doi:10.3772/j. issn. 1006-6748. 2021. 04. 007

Performance analysis of blockchain for civil aviation business data based on M/G/1 queuing theory①

Liu Yiwei (刘逸玮)*, Zhang Yanhua* **, Yang Ruizhe② * **, Gao Yuan***, Zhang Xuanyi***

(* Faculty of Information Technology, Beijing University of Technology, Beijing 100124, P. R. China)

(** Beijing Laboratory of Advanced Information Networks, Beijing University of Technology, Beijing 100124, P. R. China)

(*** Beijing Capital International Airport Co. Ltd, Beijing 100621, P. R. China)

Abstract

An Ethereum blockchain based on proof of stake (PoS) consensus mechanism is used to achieve the data sharing within the civil aviation service platform for both airport group management and passengers. Considering the Gas consumption of Ethereum, the dynamic batch-service capacity constraint by the Block Gas Limit and the priority mechanism depending on the different Gas Price of transactions, M/G/1 queuing theory with batch-service is used to construct the service model of transactions confirmation process in the proposed blockchain system, where the effects of transactions arrival rate, block capacity, service rate and number of nodes on the average confirmation time of transactions with different priority are analyzed, and eventually a performance analysis model of blockchain for civil aviation business data is proposed. The simulation results prove the usability and accuracy of the model, which can provide both theoretical basis for data sharing of civil aviation using Ethereum blockchain and the further optimization of transactions confirmation time.

Key words: blockchain, Ethereum, proof of stake (PoS) consensus mechanism, M/G/1 queuing theory, priority

0 Introduction

In recent years, with the expansion of the airport, the number of passengers has been sharply increasing, which set a higher request for the informatization ability of civil aviation. Constructing airport groups has become the key to promote the airport data sharing.

Blockchain technologies create a decentralized, trustless, transparent and tamper-proof environment for building applications in various areas, which meets the demand of the data sharing within airport groups[1]. In the weak-trust environment of blockchain system, nodes are allowed to join and exit freely without central authority, which establishes a trust mechanism to ensure the openness, transparence, traceability and unforgeability through the distributed storage, consensus mechanism, point-to-point (P2P) communication, encryption algorithm and other technologies.

Bitcoin, which is the first blockchain that gets attention has solved the double spending of electronic currency. Inspired by Bitcoin and Ethereum, a platform with mature turing-complete programming language proposed in 2013 allows users to write their own smart contracts, which leads the progress from centralized control to decentralized control[2].

Based on the technical feature of blockchain and the urgent need of civil aviation data sharing, Society International De Telecommunicatioan Aero-nautiques (SITA) took the lead in proposing the concept of intelligent access with blockchain technology in 2016, and jointly launched a pilot project called Flight-Chain with British Airways, London Heathrow Airport, Geneva Airport and Miami Airport to realize data sharing. At the same time, Dnata, an aviation and travel service provider in the Middle East, cooperated with IBM and other companies to carry out the blockchain technology in air pilot projects. Air France explored the use of blockchain to track aircraft maintenance workflow. Russian S7 Airlines proposed to use blockchain technology to solve the ticket problem. Dubai Airport planned to combine biometric verification with blockchain to achieve passport-free service. In 2018, the

① Supported by the Open Foundation of Key Laboratory of Airports Cluster Intelligent Operation (No. KLACIO201900006124), National Natural Science Foundation of China (No. 61901011), Foundation of Beijing Municipal Commission of Education (No. KM202010005017, KM202110005021) and Beijing Natural Science Foundation (No. L192002).

② To whom correspondence should be addressed. E-mail: yangruizhe@bjut.edu.cn

Received on Oct. 12, 2020

world's first aviation ecological blockchain application project called Airline and Life Networking Token came into being. International Air Transport Association (IATA), Google and other partners jointly announced the Known Passenger Digital Identity Concept based on blockchain, and planned to launch a pilot project of concept verification between Canada and the Netherlands. Brussels Airport launched an application based on blockchain to track the movement of goods from the process on the ground to freight agent. Singapore Airlines, together with KPMG and Microsoft, applied blockchain to the digital wallet of its frequent passenger program KrisFlyer[3].

The airport group in China is under construction, and solutions of data sharing within airlines and airports have been proposed. However, most of the airport data is still stored independently, which leads to the lack of information interaction within airports. To the issues discussed above, the blockchain for civil aviation business data based on Ethereum is proposed. It uses smart contracts to develop a data sharing platform for both airports and passengers, which provides a variety of business applications, including self-service check-in, flight query, luggage traceability and E-commerce. The authenticity and unforgeability are ensured by packing the data to the blockchain.

Different from the fixed block size of blockchain for Bitcoin, a dynamic adjustment mechanism called Block Gas Limit is introduced by Ethereum, that is, the Block Gas Limit can be adjusted according to the transaction number to control the transaction throughput. At present, as for the analysis of theoretical model for blockchain, Refs[4-6] used M/G/1 queuing theory to model the confirmation process of Bitcoin, and established the joint distribution of transaction quantity and service time in the queue, and discussed the influence of transactions arrival rate and block capacity on transactions confirmation time. Ref. [7] proposed a random batch-service process including block generation and blockchain construction which improved the queueing model of Ref. [5]. By solving GI/M/1 continuous Markov process, the number of transactions in the queue, the number of transactions in blocks and the average transactions confirmation time were obtained[7-8]. Ref. [9] proposed a framework consisting of machine learning and queuing theory to identify which transaction will be confirmed in the block. Ref. [10] simulated the mining process of Bitcoin system by using queuing theory. Refs[11-12] established a game theory model for the transaction priority mechanism formed by Bitcoin transaction fee, and analyzed the decision-making of the specified transaction cost of users. Ref. [13] proposed a mathematical model to analyze the evolution of block arrival and mining difficulty with time. The work above mainly focused on the Bitcoin transactions confirmation process, while there were few work about the performance analysis of Ethereum blockchain based on proof of stake (PoS) consensus mechanism, especially the impact of dynamic adjustment of Gas.

This paper takes Ethereum as the platform and adopts PoS consensus mechanism to build a blockchain for civil aviation business data to promote data sharing between internal information of airport group and service platform for users. Considering the constraint of Block Gas Limit and Gas consumption of transactions, the transactions confirmation process is modeled as a batch-service M/G/1 queueing system with a variable threshold. The number of transactions in the transaction pool at the moment before the current block has been generated is analyzed as a discrete-time Markov chain. Transactions are given different priority according to their Gas Price, and the average confirmation time of transactions with different priority is quantitatively described. Combined with the requirements of the platform for airport groups, the comparison of average confirmation time of transactions with high and low priority in blockchain is given by the simulation, which confirms the availability of the theoretical model for adjusting the parameters of Ethereum blockchain to optimize the transactions confirmation time.

1 System model

1.1 Working principle of blockchain for civil aviation business data

As shown in Fig. 1, the blockchain for civil aviation business data takes each airport as a node to record the passengers' behavior. Each passenger in the airport groups can be regarded as a light node which can record consumption, trips and inquire travel information, such as flight and luggage.

As shown in Fig. 2, the civil aviation business data in blockchain mainly consists of the following two parts. The first part is the information of civil aviation airport groups, including flight, route, luggage, etc., which is provided by the internal operation platform of each airport group, and uploaded to the blockchain periodically. The second part is the information of passengers which records the process of passengers using DAPP to initiate and inquire transactions. A distinct transaction ID will be generated after a transaction has been initiated. The date, location, longitude and latitude coordinates of the transaction can be automatically uploaded to the corresponding airport node. Self-service check-in, flight inquiry, baggage tracking and air E-commerce are included in the main functions of DAPP. On the one hand, the server of the blockchain system provides an interface for data inquiry operation. Passengers can obtain their own related information from the blockchain through DAPP, including the flight information and baggage transportation process. On the other hand, passengers can buy or book the products sold by each airport in the air E-commerce before boarding.

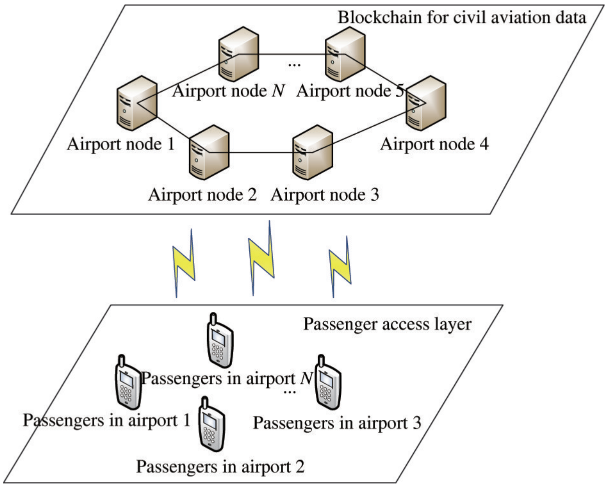

Fig. 1 System architecture of the blockchain for civil aviation business data

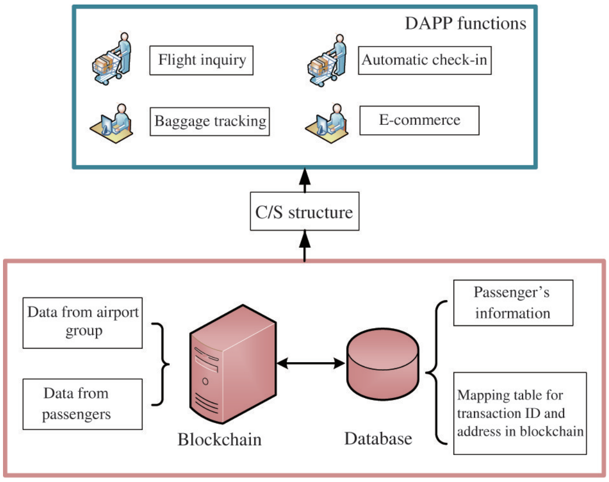

Fig. 2 System layers of the blockchain for civil aviation business data

1.2 Queueing model of blockchain system

1.2.1 Analysis of transaction arriving and service process

When an airport node n (miner node) receives the latest transactions submitted by local or broadcasted by other nodes, it will cache the transactions in its transaction pool, sort and verify the transactions according to the priority mechanism. Once the key Nonce is provided (the difficulty of finding a Nonce is related to the currency age of the node), the node obtains the right to record the ledger of the current block, and then takes B eligible transactions from its transaction pool that have been sorted and verified according to the priority mechanism to form the current block and then broadcast it in the blockchain system. After verifying the block, each node will peg it to its local blockchain. When other nodes find the Nonce before node n, node n will no longer compete for finding the current Nonce, but peg the block to its blockchain as the right of keeping the ledger has been obtained by other nodes, and then continue to compete for the right of keeping the ledger of the next block.

Based on the analysis above, this paper supposes that the process of transactions arriving at the transaction pool of any node follows the Poisson distribution with arrival rate λ. At time t, the number of transactions arriving at the transaction pool is b with the probability as

$$P_b(b = x;\ t) = \frac{(\lambda t)^x e^{-\lambda t}}{x!} \tag{1}$$

Based on the relationship between the right of recording the ledger, the currency age accumulation and clearing mechanism in PoS, it is assumed that the Nonce computation time n of each node is an independent distributed random variable (In the practical application of blockchain for civil aviation business data, each airport node has different computing power), so each node has Nonce calculation time of different random distribution parameters. In order to emphasize the impact of the number of nodes on the block generation time, each node is simplified to follow the distribution function $F_{S_n}(x)$, then the average Nonce generation time $E[S_n]$ of each node can be denoted as

$$E[S_n] = \int_0^{\infty} x \mathrm{d}F_{S_n}(x) = \frac{1}{\mu_n} \tag{2}$$

Therefore, the process of each node dealing with transactions in the blockchain can be regarded as a batch-service M/G/1 queuing system with threshold B. During the time interval from a node packing transactions into a block to the node obtaining the right of keeping the ledger to confirm the block, the new transactions arriving at the node will all remain in the transaction pool rather than enter the current block, even if the number of transactions in the current block does not exceed the block capacity, that is, the new transactions can only be served within the next block generation time of the node, which can be described as Fig. 3.

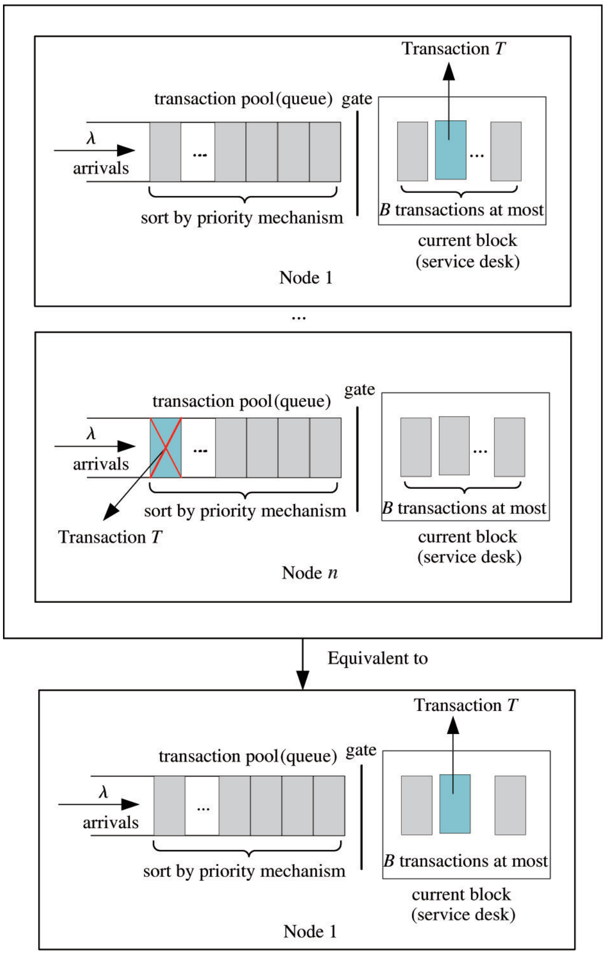

Fig. 3 A batch-service M/G/1 queuing system with threshold B

It is important to note that there is time delay in the blockchain system, and the mining computing power and the ability of packing blocks of each node are different, which will lead to the time difference of transactions broadcasted to different nodes, and the difference of the order of each node in the transaction pool at the same time. Therefore, as for a specific transaction T_r^*, it may be in the transaction pool of node A, or has entered the block packed by node B at a certain time. And at the next tick, node B may successfully obtain the right of keeping the ledger, which makes transaction T_r^* enter the blockchain and be cleared by the transaction pool of node A, or node B does not obtain the right to record the ledger so transaction T_r^* will still remain in the transaction pool of each node. This paper will analyze the service process of transactions in the whole blockchain system from the perspective of random statistical analysis rather than pay special attention to a specific process at a certain node.

Therefore, the whole blockchain system can be regarded as a batch-service M/G/1 queuing system with threshold B. Since the block generation time $S_n (n = 1, 2, 3, \cdots)$ of each node has been supposed as a independent distributed random variable following the distribution function $F_{S_n}(x)$, the distribution characteristic $F_{\overline{S_n}}$ of the average block generation time $\overline{S_n}$ and the average block confirmation time $E[\overline{S_n}]$ can be denoted as

$$F_{\overline{S_n}}(x) = 1 - \prod_{n=1}^{N} (1 - F_{S_n}(x))$$
$$E[\overline{S_n}] = \int_0^{\infty} x \mathrm{d}F_{\overline{S_n}}(x) = \frac{1}{\mu} \tag{3}$$

where N is the number of nodes mining at the same time.

1.2.2 Priority mechanism of transactions

In Ethereum, unlike the blockchain which pays Bitcoin as transaction fee, Ethereum uses Gas as the transaction fee to pay the computation and network resources consumed by nodes in processing transactions. Gas takes the Gas Limit as the maximum amount to be paid, and the Gas Price is the unit price of Gas. From the perspective of maximizing revenue, nodes will give priority to packing transactions with higher Gas Price. Therefore, nodes need to assign different priority to transactions in the transaction pool according to their Gas Price. This paper assumes that nodes divide the priority of the transactions in the transaction pool into H levels, where $g^{\to} = \{g^{\to 1}, g^{\to 2}, \cdots, g^{\to h}, \cdots, g^{\to H}, g^{\to H+1}\}$, and $g^{\to 1} = \infty$, $g^{\to H+1} = 0$, $\infty \geq g^{\to h} > g^{\to h+1} \geq 0$, $h \in [0, H]$. The priority of transactions with Gas Price g_f is h in the transaction pool only if $g^{\to 1} > g_f \geq g^{\to h+1}$. Transactions with priority h are non-preemptive to those with priority e when $e > h$. Transactions whose Gas Price has not been paid have the minimum priority H. Transactions with the same priority follow the first-come-first-served rule.

1.2.3 Maximum block capacity

Ethereum adopts a dynamic adjustment mechanism based on the Block Gas Limit, which is the maximum Gas sum of all transactions in a block. Therefore, the throughput of Ethereum can be calculated as

$$R = \frac{B}{\overline{S_n}} \tag{4}$$

where $\overline{S_n}$ is the block confirmation time, and a block contains B transactions. B is a dynamic variable according to the Block Gas Limit and Gas consumption of the current transactions. To simplify the analysis, it is assumed that B follows the distribution.

$$P_B(B = i) = P_B(i),\ i = 0, 1, 2, 3 \cdots, N \tag{5}$$

2 Average transactions confirmation time

2.1 Queueing model of blockchain system

Let L_k denote the number of transactions in the transaction pool before the kth block has been generated. Let R_k denote the number of transactions remaining in the transaction pool after the kth block with a group of transactions has been pegged to the blockchain, A_k is the number of new transactions arriving at the transaction pool within the time interval between the generation of the kth block and the $(k+1)$th block. The service intensity of the queuing system can be caculated as $\rho = \frac{\lambda}{\bar{\mu}} \cdot \gamma$. Since the block capacity is B, R_k can be expressed as

$$R_k = \begin{cases} L_k - B & L_k \geq B \\ 0 & L_k < B \end{cases} = L_k - N_B(L_k) \tag{6}$$

and N_B can be considered as $N_B(x) = \begin{cases} B & x \geq B \\ x & x < B \end{cases}$, so the transactions number L_{k+1} in the transaction pool before the generation of the $(k+1)$th block is given by

$$L_{k+1} = L_k - N_B(L_k) + A_k \tag{7}$$

Let $\{A_k\}$ denote a series of independent and identically distributed (i. i. d) random variables which follow the distribution as

$$P_{A_k}(n) = P_{A_k}(A_k = n) = \int_0^\infty P_b(b = n;\ t)\,\mathrm{d}F_{\bar{S}}(t) = \int_0^\infty e^{-\lambda t}\frac{(\lambda t)^x}{x!}\mathrm{d}F_{\bar{S}}(t) \tag{8}$$

$\{L_k: k = 1,2,\cdots\}$ and $\{A_k: k = 1,2,\cdots\}$ are mutually independent, it can be seen from Eq. (8) that $\{L_k: k = 1,2,\cdots\}$ is a discrete time Markov chain with transition probability as

$$\begin{aligned} p_{ij} &= P_r(L_{k+1} = j \mid L_k = i) \\ &= P_r(L_{k+1} = L_k - N_B(L_k) + A_k = j \mid L_k = i) \\ &\overset{N\to\infty}{=} \sum_{d=0} P_{A_k}(A_k = j - i + N_B(i))P_B(B = d) \end{aligned} \tag{9}$$

and p_{ij} can be caculated as

$$p_{ij} = \begin{cases} P_{A_k}(0)P_B(i-j) + P_{A_k}(1)P_B(i-j-1) + \cdots + \\ \quad P_{A_k}(j-1)P_B(i-1) + P_{A_k}(j)\sum_{d=i}^{\infty} P_B(d)\ (j \leq i) \\ P_{A_k}(i-j)P_B(0) + P_{A_k}(i-j-1)P_B(1) + \cdots + \\ \quad P_{A_k}(j-1)P_B(i-1) + P_{A_k}(j)\sum_{d=i}^{\infty} P_B(d)\ (j > i) \end{cases} \tag{10}$$

The Markov property of $\{L_k: k = 1,2,\cdots\}$ is determined by the transition probability matrix $\{p_{ij}\}$. It is easy to know that $\{L_k: k = 1,2,\cdots\}$ is a periodically irreducible[11]. According to Markov process, when $\{L_k: k = 1,2,\cdots\}$ is normal return, there exists a stationary distribution $\{p_{ij}\}$ satisfying

$$\sum\nolimits_{i=0}^{\infty} \pi_i p_{ij} = \pi_j (j = 0,1,2,\cdots) \tag{11}$$

Generating function is used to solve the Eq. (9). Let $\boldsymbol{\pi} = (\pi_0, \pi_1, \pi_2, \cdots)$, $\boldsymbol{Z} = (z^0, z^1, z^2, \cdots)$, $\pi(z) = \sum\nolimits_{i=0}^{\infty} \pi_i z^i$, $A(z) = \sum\nolimits_{i=0}^{\infty} P_{A_k}(i) z^i$, $P(z) = \sum\nolimits_{i=0}^{\infty} P_B(i) z^i$. If both sides of Eq. (9) are multiplied by $\boldsymbol{Z}^{\mathrm{T}}$, then

$$\boldsymbol{\pi} \cdot P(z) \cdot \boldsymbol{Z}^{\mathrm{T}} = \begin{pmatrix} \pi_0 \\ \pi_1 \\ \vdots \end{pmatrix} \cdot \begin{pmatrix} \sum_{d=0}^{\infty} P_B(d) & 0 & 0 & \cdots & \cdots & \cdots \\ \sum_{d=1}^{\infty} P_B(d) & 0 & 0 & \cdots & \cdots & \cdots \\ P_B(N) & P_B(N-1) & \cdots & P_B(0) & 0 & \cdots \\ 0 & P_B(d) & P_B(N-1) & \cdots & P_B(0) & \cdots \end{pmatrix} \cdot \begin{pmatrix} z^0 \\ z^1 \\ z^2 \\ \vdots \end{pmatrix} \cdot \boldsymbol{A}(z) = \boldsymbol{\pi}(z) \tag{12}$$

can simplified as [14]

$$\boldsymbol{\pi}(z) = \frac{A(z)\sum_{i=0}^{N-1}\sum_{j=0}^{N-1} P_B(i+j)(z^N - z^{N-j})\boldsymbol{\pi}_i}{z^N - P(z) \cdot A(z)} \tag{13}$$

When $\rho < 1$, the system reaches a steady state. The average transaction number $E[L]$ in the transaction pool at that time can be expressed as

$$E[L] = \gamma\rho + \frac{\gamma^2\rho^2 - 2\gamma^2\rho + \gamma\rho + \gamma^2 + \sigma_B^2 + \lambda^2\sigma_{\bar{S}}^2 - \sum_{i=0}^{N-1}\sum_{j=0}^{N-1} P_B(i+j)j^2\pi_i}{2\gamma(1-\rho)} \tag{14}$$

According to Little Theorem, the average waiting time $E[W]$ of transactions in the transaction pool is

$$E[W] = \frac{E[L]}{\lambda} \tag{15}$$

Let $\sigma_{\bar{S}}^2$ denote the variance of service time, and σ_B^2 denote the variance of service capacity. The average transactions confirmation time can be expressed as

$$E_\lambda[T] = E[W] + E[\overline{S_n}] = \gamma\frac{\rho}{\lambda} + \frac{\gamma^2\rho^2 - 2\gamma^2\rho + \gamma\rho + \gamma^2 + \sigma_B^2 + \lambda^2\sigma_{\bar{S}}^2 - \sum_{i=0}^{N-1}\sum_{j=0}^{N-1} p_{i+j}j^2\pi_i}{2\gamma\lambda(1-\rho)} + \frac{1}{\bar{\mu}} \tag{16}$$

The notations used in this section are listed in Table 1.

2.2 Queueing model of blockchain system

According to the above-mentioned H transaction priority level, let $1 < m < H$, transactions with m level priority are non-preemptive to those with $m + \Delta(\Delta > 0)$ level priority. Let the arrival rate of transactions with m level priority be λ_m, $\overline{\lambda_m}$ can be denoted as[15-16]

$$\overline{\lambda_m} = \sum_{h=1}^{m} \lambda_h \quad (17)$$

$E_{\lambda_m}^{m}[T]$ can be denoted as the average confirmation time of transactions with m level priority. When $m = 1$, the average transactions confirmation time is the same as those without considering priority, which can be denoted as $E_{\lambda_1}^{1}[T] = E_{\lambda=\lambda_1}[T]$. Any transactions with $(m + \Delta)$ level priority can not affect their confirmation process, then $E'_{\overline{\lambda_m}}[T]$ can be denoted as

$$E'_{\overline{\lambda_m}}[T] = \sum_{h=1}^{m} \frac{\lambda_h}{\overline{\lambda_m}} E_{\lambda_h}[T] = \sum_{h=1}^{m-1} \frac{\lambda_h}{\overline{\lambda_m}} E_{\lambda_h}[T] + \frac{\lambda_m}{\overline{\lambda_m}} E_{\lambda_m}[T] \quad (18)$$

and the average confirmation time of transactions with m level priority can be given by

$$E_{\lambda_m}^{m}[T] = \frac{1}{\lambda_m}\left(\overline{\lambda_m} E'_{\overline{\lambda_m}}[T] - \sum_{h=1}^{m-1} \lambda_h E_{\lambda_h}[T]\right) \quad m \geqslant 2 \quad (19)$$

Table 1 Notations

Parameter	Value
λ	Arrival rate
B	Maximum capacity of a block
$\bar{\mu}$	Average service rate
N	Number of nodes
L_k	Number of transactions in pool before the kth block
R_k	Number of transactions in pool after the kth block being pegged
A_k	Number of new transactions between the generation of block k and block $k+1$
ρ	Service intensity
$\{p_{ij}\}$	Transition probability matrix
$E[L]$	Average transaction number
$E[W]$	Average waiting time
$E[T]$	Average transactions confirmation time

3 Simulation results and discussion

Under the environment of Python 3.7, Monte-Carlo method is used to simulate the average transactions confirmation time. The effect of transactions arrival rate λ, service rate $\bar{\mu}$, ratio η of high and low transactions arrival rate and number of nodes N on the average transactions confirmation time with different priority are discussed in this section. To simplify the analysis, $P_B(B = i)$ is approximated to Poisson distribution, and $\lambda_B \gg 0$. M is approximated to satisfy the distribution $P_B(B = M, M > \lambda_B) = 0.01$, and Gas Limit of each transaction is approximated to a exponential distribution variable with the average value $G_L(\lambda_B)^{-1}$. The service rate of each node is supposed to follow Gaussian distribution with variance 0.001. Considering the actual demands of airport group passengers, it is obvious that passengers have the most urgent need to inquire the flight and luggage information related to themselves in the blockchain through DAPP, so the priority of related transactions is higher; while the purchase frequency in DAPP is not so high, so the priority of related transactions is lower. Stated thus, the priority of transactions can be divided into high and low levels and given different Gas Price. The arrival rate of transactions with high and low priority are λ_H and λ_L respectively and $\eta = \frac{\lambda_H}{\lambda_L}$. It can be inferred that $\lambda_H = \frac{\eta\lambda}{1+\eta}$, $\lambda_L = \frac{\lambda}{1+\eta}$, where λ is total of the arrival rate of transactions with both high and low priority. Set the total simulation time to 1000 s. The simulation results are compared with the theoretical analysis to verify the accuracy of the proposed model.

The configuration of the experiment is Intel (R) core (TM) i5-6200u CPU @ 2.30 GHz (8 CPUs), 8 GB ram, Windows 10 professional 64 bit. In order to ensure the stable operation of the simulation, $\rho < 1$ is taken. The related parameters and values involved in the experiment are shown in Table 2.

Table 2 Setting of simulation parameter

Parameter name	Value
λ	1.0 – 7.0
λ_B	100 – 300
$\bar{\mu}$	0.01 – 0.1
η	0.1 – 0.9
λ_H	1.0 – 6.0
λ_L	1.0 – 6.0
N	20 – 1000

Fig. 4 shows the average confirmation time of transactions with high and low priority under different transactions arrival rate λ ($\lambda_B = 200$, $\mu_S = 0.00042$, $\eta = 0.8$, $N = 150$). It is obvious that the difference between the simulation results and the theoretical analysis is small, and the relationship between transactions arrival rate and average transactions confirmation time can be linear. With the increase of the transactions arrival rate, the difference of the average confirmation time between transactions with high priority and low priority increases gradually. The reason is that when the transactions arrival rate is low, the number of transactions remaining in the transaction pool and the times of the block packing transactions are less, and transactions with high and low priority are more likely to be processed in the same block. When the arrival rate increases to a certain extent, the number of transactions remaining in the transaction pool increases, subsequently transactions with high priority will be earlier packed into the current block and those with low priority may be packed into the next block or later, which makes the gap between the average confirmation time of transactions with high and low priority more significant.

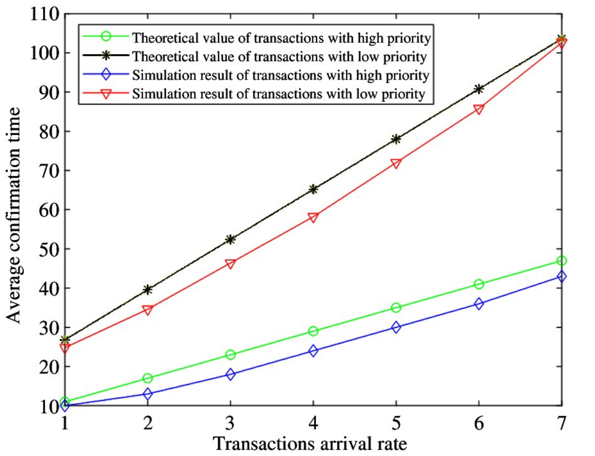

Fig. 4 Impact of transaction arrival rate λ on average confirmation time of transactions with different priority

Fig. 5 shows the theoretical analysis and simulation results of the average confirmation time of transactions with high and low priority under different average block capacity λ_B ($\lambda = 5.0$, $\mu_S = 0.00042$, $\eta = 0.8$, $N = 150$). With the increase of block capacity, the decline speed of average confirmation time of transactions with high and low priority gradually slows down. When the block capacity λ_B reaches about 200, the decline speed obviously decreases, which means raising the Block Gas Limit to expand the block capacity cannot significantly improve the transactions confirmation speed.

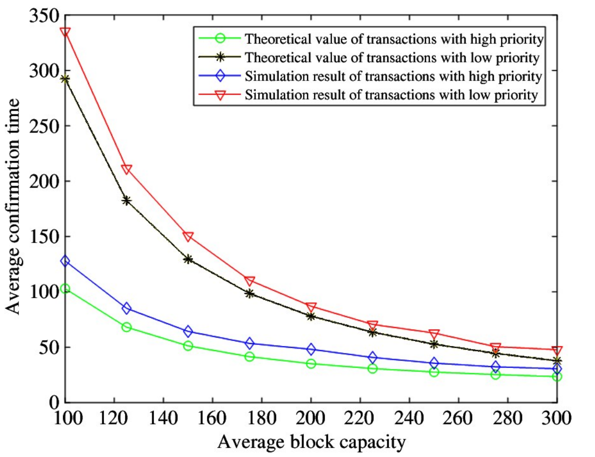

Fig. 5 Impact of average block size λ_B on average confirmation time of transactions with different priority

Fig. 6 shows the theoretical analysis and simulation results of the average confirmation time of transactions with high and low priority under different mean value of Gaussian distribution of service rates $\bar{\mu}$ ($\lambda_B = 200$, $\lambda = 5.0$, $\eta = 0.8$, $N = 150$). With the increase of $\bar{\mu}$, the average confirmation time of transactions with high and low priority decreases at a slower pace, which shows that transactions are no longer remaining in the transaction pool because of the increasing speed of packing transactions. Therefore the transactions confirmation rate cannot be improved if the service rate continues to increase.

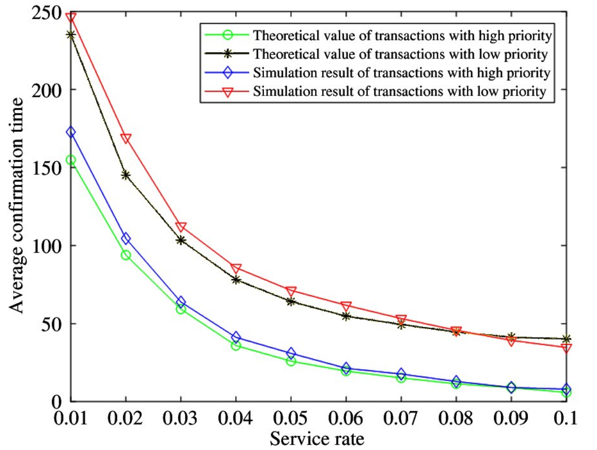

Fig. 6 Impact of service rate $\bar{\mu}$ on average confirmation time of transactions with different priority

Fig. 7 shows the average confirmation time of transactions with high and low priority under different arrival rate ratio η of high and low priority transactions

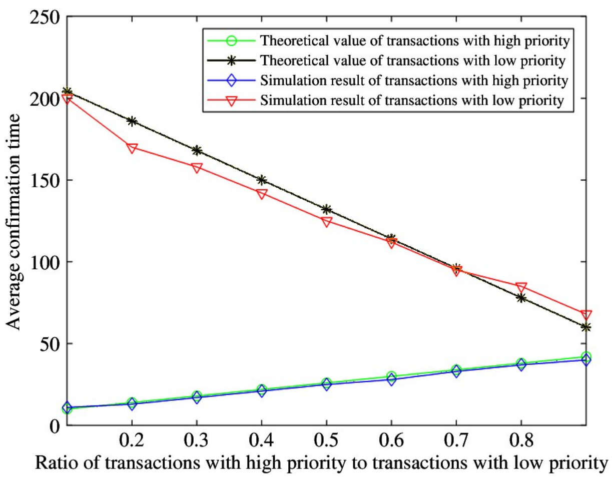

Fig. 7 Impact of ratio η of transactions with high priority to those with low priority on average confirmation time of transactions with different priority

($\lambda_B = 200, \lambda = 5.0, \mu_S = 0.00042, N = 150$). With the increase of the ratio η, the number of transactions with low priority decreases, so the average confirmation time of transactions with low priority decreases obviously, while the confirmation time of transactions with high priority increases slowly due to the increasing number of transactions with high priority. It shows that increasing η can significantly shorten the average confirmation time of transactions with low priority, and has little impact on those with high priority.

Fig. 8 shows the average confirmation time of transactions with high and low priority under different arrival rate λ_H of transactions with high priority ($\lambda_B = 200$, $\lambda_L = 1.0$, $\mu_S = 0.00042$, $N = 150$). Fig. 9 shows the average confirmation time of transactions with high and low priority under different arrival rate λ_L of transactions with low priority ($\lambda_B = 200, \lambda_H = 1.0$, $\mu_S = 0.00042$, $N = 150$). When the arrival rate of transactions with high and low priority increases, the average

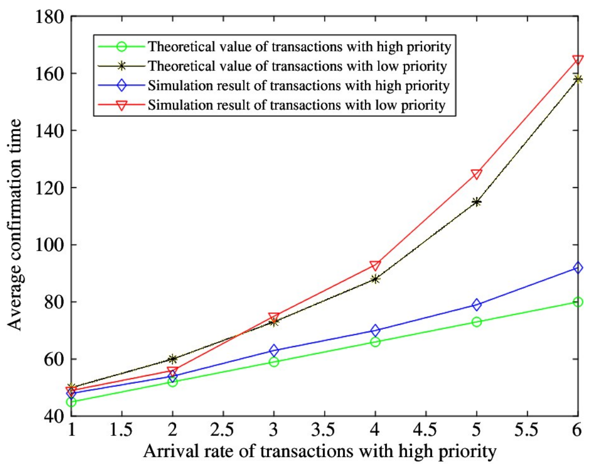

Fig. 8 Impact of arrival rate λ_H of transactions with high priority on average confirmation time of transactions with different priority

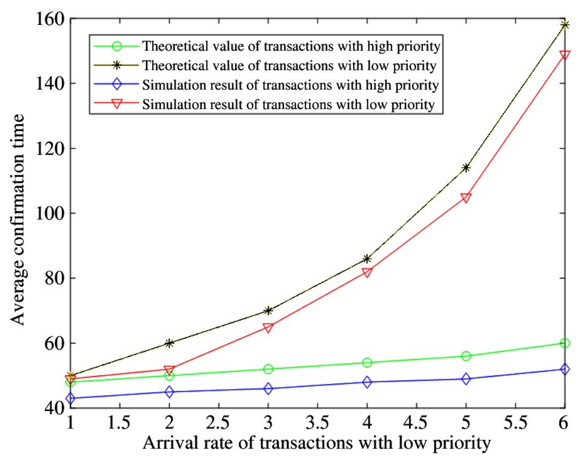

Fig. 9 Impact of arrival rate λ_L of transactions with low priority on average confirmation time of transactions with different priority

confirmation time of transactions with low priority transaction increases gradually, and that of transactions with high priority increases slowly. It shows that even if the number of transactions queued in the transaction pool is large, the confirmation time of transactions with high priority will be slightly affected, while transactions with low priority will be greatly prolonged.

Fig. 10 and Fig. 11 show the results of the average confirmation time of transactions with high and low priority under different number of nodes N($\lambda = 5.0, \lambda_B = 200, \mu_S = 0.00042, \eta = 0.8$). When $N = 20$, the statistical characteristics are relatively unstable, and the simulation performance is deviated from theoretical analysis to a certain extent. When $N = 150$ and $N = 20$, the service rate of each node is close to the average service rate, so the simulation results are similiar to the theoretical value.

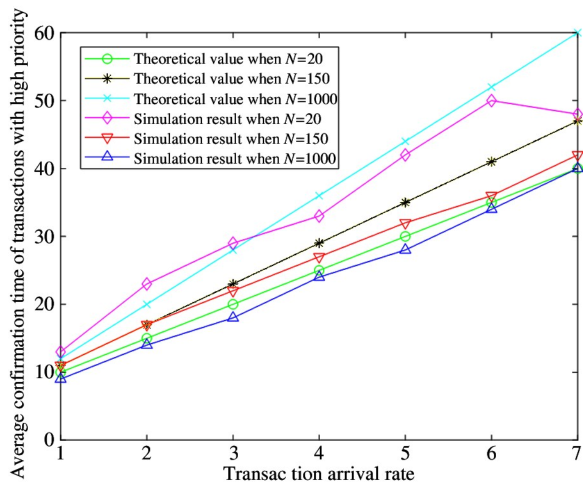

Fig. 10 Impact of transaction arrival rate λ and number of nodes N on average confirmation time of transactions with high priority

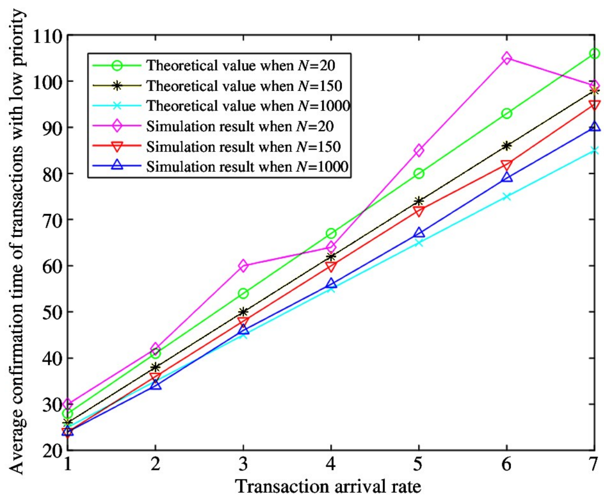

Fig. 11 Impact of transaction arrival rate λ and number of nodes N on average confirmation time of transactions with low priority

4 Conclusions

An Ethereum blockchain for civil aviation business data is proposed to promote the data sharing within civil aviation industry. A batch-service M/G/1 queuing model with variable service capacity is used to model the transactions confirmation process in the blockchain and calculate the average confirmation time of transactions with high and low priority. The effects of transactions arrival rate, average block capacity, average service rate, high-low priority ratio and number of nodes on the confirmation time of transactions with different priority are analyzed. The simulation results show that the model is effective, which provides theoretical support for the combination of civil aviation airport group and Ethereum blockchain, giving the basis for setting parameters such as transaction priority and Block Gas Limit.

References

[1] Yuan Y, Wang F Y. Blockchain: the state of the art and future trends[J]. *Acta Automatica Sinica*, 2016, 42(4): 481-494

[2] Nakamura Y, Zhang Y, Sasabe M, et al. Capability-based access control for the Internet of Things: an ethereum blockchain-based scheme[C]//2019 IEEE Global Communications Conference (GLOBECOM), Waikoloa, USA, 2019:1-6

[3] Li J, Peng Z, Liu A, et al. Analysis and future challenge of blockchain in civil aviation application[C]//2020 IEEE 6th International Conference on Computer and Communications (ICCC), Chengdu, China, 2020: 1742-1748

[4] Kasahara S, Kawahara J. Effect of Bitcoin fee on transaction-confirmation process[J]. *Journal of Industrial and Management Optimization*, 2016, 13(5):1-22

[5] Kawase Y, Kasahara S. Transaction-confirmation time for Bitcoin: a queuing analytical approach to blockchain mechanism[C]//12th International Conference on Queuing Theory and Network Applications, Qinhuangdao, China, 2017: 75-88

[6] Kawase Y, Kasahara S. A batch-service queuing system with general input and its application to analysis of mining process for Bitcoin blockchain[C]//2018 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData), Halifax, Canada, 2018: 1440-1447

[7] Li Q L, Ma J Y, Chang Y X. Blockchain queuing theory[C]//The 7th International Conference on Computational Data and Social Networks, Shanghai, China, 2018: 25-40

[8] Li Q L, Ma J Y, Chang Y X, et al. Markov processes in blockchain systems[J]. *Computational Social Networks*, 2019, 6(1): 1-28

[9] Ricci S, Ziviani A, Ferreira E, et al. Learning blockchain delays: a queuing theory approach[J]. *ACM Sigmetrics Performance Evalluation Review*, 2019, 46(3): 122-125

[10] Memon R A, Li J, Ahmed J, et al. Modeling of blockchain based systems using queuing theory simulation[C]//The 15th International Computer Conference on Wavelet Active Media Technology and Information Processing (ICCWAMTIP), Chengdu, China, 2018: 107-111

[11] Li J J, Yuan Y, Wang S, et al. Transaction queuing game in Bitcoin blockchain[C]//2018 IEEE Intelligent Vehicles Symposium (IV), Changshu, China, 2018: 114-119

[12] Li J J, Yuan Y, Wang F Y. Bitcoin fee decisions in transaction confirmation queuing games under limited multi-priority rule[C]//2019 IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI), Zhengzhou, China, 2019: 134-139

[13] Bowden R , Keeler H P, Krzesinski A E, et al. Block arrivals in the Bitcoin blockchain[EB/OL]. https://arxiv.org/abs/1801.07447: Cornell University, 2018

[14] LI Y G. On the queueing process in the system M/G/1 with stochastic bulk service[J]. *Journal of Chongqing University*, 1989(5): 98-105

[15] Biais B, Bisière C, Bouvard M, et al. The blockchain folk theorem[J]. *The Review of Financial Studies*, 2019, 32(5): 1662-1775

[16] Huang Y W, Kuang S F, Yang R L, et al. M/G/1 queuing model under nonpreemptive limited-priority[J]. *Journal of Computer Applications*, 2016, 36(7): 1779-1783

Liu Yiwei, born in 1996. She studied in Beijing University of Technology for master degree in 2018. Her research interests include blockchain, resource management and wireless communication.