Access Algorithm in Software-Defined Satellite Network

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Abstract. As the number of satellite constellations increases, a subscriber may be covered by multiple satellite networks simultaneously, and access to different satellite networks can obtain different communication qualities. In this paper, we firstly propose the access network selection algorithm based on analytic hierarchy process (AHP) method in a software-defined satellite network (SDSN) architecture. The weights obtained by AHP method do not consider the real-time changes of the network parameter values, which may result in unbalanced load. In order to solve this problem, two improved algorithms based on AHP-entropy weight method (AHP-EW) and punitive variable weight method (PVW) are proposed, respectively. In the algorithms, the weights can be dynamically modified objectively according to the real-time parameter values of the network index. The simulation results show that the improved algorithms can select the most suitable network and effectively balance the load among the networks on the basis of ensuring the service quality requirements of the subscriber.

Keywords: Software-defined satellite network · Analytic hierarchy process · Entropy weight · Punitive variable weight

1 Introduction

With the rapid development of global information services, subscribers have placed higher demands on the efficiency and diversity of communications. As an important part of the global communication system, a single satellite network cannot meet the development of diversified communication services and quality of service (QoS) requirements. Therefore, multiple satellite networks have become the future development trend. However, as the number of satellite constellations increases, the subscriber may be covered by different satellites networks simultaneously. Due to the relatively high-speed movement between low-orbit satellites and terminals, accessing to different satellite networks will obtain different forwarding path and transmission performance. Besides, the handover will occur immediately which may lead to a longer delay and packet loss when the original access is inappropriate. Under this background, the access algorithm in multiple satellite networks needs to ensure the QoS requirements of subscribers and improve wireless resource utilization rate [1, 2].

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In order to improve transmission performance and to make better use of satellite channel resources, some existing papers proposed approaches such as longest coverage time, the strongest signal, the number of available channel and the comprehensive weighting algorithm [3, 4, 5]. The single-factor-based access strategy only considers one network performance index and ignores other important network parameters, which is less effective because it cannot take into account both network performance and user service characteristics. The comprehensive weighting algorithm considers multiple performance indicators to make the decision more reasonable. According to the mathematical model adopted by the comprehensive weighting algorithm, it can be divided into access algorithms based on multiple attribute decision making (MADM) [6], utility functions, fuzzy logic [7], game theory [8] and so on.

The algorithm based on fuzzy logic can achieve good performance, but the definition of fuzzy sets and fuzzy criteria is subjective and difficult to construct. Game theory obtains the best access strategy through the bilateral game between networks and users. However, the existence proof of Nash equilibrium point and its solution are complicated. The access algorithm based on MADM can comprehensively consider multiple decision indicators to select the network. The decision result is more convincing and the algorithm complexity is moderate. Therefore, MADM is widely used in network access problems.

The key step of MADM algorithm is to get the right weights. Analytic hierarchy process (AHP) is a commonly used method for getting weights. It sets relative weights on network performance parameters based on user preferences and call quality needs. Since the weights are set by subjective factors and the final weights obtained by the AHP algorithm is a fixed value, it is easy to connect the same type of service request to the same satellite network, resulting in unbalanced load. Therefore, we need to improve the access algorithm.

The aim of our work is to improve the communication quality and balance satellite networks load. Our work is based on SDSN architecture [9]. The main work of this paper is as follows:

In AHP, index weights are only based on the preference of users. Once the weight is determined, it will not change any more. To solve the problem that the weights calculated by AHP are fixed values and does not consider the real-time changes of network parameters, which will lead to an inappropriate result, we use entropy technology to modify network parameter weights. The entropy value is sensitive to the dispersion of the network parameter. Therefore, it makes the judgment result more objective. When the available load of a satellite network is below the threshold, there is a certain possibility that new subscribers still access to this satellite network, which may cause the communication quality deteriorating. On this basis, an optimal comprehensive evaluation model of punitive variable weight is proposed while considering the role and effect of weights and index values. This effect is achieved by making the weights of the indexes change with the index values. Through this model, when the index parameter deteriorates, the impact of this index on the comprehensive evaluation function is increased.

In Sect. 2, we firstly show the SDSN architecture and comprehensive evaluation model. Then the steps to calculate network parameter weights based on AHP are introduced. In Sect. 3, we proposed two improved algorithms based on entropy weight and punitive variable weight. In Sect. 4, We do experiments under the three algorithms and analyze the simulation results. It can be seen that the proposed algorithm can effectively balance the network load while ensuring the QoS requirements of users. And conclusion is given in Sect. 5.

2 Access Selection Algorithm in SDSN

2.1 SDSN Architecture

With the rapid increase in the number of subscriber and the amount of communication data, satellites need more storage space to manage the communication network. However, the storage capacities of satellites cannot meet the requirements of storing. In this paper we use the SDSN architecture proposed in [10] to solve this problem.

The controller plane consists of ground stations and GEO satellites. The ground station is used as the main controller to collect the global status information of satellites and generate access instruction. It analyzes the service characteristics after accepting the access request, executes a corresponding algorithm based on the collected network parameters to select the satellite network, and returns the result to the data plane. GEO satellites serve as local controllers. They monitor the status of LEO satellites, and communicate with the ground master controller in real time. Data plane consists of LEO satellites (Fig. 1).

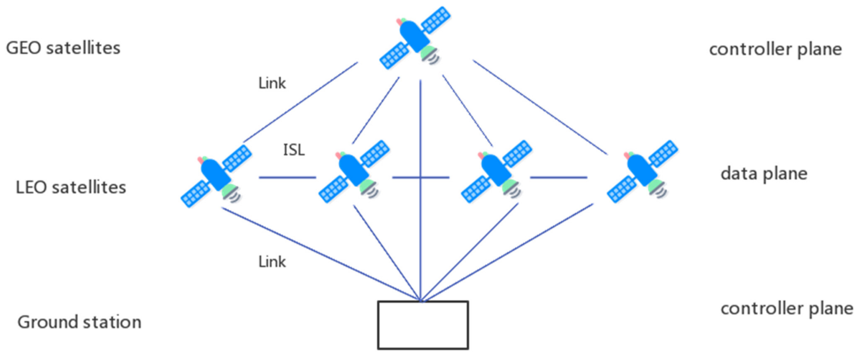

Fig. 1. The SDSN structure

2.2 Access Evaluation Model

The index that affect the selection of satellites are mainly considered from the subscriber preference and network parameters, including transmission reliability, timeliness, throughput, and network load. This paper selects delay, covered time, packet loss rate, transmission rate and load as performance evaluation indexes.

The comprehensive evaluation equation of the access algorithm is as follows:

$$f_i = \sum_{j=1}^{M} w_j * x_{ij} \tag{1}$$

where f_i is the comprehensive evaluation value of the satellite network i, w_j is the weight of the j th index, and x_{ij} is the value of j th index in the satellite network i. If the value of f_i is higher, the possibility of selecting the i th satellite network to access is higher.

In this paper, the standardization process of network parameters is as follows. Assume that there are N satellite networks and M indexes parameters. The evaluation indexes are divided into the cost type and benefit type. If the value of the cost index is smaller, the network is better for users to access. Indexes such as delay, and packet loss rate are cost type. The calculation to standardize the cost index parameter is as follows:

$$y_{ij} = \frac{max_{1 \le i \le n}\{x_{ij}\} - x_{ij}}{max_{1 \le i \le n}\{x_{ij}\} - min_{1 \le i \le n}\{x_{ij}\}} \tag{2}$$

The larger the benefit type index value is, the better networks will be. Indexes such as transmission rate, network available load and covered time are benefit type. The calculation to standardize the benefit index parameter is as follows:

$$y_{ij} = \frac{x_{ij} - min_{1 \le i \le n}\{x_{ij}\}}{max_{1 \le i \le n}\{x_{ij}\} - min_{1 \le i \le n}\{x_{ij}\}} \tag{3}$$

where y_{ij} is the standardized values of x_{ij}.

2.3 AHP Based Access Selection Algorithm

In the mid-1970s, American operations researcher T.L. Saaty formally proposed AHP. AHP is a commonly used decision analysis method, which can solve complex problems with multiple objectives [11]. This method combines quantitative analysis and qualitative analysis, and uses the experience of the decision maker to measure the relative importance between indicators. The index weights of each decision-making scheme are given, and finally the order of each scheme is obtained according to the weights. Because of its practicability and effectiveness in handling complex decision-making problems, it has quickly gained worldwide attention.

It decomposes a complex factor into several different simple factors, and quantitatively considers the dominant relationship between them, and finally forms a multi-level structure.

Establish a Hierarchy Model. According to the relationship, the hierarchy model layers are divided into decision layer, criterion layer and target layer. In this paper, the decision layer is to select the optimal satellite network to access, and the target layer is candidate satellites with different network parameters. The criterion layer is an important indicator that needs to be considered when accessing a satellite network, including network delay, covered time, packet loss rate, optional transmission rate, and network load. The hierarchy model is shown in Fig. 2.

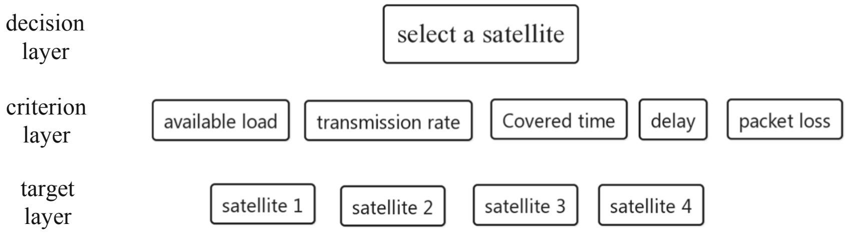

Fig. 2. The hierarchy model.

Constructing the Pairwise Comparison Matrix. Assuming that there are n elements participating in the comparison, a paired comparison matrix $A = (a_{ij})_{n\times n}$ is formed. Each value a_{ij} in the matrix reflects the relative importance between index i and other indexes j(i, j = 1, 2..., N; i ≠ j). The matrix formed by the pairwise comparison results is called the comparison matrix. The comparison matrix has the following properties:

$$a_{ij} = \frac{1}{a_{ji}} \tag{4}$$

Take voice services as example to construct a comparison matrix. Voice services have the highest requirements for real-time transmission. We set the relative importance of the five indicators in Table 1.

Table 1. The comparison matrix $A = (a_{ij})_{5\times 5}$ of indexes.

Attributes	Delay	Covered time	Loss	Load	Speed
Delay	1	2	4	6	4
Covered time	1/2	1	2	4	2
Loss	1/4	1/2	1	2	2
Load	1/6	1/4	1/2	1	1/2
Speed	1/4	1/2	1/2	2	1

Then we calculate a list of the relative weights of the factors, which is called an eigenvector. We can get the eigenvector ω corresponding with the largest eigenvalue λ_{max} from Table 1:

$$\omega = (0.8309, 0.4384, 0.2575, 0.1165, 0.1938) \tag{5}$$

Consistency Testing. Theoretical analysis shows that if the matrix is a completely consistent pairwise comparison matrix, it should satisfy $a_{ij} * a_{jk} = a_{ik}, 1 \le i, j, k \le n$.

In such a case, the w vector satisfies the equation $A\omega = \lambda_{max}\omega$. However, it is impossible to satisfy many of the above equations when constructing a pairwise comparison matrix involving human judgement. Therefore, a certain degree of inconsistency can be allowed for the pairwise comparison matrix.

The difference between λ_{max} and n is an indication of the inconsistency of the judgements. If $\lambda_{max} = n$ then judgements have turned out to be consistent. Therefore, the inconsistency of A can be measured by the value of $\lambda - n$. A consistency index is defined as:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (6)$$

λ_{max} is the largest eigenvalue and n is the number of the indexes. We can get $CI = 0.0172$ according to Eq. (6).

RI is called the average random consistency index, and it is only related to the matrix order. RI is the standard for checking the consistency of the pairwise comparison matrix A (Table 2).

Table 2. The standard value of consistency index RI.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Calculate the random consistency ratio CR of pairwise comparison matrix according to the following equation:

$$CR = \frac{CI}{RI} \quad (7)$$

If $CR < 0.1$, the comparison matrix is considered to have passed the consistency test, otherwise reconstruct the comparison matrix. According to Eq. (7), $CR = 0.0154 < 0.1$. Therefore, the matrix we construct in Table 1 have passed the consistency test. Normalize ω vector and finally get weights:

$$w_{AHP} = (0.4523, 0.2387, 0.1401, 0.0634, 0.1055) \quad (8)$$

According to Eq. (1) and (8), we can select the suitable satellite network with the largest f_i.

3 AHP-EW and PVW Based Improved Algorithm

We can find that index weights are only based on the preference of users in AHP. Once the weight is determined, it will not change any more so that the result can be unreasonable sometimes. Therefore, two improved algorithms are proposed in this section.

3.1 EW Method

According to the explanation of the basic principles of information theory, in the system information is a measure of the degree of order and entropy is a measure of the degree of disorder. According to the definition of information entropy, the entropy value can be used to judge the degree of dispersion. If the information entropy value of the index is smaller, the impact of this index on the comprehensive evaluation is greater. If values of the index parameters are all equal, this index does not play a role in the comprehensive evaluation formula. Therefore, the weight of each index can be calculated according to the actual network parameter value through the concept of information entropy, which provides a basis for comprehensive evaluation of multiple indicators.

Firstly, we calculate the entropy of each index, H_j:

$$H_j = \frac{1}{\ln n} * \sum_{i=1}^{n} y_{ij} * \ln y_{ij} \tag{9}$$

We can get index dispersion degree d_j:

$$d_j = 1 - H_j \tag{10}$$

Finally, we can get the weight w_j:

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \tag{11}$$

The weights calculated by the EW method are obtained according to the actual network parameter values instead of user preference,which can objectively reflect the influence of network indexes. Combining the entropy weights with the weights obtained by the AHP can improve the problem of excessive subjectivity of AHP.

$$w_{AHP\_EW} = \frac{w_{AHP} + w_{EW}}{2} \tag{12}$$

3.2 PVW Method

According to the previous idea of variable weights, when the value of the index parameter of a network deteriorates, in order to reduce the probability of accessing to this network, the proportion of the index weight in the comprehension evaluation function should be increased. Therefore, this paper adopts punishment variable weight method with hysteresis to modify the weights of the deterioration indexes [12, 13, 14]. When the satellite network normalization parameter y_{ij} is above the threshold y_{th}, priority is given to user preferences to ensure the QoS requirement. When y_{ij} is below to the threshold y_{th}, the index weight will be changed. The flow chart of AHP-EW and PVW based accessing algorithm is as follows (Fig. 3):

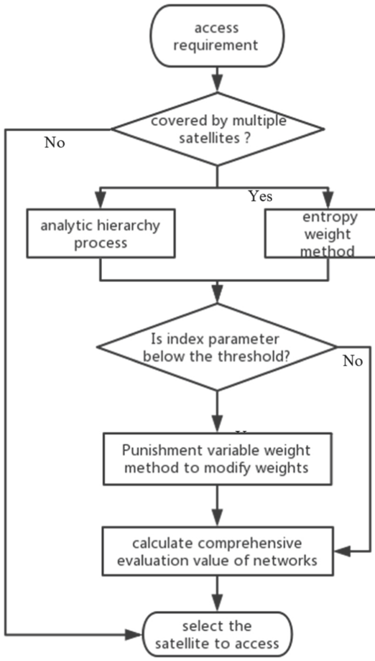

Fig. 3. Flow chart of access algorithm based on PVW method

We first define the weight correction coefficient as

$$k_{ij} = \begin{cases} 1 & y_{ij} > y_{th} \\ e^{-\theta\left|y_{ij} - y_{th}\right|} & 0 < y_{ij} \leq y_{th} \end{cases} \tag{13}$$

where $k_{ij}(i = 1, 2..., N;\ j = 1, 2..., M)$ is the correction coefficient of the j th index in satellite network i, y_{th} is the threshold and θ is the punishment index. If the value of θ is larger, the punishment will be stronger.

Then, updated weights are as follows:

$$w_{ij} = \frac{w_j * k_{ij}}{\sum_{j=1}^{m} w_j * k_{ij}} \tag{14}$$

$w_{ij}(i = 1, 2..., N;\ j = 1, 2..., M)$ is the weight value of the index j in satellite network i. According to formula (12) and (13), w_{ij} is monotonous declined with y_{ij}, which reflects the punishment for the uneven configuration of indicators.

4 Experimental Simulations

We assume that all the users want maximum speed and covered time, minimum delay and packet loss. The detailed parameters of the satellite networks are shown in Table 3.

Table 3. Simulation parameters of the satellite networks.

	Satellite 1	Satellite 2	Satellite 3	Satellite 4
Delay/ms	40	60	80	60
Loss/ %	0.09	0.08	0.06	0.06
Speed/Mbps	3	2	2.5	1
Covered-time/min	12	10	5	11
Available load/%	30	50	20	80

Assuming that in the area covered by the network overlap, the arrival of new services follows the Poisson distribution and the arrival rate $\lambda \in [0.1, 1]$, the average value of the service time is 60 s.

Here we define the user satisfaction function as

$$u_i = k_1 * y_{delay,i} + k_2 * y_{loss,i} + k_3 * y_{speed,i} \tag{15}$$

u_i is the satisfaction value of accessing to the network. y is the standardized index value of delay, packet loss ratio and transmission speed. If the satisfaction value is higher, it can meet QoS requirement better. According to formula (3) and (14), We have:

$$u_i = \{0.8004, 0.4677, 0.3513, 0.501\} \tag{16}$$

It can be seen that user satisfaction is highest when accessing to network 1, network 4 is the second one and network 3 is the worst. The influence of on variable weight coefficients θ on the comprehensive evaluation value of networks f_i is discussed as follows:

Figure 4 shows the f_i of satellite networks under different θ when the traffic load of network 1 is heavy with 10% available load. Users will choose the network with the maximum f_i to access to.

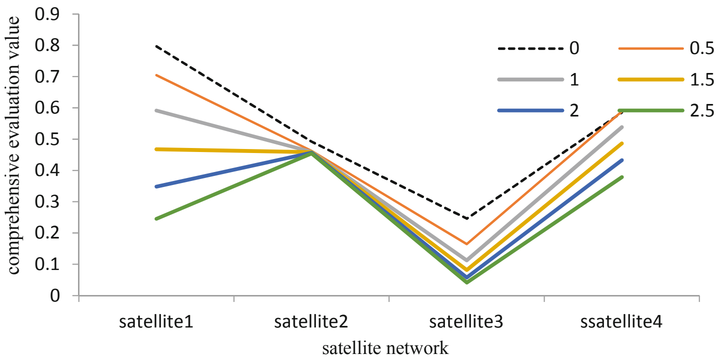

Fig. 4. Comprehensive evaluation values of the satellite networks under different θ.

We can see that when $\theta < 1.5$, network 1 obtains f_1 which is the highest value of f_i even though the user satisfaction value u_i of network 1 is also the highest according to Eq. (15). However, the traffic load of network 1 is heavy and access to network 1 is more likely to cause congestion. The effect of variable weight is not obvious while θ is small.

when $\theta > 2$, the punishment for the load index causes network 1 a low f_i. This will sacrifice QoS to balance the network load. The user will choose network 2 to access, but it is not the optimal option according to Eq. (15) because network 4 has the second highest user satisfaction value u_4. In this paper, we set $\theta = 1.5$, which not only increases the impact of the load index on f_i, but also ensure users' best QoS requirements.

Figure 5, 6 and 7 show the available loads of four satellite networks change with the increase of users under AHP, AHP-EW and PVW algorithm respectively. In Fig. 5, the user first selects the network 1 with the highest comprehensive evaluation value f_1 to access. When the number of users accessing to the network 1 reaches 28, the network 1 has no available load then user begins to select the suboptimal satellite network 4 to access, which may cause network congestion and reduce transmission quality;

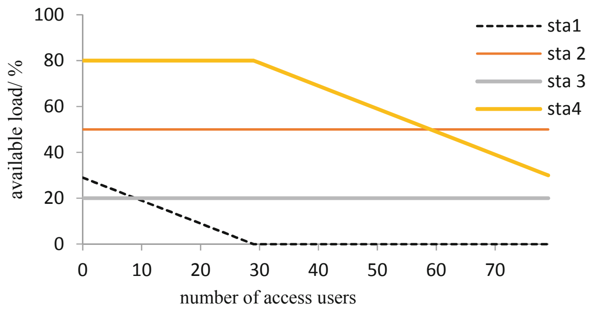

Fig. 5. The trend of available load with the increase of the number of users under AHP.

In Fig. 6, with the AHP-EW algorithm, users select satellite network 1 at first. After 4 users accessing to satellite network 1, the available load of network 1 decreases and the AHP-EW increases the weight of the available load index to increase its influence on f_i. Because the value of f_1 and f_4 are similar, users start to alternately select satellite network 1 and satellite network 4 to access.

In Fig. 7, the comprehensive evaluation value obtained by the PVW is similar as AHP method at first, because the available load of the four satellite networks has not dropped to the threshold and there is no need to modify the network index weight at the beginning. Since the available load of the network 1 drops to the threshold, the network index weights are modified. The additional user subscribers select network 4 to access.

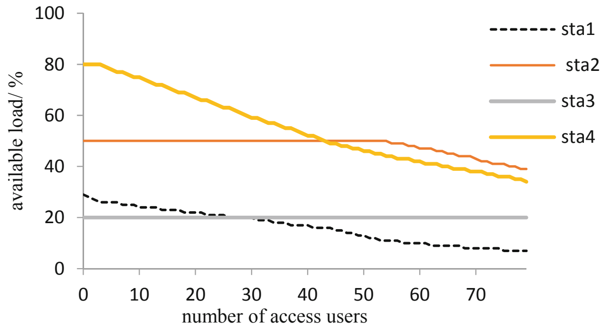

Fig. 6. The trend of available load with the AHP-EW method.

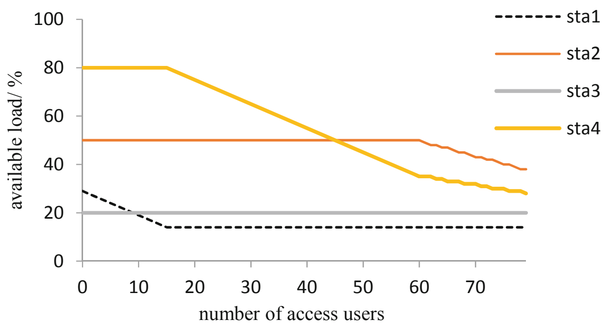

Fig. 7. The trend of available load with PVW method.

From Figs. 5, 6 and 7, since the value of u_3 and f_3 of network 3 are the lowest, that is, the performance indexes of network 3 is not suitable for user to access. Therefore, the available load of network 3 has not changed with the three algorithms.

Figure 8 shows the trend of load variance under three algorithms. We can see that as the number of access users increases, the network load variance of the AHP and PVW algorithms both increase first because the selection result is based on the user's preference. When the number of access users is 18, the load variance value of PVW reaches the maximum value and then decreases. This is because the available load parameters fell to the threshold and the PVW algorithm began to change the weight of the network parameters. When there are few access users, the load variance of AHP-EW algorithm gradually decreases, and the balancing effect is better than AHP and PVW algorithms. When the number of access users exceeds 50, the PVW algorithm has the best balance effect.

Figure 9 shows the relationship between the access blocking rate and the arrival rate of new services under three algorithms. The access algorithm based on AHP_EW and PVW can effectively reduce the blocking rate and ensure the transmission quality while balancing the network.

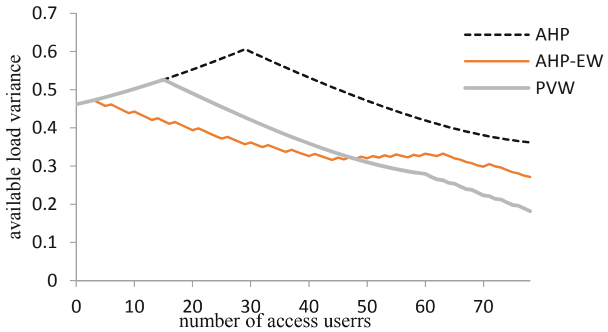

Fig. 8. The trend of load variance with three algorithms

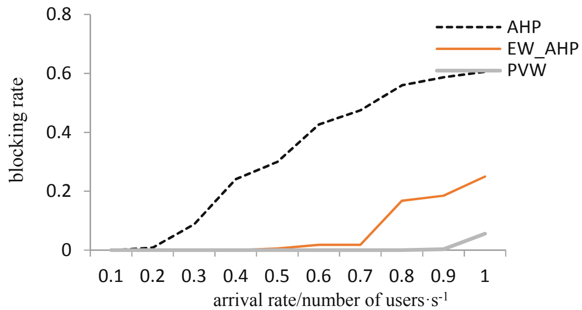

Fig. 9. The trend of the access blocking rate with three algorithms

5 Conclusion

This paper proposed two improved network access selection algorithms based on AHP. The algorithms based on the AHP-EW method calculated the comprehensive weights of the indexes. Then, the PVW method was proposed and the weights of the indexes are dynamically adjusted through the punishment variable weight function to obtain variable weights. The AHP-EW and PVW method not only considered the users' preference, but also considered the actual parameter value of the network to ensure the rationality of the judgment result.

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