A Life Extend Approach Based on Multiple Priority Queue N Strategy for Wireless Sensor Network

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Abstract

Real-time data communication among and battery lifetime of sensor nodes turn into critical issues, due to the rapid development of wireless sensor networks over recent years. This paper presents a multiple priority queue-based system involving (1) a multiple priority queue mechanism to ensure data packet transmission in a real-time system, (2) a finite-size queue for realistic circuit design, (3) an *N*-policy M/M/1/K queuing model to avoid an energy hole problem, (4) a sleep mode to reduce the battery power consumption for lifetime extension and (5) a birth-death process to compute the probabilities of the sleep, idle, busy and transmit states. The probability in each state is obtained versus the data arrival rate, the service rate, the collision probability and the queue threshold. A high priority queue is validated to provide a shorter delay time, and the power consumtion is minimized with the threshold *N* as well.

Keywords: Wireless sensor network, Priority queue, M/M/1/K queue, Energy hole problem, Real time

1 Introduction

Wireless sensor networks (WSNs) have been applied to be a wide variety of disciplines, and lead to a great number of relevant issues, e.g. inventory tracking, traffic surveillance, medical application, military sensing and disaster monitoring. In most cases, sensor nodes are scattered to detect various types of data packets, each assigned with different priority. For the purpose of real time processing, those with higher priorities are requested to be transmitted promptly. Particularly, a multitude of nodes are very likely to be deployed in extremely dangerous, or even inaccessible, zone, say a battlefield or an area full of land mines, for critical data gathering and transmission. For this sake, the operation period of a WSN is dominated by the limited amount of electricity carried by nodes. Accordingly, battery replacement or charging is seen as a major concern when in operation [1-2]. An alternative way to address the battery issue is to reduce the electricity consumed by sensor nodes using a multiple priority queue.

As explicitly pointed out in [3-4], a sensor node not only serves as a data source, but also relays data from others toward the sink node. In this context, nodes in the vicinity of the sink inevitably become heavily loaded, giving rise to the so-called energy hole problem (EHP) [5-6]. Heavily loaded nodes are supposed to run out of the carried electricity sooner than others, and a WSN ceases operation earlier than expected. As indicated in [7], up to 90% of the total electricity remains in the node batteries at the end of the lifetime of a WSN. It was suggested in [8] that electricity is mainly consumed during idle listening, overhearing, collision and packet control, and worse idle listening and overhearing do not make any contribution to the network operation.

In general, the largest amount of power is dissipated in the transmission mode, while the lowest is in the sleep mode. As indicated in [9], there are an average power dissipation of 0.003 mW in the sleep mode, 30 mW in the idle mode and 81 mW in the transmission mode. Since there is little power dissipation in the sleep mode, much effort has been made in sleep time extension using a sleep-wake up schedule [10-11]. In contrast, the issue of data packet collision remains hardly address in the literature, even though it is a key issue in terms of power consumption. As a way to suppress the collision probability, a queue is employed to store data packets waiting for transmission. There is a threshold *N* in the queue, and the sensor node remains idle if the number of the packets in the queue does not reach *N*. Otherwise, the node is enabled, tries to access transmission channels and then deliver packets until the queue is empty. As presented in [12], *N* was set to 2 for illustration purposes, and it was well validated that the collision probability, in direct relation to power consumption, is subject to the channel contention.

As presented in [13-15], power consumption is optimized with respect to the threshold *N*, but without

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taking into account the queue length and the sleep state. Yet, effect of the queue length and the sleep state on the power consumption cannot be neglected in reality. A multiple priority queue method is adopted herein for real-time data packet transmission. Furthermore, an N-policy M/M/1/K queuing model and a sleep mode are exploited to decrease power consumption and extend the life time of a WSN.

The remainder of this paper is outlined as follows. Section 2 introduced related works of this research. Section 3 details the design of the system architecture and analyzes the transition between states. Section 4 gives experimental results and verifies the efficiency of the proposed work. Finally, Section 5 concludes this paper.

2 Related Works

In an operating system, process priority is classed into preemptive priority and non-preemptive priority. The former is widely used in real-time systems, and both had been well applied to queue issues in [16-18]. As presented in [17], a preemptive priority queue is validated as an advantageous candidate to handle packets with higher priorities, since the waiting time for packets in a queue can be reduced significantly.

In regard to real-time services, quality of service (QoS) is critical when supporting data delivery. QoS is a control mechanism designed for packet transmission, and assigns different priorities to various types of packets. When meeting the request of application programs, a certain level of performance in packet transmission can be well maintained using QoS. As approved in 2005 by IEEE 802.11 amendments, IEEE 802.11e standard defines a mechanism to provide QoS for wireless local area network (WLAN) applications [19]. For the next generation of WLAN protocol, IEEE 802.11ax amendment achieves a better QoS provision for multimedia applications to meet user needs [20-21]. For supporting IEEE 802.11ax, a multi-level priority scheme [21-22] is used to avoid the QoS degrade. A probe request is assigned the highest priority. Voice, live streaming video, and interactive gaming is the second. Buffered streaming video is the third, internet application is the fourth, and channel quality indicator and radio measurement service are the lowest priority.

As its name indicates, a wake-up mechanism, commonly employed in WSNs, is to wake up a sleeping sensor node which consumes as little energy as possible for the sake of power conservation. An awake node needs to enable a wireless module for packet reception and transmission, in conformity with the MAC [23-24]. Generally, it consumes approximately the same amount of electricity to enable a wireless module, while the enabling frequency and duration are key factors to the lifespan of a battery. In compliance with the IEEE 802.11 standard [24], a node is permitted to work in the active mode, and to sleep in the power save mode. A node either stays idle listening or enters into the packet transmission state in the active mode, while neither receives nor transmits packets, but just checks whether there is any packet on a channel delivered to the node in the power save mode. If the condition is true, the sleeping node wakes up, and enables the wireless module. The power consumption in the power save mode and the average sleep mode duration were evaluated using a Markov chain [25], while the delay time suffered by a packet is contingent on the number of packets in a queue. Nonetheless, the issue of power dissipation reduction was not addressed therein.

An improved version of MAC protocols, designated as S-MAC, is presented in [11], and a mechanism is designed to made sensor nodes go to the sleep, wake-up and idle listening modes on a regular and repeated basis. The average cycle length of the S-MAC mechanism is determined by the sleep frequency which is implemented to meet the energy saving requirement using a wireless framework. However, the channel contention issue was not addressed in the S-MAC mechanism. For the sake of energy conservation, the STEM mechanism was presented in [26], where two wireless modules are employed, one of which detects whether there is a packet waiting for reception when a node falls asleep, and the other of which takes charge of packet reception and transmission when the node is awake. It is that both wireless modules are enabled only when there is a packet transmission request. Generally, STEM is permitted to collaborate with a schedule-based MAC protocol, while is short of a mechanism to ease the channel contention.

The EHP is modeled using a normal sensor node distribution in [5], and the energy consumption can be analyzed accordingly. In an attempt to ease the impact of EHP, sensor nodes are deployed in a complicated way but at a high implementation expense and at the cost of network flexibility, as in [27-28].

As reported in [13-15], packet collison probability and the extra load due to channel contention can be lowered using the M/G/1 queuing theory, and EHP can be eased using the *N*-policy to specify a threshold for a queue. Once the amount of energy consumed is minimized with respect to *N*, the latency delay suffered by the sensor nodes can be reduced significantly, assuming that there is an infinite-buffer queue. Nevertheless, the assumption must be false, since an infinite-size buffer does not exist in reality.

3 System Architecture

Figure 1 is a system architecture based on multiple priority queues in which the packet is classified according to its priority. An urgent data packet has the highest priority, represented as n_1 packet, is placed in queue 1 (q_1). Similarly, the lower priority packet can be denoted as $n_2, n_3, \ldots, n_n$ placed in queue with respect to $q_2, q_3, \ldots, q_n$. A high-intermediate data packet represented as n_2 placed in q_2. A non-urgent and non-important data packet is given the lowest priority, represented as n_n packet, is in the bottom queue. A server sends all these packets in sequence with their priority.

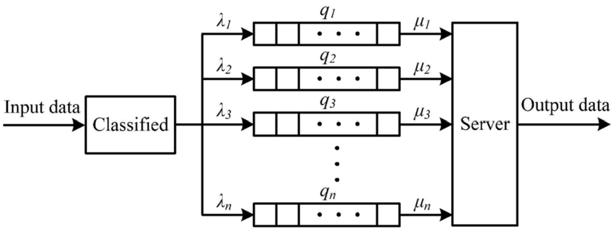


Figure 1. System architecture

A M/M/1/K queue model is utilized in proposed system, and high priority packets have preemptive priority. A Poisson distribution is applied to represent the mean arrival rate (λ) and service rate (μ) of each packet. Arrival Rates for q_1 to q_n are respectively denoted as $\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_n$, and service rates are respectively represented as $\mu_1, \mu_2, \mu_3, \ldots, \mu_n$.

A birth-death process is used herein to represent the packet transmission, each node has different priority packets, as depicted in Figure 2. Downward arrows means packets are arrival, and upward arrows means packets are transmitted.

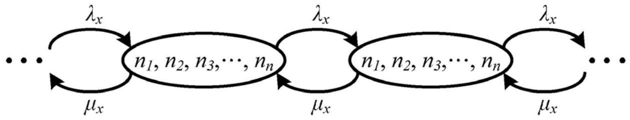


Figure 2. System state transition diagram

$$\lambda_x = \lambda_1 \mid \lambda_2 \mid \lambda_3 \mid \cdots \mid \lambda_n \text{ and } \mu_x = \mu_1 \mid \mu_2 \mid \mu_3 \mid \cdots \mid \mu_n$$

where "|" is an or function

Accordingly, a general equation can be derived to represent which packet could be transmitted.

$$\text{out} = d_i n_i + \overline{d_1}(d_{i+1} n_{i+1} + \overline{d_{i+1}}(d_{i+2} n_{i+2} + \cdots + \cdots \overline{d_{i+n-2}} d_{i+n-1} n_{i+n-1})) \quad \textbf{(1)}$$

where variable d_i can be defined as

- $d_i = 0$, there is no data in the queue.
- $d_i = 1$, there is data in the queue.

In the following, the priority is defined with three levels to guarantee the important data can be transmitted immediately for simplicity. A real-time packet is put in high priority queue, and non-real-time packet is put in the other two queues according to its importance. Therefore, high priority n_1 packet has the shortest delay, medium priority is defined as n_2 packet, and low priority n_3 packet is used for unimportant data. In this way, n_1 packet is assigned to q_1, n_2 packet is assigned to q_2, and n_3 is assigned to q_3. Consequently, Equation (1) can be re-written as $\text{out} = d_1 n_1 + \overline{d_1}(d_2 n_2 + \overline{d_2} d_3 n_3)$. If q_1 has data, then $\text{out} = n_1$. This implies n_1 packet can be transmitted firstly. If q_1 has no data but q_2 has data, then $\text{out} = n_1$. This indicates n_2 packet is transferred. If q_1 and q_2 have no data but q_3 has data, then $\text{out} = n_3$. The n_3 packet is transmitted until now.

3.1 System Operation Flowchart

In this research, a half-duplex transmission scheme is adopted due to the requirement of low-power consumption and low-rate communication. Both sides can transmit (Tx) or receive (Rx) data with each other, but not at the same time. When a sensor node receives a packet placed in the queue. The size of the queue is limited due to less power consumption and hardware overhead. As illustrated in Figure 3, the system is divided into four states, which contains sleep state, idle state, busy state and transmit state.

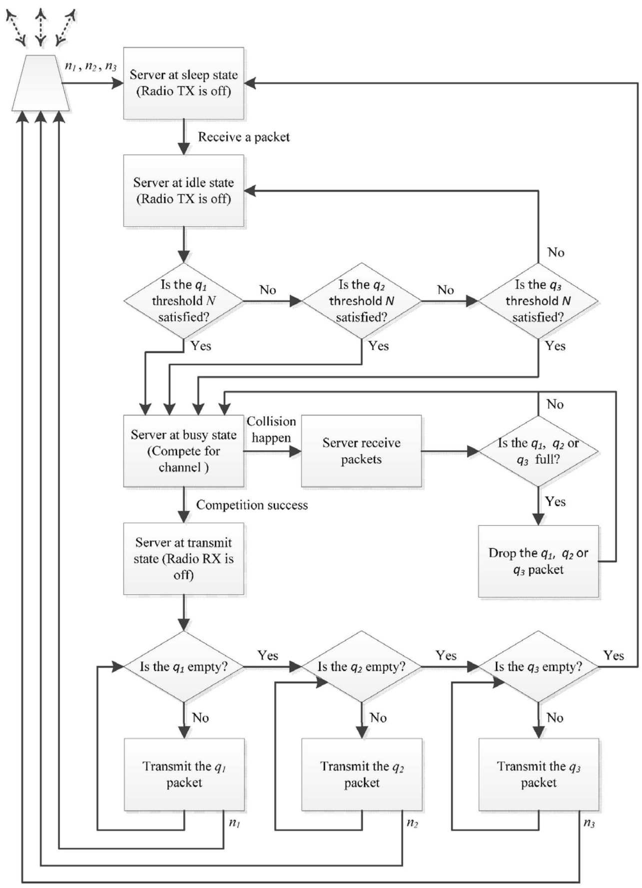


Figure 3. System operation flowchart

At the beginning, the sensor node system stays at sleep state to save power, and the q_1, q_2 and q_3 have no packet. Until a packet has arrived, the sensor node is woken up into the idle state. The system receives more packets, and assigns the n_1, n_2 and n_3 packets respectively to the q_1, q_2 and q_3. When the number of packets in q_1, q_2 or q_3 is reached to threshold *N*, the system turns into the busy state and tries to access the channel. If it is failed, the sensor node keeps receiving packets. This activity will be stopped when the number of packets in q_1, q_2 or q_3 is equal to queue size *K*. For instance, in case of q_1 is full, but q_2 and q_3 are not full. When new n_1, n_2 and n_3 packets are arrival, the new n_1 packet will be dropped but the new n_2 and n_3 packets are respectively stored in their queue. This is because the number of packets in q_2 and q_3 is less than *K*. However, if the sensor node successfully access the channel, it enters into the transmit state and stops to receive any packet. All of packets in the queues will be transmitted until empty. Therefore, the n_1 packets are firstly transmitted since high priority packets have preemptive priority, then the n_2 packets, and lastly the n_3 packets. When the number of packets in q_1, q_2 or q_3 is equal to zero, the sensor node releases the channel and goes back to sleep state. The above four states are included within one cycle time (*T*).

3.2 System Power Consumption

The system power consumption during a period of *T* is illustrated in Figure 4, where the horizontal and vertical axes indicate the time and power consumption, respectively. Initially, the system consumes less power at sleep state and has no packet in the queue. When a packet has arrived, the system is woken up into the idle state. And the power required is defined as setup energy. The system keeps accepting packets, resulting in more power wasted to hold the increased packets in the queue. As soon as the number of packets is identical to *N*, the state switches to busy. So the system consumes more power while attempts to access the channel and keeps packets in the queue. After successfully access the channel, the state changes to transmit and packets in the queue are transmitted out. The power consumption is decreased along with the gradually reduced packets.

3.3 System State Transition

A birth-death process is used to estimate each state probability, as depicted in Figure 5. Each sensor node has three queues, and a notation (n_1, n_2, n_3) denotes the number of packets in q_1, q_2 and q_3, respectively. It follows a Poisson distribution that the mean arrival rates for the n_1, n_2 and n_3 packets are, respectively, indicated as λ_1, λ_2 and λ_3, while the service rates are, respectively, denoted as μ_1, μ_2, and μ_3.

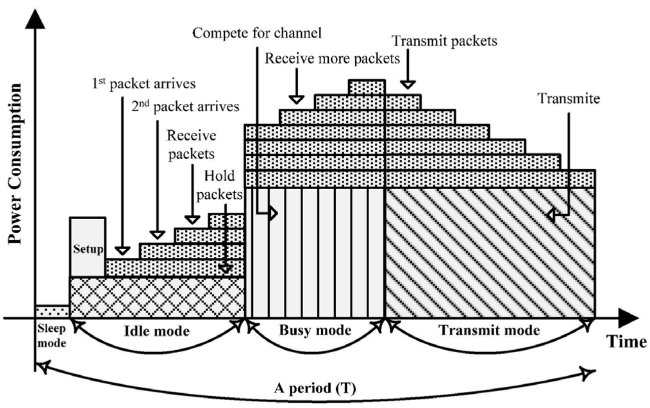


Figure 4. System power consumption

The system initially at sleep state has zero packet, while P_s is the probability of sleep state. When a packet has arrived, the system enters to idle state. The probability of idle state is represented as P_i, and the mean arrival rates for the n_1, n_2 and n_3 packets from P_s to P_i are represented as λ_1', λ_2' and λ_3', respectively. Hence, more and more packets have stored in the queues, the system changes to busy state until the number of packets in one of queues is up to *N*. It tries to access the channel, and P_b is the probability of busy state. If the access is failed that means the channel is occupied by another sensor node, while P_c is the probability of collision happen. When the number of packets in one of queues is equal to *K*, any income packet will be dropped. The P_d denotes the probability of drop packet. However, the probability of the system access the channel is represented as $(1-P_c)$, and all of the packets start to transmit out in order of priority, i.e. $n_1 > n_2 > n_3$. And the P_t is the probability of transmit state.

3.4 Balance Equation

As given on (2) to (68), the balance equations can be derived based on system state transition diagram in case of *N*=4 and *K*=7. For simplicity and ease of understanding, the case of *N*=2 and *K*=3 is used here as presented in Figure 5. The balance equation for sleep state is given on (2), the $P_t(1,0,0)$, $P_t(0,1,0)$ or $P_t(0,0,1)$ goes backs to $P_s(0,0,0)$ when a packet is transmitted out.

$$\begin{aligned} &P_s(0,0,0)(\lambda_1'+\lambda_2'+\lambda_3') \\ &= P_t(1,0,0)\mu_1 + P_t(0,1,0)\mu_2 + P_t(0,0,1)\mu_3 \end{aligned} \tag{2}$$

The balance equations for idle state are listed on (3) to (12), the number of packets is between 1 and *N*-1. After the system receives a packet at sleep state, it switches to idle state. Accordingly, the number of packets in one of (n_1, n_2, n_3) is changed from 0 to 1, as given on Equations (3) to (5).

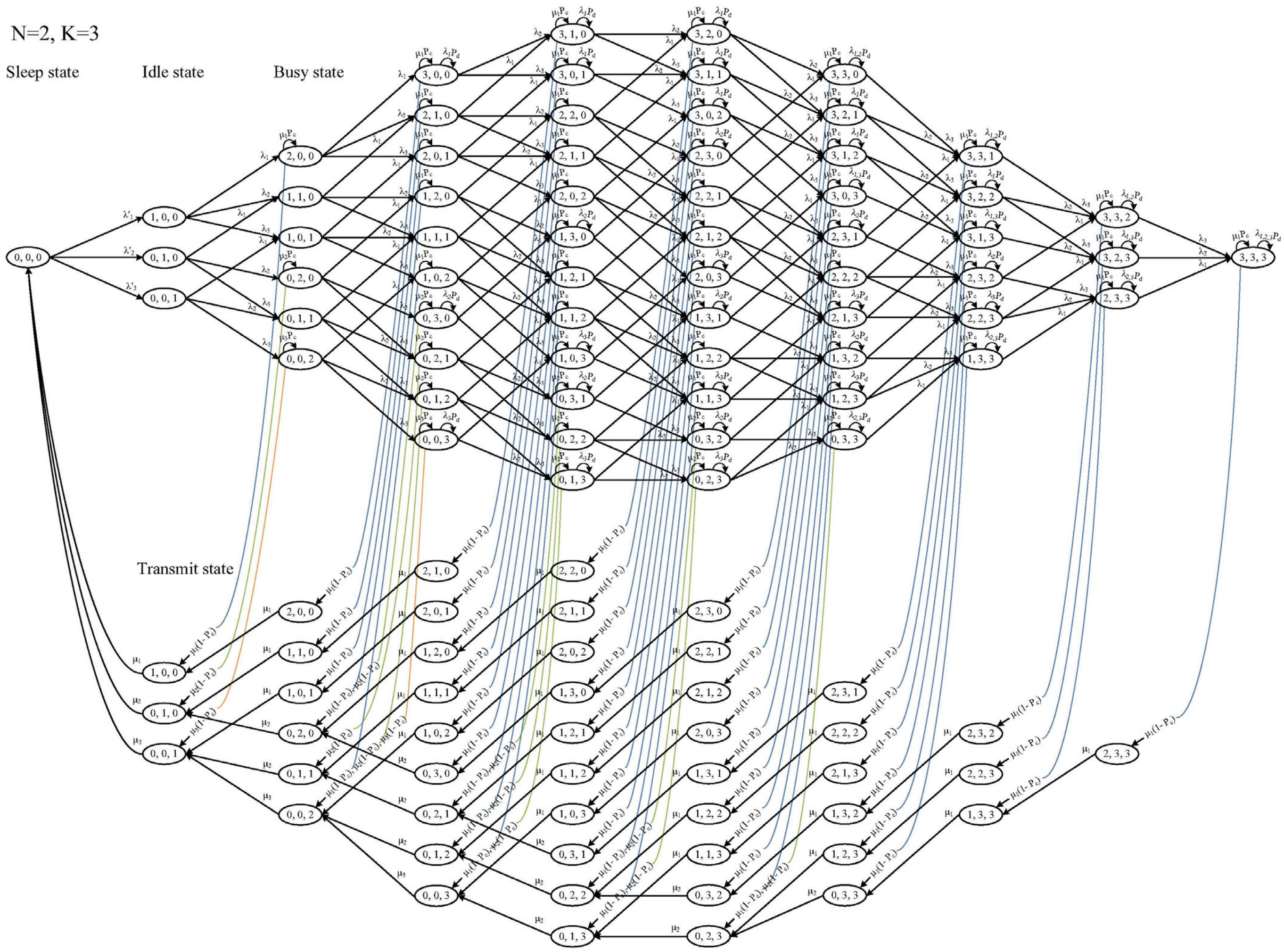


Figure 5. System state transition diagram for a 3-priority queueing model

$$P_i(1,0,0)(\lambda_1+\lambda_2+\lambda_3)=P_s(0,0,0)\lambda_1' \quad \textbf{(3)}$$

$$P_i(0,1,0)(\lambda_1+\lambda_2+\lambda_3)=P_s(0,0,0)\lambda_2' \quad \textbf{(4)}$$

$$P_i(0,0,1)(\lambda_1+\lambda_2+\lambda_3)=P_s(0,0,0)\lambda_3' \quad \textbf{(5)}$$

The number of packets is increased if system receives more packets. Equations (6) to (8) indicate that the n_1, n_2 or n_3 has at least two same packets arrived, so the possibility of last P_i is with arrival rate λ_1, λ_2 or λ_3. For example, Figure 6 is the idle state transition diagram in the case of *N*=4 and *K*=7, and the balance equation can be expressed as: $P_i(2,0,0)(\lambda_1+\lambda_2+\lambda_3)=P_i(2-1,0,0)\lambda_1$, where $2\le n_1\le 3$ and the "2" and "2–1" can be replaced as n_1 and n_1-1, respectively. Thus, the general form is obtained as Equation (6).

$$P_i(n_1,0,0)(\lambda_1+\lambda_2+\lambda_3)=P_i(n_1-1,0,0)\lambda_1 \quad 2\le n_1\le N-1 \quad \textbf{(6)}$$

$$P_i(0,n_2,0)(\lambda_1+\lambda_2+\lambda_3)=P_i(0,n_2-1,0)\lambda_2 \quad 2\le n_2\le N-1 \quad (7)$$

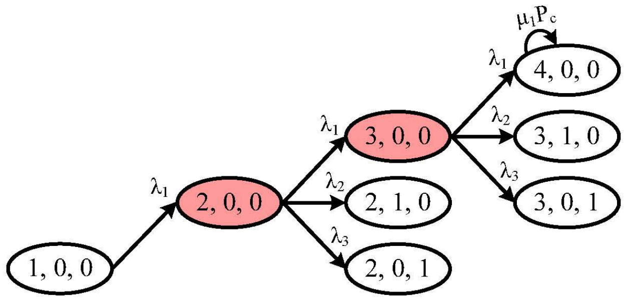


Figure 6. Idle state transition diagram

$$P_i(0,0,n_3)(\lambda_1+\lambda_2+\lambda_3)=P_i(0,0,n_3-1)\lambda_3 \quad 2\le n_3\le N-1 \quad \textbf{(8)}$$

Equations (9) to (11) denote that (n_1,n_2,n_3) has two data packet with different priorities arrived, so the possibility of last P also has two situations.

$$P_i(n_1,n_2,0)(\lambda_1+\lambda_2+\lambda_3)=P_i(n_1,n_2-1,0)\lambda_2+P_i(n_1-1,n_2,0)\lambda_1 \quad 1\le n_1\le N-1\ \&\ 1\le n_2\le N-1 \quad \textbf{(9)}$$

$$P_i(n_1, 0, n_3)(\lambda_1 + \lambda_2 + \lambda_3) = P_i(n_1, 0, n_3 - 1)\lambda_3 + P_i(n_1 - 1, 0, n_3)\lambda_1 \quad 1 \le n_1 \le N - 1 \;\&\; 1 \le n_3 \le N - 1 \tag{10}$$

$$P_i(0, n_2, n_3)(\lambda_1 + \lambda_2 + \lambda_3) = P_i(0, n_2, n_3 - 1)\lambda_3 + P_i(0, n_2 - 1, n_3)\lambda_2 \quad 1 \le n_2 \le N - 1 \;\&\; 1 \le n_3 \le N - 1 \tag{11}$$

In idle state, Equation (12) represents the (n_1, n_2, n_3) has packets, therefore, the possibility of last $P_i(n_1, n_2, n_3)$ has increased to three circumstances.

$$P_i(n_1, n_2, n_3)(\lambda_1 + \lambda_2 + \lambda_3) = P_i(n_1, n_2, n_3 - 1)\lambda_3 + P_i(n_2, n_2 - 1, n_3)\lambda_2 + P_i(n_1 - 1, n_2, n_3)\lambda_1 \quad 1 \le n_1 \le N - 1 \;\&\; 1 \le n_2 \le N - 1 \;\&\; 1 \le n_3 \le N - 1 \tag{12}$$

The system changes to busy state and attempts to access channel when the number of packets is reached to *N*. The balance equations are given on (13) to (57), and the number of packets is between *N* and *K*. Consequently, the number of packets in one of (n_1, n_2, n_3) is idential to *N*, as presented on Equations (13) to (15).

$$P_b(N, 0, 0)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_1(1 - P_c)] = P_i(N - 1, 0, 0 - 1)\lambda_1 \tag{13}$$

$$P_b(N, N, 0)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_2(1 - P_c)] = P_i(0, N - 1, 0)\lambda_2 \tag{14}$$

$$P_b(0, 0, N)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_3(1 - P_c)] = P_i(0, 0, N - 1)\lambda_3 \tag{15}$$

Equations (16) to (18) indicate that the nubmber of packet in two different priority queues is reached to *N*, and the other queue has no packet. Thus, the possibility of last P_b has two circumstances.

$$P_b(N, N, 0)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_1(1 - P_c)] = P_b(N, N - 1, 0)\lambda_2 + P_b(N - 1, N, 0)\lambda_1 \tag{16}$$

$$P_b(N, 0, N)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_1(1 - P_c)] = P_b(N, 0, N - 1)\lambda_3 + P_b(N - 1, 0, N)\lambda_1 \tag{17}$$

$$P_b(0, N, N)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_2(1 - P_c)] = P_b(0, N, N - 1)\lambda_3 + P_b(0, N - 1, N)\lambda_2 \tag{18}$$

When the number of packets in (n_1, n_2, n_3) is equal to to *N*, the possibility of last P_b is with arrival rate λ_1, λ_2 or λ_3, as given on Equation (19).

$$P_b(N, N, N)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_1(1 - P_c)] = P_b(N, N, N - 1)\lambda_3 + P_b(N, N - 1, N)\lambda_2 + P_b(N - 1, N, N)\lambda_1 \tag{19}$$

Here, Equations (20) to (22) represent the nubmber of packets in two different priority queues is reached to *N*, and the nubmber of packet in the other queue is less than *N*. So the possibility of last P_b has three situations.

$$P_b(N, N, n_3)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_1(1 - P_c)] = P_b(N, N, n_3)\lambda_3 + P_b(N, N - 1, n_3)\lambda_2 + \quad 1 \le n_3 \le N - 1 \tag{20}$$

$$P_b(N, n_2, N)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_1(1 - P_c)] = P_b(N, n_2, N - 1)\lambda_3 + P_b(N, n_2 - 1, N)\lambda_2 + \quad 1 \le n_2 \le N - 1 \tag{21}$$

$$P_b(n_1, N, N)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_1(1 - P_c)] = P_b(n_1, N, N - 1)\lambda_3 + P_b(n_1, N - 1, N)\lambda_2 + P_b(n_1 - 1, N, N)\lambda_1 \quad 1 \le n_1 \le N - 1 \tag{22}$$

In three different priority queues, the packet number of n_1 is *N*, but the packet number of n_2 and n_3 is less than *N*, as presented on Equations (23) to (25).

$$P_b(N, n_2, 0)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_1(1 - P_c)] = P_b(N, n_2 - 1, 0)\lambda_2 + P_i(N - 1, n_2, 0)\lambda_1 \quad 1 \le n_2 \le N - 1 \tag{23}$$

$$P_b(N, 0, n_3)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_1(1 - P_c)] = P_b(N, 0, n_3 - 1)\lambda_3 + P_i(N - 1, 0, n_3)\lambda_1 \quad 1 \le n_3 \le N - 1 \tag{24}$$

$$P_b(N, n_2, n_3)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_1(1 - P_c)] = P_b(N, n_3, n_3 - 1)\lambda_3 + P_b(N, n_2 - 1, n_3)\lambda_2 + P_i(N - 1, n_2, n_3)\lambda_1 \quad 1 \le n_2 \le N - 1 \;\&\; 1 \le n_3 \le N - 1 \tag{25}$$

Equations (26) to (28) indicate the packet number of n_2 is *N*, but the packet number of n_1 and n_3 is less than *N*.

$$P_b(n_1, N, 0)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_1(1 - P_c)] = P_i(n_1, N - 1, 0)\lambda_2 + P_b(n_1 - 1, N, 0)\lambda_1 \quad 1 \le n_1 \le N - 1 \tag{26}$$

$$P_b(0, N, n_3)[\lambda_1 + \lambda_2 + \lambda_3 + \mu_2(1 - P_c)] = P_b(0, N, n_3 - 1)\lambda_3 + P_i(0, N - 1, n_3)\lambda_2 \quad 1 \le n_3 \le N - 1 \tag{27}$$

$$\begin{gathered}P_b(n_1, N, n_3)[\lambda_1+\lambda_2+\lambda_3+\mu_1(1-P_c)] \\ =P_b(n_1, N, n_3-1)\lambda_3+P_i(n_1, N-1, n_3)\lambda_2+ \\ P_b(n_1, N, n_3)\lambda_1 \\ 1 \leq n_1 \leq N-1 \,\&\, 1 \leq n_3 \leq N-1\end{gathered} \tag{28}$$

Similarly, Equations (29) to (31) denote the packet number of n_3 is N, but the packet number of n_1 and n_2 is less than N.

$$\begin{gathered}P_b(n_1, 0, N)[\lambda_1+\lambda_2+\lambda_3+\mu_1(1-P_c)] \\ =P_b(n_1, 0, N-1)\lambda_3+P_b(n_1-1, 0, N)\lambda_1 \\ 1 \leq n_1 \leq N-1\end{gathered} \tag{29}$$

$$\begin{gathered}P_b(0, n_2, N)[\lambda_1+\lambda_2+\lambda_3+\mu_2(1-P_c)] \\ =P_i(0, n_2, N-1)\lambda_3+P_b(0, n_2-1, N)\lambda_2 \\ 1 \leq n_2 \leq N-1\end{gathered} \tag{30}$$

$$\begin{gathered}P_b(n_1, n_2, N)[\lambda_1+\lambda_2+\lambda_3+\mu_1(1-P_c)] \\ =P_i(n_1, n_2, N-1)\lambda_3+P_b(n_1, n_2-1, N)\lambda_2+ \\ P_b(n_1-1, n_2, N)\lambda_1 \\ 1 \leq n_1 \leq N-1 \,\&\, 1 \leq n_2 \leq N-1\end{gathered} \tag{31}$$

When more and more packet arrived, the nubmber of packets is between N+1 and K-1. Equations (32) to (34) represent only one of n_1, n_2 or n_3 has packets, and the other has no packet. As illustrated in Figure 7, the busy state transition diagram is based on the case of N=4 and K=7, and its balance equation is: $P_b(0, 0, 6)[\lambda_1+\lambda_2+\lambda_3+\mu_3(1-P_c)]=P_b(0, 0, 6-1)\lambda_3$, where $5 \leq n_3 \leq 6$ and the "6" and "6–1" can be replaced as n_3 and n_3-1, respectively. So the general form can be obtained as Equation (34).

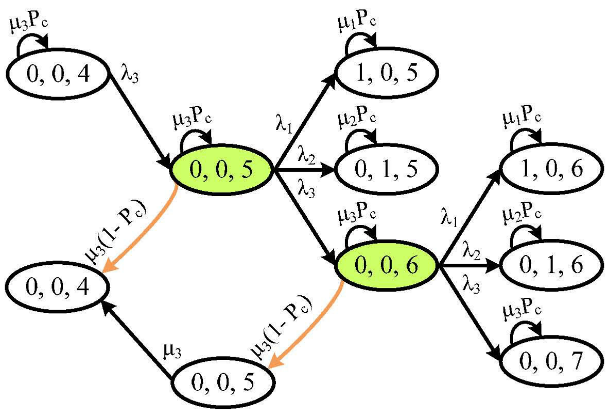


Figure 7. Busy state transition diagram

$$\begin{gathered}P_b(n_1, 0, 0)[\lambda_1+\lambda_2+\lambda_3+\mu_1(1-P_c)] \\ =P_b(n_1-1, 0, 0)\lambda_1 \\ N+1 \leq n_1 \leq K-1\end{gathered} \tag{32}$$

$$\begin{gathered}P_b(0, n_2, 0)[\lambda_1+\lambda_2+\lambda_3+\mu_2(1-P_c)] \\ =P_b(0, n_2-1, 0)\lambda_2 \\ N+1 \leq n_2 \leq K-1\end{gathered} \tag{33}$$

$$\begin{gathered}P_b(0, 0, n_3)[\lambda_1+\lambda_2+\lambda_3+\mu_3(1-P_c)] \\ =P_b(0, 0, n_3-1)\lambda_3 \\ N+1 \leq n_3 \leq K-1\end{gathered} \tag{34}$$

Equations (35) to (37) denote that any two different priority queues have packets, and the packet nubmber in one of them is N+1. The other queue has no packet, so the possibility of last P_b has two situations.

$$\begin{gathered}P_b(n_1, n_2, 0)[\lambda_1+\lambda_2+\lambda_3+\mu_1(1-P_c)] \\ =P_b(n_1, n_2-1, 0)\lambda_2+P_b(n_1-1, n_2, 0)\lambda_1 \\ N+1 \leq n_1 \leq K-1 \,\&\, 1 \leq n_2 \leq K-1 \\ 1 \leq n_1 \leq N \,\&\, N+1 \leq n_2 \leq K-1\end{gathered} \tag{35}$$

$$\begin{gathered}P_b(n_1, 0, n_3)[\lambda_1+\lambda_2+\lambda_3+\mu_1(1-P_c)] \\ =P_b(n_1, 0, n_3-1)\lambda_3+P_b(n_1-1, 0, n_3)\lambda_1 \\ N+1 \leq n_1 \leq K-1 \,\&\, 1 \leq n_3 \leq K-1 \\ 1 \leq n_1 \leq N \,\&\, N+1 \leq n_3 \leq K-1\end{gathered} \tag{36}$$

$$\begin{gathered}P_b(n_1, n_2, n_3)[\lambda_1+\lambda_2+\lambda_3+\mu_2(1-P_c)] \\ =P_b(0, n_2, n_3-1)\lambda_3+P_b(0, n_2-1, n_3)\lambda_2 \\ N+1 \leq n_2 \leq K-1 \,\&\, 1 \leq n_3 \leq K-1 \\ 1 \leq n_2 \leq N \,\&\, N+1 \leq n_3 \leq K-1\end{gathered} \tag{37}$$

Equation (38) represents the (n_1, n_2, n_3) has packets, and the packet nubmber in one of them is N+1. Hence, the possibility of last P_b is with arrival rate λ_1, λ_2 or λ_3.

$$\begin{gathered}P_b(n_1, n_2, n_3)[\lambda_1+\lambda_2+\lambda_3+\mu_1(1-P_c)] \\ =P_b(n_1, n_2, n_3-1)\lambda_3+P_b(n_2, n_2-1, n_3)\lambda_3+ \\ P_b(n_1-1, n_2, n_3)\lambda_1 \\ N+1 \leq n_1 \leq K-1 \,\&\, 1 \leq n_2 \leq K-1 \,\&\, 1 \leq n_3 \leq K-1 \\ 1 \leq n_1 \leq N \,\&\, 1 \leq n_2 \leq N \,\&\, N+1 \leq n_3 \leq K-1 \\ 1 \leq n_1 \leq N \,\&\, N+1 \leq n_2 \leq K-1 \,\&\, 1 \leq n_3 \leq K-1\end{gathered} \tag{38}$$

The queue stops to receive any packet when the nubmber of packet is equal to maximum K. Equations (39) to (41) present the nubmber of packets in one of three different priority queues is reached to maximum, but the other queues has no packet.

$$\begin{gathered}P_b(K, 0, 0)[\lambda_2+\lambda_3+\mu_1(1-P_c)] \\ =P_b(K-1, 0, 0)\lambda_1\end{gathered} \tag{39}$$

$$\begin{gathered}P_b(0, K, 0)[\lambda_1+\lambda_3+\mu_2(1-P_c)] \\ =P_b(0, K-1, 0)\lambda_2\end{gathered} \tag{40}$$

$$P_b(0,0,K)[\lambda_1+\lambda_2+\mu_2(1-P_c)] \\ = P_b(0,0,K-1)\lambda_3 \tag{41}$$

Here, Equations (42) to (44) indicate the nubmber of packets in two different priority queues is reached to K, and the other queue has no packet. Accordingly, the possibility of last P_b has two circumstances.

$$P_b(K,K,0)[\lambda_3+\mu_1(1-P_c)] \\ = P_b(K,K-1,0)\lambda_2 + P_b(K-1,K,0)\lambda_1 \tag{42}$$

$$P_b(K,0,K)[\lambda_2+\mu_1(1-P_c)] \\ = P_b(K,0,K-1)\lambda_3 + P_b(K-1,0,K)\lambda_1 \tag{43}$$

$$P_b(0,K,K)[\lambda_1+\mu_2(1-P_c)] \\ = P_b(0,K,K-1)\lambda_3 + P_b(0,K-1,K)\lambda_2 \tag{44}$$

When the number of packets in (n_1, n_2, n_3) is equal to to K, the system stops to receive any packet and the possibility of last P_b is with arrival rate λ_1, λ_2 or λ_3, as given on Equation (45).

$$P_b(K,K,K)[\mu_1(1-P_c)] = P_b(K,K,K-1)\lambda_3 + \\ P_b(K,K-1,K)\lambda_2 + P_b(K-1,K,K)\lambda_1 \tag{45}$$

When the nubmber of packet in two different priority queues is reached to K, but the other queue is acceptable to receive packets. As presented in Equations (46) to (48), the possibility of last P_b has three situations.

$$P_b(K,K,n_3)[\lambda_3+\mu_1(1-P_c)] = P_b(K,K,n_3-1)\lambda_3 + \\ P_b(K,K-1,n_3)\lambda_2 + P_b(K-1,K,n_3)\lambda_1 \\ 1 \le n_3 \le K-1 \tag{46}$$

$$P_b(K,n_2,K)[\lambda_2+\mu_1(1-P_c)] = P_b(K,n_2,K-1)\lambda_3 + \\ P_b(K,n_2-1,K)\lambda_2 + P_b(K-1,n_2,K)\lambda_1 \\ 1 \le n_2 \le K-1 \tag{47}$$

$$P_b(n_1,K,K)[\lambda_1+\mu_1(1-P_c)] = P_b(n_1,K,K-1)\lambda_3 + \\ P_b(n_1,K-1,K)\lambda_2 + P_b(n_1-1,K,K)\lambda_1 \\ 1 \le n_1 \le K-1 \tag{48}$$

Equations (49) to (51) denote that the packet number of n_1 is K, but the n_2 and n_3 are acceptable to receive packets.

$$P_b(K,n_2,K)[\lambda_2+\lambda_3+\mu_1(1-P_c)] \\ = P_b(K,n_2-1,0)\lambda_2 + P_b(K-1,n_2,0)\lambda_1 \\ 1 \le n_2 \le K-1 \tag{49}$$

$$P_b(K,0,n_3)[\lambda_2+\lambda_3+\mu_1(1-P_c)] \\ = P_b(K,0,n_3-1)\lambda_3 + P_b(K-1,0,n_3)\lambda_1 \\ 1 \le n_3 \le K-1 \tag{50}$$

$$P_b(K,n_2,n_3)[\lambda_2+\lambda_3+\mu_1(1-P_c)] \\ = P_b(K,n_3,n_3-1)\lambda_3 + P_b(K,n_2-1,n_3)\lambda_2 + \\ P_b(K-1,n_2,n_3)\lambda_1 \\ 1 \le n_2 \le K-1 \,\&\, 1 \le n_3 \le K-1 \tag{51}$$

Similarly, Equations (52) to (54) present the packet number of n_2 is K, but the n_1 and n_3 are capable of receiving packets.

$$P_b(n_1,K,0)[\lambda_1+\lambda_3+\mu_1(1-P_c)] \\ = P_b(n_3,K-1,0)\lambda_2 + P_b(n_1-1,K,0)\lambda_1 \\ 1 \le n_1 \le K-1 \tag{52}$$

$$P_b(0,K,n_3)[\lambda_1+\lambda_3+\mu_2(1-P_c)] \\ = P_b(0,K,n_3-1)\lambda_3 + P_b(0,K-1,n_3)\lambda_2 \\ 1 \le n_3 \le K-1 \tag{53}$$

$$P_b(n_1,K,n_3)[\lambda_1+\lambda_3+\mu_1(1-P_c)] \\ = P_b(n_1,K,n_3-1)\lambda_3 + P_b(n_1,K-1,n_3)\lambda_2 + \\ P_b(n_1,K,n_3)\lambda_1 \\ 1 \le n_1 \le K-1 \,\&\, 1 \le n_3 \le K-1 \tag{54}$$

Equations (55) to (57) indicate that the packet number of n_3 is K, but the n_1 and n_1 are able to receive packets.

$$P_b(n_1,0,K)[\lambda_1+\lambda_2+\mu_1(1-P_c)] \\ = P_b(n_1,0,K-1)\lambda_3 + P_b(n_1-1,0,K)\lambda_1 \\ 1 \le n_1 \le K-1 \tag{55}$$

$$P_b(0,n_2,K)[\lambda_1+\lambda_2+\mu_2(1-P_c)] \\ = P_b(0,n_1,K-1)\lambda_3 + P_b(0,n_2-1,K)\lambda_2 \\ 1 \le n_2 \le K-1 \tag{56}$$

$$P_b(n_1,n_2,K)[\lambda_1+\lambda_2+\mu_1(1-P_c)] \\ = P_b(n_1,n_2,K-1)\lambda_3 + P_b(n_1,n_2-1,K)\lambda_2 + \\ P_b(n_1-1,n_2,K)\lambda_1 \\ 1 \le n_1 \le K-1 \,\&\, 1 \le n_2 \le K-1 \tag{57}$$

When the system access channel is successful, it enters to transmit stat and balance equations are listed on (58) to (68). If (n_1, n_2, n_3) has packets, the n_1 packets are firstly transmitted due to the preemptive priority. Thus, the packet number of n_1 is changed from K to K-1, as given on Equation (58).

$$\begin{gathered} P_t(K-1, n_2, n_3)\mu_1 = P_b(K, n_2, n_3)\mu_1(1-P_c) \\ 1 \le n_2 \le K \;\&\; 0 \le n_3 \le K \end{gathered} \tag{58}$$

Equation (59) represents that the n_1 packets are transffered out, the transmission is divided into two types since the packet number of n_1 is less than *K*. One type is that the n_1 packets are transffered from busy state, and the other is that are transffered from transmit state.

$$\begin{gathered} P_t(n_1, n_2, n_3)\mu_1 = P_b(n_1+1, n_2, n_3)\mu_1(1-P_c) \\ +P_t(n_1+1, n_2, n_3)\mu_1 \\ N-1 \le n_1 \le K-2 \;\&\; 0 \le n_2 \le K \;\&\; 0 \le n_3 \le K \\ 1 \le n_1 \le K-2 \;\&\; N \le n_2 \le K \;\&\; 0 \le n_3 \le K \\ 1 \le n_1 \le K-2 \;\&\; 0 \le n_2 \le N-1 \;\&\; N \le n_3 \le K \end{gathered} \tag{59}$$

Then, the packet number of n_1 is changed from 1 to 0, as presented on Equation (60).

$$\begin{gathered} P_t(0, K, n_3)\mu_2 = P_b(1, K, n_3)\mu_1(1-P_c) \\ +P_t(1, K, n_3)\mu_1 \\ 0 \le n_3 \le K \end{gathered} \tag{60}$$

Equations (61) and (62) can be classified into two categories: the μ_1 and μ_2. One is the system transmitting high priority n_1 packets, i.e. following from the μ_1 service rate. The other is transmitting n_1 packets because n_1 packets has transferred done, i.e. following from the μ_2.

$$\begin{gathered} P_t(0, n_2, n_3)\mu_2 = P_b(1, n_2, n_3)\mu_1(1-P_c) + \\ P_b(0, n_2+1, n_3)\mu_1(1-P_c) + P_t(1, n_2, n_3)\mu_1 + \\ P_t(0, n_2+1, n_3)\mu_2 \\ N \le n_2 \le K-1 \;\&\; 0 \le n_3 \le K \\ 1 \le n_1 \le K-2 \;\&\; N \le n_2 \le K \;\&\; 0 \le n_3 \le K \\ 1 \le n_2 \le N-1 \;\&\; N \le n_3 \le K \end{gathered} \tag{61}$$

$$\begin{gathered} P_t(0, N-1, n_3)\mu_2 = P_b(0, N, n_3)\mu_2(1-P_c) + \\ P_t(1, N-1, n_3)\mu_1 + P_t(0, N, n_3)\mu_2 \\ 0 \le n_3 \le N-1 \\ 1 \le n_2 \le N-1 \;\&\; N \le n_3 \le K \end{gathered} \tag{62}$$

When the packet nubmber of the n_1 and n_1 is zero, and the packet nubmber of the n_3 is *K*, this implies the n_1 and n_2 still have packets in the queues. Therefore, Equation (63) can be classified into two categories: the packets from the service rate of μ_1 or μ_2.

$$\begin{gathered} P_t(0,0,K)\mu_3 = P_b(1,0,K)\mu_1(1-P_c) + \\ P_b(0,1,K)\mu_2(1-P_c) + P_t(1,0,K)\mu_1 + \\ P_t(0,1,K)\mu_2 \\ 1 \le n_2 \le N-1 \;\&\; N \le n_3 \le K \end{gathered} \tag{63}$$

If the n_1 and n_2 packets have been finished transmission, then the n_3 packet is start to transmit. So Equations (64) and (65) are classified into three categories: the packets from μ_1, μ_2 or μ_3.

$$\begin{gathered} P_t(0,0,n_3)\mu_3 = P_b(1,0,n_3)\mu_1(1-P_c) + \\ P_b(0,1,n_3)\mu_2(1-P_c) + P_b(0,0,n_3+1)\mu_3(1-P_c) + \\ P_t(1,0,n_3)\mu_1 + P_t(0,1,n_3)\mu_2 + \\ P_t(0,0,n_3+1)\mu_3 \\ 1 \le n_3 \le K-1 \end{gathered} \tag{64}$$

$$\begin{gathered} P_t(0,0,N-1)\mu_3 = P_b(0,0,N)\mu_3(1-P_c) + \\ P_b(1,0,N-1)\mu_1 + P_t(0,1,N-1)\mu_2 + P_t(0,0,N)\mu_3 \end{gathered} \tag{65}$$

Since the packet number in n_1, n_2 or n_3 is less than a threshold value, i.e. *N*-2, this represents (n_1, n_2, n_3) packets are sent out from transmit state, as given Equations (66) to (68).

$$\begin{gathered} P_t(0,0,n_3)\mu_3 = P_t(1,0,n_3)\mu_1 + P_t(0,1,n_3)\mu_2 \\ +P_t(0,0,n_3+1)\mu_3 \\ 1 \le n_3 \le N-2 \end{gathered} \tag{66}$$

$$\begin{gathered} P_t(0,n_2,n_3)\mu_2 = P_t(1,n_2,n_3)\mu_1 \\ +P_t(0,n_2+1,n_3)\mu_2 \\ 1 \le n_2 \le N-2 \;\&\; 0 \le n_3 \le N-1 \end{gathered} \tag{67}$$

$$\begin{gathered} P_t(n_1,n_2,n_3)\mu_1 = P_t(n_1+1,n_2,n_3)\mu_1 \\ 1 \le n_1 \le N-2 \;\&\; 0 \le n_2 \le N-1 \;\&\; 0 \le n_3 \le N-1 \end{gathered} \tag{68}$$

3.5 Ps Probability

A Poisson distribution (69) can be utilized to calculate the $P_s(0,0,0)$, which represents that the probability of n_1, n_2 and n_3 has no packet transferred into system within a period *T*.

$$Poisson(x) = \frac{e^{-\lambda t}(\lambda t)^x}{x!} \tag{69}$$

This function indicates the probability of arriving *x* packets during a period *T*. For a sleep state, there has no packet arrived, i.e. *x*=0, during a period *T*, i.e. *t*=*T*. Therefore, the probabilities of no packet arriving for n_1, n_2 and n_3 are respectively given by

$$P_s = Poisson(0) = e^{-\lambda_1 T} \tag{70}$$

$$P_s = Poisson(0) = e^{-\lambda_2 T} \quad \textbf{(71)}$$

$$P_s = Poisson(0) = e^{-\lambda_3 T} \quad \textbf{(72)}$$

As presented on Equations (73) to (76), these can be happen during a period *T*.

The probability of none of the n_1, n_2 and n_3 packet arrived:

$$(e^{-\lambda_1 T})(e^{-\lambda_2 T})(e^{-\lambda_3 T}) \quad \textbf{(73)}$$

The probability of the n_1 packet arrived, but none of the n_2 and n_3 arrived:

$$(1-e^{-\lambda_1 T})(e^{-\lambda_2 T})(e^{-\lambda_3 T}) \quad \textbf{(74)}$$

The probability of the n_2 packet arrived, but none of n_1 and n_3 packet arrived:

$$(e^{-\lambda_1 T})(1-e^{-\lambda_2 T})(e^{-\lambda_3 T}) \quad \textbf{(75)}$$

The probability of the n_3 packet arrived, but none of the n_1 and n_2 packet arrived:

$$(e^{-\lambda_1 T})(e^{-\lambda_2 T})(1-e^{-\lambda_3 T}) \quad \textbf{(76)}$$

However, packets are not transmitted simultaneously, so *Y* will not happen.

$$\begin{aligned} Y = &(1-e^{-\lambda_1 T})(1-e^{-\lambda_2 T})(e^{-\lambda_3 T}) + (1-e^{-\lambda_1 T})(e^{-\lambda_2 T}) \\ &(1-e^{-\lambda_3 T}) - (e^{-\lambda_1 T})(1-e^{-\lambda_2 T})(1-e^{-\lambda_3 T}) - (1-e^{-\lambda_1 T}) \\ &(1-e^{-\lambda_2 T})(1-e^{-\lambda_3 T}) \end{aligned} \quad \textbf{(77)}$$

Since the summation of Equations (73) to (77) is 1, the probability can be obtained by 1-*Y*. Thus, the probability of n_1, n_2 and n_3 has no packet arrived can be obtained as

$$P_s(0,0,0) = \frac{e^{-\lambda_1 T} \times e^{-\lambda_2 T} \times e^{-\lambda_3 T}}{1-Y} \quad \textbf{(78)}$$

3.6 System Power Consumption Evaluation

According to Figure 4, the power consumption during a period of *T* can be derived as

$$\begin{aligned} F(N) = &C_{hold} L_N + \frac{C_{setup}}{T} + C_{sleep} P_s + C_{idle} P_i + \\ &C_{busy} P_b + C_{transmit} P_t \end{aligned} \quad \textbf{(79)}$$

where $L_N = L_{sleep} + L_{idle} + L_{busy} + L_{transmit}$

C_{hold} : the power consumption to hold one packt

C_{setup} : the power consumption to change from sleep to idle state

C_{sleep} : the power consumption at sleep state

C_{idle} : the power consumption at idle state

C_{busy} : the power consumption at busy state

$C_{transmit}$: the power consumption at transmit state

L_N : the expected value of the number of packets in the queue

L_{sleep} : the expect value of the number of pacakets at sleep state, $L_{sleep} = 0$

L_{idle} : the expect value of the number of pacakets at idle state

L_{busy} : the expect value of the number of pacakets at busy state

$L_{transmit}$: the expect value of the number of pacakets at transmit state

3.7 Packet Delay Evaluation

A packet delay time is defined as the time required for the packet arriving at a sensor node until the packet is sent out. There are three types of delay based on different priority of n_1, n_2 and n_3 packets.

In idle state, the expected value of the n_1 packet delay can be obtained by P_i minus the probability of n_2 and n_3 having packets, as represented on Equation (81). The calculation of busy state is the same as idle state, so the expected value of the n_1 packet delay in busy state is given on Equation (82). Lastly, Equation (83) is the expected value of the n_1 packet delay in transmit state, the n_1 packet delay only requires one-third of time to finish the transfer due to its highest priority.

$$(P_i - P_i[n_2] - P_i[n_3] - P_i[n_2+n_3]) \times T \quad \textbf{(81)}$$

$$(P_b - P_b[n_2] - P_b[n_3] - P_b[n_2+n_3]) \times T \quad \textbf{(82)}$$

$$\frac{(P_b - P_b[n_2] - P_b[n_3] - P_b[n_2+n_3])}{3} \times T \quad \textbf{(83)}$$

The calculation of the n_2 packet delay is the same as n_1. But in transmit state, the n_2 packet delay needs two-third of time to finish the transfer, since the packet in q_2 has to wait until the packet in q_1 has been transferred. If there is only q_2 has packet or q_1 has no packet, it only needs one-third of time.

$$(P_i - P_i[n_1] - P_i[n_3] - P_i[n_1+n_3]) \times T \quad \textbf{(84)}$$

$$(P_b - P_b[n_1] - P_b[n_3] - P_b[n_1+n_3]) \times T \quad \textbf{(85)}$$

$$\left(\frac{(P_t[n_1+n_2] + P_t[n_1+n_2+n_3])}{3} \times 2 + \frac{(P_t[n_2] + P_t[n_2+n_3])}{3} \right) \times T \quad \textbf{(86)}$$

The calculation of the n_3 packet delay is the same as

n_1. However, packets have various priorities. In transmit state, the packet in q_3 has to wait until the packets in q_1 and q_2 have been transferred, so the q_3 has the longest packet delay.

$$(P_i - P_i[n_1] - P_i[n_2] - P_i[n_1+n_3]) \times T \quad \textbf{(87)}$$

$$(P_b - P_b[n_1] - P_b[n_2] - P_b[n_1+n_2]) \times T \quad \textbf{(88)}$$

$$(P_t[n_1+n_2+n_3]\frac{P_t[n_3]}{3} + \frac{(P_t[n_1+n_3]+P_t[n_2+n_3])}{3} \times 2) \times T \quad \textbf{(89)}$$

As a result, the packet delay can be obtain by adding up the time of packets stayed in idle state, busy state and transmit state. The n_1 packet delay is summation of Equations (81) to (83). Similary, the n_2 packet delay is summation of Equations (84) to (86). Finally, the n_3 packet delay is summation of Equations (87) to (89).

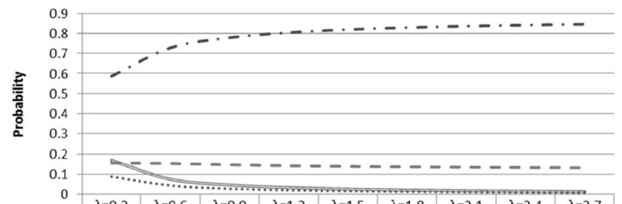
4 Experimental Results

The Equation (79) reveals the power consumption is related to the system transition at each state. In order to verify the performance, the parameters of λ, μ, P_c, N and K are varied to observe the impact on state probabilities of P_s, P_i, P_b and P_t. The experiments are conducted on Matlab platform.

4.1 The Variation of Arrival Rate

To estimate the effect of state probability P_s, P_i, P_b and P_t, the λ is varied from 0.3 to 2.7 with a step of 0.3 in corresponding to $\mu = 0.3$, $P_c = 0.1$, $N = 2$ and $K = 3$.

As charted in Figure 8, it is clear that when λ is increased, the system has higher probability to accept packets. The system becomes easier to wake up, so the probability of sleep state (P_s) is relatively small. The system stays shorter at idle state (P_i) due to higher λ, resulting in rapidly changing to the busy state. According to higher arrive rate of packets, the packet transmission time becomes longer and leads to the system stays shorter at busy state (P_b). On the other side, the gap between λ and μ has become bigger when λ becomes larger but μ is fixed. The system switches quickly to the transmit state, and stays at transmit state (P_t) longer.



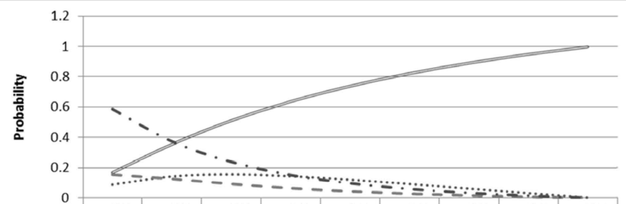
	λ=0.3	λ=0.6	λ=0.9	λ=1.2	λ=1.5	λ=1.8	λ=2.1	λ=2.4	λ=2.7
Ps	0.16879	0.07463	0.04625	0.03314	0.02570	0.02095	0.01766	0.01525	0.01341
Pi	0.08834	0.04348	0.02778	0.02017	0.01577	0.01291	0.01092	0.00945	0.00833
Pb	0.15589	0.15347	0.14705	0.14241	0.13913	0.13672	0.13490	0.13346	0.13231
Pt	0.58699	0.72841	0.77893	0.80427	0.81940	0.82942	0.83653	0.84184	0.84594

Figure 8. The variation of λ at different state probabilities

4.2 The Variation of Service Rate

To examine the impact of state probability P_s, P_i, P_b and P_t, the μ is changed from 0.3 to 2.7 with a step of 0.3 in corresponding to $\lambda = 0.3$, $P_c = 0.1$, $N = 2$ and $K = 3$.

As plotted in Figure 9, the packets in the queue are immediately transferred out due to an increased service rate. The system quickly leaves the transmit state, and the P_t becomes small. Thus, the system has higher probability to enter into sleep state, resulting in higher P_s. Besides, since the λ is gradually less than μ, and the space between them becomes larger. This implies that the packet transfer rate is faster related to receive rate, so the P_i becomes lower. Similarly, the larger μ induces the system stays at busy state time is shorter, and therefore P_b is reduced.



	μ=0.3	μ=0.6	μ=0.9	μ=1.2	μ=1.5	μ=1.8	μ=2.1	μ=2.4	μ=2.7
Ps	0.16879	0.35484	0.51127	0.63729	0.73895	0.82196	0.89073	0.94847	0.99757
Pi	0.08834	0.14414	0.15733	0.14554	0.12146	0.09214	0.06128	0.03077	0.00153
Pb	0.15589	0.12718	0.09255	0.06421	0.04287	0.02710	0.01545	0.00679	0.00030
Pt	0.58699	0.37384	0.23886	0.15297	0.09673	0.05880	0.03254	0.01397	0.00061

Figure 9. The variation of μ at different state probabilities

4.3 The Variation of Collision Probability

To investigate the influence of state probability P_s, P_i, P_b and P_t, the P_c is altered from 0.1 to 0.9 with a step of 0.1 in corresponding to $\lambda = 0.3$, $\mu = 0.3$, $N = 2$ and $K = 3$.

The P_b is affected directly by the variation of P_c, as charted in Figure 10. When collision happens, the system stays at busy state and attempts to access channel. This causes an increase of P_b. The rest of P_s, P_i and P_t are relatively reduced, since the P_b is continuously increased.

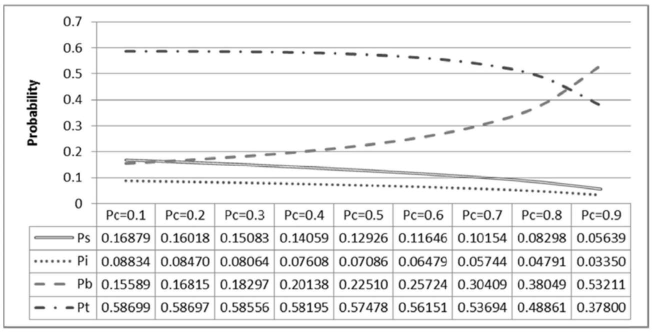


Figure 10. The variation of P_c at different state probabilities

4.4 The Variation of Queue Threshold

To evaluate the effectiveness of state probability P_s, P_i, P_b and P_t, the N is varied from 2 to 4 with a step of 1 in corresponding to $\lambda = 0.3$, $\mu = 0.3$, $P_c = 0.1$ and $K = 5$.

The queue is allowed to accept more packets at idle stat due to an increased N, therefore the P_i is raised, as plotted in Figure 11. The gap between N and K becomes smaller, then the number of packets can be received at busy state is limited. This results in the time of staying at P_b is reduced. However, the higher N indicates that more packet in the queue needs to be tranferred, that is to say, more time is required to stay at transmit state. Consequently, the P_t is raised, but the system stays shorter at P_s.

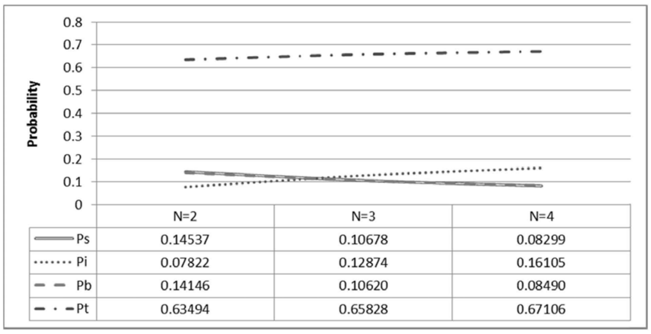


Figure 11. The variation of N at different state probabilities

4.5 The Relation Between Queue Threshold and Power Consumption

To achieve low power consumption, the N is changed from 2 to 4 with a step of 1 in corresponding to $\lambda = 0.3$, $\mu = 0.3$, $P_c = 0.1$, $K = 5$, $C_{hold} = 5$, $C_{setup} = 300$, $C_{sleep} = 1$, $C_{idle} = 50$, $C_{busy} = 500$ and $C_{transmit} = 500$.

Presented in Figure 12 is a plot of the power consumption versus the threshold N over the range between 2 and 4. The result demonstrates that the system has the lowest power when the N is set to 4. Therefore, this optimal N can be used to extend the operational lifetime of sensor node.

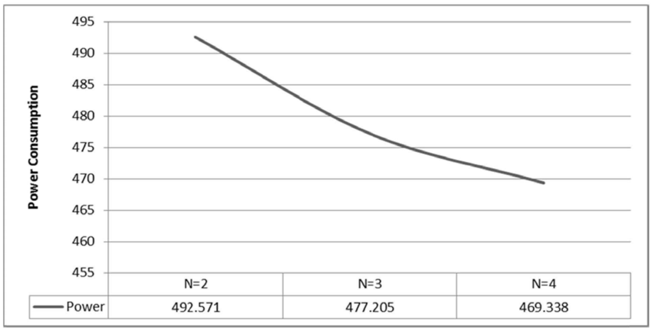


Figure 12. The relation between N and power consumption

4.6 The Relation Between Queue Threshold and Delay Time

To observe the delay time effect, the N is changed from 2 to 4 with a step of 1 in corresponding to $\lambda = 0.3$, $\mu = 0.3$, $P_c = 0.1$ and $K = 5$.

Figure 13 is the delay of three different priority packets stay at sensor node. It is obviously that the high priority packet n_1 has the lowest delay. In contract, the low priority packet n_3 has the highest delay because it has to wait until n_1 and n_2 packets have been transmitted.

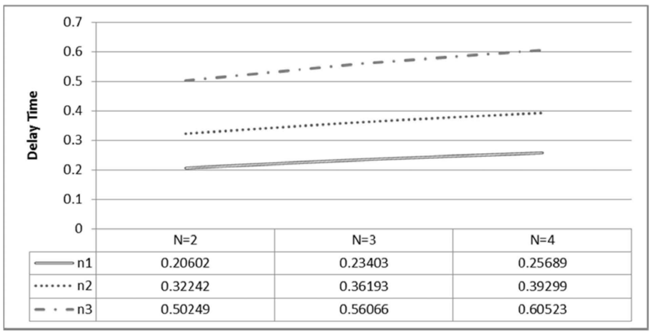
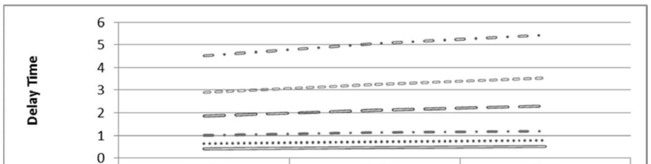


Figure 13. The relation between N and delay time

Presented in Figure 14 is the delay when a packet transferred between three and ten sensor nodes. The delay is related to the value of N, so the higher value of N has the longer packet delay. Additionally, the delay gap becomes bigger when the transfer frequency is raised.



	N=2	N=3	N=4
n1_3	0.41205	0.46805	0.51378
n2_3	0.64483	0.72386	0.78599
n3_3	1.00498	1.12132	1.21045
n1_10	1.85421	2.10624	2.31199
n2_10	2.90174	3.25736	3.53694
n3_10	4.52239	5.04595	5.44704

Figure 14. The delay time of numerous sensor nodes

5 Conclusion

This paper presents a mutiple priority queue to ensure a shorter time delay for urgent and high priority data packet transmission. A threshold N is employed in a queue to reduce the collision probability. In addition, a sleep mode is used for the lifetime extension of sensor nodes. By doing so, the EHP can be eased, and the system performance can be improved significantly as well. Besides, the state transition diagram and balanced equations are presented to calculate the probabilities of the sleep, idle, busy and transmit states. The power consumption is minimized with respect to the threshold N, and the advantage of fast packet transmission is seen when there are data in a high priority queue. Therefore, this system can be applied to real-time data delivery, and can meet the energy efficiency requirement for WSN design.

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