# System model

Our research explores the combination of WSN and energy harvesting, which allows sensors to receive energy from both renewable sources and reliable energy sources like regular batteries. We divide packets into two groups based on urgency: emergent, and non-emergent. Emergent packets contain time-critical information, like alerts for fires, earthquakes, or foreign objects, and must be delivered immediately. In contrast, non-emergent packets contain non-real time information, such as weather forecasts and smart meter data. Both emergent and non-emergent groups can transmit one packet or more packets at a time. Each packet is time-sensitive and may be discarded if it fails to meet a certain deadline, indicating that it is no longer useful. There are two possible energy sources, either harvested from the environment or supplied by the regular battery, which can be used to transmit each data packet. The energy requirement of each packet is the same.

With the information provided above, we explore two scenarios in our study: (1) only one sensor node is considered and the packets comes in batches with different priority where each batch consists of one packet or two packets, (2) a simplified WSN comprising three interconnected nodes is considered and the way packets come at node 1 is same as scenario 1.

To provide further explanation, we model each node in the WSN as a variation of the M/M/1/K system, which includes a finite packet queue, a finite energy queue, and a regular battery. Both packets and energy units arrive according to a Poisson process, and the time that each packet can wait in the queue and the time required for its service are defined as exponential distributions. Depending on their application, the arrived packets are roughly classified into two categories: high priority (HP) and low priority (LP). The way that packets come can be divided into two groups: HP and LP. If there is only one seat and here comes two HP or LP packets at once, one of them will be blocked and the other will enter the packet queue followed the rule below. HP packets have a non-preemptive priority over LP packets, and packets with the same priority follow a first-come, first-served (FCFS) approach. Specifically, when a new HP packet arrives, it is placed in front of any LP packets in the queue, pushing them to the back. However, if an LP packet is already being served, the HP packet at the head of the queue must wait its turn due to the non-preemption policy.

When a node receives a packet, it is either added to the packet queue or rejected and discarded due to queue overflow. If there is enough energy available in the energy queue, the packet at the head of the packet queue will use the corresponding harvested energy to start processing. However, if there is insufficient energy available, a probability value is used to determine if the regular battery can be used as an alternative energy source. If not, the packet will remain in the queue until the next state transition.

In our network setup, we have three interconnected nodes. The first node acts as the entry node, the second node acts as the exit node, and the third node acts as the control node. After completing its service at each node, a packet is directed to the next node based on a predetermined routing probability. It's important to note that packets originating from the entry and exit nodes are only allowed to pass through the control node once before being sent back to their respective previous nodes. Additionally, incoming packets are only permitted to enter the system through the entry node and exit after being serviced at the exit node or due to impatience.

## Scenario 1

Within this scenario of study, we focus our attention on a single sensor node. For the purposes of our investigation, we will assume that each packet - regardless of its priority level - has an energy requirement of one unit. Subsequently, we analyze the influence of different system parameters, e.g., energy usage on the overall performance of the node.

## Scenario 2

Within this unit of study, we examine a network that consists of three interconnected nodes, and this network is an extension of the one considered in Scenario 1. It is assumed that both high priority and low priority packets have an energy requirement of one unit. Subsequently, we investigate different system parameters, e.g., how the energy consumption affects not only the overall network but also each individual node within the network.

# Analytical model

In this section, we outline and clarify the analytical models in a step-by-step manner for two situations: (1) there is only a single node with single and batch arrival, and each packet consumes the same amount of energy, and (2) there are three interconnected nodes with single and batch arrival in the network, and each packet consumes the same amount of energy.

## Scenario 1

In this section, we focus on a scenario where packets coming with single or batch arrival can be divided into two priorities: high priority (HP) and low priority (LP), and both types of packets require the same amount of energy. Within each priority level, the packets are serviced in a first-come, first-served (FCFS) order. Once a packet enters the queue, it cannot be preempted, which means that an HP packet can always overtake an LP packet in the queue, but once an LP packet is in service, it cannot be interrupted. Additionally, there is a chance that a packet waiting in the queue may leave the system due to impatience. It is worth noting that when a packet is ready to be serviced, it first checks if there is enough energy in the energy queue. If there isn't enough energy, the packet may use a regular battery with a given probability. The model diagram, state balance equations, iterative algorithm, and performance metrics can be found below.

### Model diagram

Fig. 3 - 1 illustrates the components of the model used in scenario 1, which include a finite packet queue, a finite energy queue, a regular battery, and a single server. The size of the packet queue is denoted by , while the energy queue size is represented by . The regular battery has an infinite supply of energy, and each of HP and LP packets requires one energy unit. The arrivals of single HP batches (one packet per batch), single LP batches (one packet per batch), double HP batches (two packets per batch), double LP batches (two packets per batch), and energy units are governed by Poisson processes, with respective arrival rates , , , and . The impatient time for each HP and LP packet waiting in the queue is determined by an exponential distribution, with corresponding rates and . The service time for each of HP and LP packets in the server is exponentially distributed, with associated rates and , respectively. Additionally, when the amount of harvested energy available in the energy queue is insufficient to support an HP or LP packet, the regular battery will be used based on probabilities and , respectively.

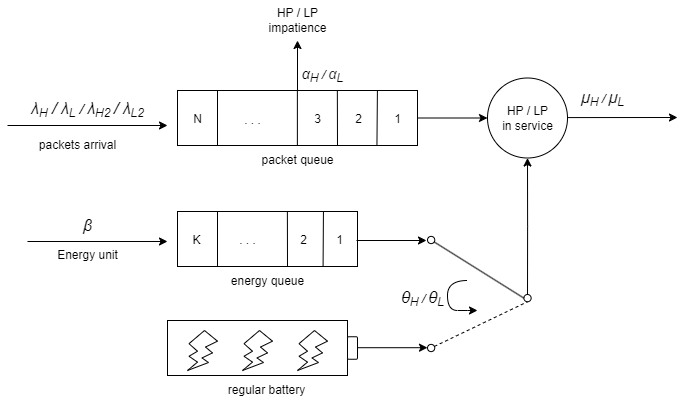


Fig. 3 - 1: The model diagram for scenario 1

### State balance equations

The system is modeled as a Markov chain with four dimensions: , where represents the number of high-priority (HP) packets in the system, represents the number of low-priority (LP) packets in the system, represents the number of energy units in the energy queue, and represents the server status and the energy source used. The value of can take on five different values: (1) "" indicates that the server is idle; (2) "" indicates that an LP packet has entered the server and consumed one energy unit from the energy queue; (3) "" indicates that an HP packet has entered the server and consumed one energy unit from the energy queue; (4) "" indicates that an LP packet has entered the server and consumed one energy unit from the regular battery; (5) "" indicates that an HP packet has entered the server and consumed one energy unit from the regular battery. The steady state probability of the system is represented by , and the state space is defined as follows:

(3-1)

As a result, we can calculate the total count of possible states  
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Based on the model description, there are 190 possible cases for the total system states. The balance equations for each of these cases are presented below.

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1. For,,,and,

Since there are many equations presented above, discussing each one separately would be challenging. Therefore, we focus on a relatively complicated case, specifically case 159, to provide an illustrative example. This state occurs when there are more than or equal to three but less than or equal to N-3 HP packets and N-i LP packets in the system, and there is only one seat left in the packet queue, while the energy queue is empty. The HP packet being served in the server is using the regular battery. The corresponding detailed state transition diagram can be found in Fig. 3 - 2.

1. For,,,and,

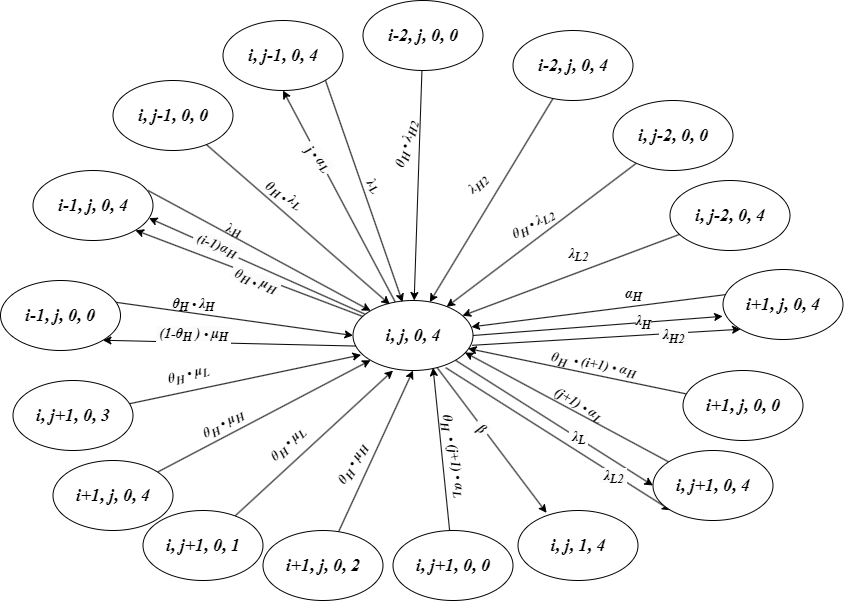


Fig. 3 - 2: The state transition diagram for ,,,and *.*

### Iterative algorithm

Using the iterative algorithm provided below, we perform calculations on the state balance equations until they converge, allowing us to determine the steady-state distribution of the system.

#### **Iterative algorithm:**

Step 1: Select a group of initial values for , , where is the total number of feasible states.

Step 2: Substitute into *Case 1* to *Case 190* to find , .

Step 3: Normalize , .

Step 4: If , stop the iterative algorithm, where is the stopping criterion. Otherwise, set , and return to Step 2.

In the analytical experiments, we set . It takes about 200 to 7000 iterations for the algorithm to converge.

### Performance measures

We obtain different performance measures of interest from the steady-state probability in order to evaluate the system's measures of effectiveness. These measures are presented below.

#### , the expected number of all packets in the system, is provided below.

(3-2)

(3-3)

(3-4)

#### , the expected number of all packets in the queue, is provided below.

(3-5)

(3-6)

(3-7)

#### , the throughput of all packets, is provided below.

(3-8)

(3-9)

(3-10)

#### , the blocking probability of each arrived packet, without considering its priority, is provided below.

(3-11)

#### , the energy loss probability, is provided below.

(3-12)

#### , the mean waiting time of all packets in the system, , which refers to all packets that have exited the system, either after receiving service or due to impatience, is provided below.

(3-13)

(3-14)

(3-15)

#### , the impatient loss probability of arrived packets, is provided below.

(3-16)

(3-17)

(3-18)

#### , the impatient loss probability of admitted packets, is provided below.

(3-19)

(3-20)

(3-21)

#### , the total loss probability of arrived packets, is provided below.

(3-22)

(3-23)

(3-24)

#### , the regular energy consumption ratio of all packets, is provided below.

(3-25)

(3-26)

(3-27)

## Scenario 2

In this section we discuss a network with three connected nodes, where packets come in batches and each batch consists of one packet or two packets. All batches can be divided into two priorities: high priority (HP) and low priority (LP). Both types of packets require the same amount of energy. The first node is an "entry node", the second node is an "exit node", and the third node is a "control node". After passing through the control node, packets are directed to the correct path to the exit node and leave the network. Impatient packets may leave the queue at any time. Whenever a node is ready to serve a packet, it first checks the energy queue for sufficient energy units. If there are not enough energy units, the packet may use a regular battery with a given probability. The model diagram, state balance equations, iterative algorithm, and performance measures are provided below.

### Model diagram

In scenario 2, as illustrated in Fig. 3 - 5, we have an open network model with three nodes. Each node in the network consists of a finite packet queue, a finite energy queue, a regular battery, and a single server. The packet queue size is denoted by , , the energy queue size is denoted by , , and the regular battery has an unlimited supply of energy. HP and LP packets have the same energy requirement, which is one energy unit. The arrivals of HP and LP packets from outside the system follow a Poisson process with specific arrival rates , and , respectively. The arrivals of energy units of node follow a Poisson process with arrival rate . The waiting time for each HP (LP) packet in node 's queue is determined by an exponential distribution with corresponding rates (). Node 's service time for each HP (LP) packet is assumed to follow an exponential distribution with rates (), respectively. We assume that when the energy queue lacks the necessary harvested energy to support an HP or LP packet, the regular battery will be used based on probabilities and , respectively. Additionally, when a packet finishes service at node , it is either removed from the network or forwarded to the next node with an assigned routing probability , where and . However, there are some restrictions on the routing policy. First, packets cannot be routed from the exit node to the entry node. Second, packets from the entry and exit nodes are only permitted to pass through the control node once before being forwarded to the previous node.

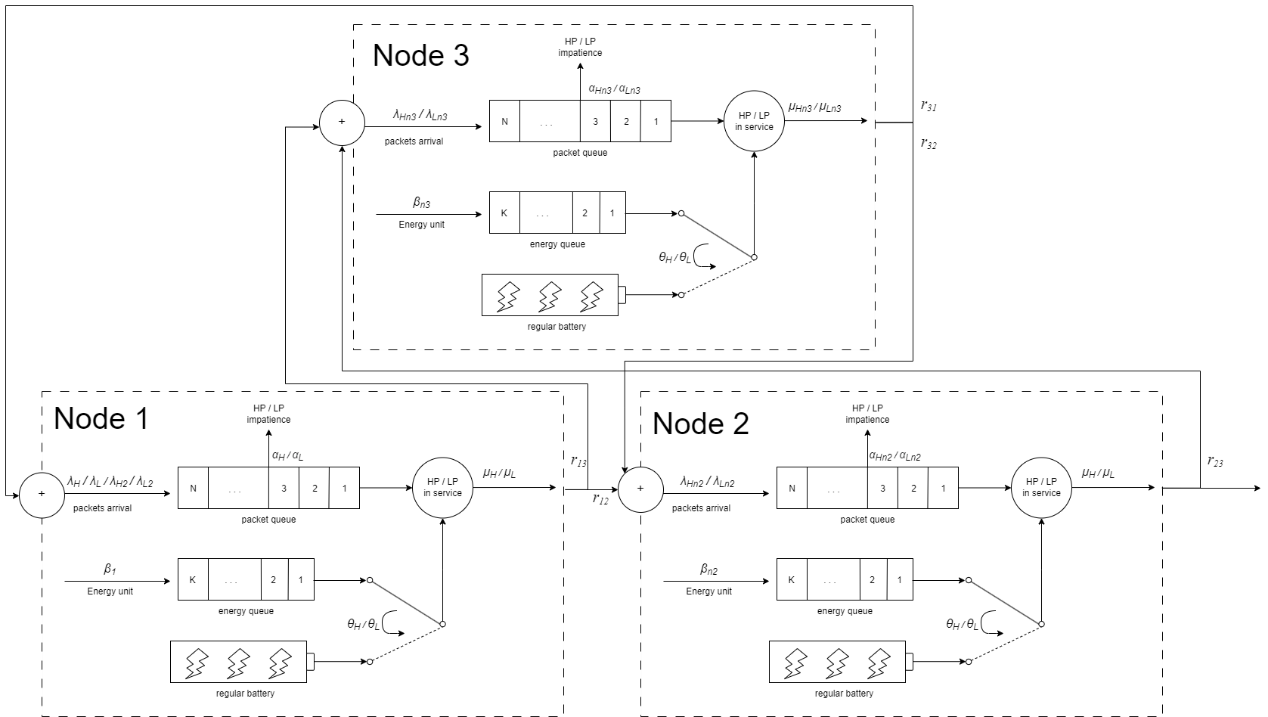


Fig. 3 - 3: The model diagram for scenario 2

### State balance equations

To achieve a simplification in the derivation, we assume that each node in the network is independent of the other nodes. We can represent node as a four-dimensional Markov chain with the state , where represents the number of HP packets in node , represents the number of LP packets in node , represents the number of harvested energy units in the energy queue in node , and represents the server status and the energy resource being used in node . Note that can take five values: (1) "" indicates that the server is idle; (2) "" indicates that an LP packet has entered the server and consumed one energy unit from the energy queue; (3) "" indicates that an HP packet has entered the server and consumed one energy unit from the energy queue; (4) "" indicates that an LP packet has entered the server and consumed one energy unit from the regular battery; (5) "" indicates that an HP packet has entered the server and consumed one energy unit from the regular battery. The steady state probability of the system is represented by , and the state space is defined as follows:

(3-28)

As a result, we can calculate the total count of feasible states  
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In addition, the analysis of the arrival rate of each node should take into account five internal arrival rates.

To begin with, we calculate the arrival rates of HP and LP packets from node 1 to node 3.

(3-29)

The equation's right-hand side has two parts. The first part shows the percentage of HP or LP packets completing service in node 1 and then directed to node 3. The denominator shows the total HP or LP packet arrival rate for node 1, including the unblocked arrival rates from outside and node 3. The numerator represents the unblocked arrival rate from outside, which is directed to node 3 according to . It should be noted that in this scenario, only external packets can be routed to node 3, as each packet can visit node 3 only once.

Next, we calculate the arrival rates of HP and LP packets from node 3 to node 1.

(3-30)

The equation's right-hand side has two parts. The first part shows the percentage of HP or LP packets that have completed their service at node 3 and will be sent back to node 1. The denominator shows the total HP or LP packet arrival rate of node 3, which includes the unblocked arrival rates from node 1 and node 2. The numerator indicates the unblocked arrival rate from node 1. It should be noted that all packets that pass through the control node will be forwarded to the previous node, so the packets that have finished service at node 3 will be routed back to node 1.

Next, we calculate the arrival rates of HP and LP packets from node 1 to node 2.

(3-31)

The equation's right-hand side calculates the HP or LP packet arrival rates from node 1 to node 2. The first term indicates the proportion of HP or LP packets finishing service in node 1 and moving on to node 2. The denominator part represents the total HP or LP packet arrival rate of node 1, which includes those unblocked arrival rates from outside and node 3. The numerator part represents the unblocked arrival rates from outside that is routed to node 2 based on and the unblocked arrival rates from node 3. It is important to note that each packet passing through the control node will be forwarded to the previous node, so the packets that have completed service at node 1 will be routed back to node 2.

Next, we calculate the HP and LP packet arrival rates from node 2 to node 3.

(3-32)

To calculate the HP and LP packet arrival rates from node 2 to node 3, we use the equation. The first term on the right-hand side shows the proportion of HP or LP packets that complete service at node 2 and are routed to node 3. The denominator of this term indicates the total HP or LP packet arrival rate of node 2, including the unblocked arrival rates from node 1 and node 3. The numerator represents the unblocked arrival rate from node 1. The second term on the right-hand side shows the portion of HP or LP packets that complete service at node 1 and are routed to node 3. The denominator of this term shows the HP or LP packet arrival rates being routed from node 1 to node 2, which includes the arrival rates from node 3 to node 1 and the outside arrival rates that are routed to node 2 based on . The numerator of the second term shows the outside packet arrival rates from node 1 routed to node 2 based on and then routed to node 3 based on .

Last, we calculate the HP and LP packet arrival rates from node 3 to node 2.

(3-33)

In this equation, the first term on the right-hand side indicates the fraction of HP or LP packets that will be directed from node 3 to node 2 after finishing their service in node 3. The denominator represents the total arrival rate of HP or LP packets at node 3, which includes the unblocked arrival rates from node 1 and node 2. The numerator represents the unblocked arrival rate from node 2. It is important to note that any packet that passes through the control node will be forwarded to the previous node. Therefore, packets that have finished their service at node 3 will be sent back to node 2.

Based on the explanation of the model provided earlier, the HP and LP packet arrival rates, denoted as and , respectively, are determined for each node *n*.

, (3-34)

, (3-35)

Furthermore, the system states of node 1 can be classified into 190 cases and numbered as case A1, A2, A3, and so on. The system states of node 2 and 3 can be classified into 101 cases and numbered as case B1, B2, B3, and so on. The corresponding equations for balancing the states are demonstrated below:

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Since there are many equations presented above, discussing each one separately would be challenging. Therefore, we focus on a relatively complicated case, specifically case *A103*, to provide an illustrative example. This state occurs when there are more than or equal to three but less than or equal to N-1 LP packets and 0 HP packet in the system, and there are at least 2 seats left in the packet queue, while the energy queue is empty. The LP packet being served in the server is using the regular battery. The corresponding detailed state transition diagram can be found in Fig. 3 - 4.

1. For,,,and,

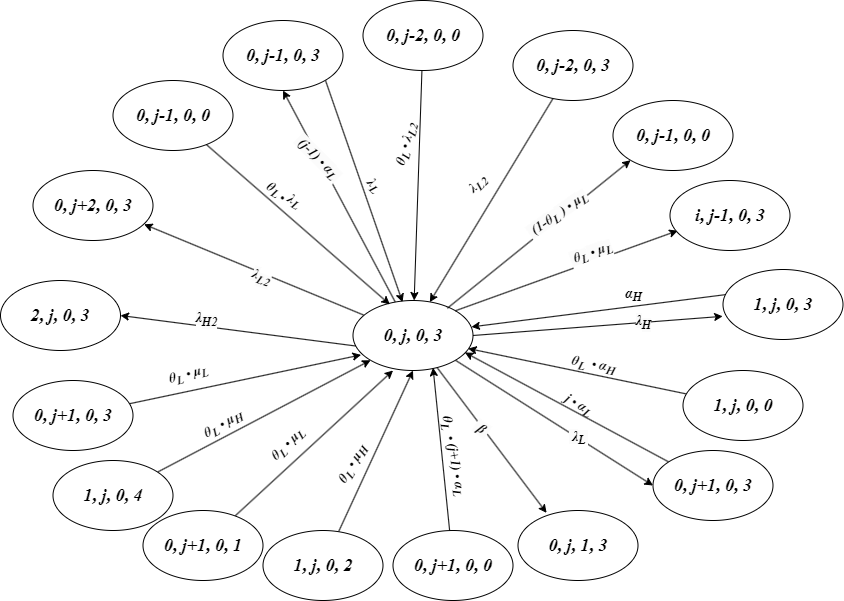


Fig. 3 - 4: The state transition diagram for ,,,and *.*

1. For , , , and ,
2. For , , , and ,
3. For , , , and ,
4. For , , , and ,
5. For , , , and ,
6. For , , , and ,
7. For , , , and ,
8. For , , , and ,
9. For , , , and ,
10. For , , , and ,
11. For , , , and ,
12. For , , , and ,
13. For , , , and ,
14. For , , , and ,
15. For , , , and ,
16. For , , , and ,
17. For , , , and ,
18. For , , , and ,
19. For,,,and,
20. For,,,and,
21. For,,,and,
22. For,,,and,
23. For,,,and,
24. For,,,and,
25. For,,,and,
26. For,,,and,
27. For,,,and,
28. For,,,and,
29. For,,,and,
30. For,,,and,
31. For,,,and,
32. For,,,and,
33. For,,,and,
34. For,,,and,
35. For,,,and,
36. For,,,and,
37. For,,,and,
38. For,,,and,
39. For,,,and,
40. For,,,and,
41. For,,,and,
42. For,,,and,
43. For,,,and,
44. For,,,and,
45. For,,,and,
46. For,,,and,
47. For,,,and,
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49. For,,,and,
50. For,,,and,
51. For,,,and,
52. For,,,and,
53. For,,,and,
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55. For,,,and,
56. For,,,and,
57. For,,,and,
58. For,,,and,
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64. For,,,and,
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92. For, ,,and,
93. For,,,and,
94. For,,,and,
95. For,,,and,
96. For,,,and,
97. For,,,and,
98. For,,,and,
99. For,,,and,

1. For,,,and,

1. For,,,and,

Since there are many equations presented above, discussing each one separately would be challenging. Therefore, we focus on a relatively complicated case, specifically case *B38*, to provide an illustrative example. This state occurs when there are more than or equal to two but less than or equal to N HP packets and 0 LP packet in the system, and there are more than 1 seat left in the packet queue, while the energy queue is empty. The HP packet being served in the server is using the harvested energy. The corresponding detailed state transition diagram can be found in Fig. 3 - 5.

1. For,,,and,

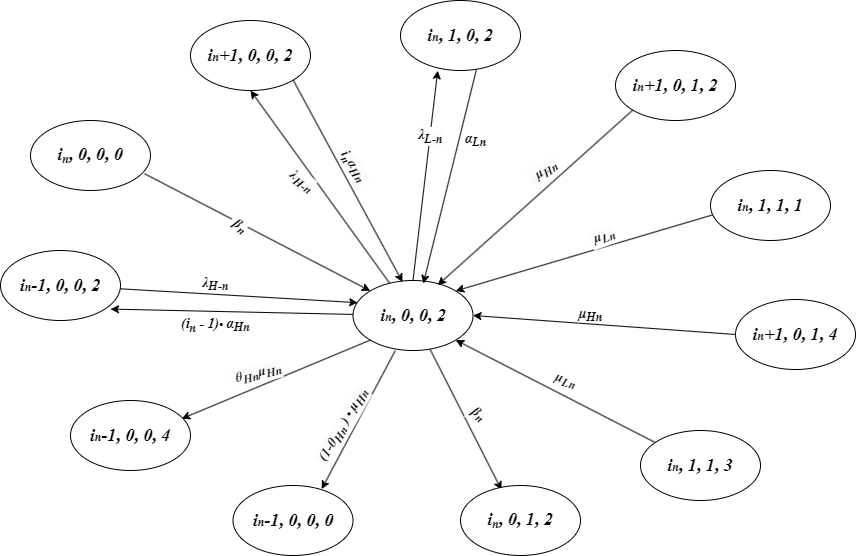
**

Fig. 3 - 5: The state transition diagram for ,,,and *.*

### Iterative algorithm

Using the iterative algorithm provided below, we perform calculations on the state balance equations until they converge, allowing us to determine the steady-state distribution of the system.

#### **Iterative algorithm:**

Step 1: Select a group of initial values for , , where is the total number of feasible states for node , .

Step 2: Calculate , , and based on , .

Step 3: Substitute , , and into eqs. (3-29) - (3-35) to find and , .

Step 4: Substitute into *Case A1* to *Case A190* and *Case B1* to *Case B101* to find , , , respectively.

Step 5: Normalize , , .

Step 6: If , stop the iterative algorithm, where is the stopping criterion. Otherwise, set , and return to Step 2.

In the analytical experiments, we set . It takes about 200 to 7000 iterations for the algorithm to converge.

### Performance measures

To evaluate the network's effectiveness, we obtain several performance measures of interest from the steady-state probability of each node , as presented below.

#### (, the expected number of all packets in node , is provided below.

(3-36)

(3-37)

(3-38)

#### , the expected number of all packets for the network, is provided below.

(3-39)

(3-40)

(3-41)

#### , the expected number of all packets in the queue of node , is provided below.

(3-42)

(3-43)

(3-44)

#### , the expected number of all packets in the queue , is provided below.

(3-45)

(3-46)

(3-47)

#### , the throughput of all packets for node , is provided below.

(3-48)

(3-49)

(3-50)

#### , the throughput of all packets for the network, is provided below.

(3-51)

(3-52)

(3-53)

#### , the blocking probability of each arrived packet for node , regardless of priority, is provided below.

(3-54)

#### , the blocking probability of each arrived packet for the network, regardless of priority, is provided below.

(3-55)

#### , the energy loss probability for node , is provided below.

(3-56)

#### , the energy loss probability for the network, is provided below.

(3-57)

#### , the mean waiting time of all packets in node , including those that have finished their service and those that left the network due to impatience, is provided below.

(3-58)

(3-59)

(3-60)

#### , the mean waiting time of all packets in the network, including those that have finished their service and those that left the network due to impatience, is provided below.

(3-61)

(3-62)

(3-63)

#### , the impatient loss probability of arrived packets for node , is provided below.

(3-64)

(3-65)

(3-66)

#### , the impatient loss probability of arrived packets for the network, is provided below.

(3-67)

(3-68)

(3-69)

#### , the impatient loss probability of admitted packets for node , is provided below.

(3-70)

(3-71)

(3-72)

#### , the impatient loss probability of admitted packets for the network, is provided below.

(3-73)

(3-74)

(3-75)

#### , the total loss probability of arrived packets for node , is provided below.

(3-76)

(3-77)

(3-78)

#### , the total loss probability of arrived packets for the network, is provided below.

(3-79)

(3-80)

(3-81)

#### , the regular energy consumption ratio of all packets for node , is provided below.

(3-82)

(3-83)

(3-84)

#### , the regular energy consumption ratio of all packets for the network, is provided below.

(3-85)

(3-86)

(3-87)