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Research on Virtual Channel Multiplexing Algorithm Based on Advanced Orbiting Systems

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ABSTRACT To address multiple data types and high speeds in a business satellite network based on the virtual channel multiplexing technology of advanced orbiting systems (AOSs), an AOS virtual channel multiplexing system model is established. AOS queue management problems and the constraint problems in virtual channel scheduling are analyzed. On this basis, a priority adaptive random early detection and vaccine updating immune genetic algorithm is proposed. In queue management, based on the scheme of a multi-queue sharing cache with a minimum allocation, the algorithm adaptively adjusts packet dropping probability according to the packet priority. Based on an immune genetic algorithm, virtual channel scheduling automatically updates the vaccine database according to the matching degree of the vaccines and population. Meanwhile, the algorithm efficiently combines queue management and virtual channel scheduling. Experimental results show that the algorithm has excellent evolution performance and can maintain smaller queue lengths, smaller packet loss rates, less delay for high-priority virtual channels, and also has preferable fairness.

INDEX TERMS Advanced orbiting systems, queue management, virtual channel scheduling.

I. INTRODUCTION

With the development of aerospace technologies, satellite networks can be combined with terrestrial Internet, emergency communication systems and the like, which can relieve the problem of insufficiency in ground network bandwidth resources and can satisfy emergency communication demands such as rescue and relief work. The standard of Advanced Orbiting Systems (AOS) proposed by Consultative Committee for Space Data Systems (CCSDS) supports a large scope of bit rates and multiple business types, has network access function. It's becoming an important standard for satellite network protocol design [1]–[4]. By dividing virtual channels, AOS adopts time division multiplexing, designs effective virtual channel multiplexing strategies, wherein multi-user and large-capacity information can form a uniform high-speed mixed data flow that can be transmitted efficiently on a physical channel.

The data of the satellite network includes data generated by spacecrafts and data from terrestrial Internet. With the increasing complexity of space missions, the types of spacecrafts' payloads continue to increase. In addition to conventional remote-control data, telemetry data and tracking data, the spacecrafts also generate static images data, audio data, video data, scientific experimental data, delayed playback data and so on. With the increase of user demand, the data traffic of terrestrial Internet is increasing exponentially, and the data types are complex [5], [6]. Therefore, the data types generated and converged in the satellite network are diverse, with the following transmission requirements: first, different types of business have different degrees of importance and different requirements for transmission timeliness; Second, with continuous increase of space business types, the quantity of virtual channels also increases continuously, virtual channel scheduling will have obvious resource constraints and time constraints. Virtual channel scheduling is NP-hard problems under multiple constraint conditions [7], [8]. Data multiplexing technology must take account of the above characteristics of satellite network business to achieve efficient sharing. The current AOS virtual channel multiplexing technology cannot meet the above requirements.

AOS virtual channel multiplexing includes queue management and virtual channel scheduling. The queue management algorithm on network routing nodes can effectively manage queue length and can send congestion instructions to the source nodes with a few packet losses [9]. Virtual channel scheduling algorithm selects a virtual channel at each time slot, takes out frames from its cache and transmits them. From the perspective of the whole AOS virtual channel multiplexing system, queue management and virtual channel scheduling should support each other and cannot be separated. Nevertheless, in traditional research, queue management and virtual channel scheduling are mutually independent and lack correlation, and the effective application of cache memory resources and processing resources cannot be realized.

Aiming at the above problems, the paper researches queue management algorithm and virtual channel scheduling algorithm based on AOS, further effectively combines queue management with virtual channel scheduling and puts forward the priority adaptive random early detection combined with vaccine updating immune genetic algorithm (PARED-VUIGA). The algorithm can meet the transmission needs of multiple types of business in satellite network, and effectively use cache memory resources and processing resources to improve transmission efficiency.

The main contributions of this paper are as follows:

Firstly, the AOS queue management problem model and the AOS virtual channel scheduling problem model are established, which can provide an overall framework for the research of virtual channel multiplexing algorithm.

Secondly, since different types of AOS business have different degrees of importance, based on the SMA scheme, the packet dropping probability is adaptively adjusted according to the business priority, and a priority adaptive random early detection (PARED) algorithm based on multi-queue SMA is proposed. This algorithm can make important data discarded at low probability and improve cache utilization.

Thirdly, since different types of AOS business have different degrees of importance and different real-time requirements, based on multi-constraint characteristic of scheduling, by designing immune operators and basic genetic operators, an AOS virtual channel scheduling algorithm based on vaccine updating immune genetic algorithm (VUIGA) is proposed. The algorithm can improve convergence speed and meet the transmission requirements of different types of AOS business.

Finally, through the priority and queue length of each virtual channel, the queue management and virtual channel scheduling are combined to optimize the cache memory resources and processing resources.

The rest of this paper is organized as follows: The related works are introduced in Section II. Section ćó describes the structure of AOS virtual channel multiplexing system, establishes the AOS queue management problem model and the AOS virtual channel scheduling problem model. In Section ćô, the PARED algorithm based on multi-queue SMA and the AOS virtual channel scheduling algorithm based on VUIGA are proposed, PARED-VUIGA algorithm flow is described. Simulation results and performance analysis are described in detail in Section ĞX. Finally, Section ćö summarizes the paper.

II. RELATED WORK

The current queue management mainly adopts active queue management (AQM) mechanism. Typical AQM algorithms include random early detection (RED) [10], adaptive RED (ARED) [11], stabilized RED (SRED) [12], and so on. The above algorithms have a problem of parameter setting sensitivity.

Based on the above algorithms, some improved AQM algorithms have been proposed. Jamali *et al.* [13] introduce queue length growth velocity and drop rate velocity to measure the congestion level and produce appropriate congestion feedbacks, reduces the packet loss rate and achieves high utilization by dynamically tuning of RED's parameters. In [14], an active queue management algorithm which takes the self-similarity of traffic into account is devised, the degree of the self-similarity is determined by Hurst parameter, in the case of congestion event, only those packets in queue which have caused congestion are dropped and their influence on other queues is avoided. In [15] and [16], an active queue management algorithm for non-adaptive flows is proposed, packet dropping probability is estimated based on flow matching rate, the low queuing delay and inter-flow fairness can be achieved simultaneously without the queue isolation. In the above references, the algorithms' performances are improved by adjusting parameters, cache partition and other strategies. However, the difference importance degrees of different types of business is not considered, and the dropping probability cannot be adjusted adaptively according to the priorities of business, so the problems in queue management of multiple types of business in AOS cannot be effectively solved. Hence, a queue management algorithm will be designed in this paper to address the characteristics of different business data in AOS.

At present, classical AOS virtual channel scheduling algorithms mainly include the time slice polling scheduling algorithm [17], the static priority scheduling algorithm [18], the surplus priority scheduling algorithm [19], and so on. These algorithms are all scheduling with a single parameter. However, the types of business in satellite networks are diverse, their transmission requirements are different and need to be considered comprehensively. Therefore, the classical scheduling algorithms cannot meet the transmission requirements of multiple types of business in AOS.

Based on the above algorithms, some scholars have proposed some improved virtual channel scheduling algorithms. In [20], a time slice boundary movable virtual channel multiplexing method is proposed, the facts of data type, urgency, injection rate and max waiting time are considered, experiment shows that the real-time performance is improved, and

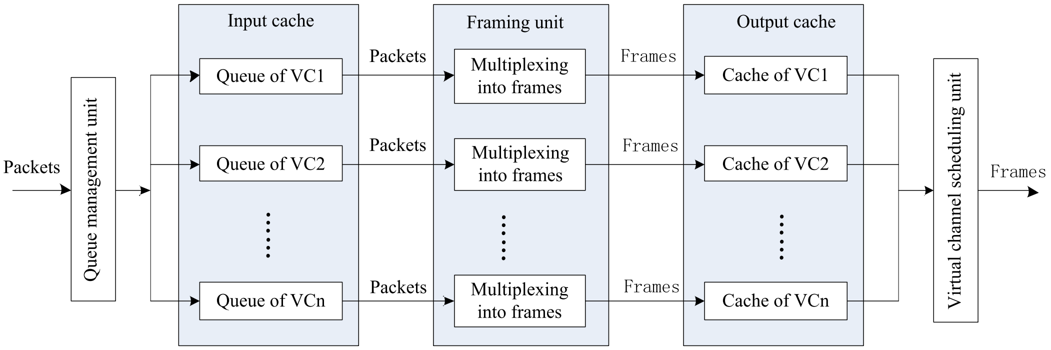

FIGURE 1. Structure of AOS virtual channel multiplexing system.

the output bandwidth is utilized efficiently. In [21], an AOS virtual channels scheduling algorithm based on separate evaluation of virtual channels and frames is proposed, virtual channels urgent degree and frame urgent degree are joined together to form a new urgent degree function, which can provide lower scheduling delay and less cache remainder for the important virtual channels, satisfy the transmission demand of various data sources. In [22], a comprehensive model for virtual channels scheduling is established, the model considers delay, jitter, throughput and loss packet rate, genetic algorithm (GA) based method is designed to solve the model, which can meet the different quality of service for six types of data. The above virtual channel scheduling algorithms can satisfy the different transmission requirements of multiple types of business and can improve the channel utilization to a certain extent. However, these scheduling algorithms are applicable when there are only a few virtual channels in the system. When the number of virtual channels is greatly increased, they cannot be optimized according to the multi-constraint condition of scheduling tasks. Hence, an AOS virtual channel scheduling algorithm shall be designed based on multi-constrain characteristics.

In addition, these queue management algorithms and virtual channel scheduling algorithms are independent, so the cache memory resources and processing resources cannot be used effectively. Therefore, considering the transmission requirements of multiple types of business in AOS, the paper addresses the priority and queue length of each virtual channel as the linkage, effectively combines queue management with virtual channel scheduling, and puts forward a priority adaptive random early detection combined with vaccine updating immune genetic algorithm (PARED-VUIGA).

III. MODEL OF AOS VIRTUAL CHANNEL MULTIPLEXING

A. STRUCTURE OF AOS VIRTUAL CHANNEL MULTIPLEXING SYSTEM

As a routing node of a satellite network, spacecrafts' data contain their own data as well as data from other nodes in the network. Data types are diversified. Data size ranges from bits to hundreds of megabytes, and the transmission time requirements are different. To efficiently share the same physical channel, AOS transmits the data in different virtual channels via time division multiplexing. Because of the different transmission requirements of each type of business data, this study distributes a virtual channel for each type of business data, wherein a priority is distributed for each virtual channel, and packets of the same virtual channel contain the same priority.

Fig. 1 shows the structure of an AOS virtual channel multiplexing system. Packets arriving at each virtual channel first enter its corresponding input cache queue. The queue management unit determines the probability for each packet to enter the input cache queue according to the designed queue management algorithm. The framing unit multiplexes packets of each virtual channel into frames and temporarily stores them in the relevant output cache. The virtual channel scheduling unit selects a virtual channel at each time slot according to the designed scheduling algorithm, extracts the frames from its output cache and transmits them. At the queue input end, the queue management unit distributes cache resources in the current spacecraft. At the queue output end, the virtual channel scheduling unit takes charge of bandwidth distribution and delay adjustment. The queue management unit coordinates with the virtual channel scheduling unit to carry out the complete virtual channel multiplexing operations.

B. MODEL OF AOS QUEUE MANAGEMENT PROBLEM

Queue management is applied in space route nodes. When a packet arrives at the front end of a queue, the queue management mechanism decides whether the packet is allowed to enter an input cache queue according to certain strategies and queue information, informs the source end of the occurrence of congestion by a few packet losses, and reduces the sending rate of the source end so that losses of more packets can be avoided.

At present, most queue management algorithms are based on a single queue and cannot effectively solve the queue management problem of multiple types of business in AOS. On this basis, aiming at the transmission requirements of different types of business data, the input cache of the queue management unit adopts the scheme of sharing with a

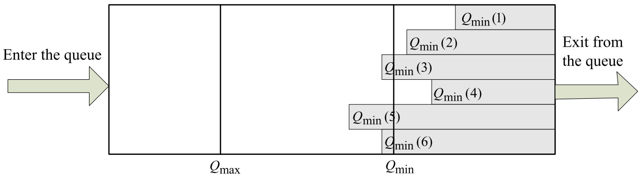

FIGURE 2. **Diagram of cache distribution scheme.**

minimum allocation (SMA): it reserves certain cache for each virtual channel according to the average business volume of each virtual channel to ensure the minimum value of its cache. During a certain period, the minimum cache of each virtual channel is fixed. The remaining caches are shared by all virtual channels. During the continuous arrival of packets and system handling, the cache size occupied by each virtual channel is related to its queue length. The cache distribution scheme is shown in Fig. 2.

Based on the multi-queue SMA scheme, this study adaptively adjusts packet dropping probability according to packet priority and puts forward a priority adaptive RED (PARED) algorithm.

C. MODEL OF AOS VIRTUAL CHANNEL SCHEDULING PROBLEM

The AOS virtual channel scheduling problem is a problem of constraint satisfaction combination optimization. Constraints in the scheduling problem mainly include business priority constraints and transmission urgency constraints.

1) BUSINESS PRIORITY CONSTRAINTS

With the continuous upgrade of users' demands and the continuous progress of aerospace science and technology, the complexity of space data systems is continuously enhanced. Business data transmitted by AOS includes spacecraft telemetry, spacecraft telecontrol, orbit measurement and positioning as well as other engineering business; effective loading business of communication type, ground observation type, and navigation and positioning type; delay playback business; emergency business such as spacecraft failures, earthquake monitoring, and rescue and relief work. There are multiple business types, and different business has different degrees of importance, so their requirements for timeliness and reliability are different. In the AOS virtual channel multiplexing system, these requirements are manifested by the differences in business priority. Business with a higher priority has higher requirements for timeliness and reliability; namely, it requires less delay and a low packet loss rate. Business with a low priority has lower requirements for timeliness and reliability; namely, it has lower requirements for delay and packet loss rate.

Hence, the business priority constraint puts forward different requirements of delay and packet loss rate for different virtual channels. The AOS virtual channel scheduling system shall consider the priority constraints of different types of business.

2) COMPREHENSIVE TRANSMISSION URGENCY CONSTRAINT OF VIRTUAL CHANNEL

Transmission urgency embodies the urgency degree for each virtual channel to wait for the transmission. Comprehensive transmission urgency of a virtual channel is related to queue length, packet loss rate and delay of the virtual channel. $U_{\mathrm{RG}i}$ is set as the comprehensive transmission urgency of the i-th virtual channel, which can be expressed as follows:

$$U_{\mathrm{RG}i} = \log_2(L_i + 1) + \log_2(R_{\mathrm{DIS}i} + 1) + \log_2(D_{\mathrm{EL}i} + 1) \tag{1}$$

where L_i refers to the queue length of the i-th virtual channel. The average queue length of input cache of the i-th virtual channel is set to be $L_{\mathrm{AVG}i}$. The quantity of frames in the output cache is set to be $Q_{\mathrm{OUT}i}$. Frame length is L_{f}. Packet length is L_{p}. Thus, L_i is:

$$L_i = L_{\mathrm{AVG}i} + \frac{L_{\mathrm{f}}}{L_{\mathrm{p}}} \cdot Q_{\mathrm{OUT}i} \tag{2}$$

$R_{\mathrm{DIS}i}$ denotes the packet loss rate of the i-th virtual channel, namely, the ratio between the total quantity of discarded packets and the total quantity of arriving packets. It is caused by overtime and cache overflow.

$D_{\mathrm{EL}i}$ denotes the delay of the i-th virtual channel, which can be expressed by the delay cardinal number. At the initial slot time, $D_{\mathrm{EL}i}$ is:

$$D_{\mathrm{EL}i} = \begin{cases} 1, & L_i \geq L_{\mathrm{f}}/L_{\mathrm{p}} \\ 0, & L_i < L_{\mathrm{f}}/L_{\mathrm{p}} \end{cases} \tag{3}$$

When each scheduling time slot ends, with regard to the transmitted virtual channel obtained at the current time slot, $D_{\mathrm{EL}i}$ is set as 0. With regard to virtual channels that have not been transmitted at the current time slot, if $L_i \geq L_f/L_p$, $D_{\mathrm{EL}i}+1 \rightarrow D_{\mathrm{EL}i}$ can be satisfied.

At different scheduling moments, the comprehensive transmission urgencies of the same virtual channel are different. In the virtual channel scheduling algorithm, virtual channels with high comprehensive transmission urgencies shall be transmitted as soon as possible.

3) MODEL OF AOS VIRTUAL CHANNEL SCHEDULING PROBLEM

AOS virtual channel scheduling refers to a situation where under the conditions of business priority constraint and virtual channel comprehensive transmission urgency constraint, limited system resources are distributed to multiple virtual channels to optimize the throughput of the system. This study comprehensively considers business priority constraints and virtual channel comprehensive transmission urgency constraints and establishes an AOS virtual channel scheduling model as follows:

$$\max \quad F = \frac{\sum_{i=1}^{n} P_{\mathrm{OS}i} \cdot P_{\mathrm{RI}i} \cdot U_{\mathrm{RG}i}}{\sum_{i=1}^{n} P_{\mathrm{RI}i}} \tag{4}$$

In the formula, F denotes a scheduling target function; $P_{\mathrm{OS}i}$ denotes the position weight of the i-th virtual channel; $P_{\mathrm{RI}i}$ denotes the priority of the i-th virtual channel and embodies transmission timeliness and reliability requirements;$U_{\mathrm{RG}i}$ denotes the comprehensive transmission urgency of the i-th virtual channel. After $P_{\mathrm{OS}i}$ weighting processing, the virtual channel with a larger $PRI_i \cdot U_{\mathrm{RG}i}$ value has more advancing position among the individuals, which leads to the larger F of scheduling target function. The scheduling target of the virtual channel scheduling model is max F, namely, the F value is maximum.

At present, most AOS virtual channel scheduling algorithms are applicable when there are only a few virtual channels. When the quantity of virtual channels increases, under multiple constraint conditions, virtual channel scheduling is an NP-hard problem. The genetic algorithm (GA) is an intelligent search algorithm based on biological evolution theories and is suitable for solving problems of complex constraints to satisfy optimization scheduling. GA only applies a fitness function value to evaluate individuals and guide search and fails to make full use of characteristics of the problem, leading to low search efficiency and slow convergence. Sometimes, it fails to converge to the globally optimal solution. Enlightened by principles of biological immunity systems, the immune genetic algorithm (IGA) adds three immunity operators, including vaccine extraction, vaccination and immunity detection, in GA and carries out vaccination aiming at information on the problem to improve individual fitness and enhance the global searching ability of the algorithm. IGA has been applied in fields such as cognitive radio network resource allocation [23] and workflow scheduling in cloud computing [24], and many research achievements have been obtained. It is expected to be fully applied in virtual channel scheduling. Based on the excellent performance of IGA in solving optimization scheduling problems, this study updates the vaccine database according to accumulated results of immunity detection and puts forward an AOS virtual channel scheduling algorithm based on the vaccine updating immune genetic algorithm (VUIGA).

In the AOS virtual channel multiplexing system, this study effectively combines queue management with virtual channel scheduling and puts forward a priority adaptive random early detection combined with vaccine updating immune genetic algorithm (PARED-VUIGA).

IV. PARED-VUIGA ALGORITHM DESIGN

A. PARED ALGORITHM BASED ON MULTI-QUEUE SMA

The average queue length of a sharing cache area is set as L_{AVG}; the maximum queue length threshold value is L_{MAX}; and the minimum queue length threshold is L_{MIN}. Regarding the i-th virtual channel, the priority is $P_{\mathrm{RI}i}$; the average queue length is $L_{\mathrm{AVG}i}$; and the reserved minimum cache is $L_{\mathrm{MIN}i}$, so the dropping probability P_{b} of packets entering the current virtual channel is as follows:

$$P_{\mathrm{b}} = \begin{cases} 0, & L_{\mathrm{AVG}i} \leq L_{\mathrm{MIN}\,i} \; or \; L_{\mathrm{AVG}} \leq L_{\mathrm{MIN}} \\ P_{\mathrm{b}}^{'}, & L_{\mathrm{AVG}\,i} > L_{\mathrm{MIN}\,i},\; L_{\mathrm{MIN}} < L_{\mathrm{AVG}} \leq L_{\mathrm{MAX}} \\ P_{\mathrm{MAX}\,i}, & L_{\mathrm{AVG}\,i} > L_{\mathrm{MIN}\,i},\; L_{\mathrm{AVG}} > L_{\mathrm{MAX}} \end{cases} \tag{5}$$

where $P_{\mathrm{MAX}i}$ denotes the maximum packet dropping probability of the i-th virtual channel and is related to the priority. A higher priority leads to a smaller value of $P_{\mathrm{MAX}i}$. The number of virtual channels is set to be n, so $P_{\mathrm{MAX}i}$ can be expressed as follows:

$$P_{\mathrm{MAX}i} = \log_2\left[1 + \frac{P_{\mathrm{RI}i}}{\max\left(P_{\mathrm{RI}1}, P_{\mathrm{RI}2}, \cdots, P_{\mathrm{RI}n}\right)}\right] \tag{6}$$

P_{b}' is related with L_{AVG} and $P_{\mathrm{RI}i}$ and can be expressed as follows:

$$P_{\mathrm{b}}^{'} = \frac{\log_2[P_{\mathrm{RI}i} + 1] \cdot (L_{\mathrm{AVG}} - L_{\mathrm{MIN}})}{q \cdot (L_{\mathrm{MAX}} - L_{\mathrm{MIN}})} P_{\mathrm{MAX}i} \tag{7}$$

$$q = \log_2[\max(P_{\mathrm{RI}1}, P_{\mathrm{RI}2}, \cdots P_{\mathrm{RI}n}) + 1] \tag{8}$$

The PARED algorithm based on multi-queue SMA ensures the minimum cache of each virtual channel; it adaptively adjusts the packet dropping probability according to the average queue length of the sharing cache area and packet priority to ensure low-probability loss of high-priority data and the increase cache utilization rate.

B. AOS VIRTUAL CHANNEL SCHEDULING ALGORITHM BASED ON VUIGA

1) DESIGN OF IMMUNE OPERATOR

In general, the immune operator contains three steps, including vaccine extraction, vaccination and immunity detection. Some rational virtual channel scheduling sequences are determined through immunity operations. These sequences are put into individuals so that individuals can have high fitness at the earlier stage of evolution. With continuous evolution of the population, vaccines extracted at the earlier stage may not have the correct guidance significance any longer, so that inoculated individuals suffer from a large probability of degeneration. Excellent vaccines shall have good problem fitness and will always be able to improve problem solutions during the population evolution. Using only interactions and the co-evolution of the population and vaccine database, the convergence speed of the algorithm can be increased greatly. On this basis, this study adds a vaccine update function in the immune operator, namely, vaccines are automatically updated during evolution according to the matching degree between vaccines and population. In this way, the effectiveness and rationality of vaccines can be ensured, and the convergence speed of the algorithm can be increased.

a: VACCINE EXTRACTION

This study generates vaccines by heuristic information. Meanwhile, to reduce similarity of vaccines and increase diversity of them, this study selects vaccines by vaccine relevancy. Vaccines are extracted by the following method: m virtual channels are selected randomly, and dynamic priorities of the m virtual channels are calculated respectively.

$$\begin{aligned} D_{\mathrm{P}i} = \alpha \cdot P_{\mathrm{RI}i} + \beta \cdot \log_2(L_i + 1) \\ + \gamma \cdot \log_2(R_{\mathrm{DIS}i} + 1) + \theta \cdot \log_2(D_{\mathrm{EL}i} + 1) \end{aligned} \tag{9}$$

where α, β, γ and θ are generated randomly; $0 \leq \alpha, \beta, \gamma, \theta \leq 1$ and $\alpha+\beta+\gamma+\theta = 1$. The m virtual channels are sequenced from high dynamic priority to low dynamic priority. The scheduling sequence is taken as a vaccine.

As for the vaccine generated currently, the relevancy between it and existing vaccines is calculated. It is set that vaccines X_i and X_j are as follows:

$$X_i = \{x_{i1}, x_{i2}, \cdots x_{im}\} \tag{10}$$

$$X_j = \left\{x_{j1}, x_{j2}, \cdots x_{jm}\right\} \tag{11}$$

The relevancy between X_i and X_j is as follows:

$$S_{ij} = \sum_{k=1}^{m} r_k \tag{12}$$

where:

$$r_k = \begin{cases} 0, & x_{ik} = x_{jk} \\ 1, & x_{ik} \neq x_{jk} \end{cases} \tag{13}$$

As for the given threshold value S_{MAX}, if the relevancy satisfies $S_{ij} < S_{\mathrm{MAX}}$, then the currently generated vaccine is accepted; otherwise, new vaccines are re-generated. The above courses are repeated until the required number of vaccines is obtained.

b: VACCINATION

Vaccination refers to inserting selected vaccines into an individual according to a certain probability so that individual fitness can be improved with a large probability. Vaccination can accelerate the reproduction of excellent modes and repair excellent individuals that are damaged by crossover and mutation. Vaccination can improve individual fitness through fine adjustment. It is applicable to individuals with high fitness. In a population G_i, if the fitness of individual x_j is $F(x_j)$, then the immunity probability of this individual is as follows:

$$P_v = \frac{F(x_j)}{\max\{F(x_l)|x_l \in G_i\}} \tag{14}$$

The steps of vaccination are as follows:

Step 1: The first individual in the current population is taken as the father individual, then Step 2 is started;

Step 2: A random number within the interval [0, 1] is generated. Whether it is smaller than the immunity probability of the father individual is determined; if the answer is yes, Step 3 is started; otherwise, Step 5 is started;

Step 3: One or multiple vaccines are selected randomly and taken as injection vaccines of the father individual. Step 4 is then started;

Step 4: Vaccination is carried out, namely, as for each selected vaccine, the scheduling sequence corresponding to two virtual channels in the father individual is made consistent with the sequence in the vaccine. Step 5 is then started;

Step 5: If the current individual is the last individual in the population, the step will be ended; otherwise, the next individual in the population is selected, and Step 2 is started.

c: IMMUNITY DETECTION

Immunity detection refers to fitness detection of individuals that have been vaccinated. The total number N_{total} of vaccinated individuals is recorded. The fitness of new vaccinated individuals is compared with that of the father individual. If the fitness of the new individual is higher than that of father individual, the new individual can be accepted; otherwise, it is deemed that the new individual suffers from obvious degeneration because of vaccination. The new individual will not be accepted. The total number N_d of individuals suffering from the degeneration is recorded.

d: VACCINE UPDATE

Through a combination of heuristic information and excellent individual extraction, the vaccine update composes a vaccine database by heuristic vaccines and excellent individual vaccines, can ensure diversity and advancement of vaccine database, can increase the convergence rate and can also avoid local convergence. The vaccine update steps are as follows:

Step 1: Update threshold H is set; immunity degeneration probability P_d is calculated.

$$P_d = \frac{N_d}{N_{total}} \tag{15}$$

where N_{total} denotes the total number of individuals that are vaccinated during the evolution from the latest vaccine database update till now. N_d denotes the total number of individuals suffering from degeneration among the N_{total} individuals. Step 2 is started.

Step 2: If $P_d < H$ is satisfied, the vaccine database need not be updated, and the step is ended; otherwise, the vaccine base will be updated, and Step 3 is started.

Step 3: The quantity of vaccines in the vaccine base is set to be n. k heuristic vaccines are generated by the heuristic information, and $k < n$. The specific approach is the same with the initial vaccine extraction method. Step 4 is started.

Step 4: Excellent individuals are used for vaccine update, namely, n-k excellent individuals are selected from each generation of the population, and some virtual channel scheduling sequences are selected from these excellent individuals as the updated vaccines to generate n-k excellent individual vaccines. The step is ended.

2) BASIC GENETIC OPERATOR

Basic genetic operators include the crossover operator, the mutation operator and the selection operator.

a: CROSSOVER OPERATOR AND MUTATION OPERATOR

In adaptive genetic algorithm (AGA) proposed by Srinivas, crossover probability and mutation probability are adjusted linearly with the individual fitness. For an individual whose fitness is higher than the average population fitness, low crossover probability and mutation probability are provided so that it can be protected and enter the next generation. For an individual whose fitness is lower than the average fitness, high crossover probability and mutation probability are provided so that it can be completely broken, and thus the space search ability can be enhanced. Hence, the paper adopts adaptive crossover probability and mutation probability, wherein crossover probability P_c and mutation probability P_m are respectively as follows:

$$P_{\mathrm{c}} = \begin{cases} \dfrac{k_1(F_{\max} - F_c)}{F_{\max} - F_{\mathrm{avg}}} & F_c \geq F_{\mathrm{avg}} \\ k_2 & F_c < F_{\mathrm{avg}} \end{cases} \tag{16}$$

$$P_{\mathrm{m}} = \begin{cases} \dfrac{k_3(F_{\max} - F_m)}{F_{\max} - F_{\mathrm{avg}}} & F_m \geq F_{\mathrm{avg}} \\ k_4, & F_m < F_{\mathrm{avg}} \end{cases} \tag{17}$$

where F_{max} denotes the maximum fitness of individuals in each generation of the population; F_{avg} denotes the average fitness of each generation of the population; F_c denotes the larger fitness in two individuals that join the crossover; and F_m denotes the fitness of the mutated individual. k_1, k_2, k_3 and k_4 are values within the interval (0,1). P_c and P_m can be adaptively adjusted.

The crossover probabilities of individuals are calculated according to Formula (16). Crossover operations are carried out according to Syswerda sequence crossover operator. Operations are as follows: two individuals to be crossed are set as father individual and mother individual. c crossover points are selected randomly in the father individual, and virtual channel numbers corresponding to them are found; the c virtual channel numbers are selected in the mother individual, rearranged according to the sequence of c virtual channel numbers in the father individual, and then put at gene positions corresponding to the mother individual in the new individual; other gene positions in the mother individual are unchanged and directly inserted into the new individual. Then, the crossover operation is complete.

Individual mutation probability is calculated according to Formula (17). m mutation points are selected randomly from the father individual to be mutated, and $m \geq 2$. From front to rear positions, virtual channel numbers corresponding to every two adjacent mutation points are interchanged successively so that mutation operations can be completed.

b: SELECTION OPERATOR

During the selection operation, survival probability of an individual is determined according to the individual's fitness so that the average fitness of the population can be increased continuously. Based on the father-son competition mechanism, the paper adopts a selecting operator through a combination of a proportional selection strategy and an elitism preservation strategy. This is beneficial for preserving excellent individuals in father and son generations and increasing the convergence rate of the algorithm. If the population scale of population G_i is M, then the fitness of individual x_j is $F(x_j)$, and the selection probability is as follows:

$$P_s = \begin{cases} 1, & F(x_j) = \max(F(x_l) | x_l \in G_i) \\ \dfrac{F(x_j)}{\sum\limits_{k=1}^{M} F(x_k)}, & F(x_j) < \max(F(x_l) | x_l \in G_i) \end{cases} \tag{18}$$

3) ANALYSIS OF THE ALGORITHM

a: ANALYSIS OF ALGORITHM'S CONVERGENCE

It is found from Formula (16) to Formula (18) that in the VUIGA algorithm, P_c, which refers to the crossover probability of the individual with the highest fitness in each generation, is 0; P_m, which refers to its mutation probability, is 0; and P_s, which refers to the probability for it to be selected into the next generation, is 1. Hence, VUIGA has the characteristics of an elitist reserved genetic algorithm. It is theoretically proved that the probability for convergence to a globally optimal solution of the elitist reserved genetic algorithm (EGA) is 1 [25]. In addition, VUIGA is based on IGA. In [26], the strong convergence of IGA is proved by analyzing some characteristics of the complement set of the global optima set. Hence, VUIGA can converge to the globally optimal solution. In addition, VUIGA automatically updates the vaccine database according to accumulated results of immunity detection to strengthen the matching degree between vaccines and population during evolution to increase the convergence rate of the algorithm.

b: ANALYSIS OF ALGORITHM'S EXECUTION TIME

The population scale is set as M. The evolution generation is G when the algorithm reaches convergence. The time of executing a vaccine extraction is t_{ve}. The time of executing a vaccination is t_{vn}. The time of executing an immunity detection is t_{id}. The time of executing a vaccine update is t_{vu}. The time of executing a crossover operator is t_c. The time of executing a mutation operator is t_m. The time of executing a selection operator is t_s.

When the evolution generation is G, the times of vaccine extraction, vaccination, immunity detection and vaccine update are G, the times of crossover operator is $G \cdot M/2 \cdot P_c$, the times of mutation operator is $G \cdot M \cdot P_m$, and the times of selection operator is $G \cdot M$. Hence, when the population reaches convergence state, the execution time is as follows:

$$\begin{aligned} T &= G \cdot t_v + G \cdot \frac{M}{2} \cdot P_c \cdot t_c + G \cdot M \cdot P_m \cdot t_m + G \cdot M \cdot t_s \\ &= G\left[t_v + M(\frac{P_c}{2} \cdot t_c + P_m \cdot t_m + t_s)\right] \end{aligned} \tag{19}$$

where:

$$t_v = t_{ve} + t_{vn} + t_{id} + t_{vu} \tag{20}$$

In formula (19), t_v, t_c, t_m and t_s of each generation are determined by population scale M. Hence, the execution time T is related to population scale M and evolution generation G. G is a finite value. Therefore, when the population scale M is not very large, the algorithm can be completed in a short time.

C. PROCESSES OF PARED-VUIGA ALGORITHM

The paper carries out AOS virtual channel multiplexing based on the PARED-VUIGA algorithm. According to the priority and queue length of each virtual channel, the algorithm organically combines queue management and virtual channel scheduling. Queue management adopts the PARED algorithm based on multi-queue SMA and takes charge of the distribution of cache resources; virtual channel scheduling adopts the virtual channel scheduling algorithm based on VUIGA, determines the transmission sequence of each virtual channel and takes charge of the distribution of bandwidth resources. The steps of the PARED-VUIGA algorithm are as follows:

Step 1: Time slot is initialized. Priority of each virtual channel is defined. Minimum cache is distributed for each virtual channel. Maximum queue length threshold and minimum queue length threshold of the sharing cache area are defined. The maximum transmission frame number N_{MAX} of each virtual channel in each scheduling is set.

Step 2: Whether packets arrive within the current time slot is determined. If the answer is yes, Step 3 will be started; otherwise, Step 5 is started.

Step 3: Average queue length L_{AVG} of the sharing cache area, and average queue length $L_{\mathrm{AVG}i}$ of each virtual channel are calculated. Dropping probability P_{b} of each packet is calculated. Step 4 is then started.

Step 4: At the probability of 1-P_{b}, each packet enters the queue of the corresponding virtual channel. Step 5 is started.

Step 5: A Non-null virtual channel set TASK is determined. If TASK=Φ, then Step 2 is started; otherwise, Step 6 is started.

Step 6: Packet loss rate $R_{\mathrm{DIS}i}$ and delay $D_{\mathrm{EL}i}$ of each non-null virtual channel are calculated. Step 7 is then started.

Step 7: Vaccine extraction operations are carried out. Step 8 is started.

Step 8: An initial population is generated randomly. The scheduling target function F is taken as the fitness function. The fitness of each individual is calculated. Step 9 is started.

Step 9: Crossover operations are carried out. The fitness of new individuals is calculated. Step 10 is started.

Step 10: Mutation operations are carried out. The fitness of new individuals is calculated. Step 11 is started.

Step 11: Vaccination operations are carried out. The fitness of new individuals is calculated. Step 12 is carried out.

Step 12: Immunity detection operations are carried out. Step 13 is started.

Step 13: Vaccine update operations are carried out. Step 14 is started.

Step 14: Selection operations are carried out. The fitness of each individual is calculated. Step 15 is started.

Step 15: Whether convergence occurs is determined; if the answer is yes, the converged individual is taken as the transmission sequence of each virtual channel, and Step 16 is started; otherwise, Step 9 is started.

Step 16: According to the transmission sequence of each virtual channel, the frames in each virtual channel are transmitted successively. N_i denotes the number of frames to be transmitted in each virtual channel. If $N_i < N_{\mathrm{MAX}}$, the number of transmitted frames of the i-th virtual channel during the scheduling is N_i; otherwise, the number of transmitted frames of the i-th virtual channel during the scheduling is N_{MAX}. Step 2 is started at the next time slot.

In conclusion, using the minimum allocation sharing scheme, the PARED algorithm adaptively adjusts packet dropping probability according to the average queue length of the sharing cache area and packet priority, which can increase the cache utilization rate. The VUIGA algorithm comprehensively considers the business priority constraint and the virtual channel comprehensive transmission urgency constraint, which can satisfy the transmission requirements of different types of business in AOS, to optimize the throughput of the system.

V. SIMULATION EXPERIMENT AND ANALYSIS

According to the system model shown in Fig. 1, the simulation experiment was carried out on the PARED-VUIGA algorithm. The number of virtual channels was set to be 20. Packet arrival was a Poisson process. The average packet arrival rate of each virtual channel was 116670 packets/s, and 5 packets were encapsulated in a frame on average, so the average frame arrival rate of each virtual channel was 23334 frames/s. Priorities of all virtual channels were sequenced from high to low levels.

A. CONVERGENCE SIMULATION OF VUIGA

Fig. 3 shows the curves of fitness, which changed with the number of iterations for two algorithms, including VUIGA and IGA. It is shown in the figure that at the initial stage of evolution, IGA has better variation rules of fitness. However, when the evolution continued to about the 14th generation, IGA fell into local optimization, while it got rid of local optimization till about the 35th generation. Fitness of VUIGA increased obviously at multiple positions, such as the 10th, 19th and 24th generations, while it stably converged to the globally optimal solution because VUIGA can automatically update the vaccine database with evolution situations and promote faster evolution of the algorithm to the optimal solution. Hence, VUIGA can more easily get rid of local optimization than IGA and has a higher convergence speed.

B. PERFORMANCE ANALYSIS OF PARTIAL VIRTUAL CHANNELS UNDER PARED-VUIGA ALGORITHM

The number of virtual channels is larger in the system. To facilitate observation, the simulation shows the performance of only the first six virtual channels.

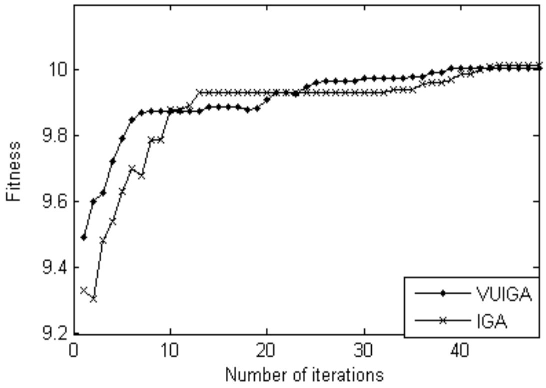

FIGURE 3. Evolution curve.

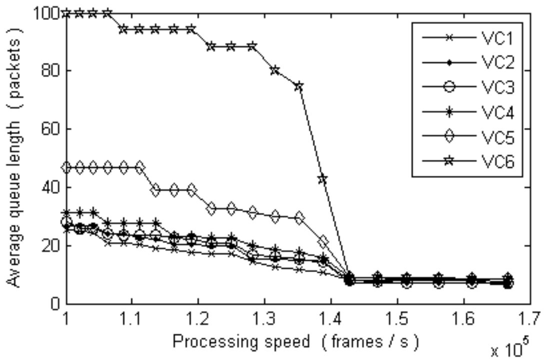

FIGURE 4. Average queue length of the first six virtual channels.

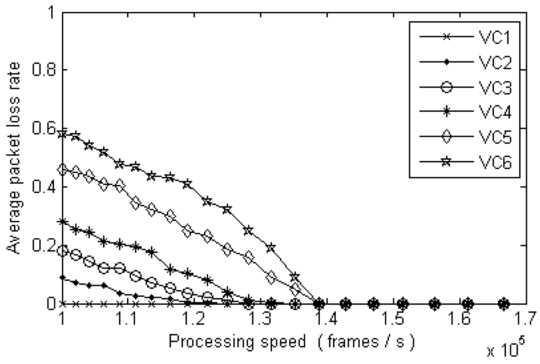

FIGURE 5. Average packet loss rate of the first six virtual channels.

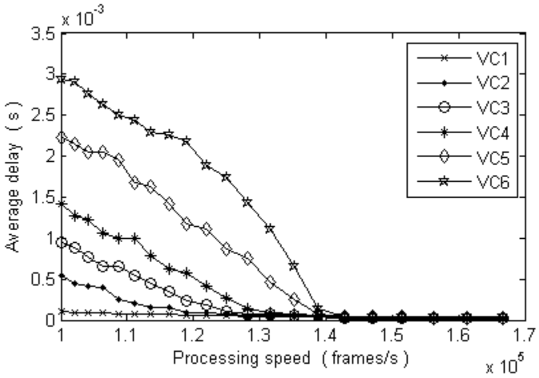

FIGURE 6. Average delay of the first six virtual channels.

Fig. 4 shows curves of average queue length of the first six virtual channels, which changed with the processing speed under the PARED-VUIGA algorithm. It is shown in the figure that, when the processing speed was lower than 140004 frames/s (total frame arrival rate of the first six virtual channels), real-time processing could not be realized. With a continuous decrease of processing speed, the average queue length of each virtual channel increased gradually. VC6 with the lowest priority had the maximum average queue length; VC5 and VC4 ranked second; and VC1 with the highest priority had the minimum average queue length. When the processing speed exceeded 140004 frames/s, the average queue length of each virtual channel was very small and could be processed in real time.

Fig. 5 shows the curve of the average packet loss rate of the first six virtual channels, which changed with the processing speed under the PARED-VUIGA algorithm. It is shown in the figure that, when the processing speed was lower than 140004 frames/s, with decrease of the processing speed, the average packet loss rate of each virtual channel increased continuously. Lower priority led to higher average packet loss rate. When the processing speed exceeded 140004 frames/s, the average packet loss rate of each virtual channel was 0, and the system could carry out real-time processing.

Fig. 6 shows the curve of average delay of the first six virtual channels, which changed with the processing speed. It is shown in the figure that, when the processing speed was lower than 140004 frames/s, with a decrease of the processing speed, the average delay of VC1 and VC2 with higher priorities changed very slightly; VC6 and VC5 with lower priorities showed obvious delay. When the processing speed exceeded 140004 frames/s, the average delay of each virtual channel approached 0.

In conclusion, the PARED-VUIGA algorithm can adaptively adjust packet dropping probability according to the packet priority at the queue management stage and can effectively reduce the packet loss rate of high-priority data. Meanwhile, at the virtual channel scheduling stage, a scheduling target function is designed according to the virtual channel's priority, queue length, packet loss rate and delay. Based on timely transmission of high-priority virtual channels, by proper reduction of performance of some middle-priority virtual channels, the performance of low-priority virtual channels can be improved. The algorithm has good fairness.

VI. CONCLUSION

Through analysis of AOS virtual channel multiplexing problems and aiming at characteristics of space business data, the paper puts forward a PARED-VUIGA algorithm that combines queue management and virtual channel scheduling. The queue management algorithm PARED is based on is the

SMA scheme, which can fully consider the importance of different types of business and can adaptively adjust packet dropping probability according to priority. The virtual channel scheduling algorithm VUIGA is based on the immune genetic algorithm and automatically updates the vaccine database according to accumulated results of immunity detection, which ensures the effectiveness of vaccines to increase the convergence speed of the algorithm. Experimental results show that the VUIGA algorithm has a quicker convergence speed than the IGA algorithm. The PARED-VUIGA algorithm can ensure small queue length, small packet loss rate and less delay for high-priority virtual channels. It also has good fairness and can satisfy the transmission requirements of different types of business in AOS. The PARED-VUIGA algorithm can increase the processing efficiency of a virtual channel multiplexing system.

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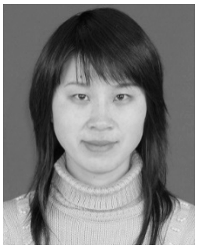

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