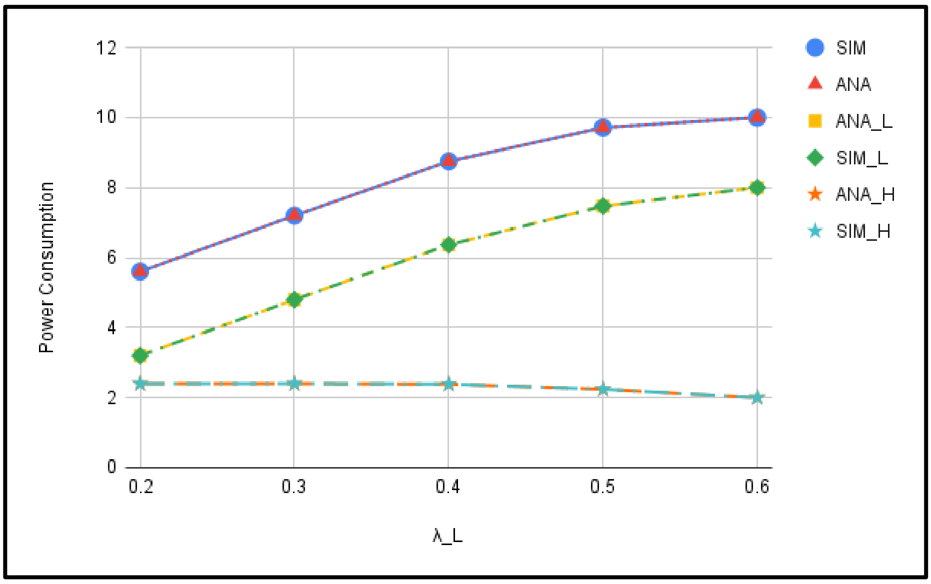


Fig 5. 27: The power consumption of all $(LBER, HBER)$ packets and LBER packet arrival rate under a FIFO queueing discipline

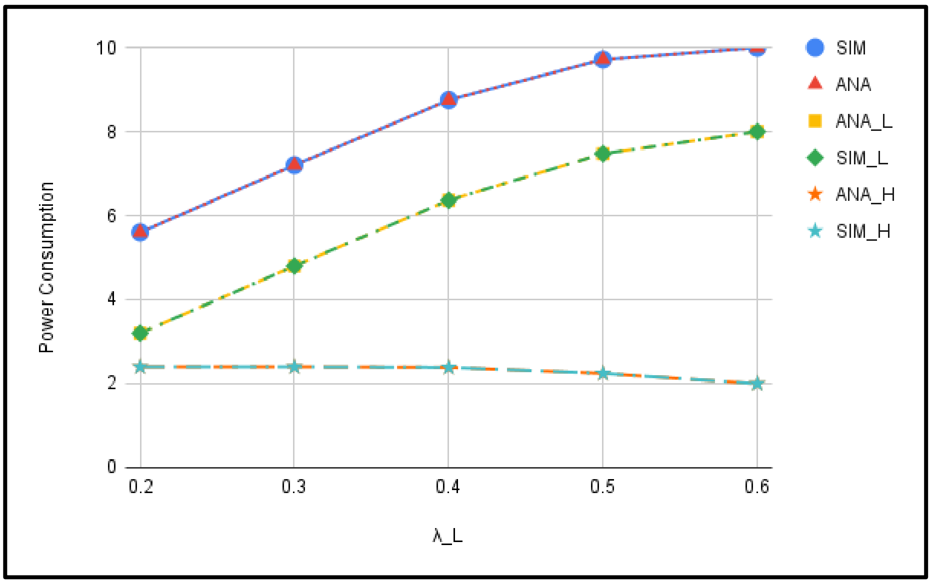


Fig 5. 28: The power consumption of all $(LBER, HBER)$ packets and LBER packet arrival rate under a priority queueing discipline

5.2.2 LBER packet delivery probability

We increment the LBER delivery probability by 0.2 and compare it against several performance indices such as: $L, L_q, Pb, Power, TH, W, Wq$.

Fig. 5-29 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the system L (L_L, L_H) and LBER packet delivery probability α_L under a FIFO queueing discipline. As α_L increases, the number of LBER packets in the system declines correspondingly. Before $\alpha_L = 0.5$, the number of LBER packets will slightly exceeds the number of HBER packets in the system since $\alpha_H = 0.5$. At $\alpha_L = 0.5$, $L_L = L_H$. Beyond this point, the number of LBER packets in the system will be less than HBER packets. Moreover, as α_L increases, the LBER packets have a higher chance of being transmitted in state 0, causing L to decrease. Lastly, the analytical results align well with the simulation results.

Fig. 5-30 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the system L (L_L, L_H) and LBER packet delivery probability α_L under a priority queueing discipline. As α_L increases, the number of packets in the system declines correspondingly. Furthermore, compared to Fig. 5-29, the number of LBER packets is fewer since they are given higher priority. Conversely, the number of HBER packets is more than that in Fig. 5-29 since they are placed after LBER packets in the queue. Moreover, as α_L increases, the LBER packets have a higher chance of being transmitted in state 0, causing L to increase. Lastly, the analytical results align well with the simulation results.

Fig. 5-31 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the queue L_q $\left(L_{qL}, L_{qH}\right)$ and LBER packet delivery probability α_L under a FIFO queueing discipline. As α_L increases, the number of LBER packets in the queue declines correspondingly. Since $\lambda_L = \lambda_H = 0.3$, $L_{qL} = L_{qH}$. Moreover, as α_L increases, the LBER packets have a higher chance of being transmitted in state 0, causing L_q to decrease. Lastly, the analytical results align well with the simulation results.

Fig. 5-32 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the system L_q $\left(L_{qL}, L_{qH}\right)$ and LBER packet delivery probability α_L under a priority queueing discipline. As α_L increases, the number of packets in the queue declines correspondingly. Furthermore, compared to Fig. 5-31, the number of LBER packets is fewer since they are given higher priority. Conversely, the number of HBER packets are more than that in Fig. 5-31 since they are placed after LBER packets in the queue. Moreover, as α_L increases, the LBER packets have a higher chance of being transmitted in state 0, causing L_q to increase. Lastly, the analytical results align well with the simulation results.

Fig. 5-33 illustrates the relationship between the system's waiting time for all $(LBER, HBER)$ packets $W\ (W_L, W_H)$ and LBER packet delivery probability α_L under a FIFO queueing discipline. As α_L increases, the waiting time in the system declines correspondingly. Before $\alpha_L = 0.5$, the waiting time of LBER packets will slightly exceed the waiting time of HBER packets in the system since $\alpha_H = 0.5$. At $\alpha_L = 0.5$, $W_L = W_H$. Beyond this point, the waiting time of LBER packets in the system will be less than the HBER packets' waiting time. Furthermore, as α_L increases, the LBER packets have a higher chance of being transmitted in state 0. Consequently, each packet does not wait as long as before, leading to a decrease in W. Lastly, the analytical results match well with the simulation results.

Fig. 5-34 illustrates the relationship between the system's waiting time for all $(LBER, HBER)$ packets $W\ (W_L, W_H)$ and LBER packet delivery probability α_L under a priority queueing discipline. As α_L increases, the LBER packets have a higher chance of being transmitted in state 0, and the waiting time in the system declines correspondingly. Furthermore, compared to Fig. 5-33, the waiting time of LBER packets becomes shorter since LBER packets have higher priority. Lastly, the analytical results match well with the simulation results.

Fig. 5-35 illustrates the relationship between the waiting time in the queue for all $(LBER, HBER)$ packets $W_q\ \left(W_{qL}, W_{qH}\right)$ and LBER packet delivery probability α_L under a FIFO queueing discipline. As α_L increases, the waiting time in the queue declines correspondingly. Since $\lambda_L = \lambda_H = 0.3$, $W_{qL} = W_{qH}$. Moreover, as α_L increases, the LBER packets have a higher chance of being transmitted in state 0, causing total waiting time in queue W_q to decrease. Lastly, the analytical results align well with the simulation results.

Fig. 5-36 illustrates the relationship between the waiting time in the queue for all $(LBER, HBER)$ packets $W_q\ \left(W_{qL}, W_{qH}\right)$ and LBER packet delivery probability α_L under a priority queueing discipline. As α_L increases, the LBER packets have a higher chance of being transmitted in state 0, and the waiting time in the queue declines correspondingly. Furthermore, compared to Fig. 5-35, the waiting time of LBER packets becomes shorter since LBER packets have higher priority. Lastly, the analytical results match well with the simulation results.

Fig. 5-37 illustrates the relationship between the blocking probability for all $(LBER, HBER)$ packets $Pb\ (Pb_L, Pb_H)$ and LBER packet delivery probability α_L under a FIFO queueing discipline. As α_L increases, the blocking probability declines because LBER packets have more chance to be transmitted in state 0, causing the number in the system decreases. Furthermore, the blocking probabilities of LBER packet and HBER packet will be identical since all packets are blocked upon arrival if the system is full. Lastly, the analytical results match well with the simulation results.

Fig. 5-38 illustrates the relationship between the blocking probability for all $(LBER, HBER)$ packets Pb (Pb_L, Pb_H) and LBER packet delivery probability α_L under a priority queueing discipline. As α_L increases, the blocking probability declines because LBER packets have more chance to be transmitted in state 0, causing the number in the system decreases. However, compared to Fig. 5-37, the blocking probability is higher at the beginning since LBER packets are placed at the head of the queue, but they have lower delivery probability, leads to a higher number in queue. Furthermore, the blocking probabilities of LBER packet and HBER packet will be identical since all packets are blocked upon arrival if the system is full. Lastly, the analytical results match well with the simulation results.

Fig. 5-39 illustrates the relationship between the throughput for all $(LBER, HBER)$ packets TH (TH_L, TH_H) and LBER packet delivery probability α_L under a FIFO queueing discipline. As α_L increases, the throughput rises correspondingly, and it eventually achieves 0.6 since the arrival probability $\lambda_L + \lambda_H = 0.6$. And the throughput of LBER and HBER will be identical. Lastly, the analytical results match well with the simulation results.

Fig. 5-40 illustrates the relationship between the throughput for all $(LBER, HBER)$ packets TH (TH_L, TH_H) and LBER packet delivery probability α_L under a priority queueing discipline. As α_L increases, the throughput rises correspondingly, and it eventually achieves 0.6 since the arrival probability $\lambda_L + \lambda_H = 0.6$. And the throughput of LBER and HBER will be identical since both LBER and HBER packets are blocked upon arrival if the system is full. Lastly, the analytical results match well with the simulation results.

Fig. 5-41 illustrates the relationship between the power consumption for all $(LBER, HBER)$ packets P (P_L, P_H) and LBER packet delivery probability α_L under a FIFO queueing discipline. As α_L increases, the power consumption of LBER packets rises because they have higher chance to be transmitted in state 0. Conversely, the P_H remains the same since α_H remains 0.5 in the system. Moreover, since LBER packets require higher energy to transmit, when $\alpha_L = \alpha_H = 0.5$, the power consumption $P_L > P_H$ under the same condition. Lastly, the analytical results match well with the simulation results.

Fig. 5-42 illustrates the relationship between the power consumption for all $(LBER, HBER)$ packets P (P_L, P_H) and LBER packet delivery probability α_L under a priority queueing discipline. As α_L increases, the power consumption of LBER packets rises because they have higher chance to be transmitted in state 0. Conversely, the P_H remains the same since α_H remains 0.5 in the system. Moreover, since LBER packets require higher energy to transmit, when $\alpha_L = \alpha_H = 0.5$, the power consumption $P_L > P_H$ under the same condition. Lastly, the analytical results match well with the simulation results.

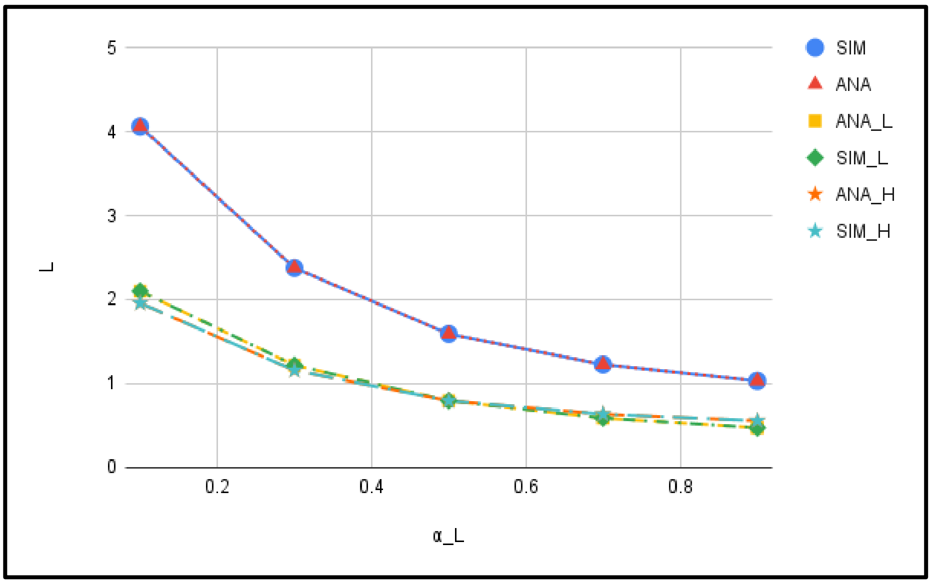


Fig 5. 29: The number of all $(LBER, HBER)$ packets in the system and LBER packet delivery probability under a FIFO queueing discipline

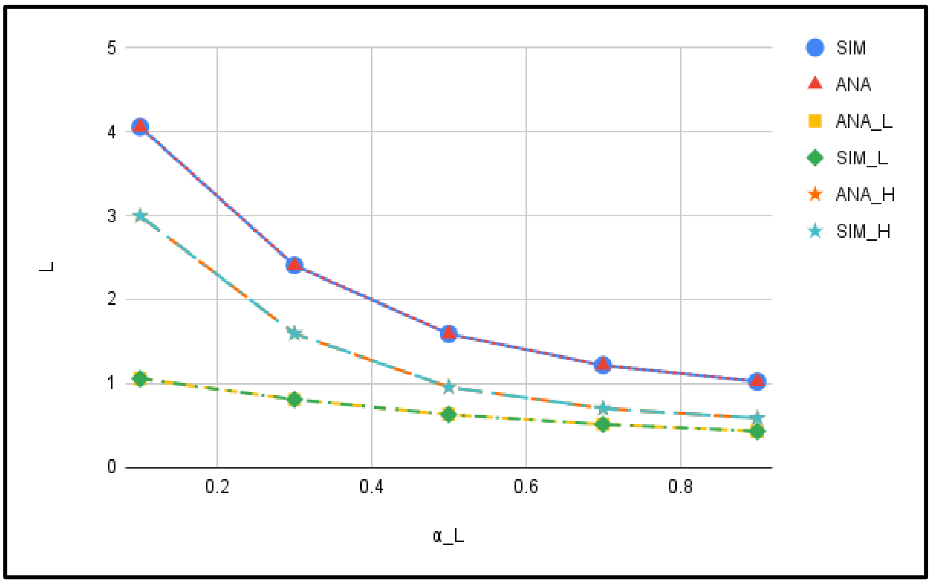


Fig 5. 30: The number of all $(LBER, HBER)$ packets in the system and LBER packet delivery probability under a priority queueing discipline

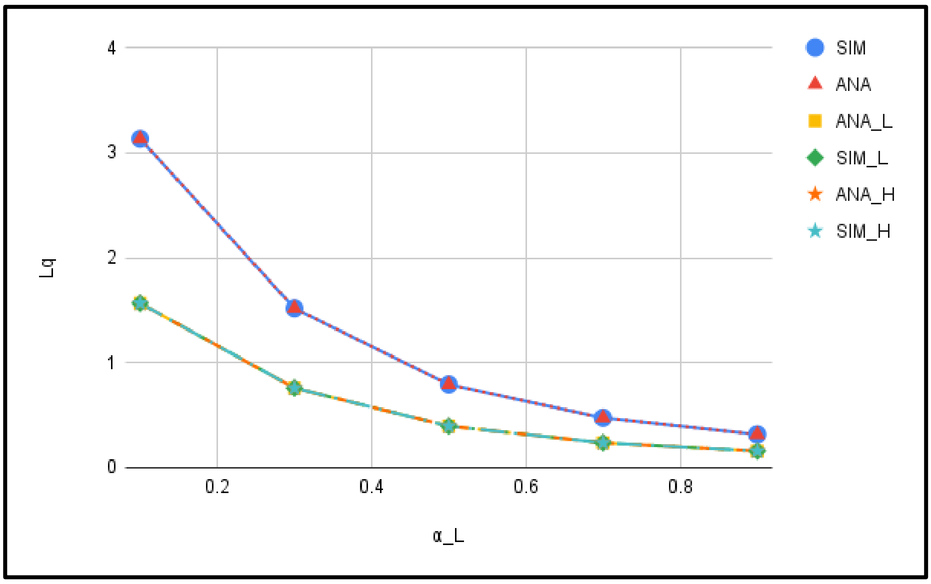


Fig 5. 31: The number of all $(LBER, HBER)$ packets in the queue and LBER packet delivery probability under a FIFO queueing discipline

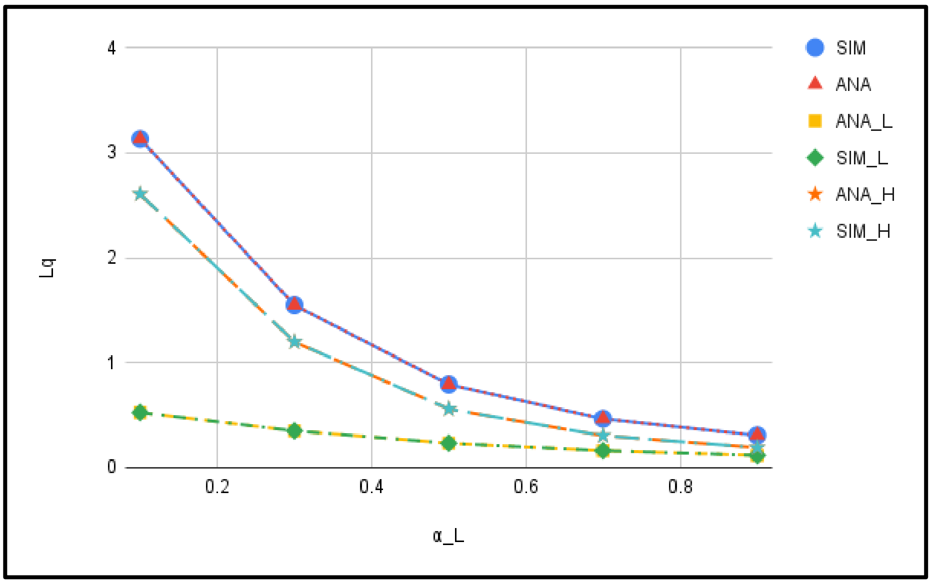


Fig 5. 32: The number of all $(LBER, HBER)$ packets in the queue and LBER packet delivery probability under a priority queueing discipline

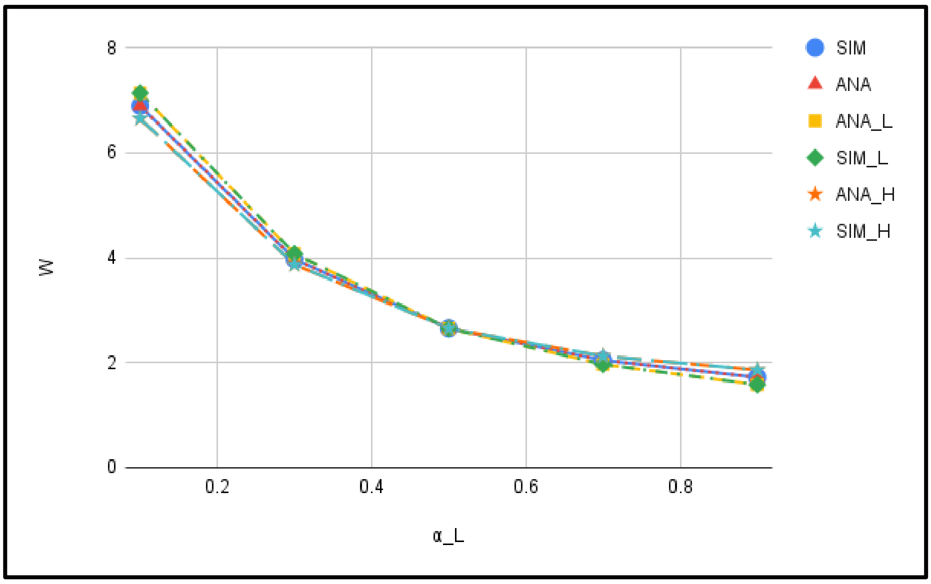


Fig 5. 33: The waiting time of all $(LBER, HBER)$ packets in the system and LBER packet delivery probability under a FIFO queueing discipline

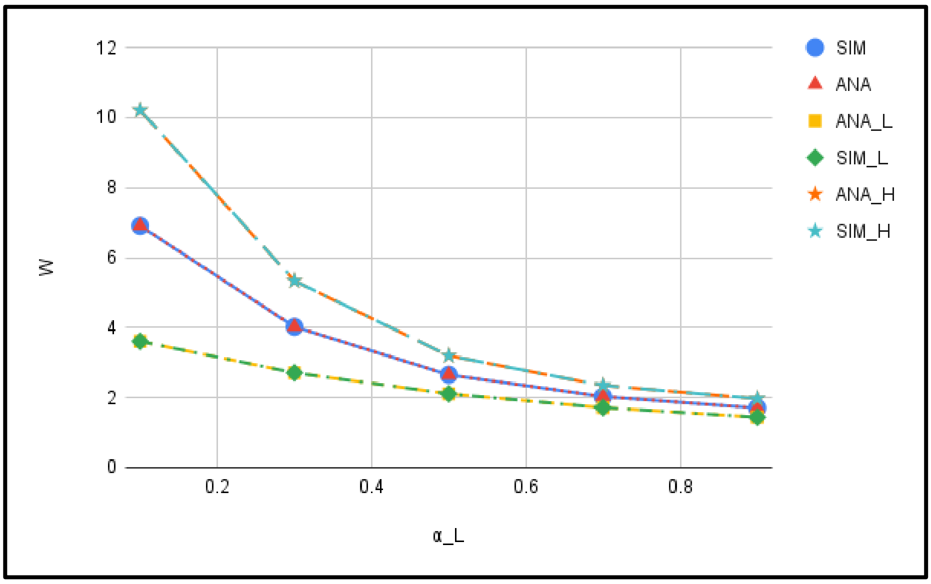


Fig 5. 34: The waiting time of all $(LBER, HBER)$ packets in the system and LBER packet delivery probability under a priority queueing discipline

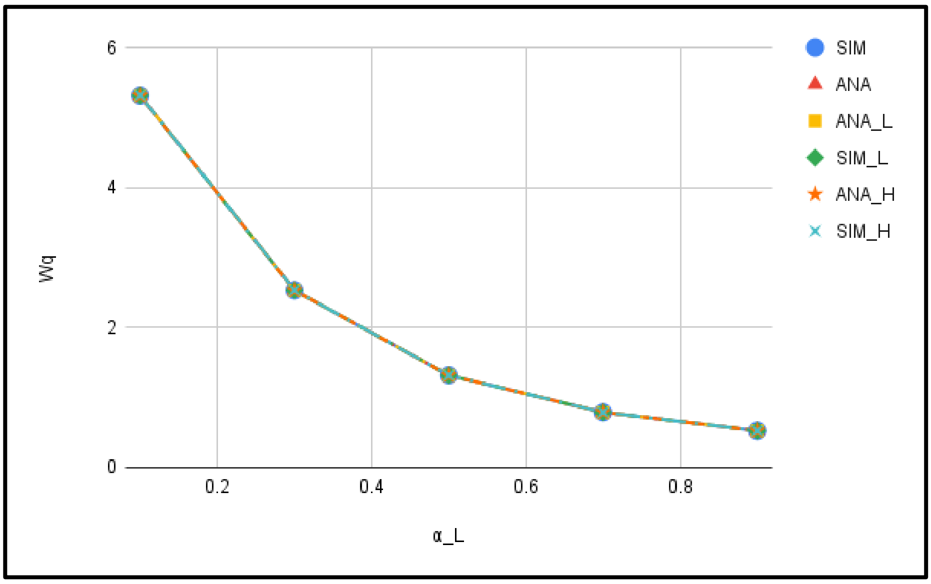


Fig 5. 35: The waiting time of all $(LBER, HBER)$ packets in the queue and LBER packet delivery probability under a FIFO queueing discipline

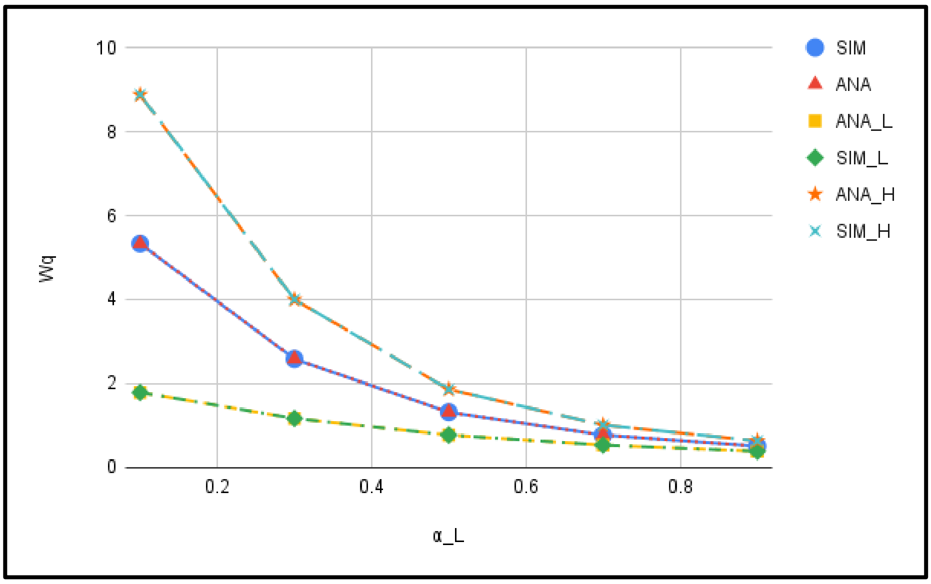


Fig 5. 36: The waiting time of all $(LBER, HBER)$ packets in the queue and LBER packet delivery probability under a priority queueing discipline

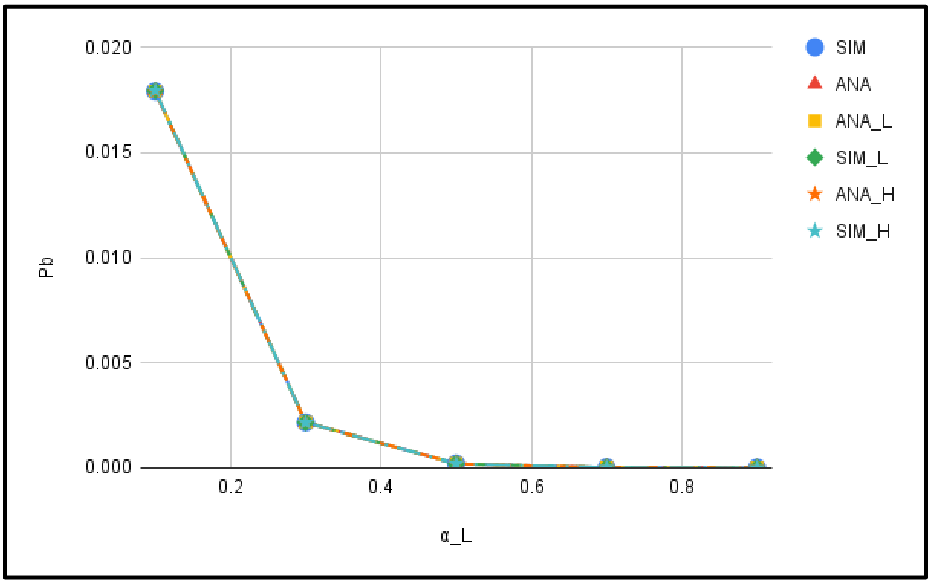


Fig 5. 37: The blocking probability of all $(LBER, HBER)$ packets and LBER packet delivery probability under a FIFO queueing discipline

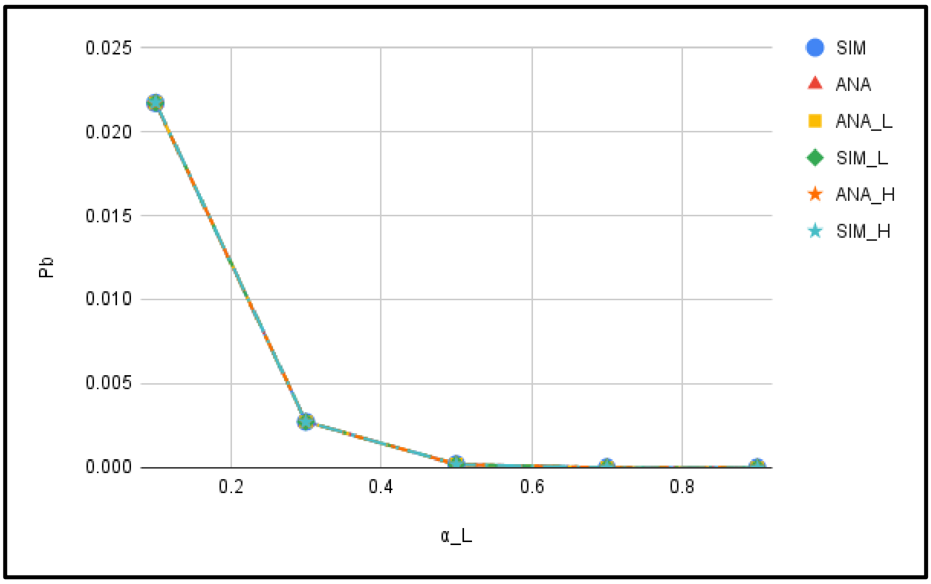


Fig 5. 38: The blocking probability of all $(LBER, HBER)$ packets and LBER packet delivery probability under a priority queueing discipline

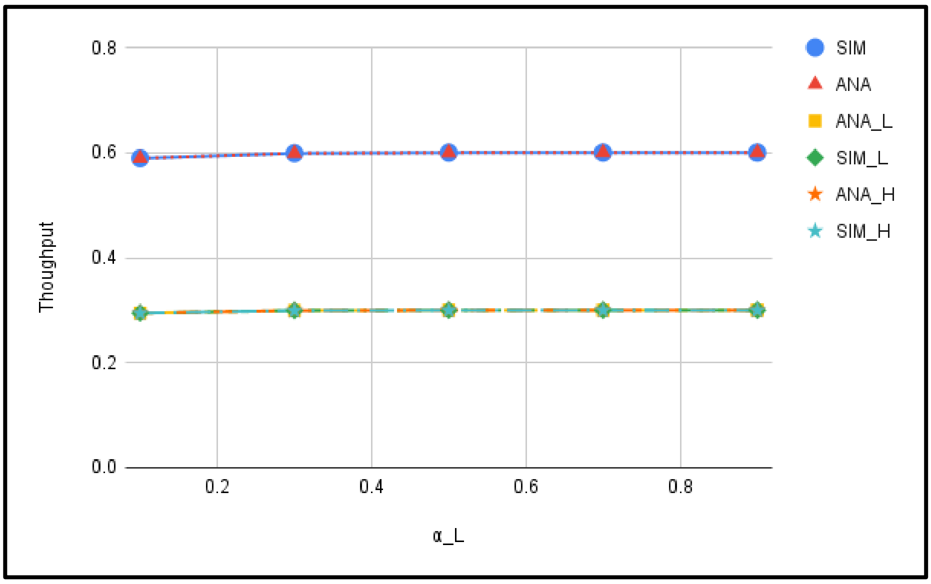


Fig 5. 39: The throughput of all $(LBER, HBER)$ packets and LBER packet delivery probability under a FIFO queueing discipline

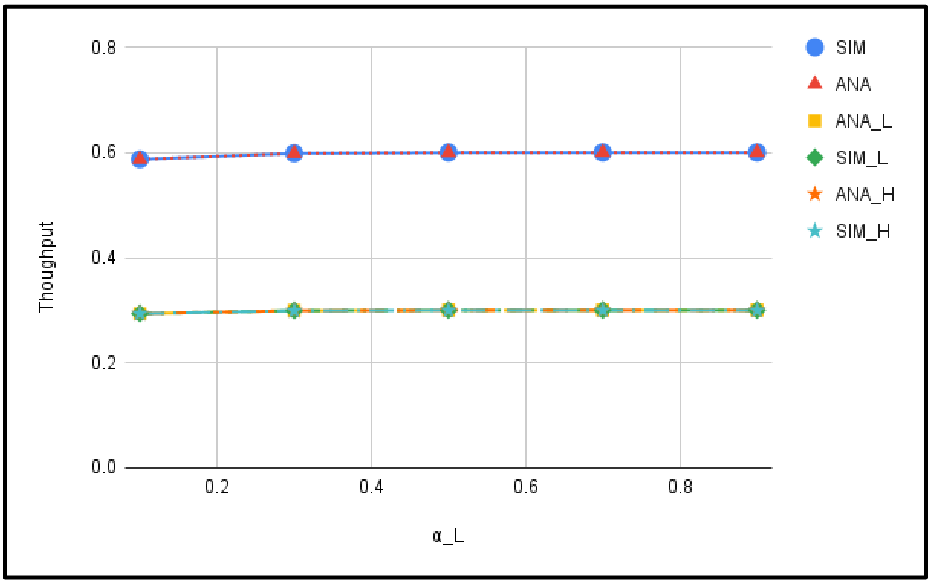


Fig 5. 40: The throughput of all $(LBER, HBER)$ packets and LBER packet delivery probability under a priority queueing discipline

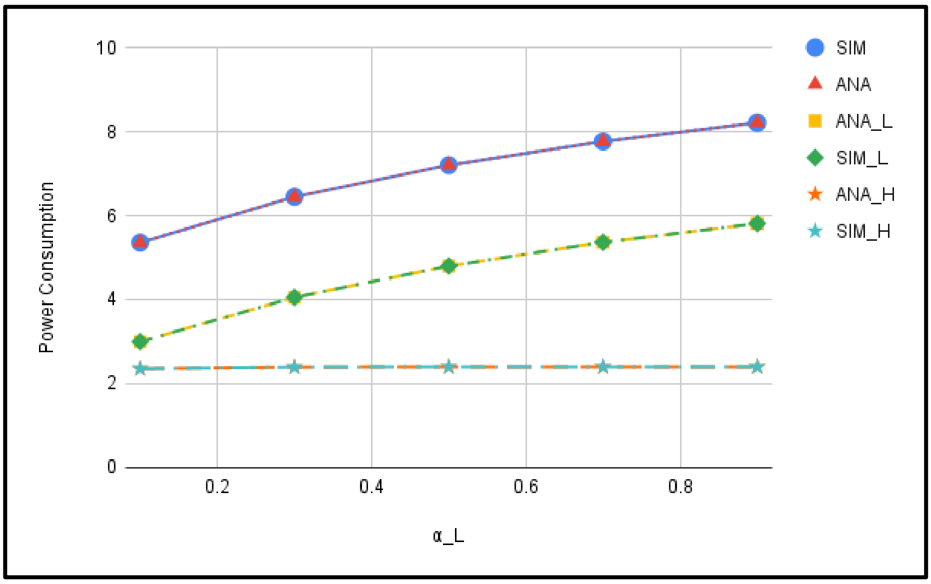


Fig 5. 41: The power consumption of all $(LBER, HBER)$ packets and LBER packet delivery probability under a FIFO queueing discipline

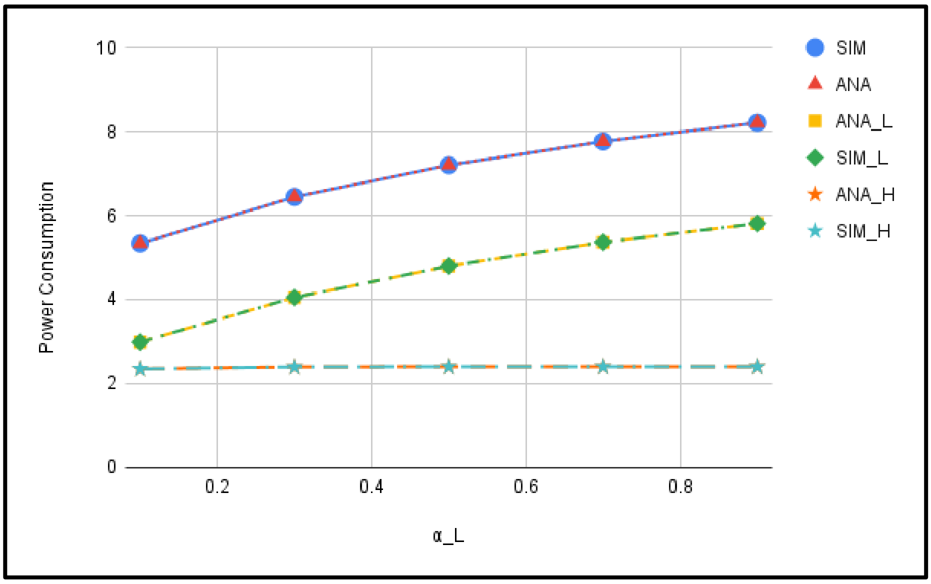


Fig 5. 42: The power consumption of all $(LBER, HBER)$ packets and LBER packet delivery probability under a priority queueing discipline

5.3 Scenario 3

The input parameters in model 3, applicable to both FIFO and priority queuing disciplines, are as provided below: $K,\ \lambda_L,\ \lambda_H,\ \alpha_{L1},\ \alpha_{L2},\ \alpha_{H1},\ \alpha_{H2},\ \varepsilon,\ \gamma$. To assess their impact on the system, we will adjust only one parameter at a time. Additionally, the system size (K) is set to 10. The default values are provided below: $\lambda_L = 0.3,\ \lambda_H = 0.3,\ \alpha_{L1} = 0.0,\ \alpha_{L2} = 0.5,\ \alpha_{H1} = 0.5,\ \alpha_{H2} = 0.5,\ \varepsilon = 5,\ \gamma = 0.5$.

5.3.1 HBER packets delivery probability under threshold

We increment the HBER delivery probability by 0.2 and compare it against several performance indices such as: $L,\ L_q,\ Pb,\ Power,\ TH,\ W,\ Wq$.

Fig. 5-43 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the system $L\ (L_L, L_H)$ and HBER packet delivery probability under threshold α_{H1} under a FIFO queueing discipline. As α_{H1} increases, the numbers of HBER and LBER packets in the system decline correspondingly. However, L_L is slightly more than L_H since $\alpha_{L1} = 0.0 < \alpha_{H1}$. When the total number of packets in the queue is less than or equal to ε, LBER packets prefer to wait until the channel is in state 1 to reduce power consumption because they require higher energy to transmit in state 0. Lastly, the analytical results align well with the simulation results.

Fig. 5-44 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the system $L\ (L_L, L_H)$ and HBER packet delivery probability under threshold α_{H1} under a priority queueing discipline. As α_{H1} increases, the numbers of HBER and LBER packets in the system decline correspondingly. Furthermore, compared to Fig. 5-43, the number of LBER packets is fewer since they are given higher priority. Conversely, the number of HBER packets is more than that in Fig. 5-43 since they are placed after LBER packets in the queue. Moreover, as α_{H1} increases, the HBER packets have a higher chance of being transmitted in state 0, causing L to increase. Lastly, the analytical results align well with the simulation results.

Fig. 5-45 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the queue $L_q\ \left(L_{qL}, L_{qH}\right)$ and HBER packet delivery probability under threshold α_{H1} under a FIFO queueing discipline. As α_{H1} increases, the numbers of HBER and LBER packets in the system decline correspondingly. Since $\lambda_L = \lambda_H = 0.3$, $L_{qL} = L_{qH}$. Moreover, as α_{H1} increases, the HBER packets have a higher chance of being transmitted in state 0, causing L_q to decrease. Lastly, the analytical results align well with the simulation results.

Fig. 5-46 illustrates the relationship between the number of all $(LBER, HBER)$ packets in the system L_q $\left(L_{qL}, L_{qH}\right)$ and HBER packet delivery probability under threshold α_{H1} under a priority queueing discipline. As α_{H1} increases, the number of packets in the queue declines correspondingly. Furthermore, compared to Fig. 5-45, the number of LBER packets is fewer since they are given higher priority. Conversely, the number of HBER packets is more than Fig. 5-45 since they are placed after LBER packets in the queue. Moreover, as α_{H1} increases, the HBER packets have a higher chance of being transmitted in state 0, causing L_q to decrease. Lastly, the analytical results align well with the simulation results.

Fig. 5-47 illustrates the relationship between the system's waiting time for all $(LBER, HBER)$ packets W (W_L, W_H) and HBER packet delivery probability under threshold α_{H1} under a FIFO queueing discipline. As α_{H1} increases, the waiting time in the system declines correspondingly. However, W_L is slightly more than W_H since $\alpha_{L1} = 0.0 < \alpha_{H1}$. When the total number of packets in the queue is less than or equal to ε, LBER packets prefer to wait until the channel is in state 1 to reduce power consumption because they require higher energy to transmit in state 0. Lastly, the analytical results match well with the simulation results.

Fig. 5-48 illustrates the relationship between the system's waiting time for all $(LBER, HBER)$ packets W (W_L, W_H) and HBER packet delivery probability under threshold α_{H1} under a priority queueing discipline. As α_{H1} increases, the HBER packets have a higher chance of being transmitted in state 0, and the waiting time in the system declines correspondingly. Furthermore, compared to Fig. 5-47, the waiting time of LBER packets becomes shorter since LBER packets have higher priority. Lastly, the analytical results match well with the simulation results.

Fig. 5-49 illustrates the relationship between the waiting time in the queue for all $(LBER, HBER)$ packets W_q $\left(W_{qL}, W_{qH}\right)$ and HBER packet delivery probability under threshold α_{H1} under a FIFO queueing discipline. As α_{H1} increases, the waiting time in the queue declines correspondingly. Since $\lambda_L = \lambda_H = 0.3$, $W_{qL} = W_{qH}$. Moreover, as α_{H1} increases, the HBER packets have a higher chance of being transmitted in state 0, causing total waiting time in queue W_q to decrease. Lastly, the analytical results align well with the simulation results.

Fig. 5-50 illustrates the relationship between the waiting time in the queue for all $(LBER, HBER)$ packets W_q $\left(W_{qL}, W_{qH}\right)$ and HBER packet delivery probability under threshold α_{H1} under a priority queueing discipline. As α_{H1} increases, the HBER packets have a higher chance of being transmitted in state 0, and the waiting time in the queue declines correspondingly. Furthermore, compared to Fig. 5-49, the waiting time of LBER packets are shorter since LBER packets have higher priority. Lastly, the analytical results match well with the simulation results.

Fig. 5-51 illustrates the relationship between the blocking probability for all $(LBER, HBER)$ packets $Pb\,(Pb_L, Pb_H)$ and HBER packet delivery probability under thresholdα_{H1} under a FIFO queueing discipline. As α_{H1} increases, the blocking probability declines because HBER packets have more chance to be transmitted in state 0, causing the number in the system to decrease. Furthermore, the blocking probabilities of LBER and HBER packets will be identical since both LBER and HBER packets are blocked upon arrival if the system is full. Lastly, the analytical results match well with the simulation results.

Fig. 5-52 illustrates the relationship between the blocking probability for all $(LBER, HBER)$ packets $Pb\ (Pb_L, Pb_H)$ and HBER packet delivery probability under threshold α_{H1} under a priority queueing discipline. As α_{H1} increases, the blocking probability declines because HBER packets have more chance to be transmitted in state 0, causing the number in the system to decrease. Furthermore, the blocking of LBER and HBER packets will be identical since both LBER and HBER packets are blocked upon arrival if the system is full. Lastly, the analytical results match well with the simulation results.

Fig. 5-53 illustrates the relationship between the throughput for all $(LBER, HBER)$ packets $TH\ (TH_L, TH_H)$ and HBER packet delivery probability under threshold α_{H1} under a FIFO queueing discipline. As α_{H1} increases, the throughput rises correspondingly, and it eventually achieves 0.6 since the total arrival probability $\lambda = \lambda_L + \lambda_H = 0.6$. And the throughput of LBER and HBER will be identical since all packets are blocked upon arrival if the system is full. Lastly, the analytical results match well with the simulation results.

Fig. 5-54 illustrates the relationship between the throughput for all $(LBER, HBER)$ packets $TH\,(TH_L, TH_H)$ and HBER packet delivery probability α_{H1} under a priority queueing discipline. As α_{H1} increases, the throughput rises correspondingly, and it eventually achieves 0.6 since the arrival probability $\lambda = \lambda_L + \lambda_H = 0.6$. And the throughput of LBER and HBER will be identical since both LBER and HBER packets are blocked upon arrival if the system is full. Lastly, the analytical results match well with the simulation results.

Fig. 5-55 illustrates the relationship between the power consumption for all $(LBER, HBER)$ packets $P\ (P_L, P_H)$ and HBER packet delivery probability under threshold α_{H1}

under a FIFO queueing discipline. As α_{H1} increases, the power consumption of HBER packets rises because they have higher chance to be transmitted in state 0. Conversely, P_L decreases since if the number of packets in the queue is less than or equal to threshold, the LBER packets would rather wait until channel in state 1 and use less energy. Lastly, the analytical results match well with the simulation results.

Fig. 5-56 illustrates the relationship between the power consumption for all $(LBER, HBER)$ packets P (P_L, P_H) and HBER packet delivery probability under threshold α_{H1} under a priority queueing discipline. As α_{H1} increases, the power consumption of HBER packets rises because they have higher chance to be transmitted in state 0. Conversely, P_L decreases since if the number of packets in the queue is less than or equal to threshold, the LBER packets prefer to wait until the channel is in state 1 and thereby use less energy. Moreover, P_L is slightly greater than P_H since LBER packets are placed at the head of queue. However, LBER packets would rather wait until the channel turns to state 1, leading to a queue length that exceeds the transmission threshold, eventually resulting in higher energy usage for transmission. Lastly, the analytical results match well with the simulation results.

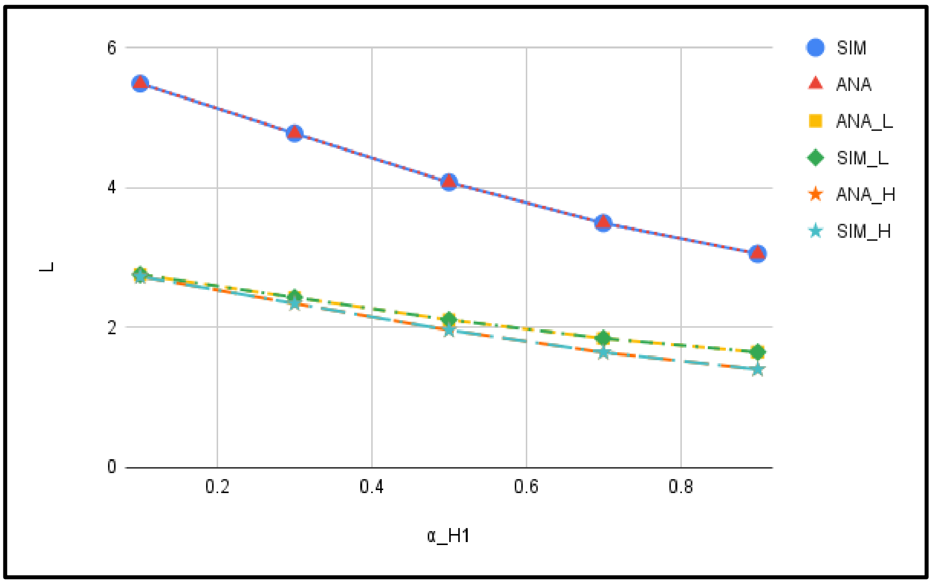


Fig 5. 43: The number of all $(LBER, HBER)$ packets in the system and HBER packet delivery probability under threshold under a FIFO queueing discipline

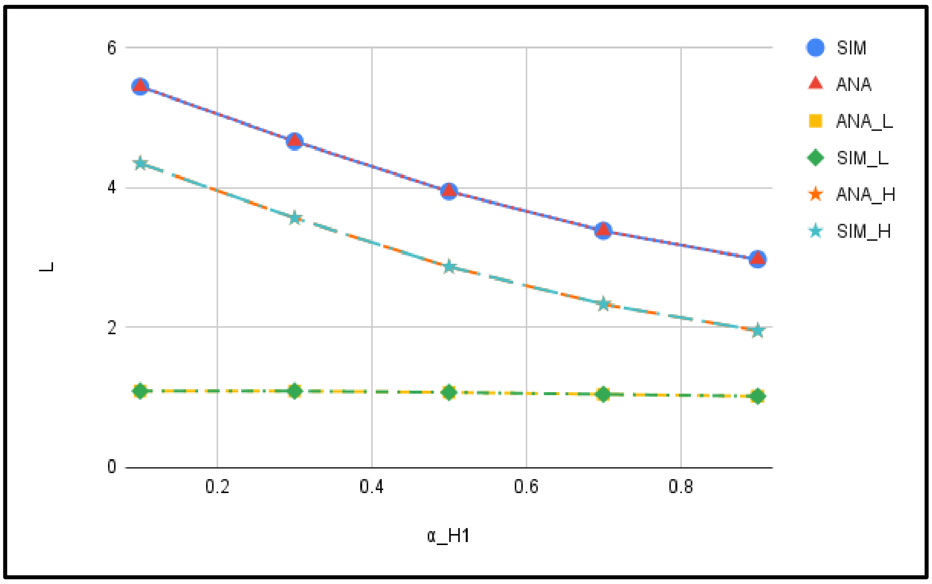


Fig 5. 44: The number of all $(LBER, HBER)$ packets in the system and HBER packet delivery probability under threshold under a priority queueing discipline

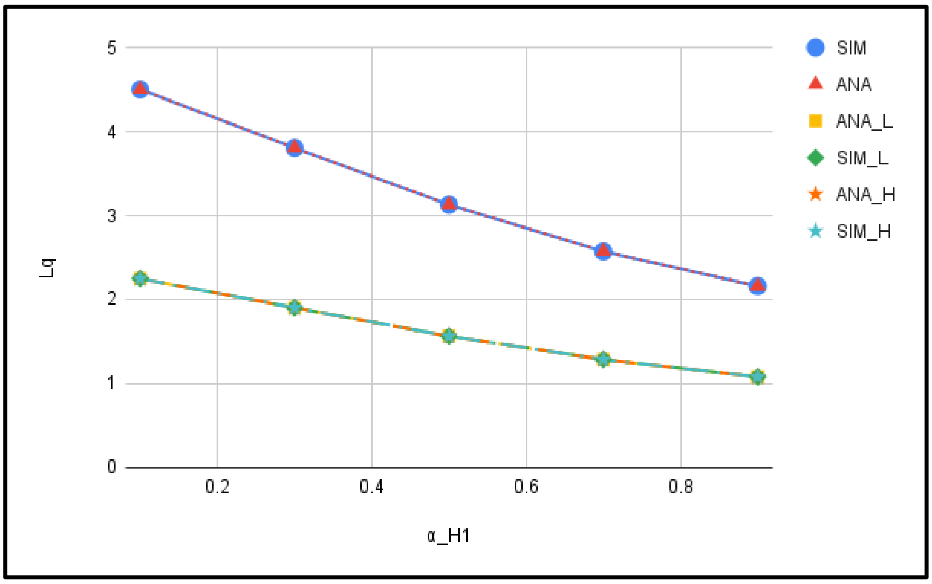


Fig 5. 45: The number of all $(LBER, HBER)$ packets in the queue and HBER packet delivery probability under threshold under a FIFO queueing discipline

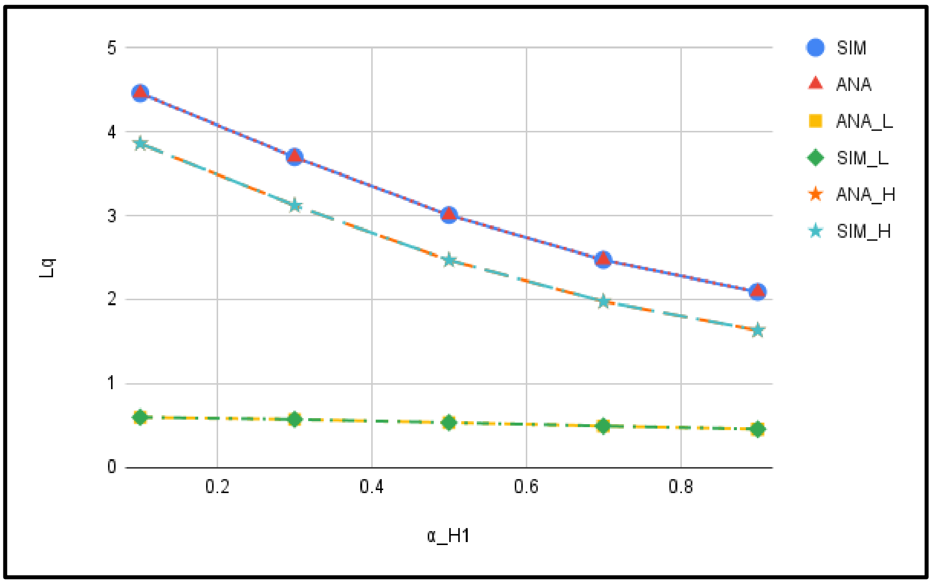


Fig 5. 46: The number of all $(LBER, HBER)$ packets in the queue and HBER packet delivery probability under threshold under a priority queueing discipline

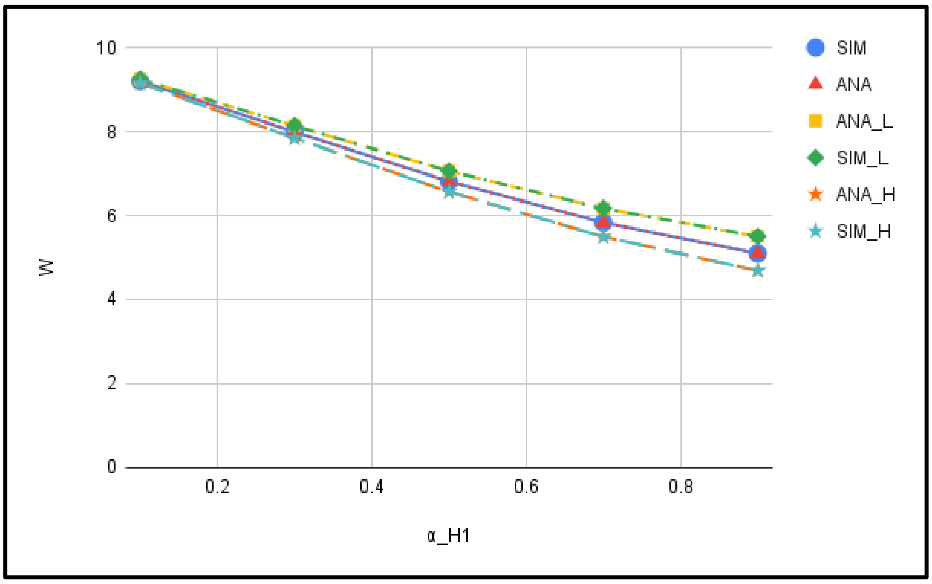


Fig 5. 47: The waiting time of all $(LBER, HBER)$ packets in the system and HBER packet delivery probability under threshold under a FIFO queueing discipline

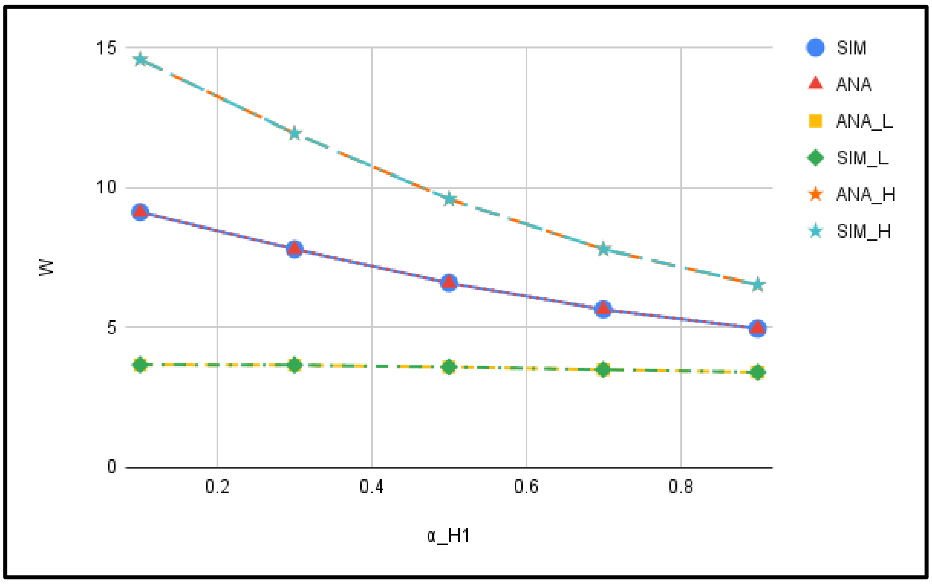


Fig 5. 48: The waiting time of all $(LBER, HBER)$ packets in the system and HBER packet delivery probability under threshold under a priority queueing discipline

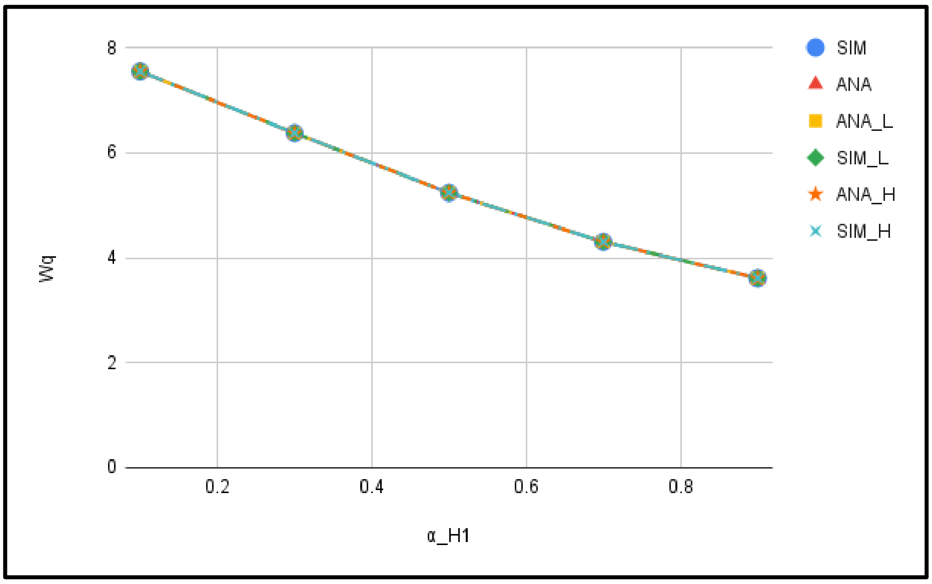


Fig 5. 49: The waiting time of all $(LBER, HBER)$ packets in the system and HBER packet delivery probability under threshold under a FIFO queueing discipline

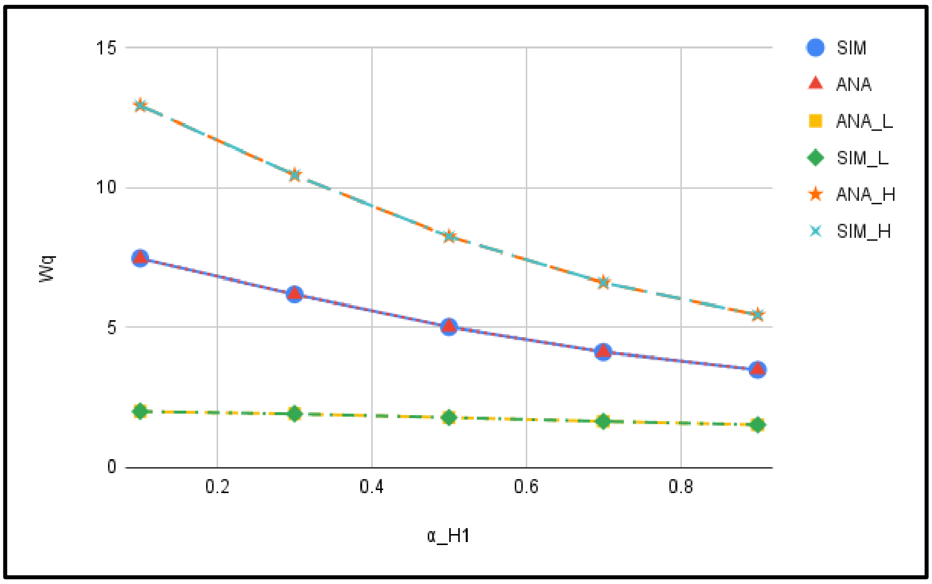


Fig 5. 50: The waiting time of all $(LBER, HBER)$ packets in the system and HBER packet delivery probability under threshold under a priority queueing discipline

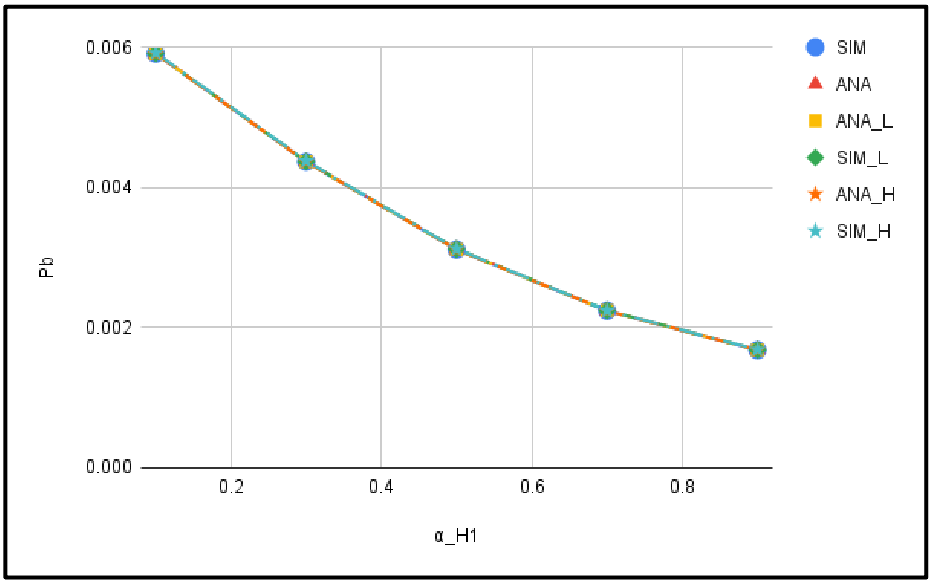


Fig 5. 51: The blocking probability of all $(LBER, HBER)$ packets and HBER packet delivery probability under threshold under a FIFO queueing discipline

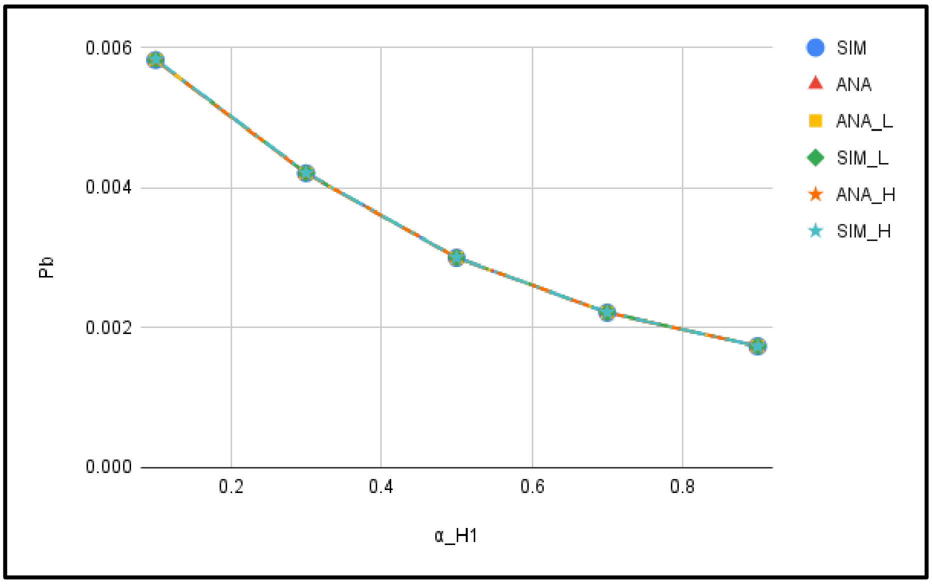


Fig 5. 52: The blocking probability of all $(LBER, HBER)$ packets and HBER packet delivery probability under threshold under a priority queueing discipline

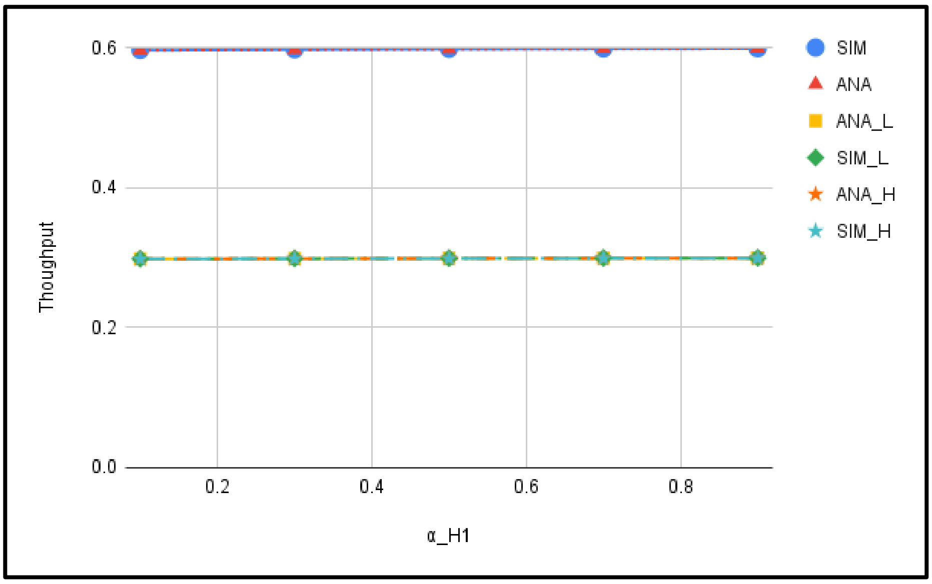


Fig 5. 53: The throughput of all $(LBER, HBER)$ packets and HBER packet delivery probability under threshold under a FIFO queueing discipline

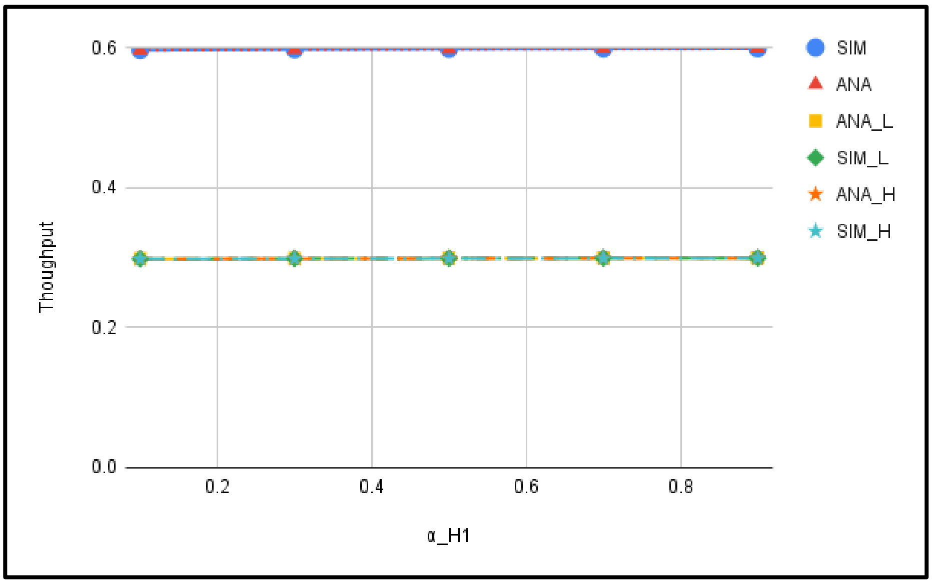


Fig 5. 54: The throughput of all $(LBER, HBER)$ packets and HBER packet delivery probability under threshold under a priority queueing discipline

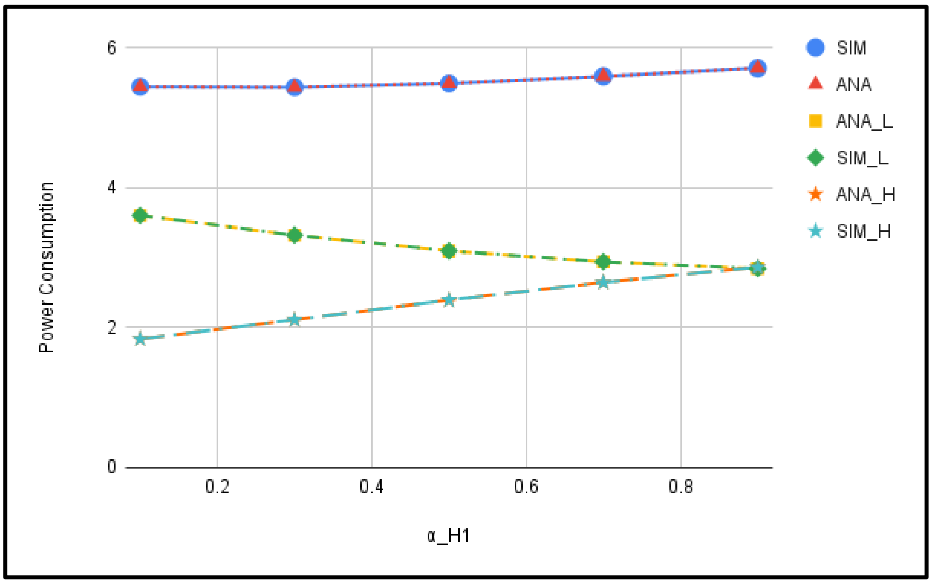


Fig 5. 55: The power consumption of all $(LBER, HBER)$ packets and HBER packet delivery probability under threshold under a FIFO queueing discipline

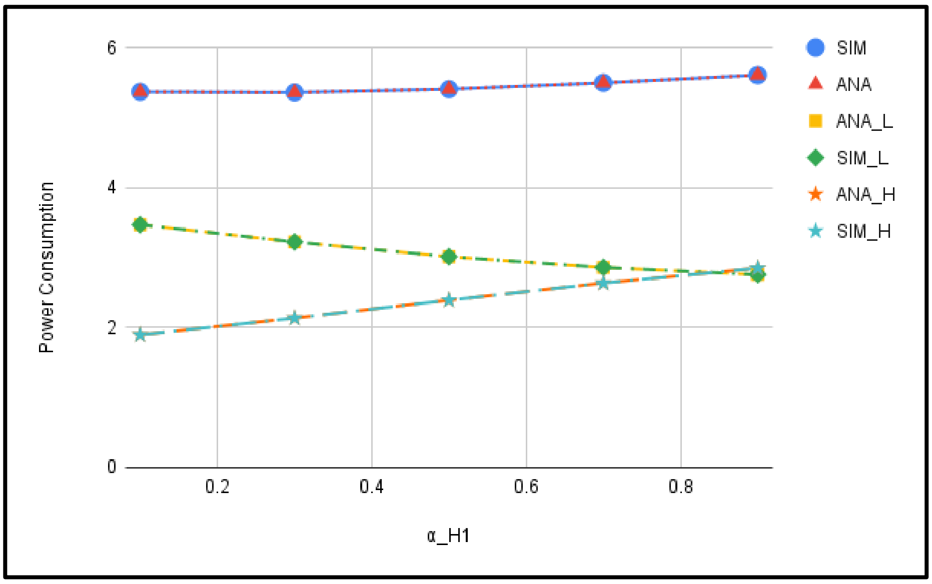


Fig 5. 56: The power consumption of all $(LBER, HBER)$ packets and HBER packet delivery probability under threshold under a priority queueing discipline

Table 5. 1: Numerical results of three scheduling policies

	PCCP (Scenario 1)	**ADP (Scenario 2)**	**TTP (Scenario 3)**
Power	2.991	7.199	5.606
W	16.353	2.654	5.098
Wq	14.353	1.320	3.607
L	8.152	1.592	3.053
Lq	7.155	0.7920	2.161
TH	0.4985	0.5999	0.5990
Pb	0.1691	0.0001955	0.001679

($\lambda_L = 0.3,\ \lambda_H = 0.3,\ \alpha_{L1} = 0.0,\ \alpha_{L2} = 0.5,\ \alpha_{H1} = 0.9,\ \alpha_{H2} = 0.5,\ \theta = 5,\ \gamma = 0.5.$)

6. Conclusions

In our study, we consider three different scheduling policies and trade-off between power consumption and waiting time: (1) Power Consumption Control Policy (PCCP) focuses on minimizing the system's power consumption, (2) Adaptive Delivery Policy (ADP) adapts the transmissions based on the delivery probability when the channel is in state 0, and (3) Threshold-based Transmission Policy (TTP) sets a transmission threshold and alternates between different delivery probabilities based on this threshold.

The contributions of this study are three-fold. First, we derive that analytical models based on 4-dimensional discrete time Markov chains for the three scenarios considered and compute the performance measures of interest. Second, we develop the simulation programs to show our analytical results are accurate. Third, the performance comparison of three scheduling policies are performed. Specifically, according to the numerical results, PCCP results in low power consumption, but conversely, it leads to significant waiting times because packets cannot be transmitted when the channel is in state 0. For ADP, by allowing for packet transmission even when the channel is in state 0 based on some delivery probability, waiting times are reduced compared to PCCP, but it increases power consumption due to the higher energy required for transmission in state 0. Finally, for TTP, a transmission threshold is set, and a better tradeoff between power consumption and waiting time is achieved, compared to PCCP and ADP.

As a final point, future research could explore several areas to enhance the scheduling policies discussed. First, one avenue is the development of adaptive scheduling algorithms that adjust transmission thresholds based on real-time conditions. Second, energy harvesting systems may be included for power efficiency. Third, cross-layer optimization, e.g., physical and MAC layers, for specific user behaviors and application requirements are also crucial for future advancements.

References

[1] B. Chang, G. Zhao, M. A. Imran, Z. Chen, and L. Li, "Dynamic Wireless QoS Analysis for Real-Time Control in URLLC," *IEEE Globecom Workshops (GC Wkshps)*, 2018, pp. 1-5, doi: 10.1109/GLOCOMW.2018.8644110.

[2] C. Yu, "Performance Analysis of the LWA Wi-Fi AP with Non-Saturated Wi-Fi Traffic," *NTUST Master Thesis*, 2021, pp. 3-7.

[3] Z. Zhou, T. Lin, K. Thulasiraman, G. Xue, and S. Sahni, "Cross-Layer Network Survivability under Multiple Cross-Layer Metrics," *Journal of Optical Communications and Networking*, 2015, vol. 7, no. 6, pp. 540-553, doi: 10.1364/JOCN.7.000540.

[4] D. Zhang and K. M. Wasserman, "Transmission Schemes for Time-Varying Wireless Channels with Partial State Observations," *Proceedings.Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies*, 2002, pp. 467-476, doi: 10.1109/INFCOM.2002.1019291.

[5] C. Wang, B. Li, K. Sohraby, M. Daneshmand, and Y. Hu, "Upstream Congestion Control in Wireless Sensor Networks through Cross-Layer Optimization," *IEEE Journal on Selected Areas in Communications*, 2007, vol. 25, no. 4, pp. 786-795, doi: 10.1109/JSAC.2007.070514.

[6] F. Shi, D. Yuan, and L. Xu, "Performance Analysis of Type-III HARQ Scheme in Cross-Layer Design for QoS-Guaranteed Traffic," *International Workshop on Cross Layer Design*, 2007, pp. 133-137, doi: 10.1109/IWCLD.2007.4379055.

[7] K. Cho and D. Yoon, "On the General BER Expression of One- and Two-Dimensional Amplitude Modulations," *IEEE Transactions on Communications*, 2002, vol. 50, no. 7, pp. 1074-1080, doi: 10.1109/TCOMM.2002.800818.

[8] M. C. Utami, D. R. Sabarkhah, E. Fetrina, and M. Q. Huda, "The Use of FIFO Method For Analysing and Designing the Inventory Information System," *International*

Conference on Cyber and IT Service Management (CITSM), 2018, pp. 1-4, doi: 10.1109/CITSM.2018.8674266.

[9] T. V. Pham, T. V. Nguyen, and A. T. Pham, "A General Conditional BER Expression of Rectangular QAM in the Presence of Phase Noise," *IEEE Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, 2021, pp. 422-427, doi: 10.1109/PIMRC50174.2021.9569320.

[10] D. Han and W. Chen, "QoS Differential Scheduling of URLLC under FIFO Service Discipline: A Cross-Layer Approach," *IEEE Wireless Communications Letters*, 2020, vol. 9, no. 9, pp. 1370-1373, doi: 10.1109/LWC.2020.2990676.