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The Performance Analysis of Virtual Queues for Space-Ground Integrated Networks

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ABSTRACT In the space-ground integrated networks, many tasks come from different access networks, such as cellular network, Wireless Fidelity (WIFI), Satellite network, Unmanned Aerial Vehicle (UAV) and so on. And these tasks have different priorities in general. Therefore, how to couple these tasks in the core network and design a low computational complexity and high-efficiency task processing strategy is a big challenge. In this paper, the concept of virtual queues is introduced to improve the performance of the space-ground integrated networks. The task queue can be split into several virtual queues according to their priorities and the type of access networks. To evaluate the performance of virtual queues, the system performance index is defined. Finally, the system performance of the space-ground integrated networks is analyzed in detail. The result can be applied into the design of the space-ground integrated networks.

INDEX TERMS Performance analysis, virtual queue, space-ground integrated networks.

I. INTRODUCTION

The next-generation cellular networks are expected to provide communication services for different application users anywhere and anytime, such as traditional voice/video, smart city, automotive car or ship, unmanned aerial vehicle, marine monitoring, IoT and intelligent industry [1]–[7]. The space-ground integrated network is a promising solution to achieve this goal [8]. The integrated networks can solve coverage constraint of 5G communications and provide seamless global coverage. This requires non-ground communication network, especially satellite communication network, UAV network and ground network to form a space-ground integrated network together to supplement the cost effectiveness, seamless and ubiquitous service availability of ground network. At the same time, UAV communication also faces great challenges, such as serious interference [9]. In addition, it can satisfy booming traffics and links brought by emerging different kinds of applications.

In beyond 5G and future 6G communication systems, the high demand on data rate certainly will cause ultra-densified and heterogeneous BSs/APs deployment. However, heterogeneous networks need to be interconnected, so many problems are raised in terms of routing [10], protocol [11] and task assignment [12]. In the space-ground integrated network, various networking technologies have their own advantages and disadvantages in coverage, transmission delay, throughput, reliability and other aspects, and different network segments can cooperate to support seamless service access [13]. The space-ground integrated networks can be a layered heterogeneous architecture in nature. In an integrated system, the efficiency of dynamic cooperation of multi-dimensional heterogeneous resources is crucial for data transmission, processing, perception and caching [14], [15].

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In [16], the authors consider the task scheduling as in-network dispersed computing paradigms that leverage the computing capabilities of heterogeneous resources to process a massive amount of data, and propose a virtual queuing network encoding the state of the network, finally prove that Max-Weight policy they proposed is throughput-optimal. Being different from the existing studies that mainly focus on the issue of computation offloading, [17] investigates the problem of cooperative data sharing among peers to overcome the data dissymmetry, especially with the presence of dynamic and heterogeneous network. They design a data downloading/uploading queuing mechanism and propose an online algorithm which could obtain a utility arbitrarily close to the offline optimum. In [18], the authors introduce the Local Shortest Queue (LSQ) family of load balancing algorithms to reduce the large communication overhead due to herd behavior in such heterogeneous systems. In [19], the authors propose an adaptive multicast algorithm based on Lyapunov's optimization theory to optimize the long-term QoE for all subscribers, by striking a compelling trade-off between the system's utility and its queue stability. In [20], the authors investigate the data-delivery latency in the context of intermittent vehicle-to-UAV (V2U) communications by modeling the vehicles' OnBoard Units'(OBUs') buffers as single-server queuing systems. In [21], the authors establish a joint communication and computation optimization model for a MEC enabled UAV network by using stochastic geometry and queuing theory to achieve the optimal response delay. In [14], the authors propose a novel framework which combines two parts as follows: first, cooperative game that enables the content providers to form coalitions in which all subscribers can exchange content via D2D links, thereby reducing content transfer costs and delays; second, Lyapunov optimization based dynamic channel and UAVs' activity allocation policy of the operator. In [22], a distributed algorithm based on the machine learning framework of liquid state machine (LSM) is proposed. It also enables the UAVs to autonomously choose the optimal resource allocation strategies that maximize the number of users with stable queues depending on the network states. In [23], the authors rely on queuing theory and Lyapunov optimization to strike a power- delay trade-off by jointly optimizing the computational task scheduling and resource allocation in the heterogeneous cloud architecture, which is comprised of an edge cloud and a powerful remote cloud. In [24], the authors classify data packets in UAVs at each layer of a multi-layer UAV network into incumbent packets and relayed packets, and propose a traffic service scheme for variable classes of packets. Finally, they minimum total packet delay is achieved by optimally allocating spectrum and power resources among layers of the UAV network.

However, few works focus on the performance analysis of queues for space-ground integrated networks. In the space-ground integrated networks, many tasks come from different access networks, and they have different priorities. Therefore, how to couple these tasks in the core network and design a low computational complexity and high-efficiency task processing scheme is a big challenge. In this paper, the concept of virtual queues is introduced to improve the performance of the space-ground integrated networks. The task queue can be split into two or several virtual queues according to their priorities and the type of access networks. And the computing resource is also divided into two or several parts to handle different virtual queues.

The main contributions of this paper are summarized as follows:

(1) the concept of virtual queues is introduced to handle the tasks.

(2) the peformance index of the virtual queues is presented to better evaluate the system performance.

(3) the performance of virtual queues for space-ground integrated networks is analyzed in detail based on queuing theory.

The rest of this paper is organized as follows. In section II, system model is presented and described. The system performance in term of the cost function for space-ground integrated networks is analyzed in section III. Simulation results are provided and discussed in section IV and the paper is concluded in section V.

II. SYSTEM MODEL

In the space-ground integrated networks, there are several access networks, such as cellular network, WiFi, satellite network and so on. The access networks can serve for different mobile terminals (MTs), as shown in Figure 1. The set of the access networks can be denoted as $a = \{a_1, a_2, \ldots, a_n\}$, where n is the number of the access network type. We assume that the arrivals of the tasks from the access network a_i are determined by a Poisson process with parameter λ_i. Then we have the total arrival rate as $\lambda = \sum_{i=1}^{n} \lambda_i$. In general, the size of the task can be modeled as the zipf distribution. Without loss of generality, we consider that the service time for every task is also proportional to the size of the tasks. Then the task processing can be modeled as a M/Z/1 queue. Here, M represents that arrivals are determined by a Poisson process and Z represents that service time follows a zipf distribution. And we denote the average service time as τ. Then the Probability Mass Function (PMF) of τ can be written as

$$f(\tau) = \frac{\frac{1}{\tau^s}}{\sum_{n=1}^{N} \frac{1}{n^s}} \tag{1}$$

Here, N is the number of tasks and s is the value of the exponent characterizing the distribution.

III. PERFORMANCE ANALYSIS

A. PERFORMANCE ANALYSIS OF THE CONVENTIONAL SINGLE QUEUE

For the space-ground integrated networks, the arrival process of the tasks can be modeled as M/Z/1 queue. For the M/Z/1 queue, we can let $H_{N,s} = \sum_{n=1}^{N} \frac{1}{n^s}$. Here, $H_{N,s}$ is the

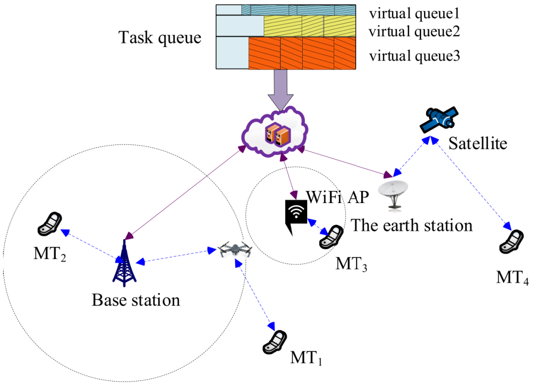

FIGURE 1. System model of the space-ground integrated networks.

Nth generalized harmonic number. Then the mean value of the average service time τ can be calculated as

$$E(\tau) = \frac{H_{N,s-1}}{H_{N,s}} = \frac{1}{\mu} \tag{2}$$

Here, u is departure rate.

Next, the variance of τ can be obtained as

$$Var(\tau) = \frac{H_{N,s-2}}{H_{N,s}} - \frac{H_{N,s-1}^2}{H_{N,s}^2} = \frac{a}{u} - \frac{1}{u^2} \tag{3}$$

Here, $a = \frac{H_{N,s-2}}{H_{N,s-1}}$.

Corollary 1: When $s = 1$, we can get that the mean value and variance of τ are approximate to $\frac{N}{\ln N}$ and $\frac{N(N+1)}{2\ln N} - \frac{N^2}{\ln^2 N}$, respectively.

Proof: when $s = 1$, we have $E(\tau) = \frac{H_{N,0}}{H_{N,1}} = \frac{N}{H_{N,1}}$. Usually, N is far greater than 1. Therefore, we have $H_{N,1} = \sum_{n=1}^{N} \frac{1}{n} \approx \ln N + C \approx \ln N$. Here, C is a Euler's number and $C \approx 0.57722$. Obviously, it is easy to obtain the mean value of τ as $E(\tau) = \frac{N}{\ln N}$.

Next, we can get the variance of τ as $Var(\tau) = \frac{H_{N,-1}}{H_{N,1}} - \frac{H_{N,0}^2}{H_{N,1}^2} \approx \frac{N(N+1)}{2\ln N} - \frac{N^2}{\ln^2 N}$.

Corollary 2: When s=2, we can get that the mean value and variance of τ are approximate to $\frac{6\ln N}{\pi^2}$ and $\frac{6N}{\pi^2} - \frac{36\ln^2 N}{\pi^4}$, respectively.

Proof: It is widely known that there is the sequence summation formula $\sum_{n=1}^{\infty} \frac{1}{n^2} = 1 + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \frac{1}{5^2} + \cdots = \frac{\pi^2}{6}$. Meanwhile, the sequence is convergent. Considering that N is big enough in general, we can get $\sum_{n=1}^{N} \frac{1}{n^2} \approx \frac{\pi^2}{6}$.

According the above caculation and Corollary 1, when $s = 2$, we can calculate the mean value of as $E(\tau) = \frac{H_{N,0}}{H_{N,1}} \approx \frac{6\ln N}{\pi^2}$. Finally, we can get the variance of τ as $Var(\tau) = \frac{H_{N,s-2}}{H_{N,s}} - \frac{H_{N,s-1}^2}{H_{N,s}^2} \approx \frac{6N}{\pi^2} - \frac{36\ln^2 N}{\pi^4}$.

According to Pollaczek-Khinchine formula, the mean number of the tasks in the M/Z/1 queue can be calculated as

$$L = \rho + \frac{\rho^2 + \lambda^2 Var(\tau)}{2(1-\rho)} = \rho(1 + \frac{a\lambda}{2(1-\rho)}) \tag{4}$$

Here, $1/\mu$ is the mean of the service time τ, $\rho = \lambda/\mu$ is the utilization. So it can be seen that the length of task queue is closely related to λ, μ and the variance of τ.

It is well known that the system time consists of waiting time and serving time. Now, we denote the mean system time for the tasks as W. Then we have $W = W' + \tau^{-1}$. Here, W' is the mean waiting time. According to Little's law, we have $L = \lambda W$. Therefore, we can calculate the mean value of the system time as

$$W = \frac{\rho + \lambda u Var(\tau)}{2(u-\lambda)} + \tau^{-1} = \frac{a\lambda}{2(u-\lambda)} + \frac{1}{u} \tag{5}$$

Next, the average waiting time can be obtained as $W' = \frac{\rho + \lambda u Var(\tau)}{2(u-\lambda)}$. Likewise, it can be seen that the system time and waiting time are also closely related to λ, μ and the variance of τ.

B. PERFORMANCE ANALYSIS OF THE VIRTUAL QUEUES

For space-ground integrated networks, the tasks maybe come from different access networks, such as cellular network, WiFi, satellite network and so on. For the same task, different transmission networks will result in different transmission delays. In order to balance system peformance in term of the delays of all tasks, we should primarily deal with the tasks with high priority and long transmission delay. Therefore, the weight value is introduced for every task to represente the priority. Meanwhile, the the weight value is also introduced for different access network type to represente the transmission delay.

In space-ground integrated networks, there are several access networks in general. And we denote the set of the access networks as $a = \{a_1, a_2, \ldots, a_n\}$. Here, n is the number of type of all access networks. Then we can define the weight factor of the access networks as

$$f(a_i) = \frac{\overline{t(a_i)}}{\sum_{i=1}^{n} \overline{t(a_i)}} \tag{6}$$

Here, $\overline{t(a_i)}$ is the average transmission time of access network type a_i.

Considering the same task maybe come from different access networks. So we should combine the two fators in term of access network type and priority of the task. Then, we define the weight factor of task k as

$$w_k = f(g(T_k)) * P_k \tag{7}$$

Here, $g(T_k)$ is the function which returns the access network type of the task k, and P_k is the priority of the task k. For the tasks, the task with smaller size has higher priority in general. Generally speaking, the task with smaller packet length is more urgent and more sensitive to delay. Therefore, according to Zipf's law, we can define the priority of the task k according to its size as

$$P_k = \frac{\frac{1}{k}}{\sum_{n=1}^{N} \frac{1}{n}} \tag{8}$$

As mentioned above, transmission delay is closely related to system waiting time. Hence, we define a cost function combing transmission delay and the priority as

$$C = \sum_{k=1}^{N} w_k \bar{W}_k \tag{9}$$

Here, $\bar{W}_k$ is the average waiting time of task k.

In this situation, single queue is not optimal in the absence of considering transmission delay of different access network and priority of tasks. According to this situation, we introduce virtual queues to improve system performance of the space-ground integrated network in this paper. In the space-ground integrated network, there is a task processor to handle these tasks from different access networks. We denote the total computing resource of the task processor as C_r. And C_r can be divided to k parts: $p_i C_r$, where $\sum_{i=1}^{k} p_i = 1$. At the same time, the task queue can be split into k virtual queues according to the collating sequence of the weights of all tasks, and the cut-off points of the sequence are denoted as m_i, $i = \{1, 2, \ldots, k\}$.

In this case, we can calculate the mean value of service time τ_i of the ith virtual sequence as

$$E(\tau_i) = \frac{H_{m_i,s-1} - H_{m_{i-1},s-1}}{p_i(H_{m_i,s} - H_{m_{i-1},s})} = \frac{1}{\mu_i} \tag{10}$$

Here, we assume that $H_{m_0,s} = H_{m_0,s-1} = H_{m_0,s-2} = 0$.

Next, the variance of service time τ_i of the ith virtual sequence can be obtained as

$$Var(\tau_i) = \frac{H_{m_i,s-2} - H_{m_{i-1},s-2}}{p_i^2(H_{m_i,s} - H_{m_{i-1},s})} - \frac{(H_{m_i,s-1} - H_{m_{i-1},s-1})^2}{p_i^2(H_{m_i,s} - H_{m_{i-1},s})^2} \tag{11}$$

We let $b_{m_i} = \frac{H_{m_i,s-2} - H_{m_{i-1},s-2}}{H_{m_i,s-1} - H_{m_{i-1},s-1}}$, then we can rewrite and calculate the formula (11) as

$$Var(\tau_i) = \frac{b_{m_i}}{p_i u_i} - \frac{1}{u_i^2} \tag{12}$$

We denote the utilization of virtual queue i as $\rho_i = \lambda_i/\mu_i$. Then we can obtain the length of virtual queue i as

$$L_i = \rho_i + \frac{\rho_i^2 + \lambda_i^2 Var(\tau_i)}{2(1-\rho_i)} = \rho_i\left(1 + \frac{b_{m_i}\lambda_i}{2(1-\rho_i)}\right) \tag{13}$$

Then, the average length of the task queue is calculated as

$$\bar{L} = \sum_{i=1}^{i=k} \frac{H_{m_i,s} - H_{m_{i-1},s}}{H_{N,s}} L_i \tag{14}$$

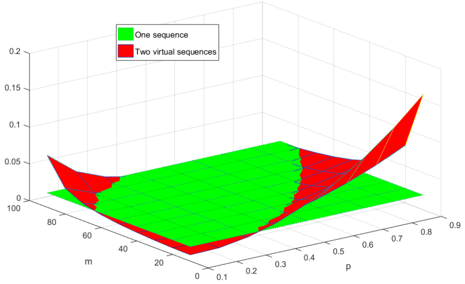

FIGURE 2. The relationship among the cost function and parameter *p* and *m*.

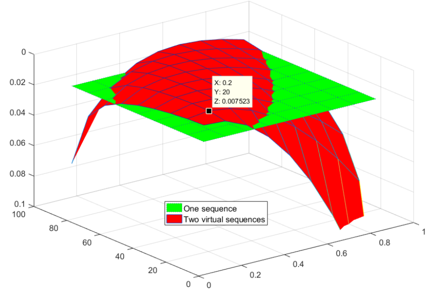

FIGURE 3. The hook face of cost function.

Next, according formula (5), we can obtain the average wait time of tasks in virtual queue i as

$$\bar{W}_i = \frac{b_{m_i}\lambda_i}{2(u_i - \lambda_i)} + \frac{1}{u_i} \tag{15}$$

Finally, combing performance of the virtual queue and the weight factors of the tasks, the system performance index of the space-ground integrated networks can be defined as

$$C = \sum_{i=1}^{k} \sum_{j=m_{i-1}}^{m_i} w_j \bar{W}_i \tag{16}$$

IV. RESULTS AND DISCUSSIONS

A. SIMULATION SETUP AND PARAMETER SETTING

In this subsection, we assume that M task nodes and one center task server randomly locate in the space-ground integrated networks. Without loss of generality, we consider that all task nodes have the same task request rate, and denoted it as λ. In space-ground integrated networks, we consider that there are N tasks which follow a Zipf distribution with parameter s. For every task node, $\lambda = 0.00001$. Other simulation parameters are set as: $N = 100$, $s = 1$, $M = 100$.

B. NUMERICAL RESULTS

Without loss of generality, we consider three-dimensional figure for the case of two virtual queues to better illustrate the simulation result. Figure 2 depict the system performance index in regard to parameter p and m. From this figure, it can be seen that the conventional one queue scheme get worst system performance in most cases because the scheme is inflexible. Leveraging the proposed virtual queues strategy, we can efficiently improve the system performance by means of selecting optimal p and m. To better visualize the bottom of Figure 2, Figure 3 shows the hook face of system performance index reversely. It can be seen that we can get best system performance when $p = 0.2$ and $m = 20$. This valid the efficiency of the proposed virtual queues strategy.

V. CONCLUSION

In this paper, a low computational complexity and high-efficiency task processing method based on the concept of virtual queues for space-ground integrated networks is proposed. The task flow from different access network are mutually independent and follow a Poisson process. To optimally handle the tasks, the virtual queues are introduced to process the tasks. And the virtual queues are modeled as the M/Z/1 queues. Considering transmission delay of different access network and priority of tasks, a system performance index is presented to better evaluate the system performance. Then the system performance is analyzed based on the analysis of the waiting time and the length of the queue. We can get and set the optimal parameters to efficiently improve the system performance. Simulation result validate the efficiency of the proposed virtual queues strategy.

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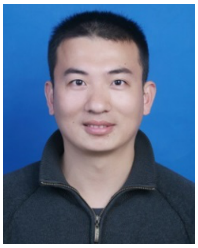

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