Towards Self-organized Networking in Large-Scale Nano-satellite Networks

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Abstract. Nano-satellites have developed rapidly in the fields of communications and remote sensing due to their small size, low cost and flexibility, the number of which has increased dramatically. However, massive amounts of data cannot be effectively transmitted through ground stations or satellite networks due to the growth of transmission demand. To overcome the problem, the nano-satellite network clustering algorithm was designed. Specifically, by clustering nano-satellites, the cluster head can gather remote sensing data and control directives of satellite nodes in the cluster, reduce the collision probability of random transmission, improve the utilization of communication resources and network throughput. We established a random access model of nano-satellites based on a two-dimensional Markov chain, which characterizes the features of the satellite network multiple access process without a carrier sensing mechanism. We also deduce the throughput of the nano-satellite network. We obtain the optimal number of clusters according to the nano-satellite scale, link rate and traffic arrival rate. The performance of non-clustered networks and clustered networks is compared and analyzed by simulation. The result shows that the clustered network reduces the average delay and improves the efficiency of information transmission compared with the non-clustered network.

Keywords: Large-scale Nano-satellite · Multiple access · Markov Chain · Clustering network

1 Introduction

Whether in military communications or civil communications, nano-satellites have great development trends and application prospects [13]. Due to the growth of transmission demand, resource-limited satellite networks face tremendous transmission pressure, since the deployment of ground stations is highly costly. Even worse, the existing clustering algorithm does not consider the optimal number of clusters or give an analysis method for the number of clusters, leading to uneven network clustering [4, 13]. If there are too many clusters, the collision probability between cluster heads will increase and the channel reuse rate will be reduced. Furthermore, efficient access protocols for clustered satellite networks are missing.

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In fact, there are many excellent clustering-related works. As in [5], the clustering algorithm assigns unique identifiers to the nodes and selects the node with the smallest ID number as the cluster head node, which is easy to calculate and implement. However, it will cause uneven resources for different clusters. And the selected cluster head will not change, such that the continuous use of cluster head can cause fast energy consumption. In [6], an algorithm based on the geographical location of the cluster head node is proposed, which can artificially control the size of the cluster according to user needs, such that the network load is balanced. However, it does not indicate how to calculate the optimal number of clusters. In [7], an algorithm based on node weights is proposed. The advantage of this algorithm is that it can comprehensively consider a variety of factors, but because the weights are difficult to determine, the selected cluster head may not be the best cluster head in the current network environment. In [8], a LEACH clustering algorithm was proposed. The disadvantage of this algorithm is that the cluster heads are unevenly distributed, because the cluster heads may appear concentrated in a certain area of the network. In [9], the enhanced LEACH is proposed. This algorithm considers the remaining energy of nodes when selecting cluster heads. However, factors such as the optimal number of clusters and node mobility are not considered. Therefore, the existing algorithms can be improved.

To solve the problem, we established a random access model of nano-satellites based on a two-dimensional Markov chain, which characterizes the features of the satellite network multiple access process without a carrier sensing mechanism. We also deduce the throughput of the nano-satellite network under the access mechanism. In order to maximize the throughput, a nano-satellite network clustering algorithm is designed, which considers the arrival rate, the scale of the nano-satellite and the link rate. Finally, we compare and analyze the performance of clustered networks and non-clustered networks through simulation, and the results prove that the clustering algorithm effectively improves the network performance.

2 System Model

In this paper, a random access model of nano-satellites based on two-dimensional Markov chains is established, which characterizes the features of the multiple access process of satellite networks without carrier sensing mechanism. Since the traffic of nano-satellites is not saturated, this paper based on Malone's analysis method [10], calculates the probability τ, which represents a station sending a packet in a slot.

Based on Bianchi's model [11], Malone introduced new states $(0, \mathrm{k_e})$ for $k \in [0, W_0 - 1]$, representing a station which has just sent a packet without waiting. The Markov chain model is shown in Fig. 1.

According to the probability distribution of Markov chain, it can be known that τ is:

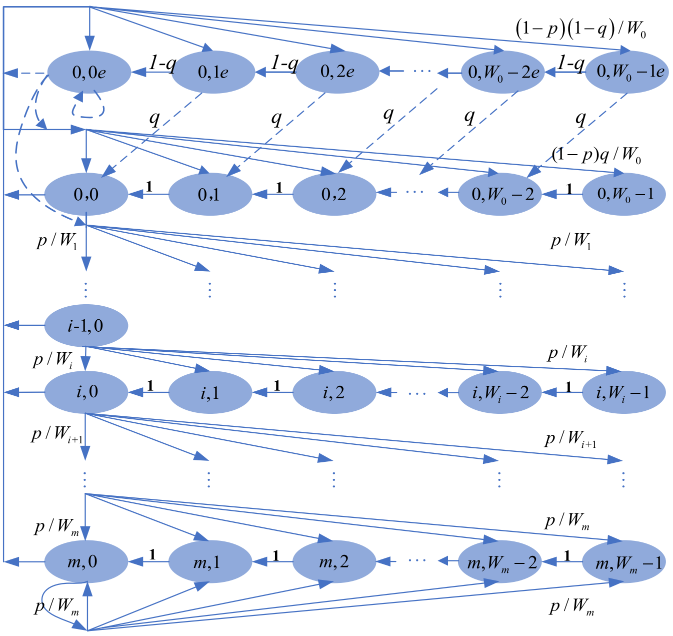

Fig. 1. Unsaturated Markov chain

$$\tau = \left(\frac{q^2W_0}{(1-p)(1-q)(1-(1-q)W_0)} - \frac{q^2P_{idle}}{1-q}\right) / \left[\begin{array}{l} (1-q) + \frac{q^2W_0(W_0+1)}{2(1-(1-q)W_0)} + \frac{q(W_0+1)}{2(1-q)} \\ \times(\frac{q^2W_0}{1-(1-q)W_0} + (1-P_{idle})(1-q) - qP_{idle}(1-p)) \\ + \frac{pq^2}{2(1-p)(1-q)} \times (\frac{W_0}{1-(1-q)W_0} - (1-p)P_{idle}) \\ \times(2W_0\frac{1-p-p(2p)^{m-1}}{1-2p} + 1) \end{array}\right] \tag{1}$$

It can be seen that τ depends on p, q, P_{idle}, W_0 and m. The specific analysis will be introduced in detail in the performance analysis.

Also, we can know the probability q can be written as:

$$q = \min(E_s/\text{mean inter-packet time}, 1) \tag{2}$$

3 Clustering Algorithm

Aiming at the low efficiency of mass information transmission in large-scale nano-satellite communication scenarios, a new and efficient clustering algorithm is designed. The communication scene of a large-scale nano-satellite is shown in Fig. 2, which is composed of a nano-satellite, a low-orbit constellation and a ground station.

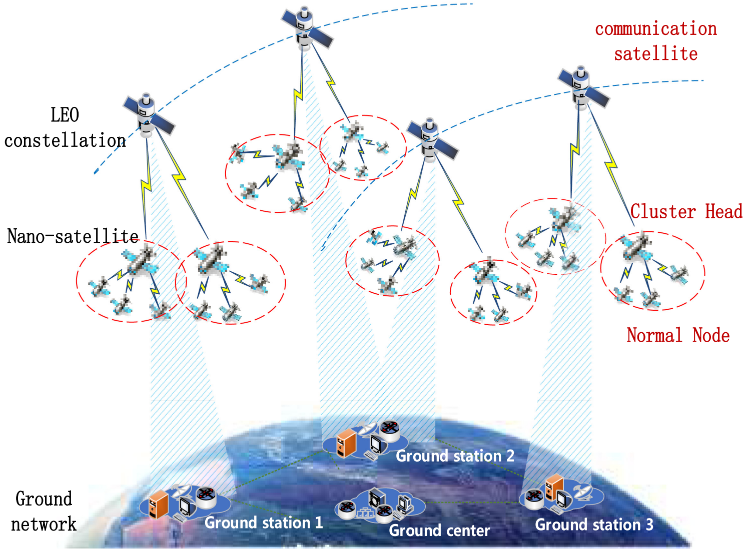

Fig. 2. Communication scenarios of large-scale nano-satellites

Ordinary nodes can use the polling method by cluster head nodes to avoid conflicts; the distributed competition method based on RTS/CTS is used between cluster head nodes to complete the channel resources. The cluster head nodes and ordinary nodes access mode are shown in Fig. 3.

The number N of nano-satellites within the coverage of each satellite can be calculated based on the scale of nano-satellites. If $N < M_{best}$, there is no need to cluster the satellites, the satellites can be directly connected to the communication satellites through competing channel resources. If $N > M_{best}$, the satellites need to be clustered, and M_{best} satellites are considered as the cluster head nodes among N satellites (Fig. 4).

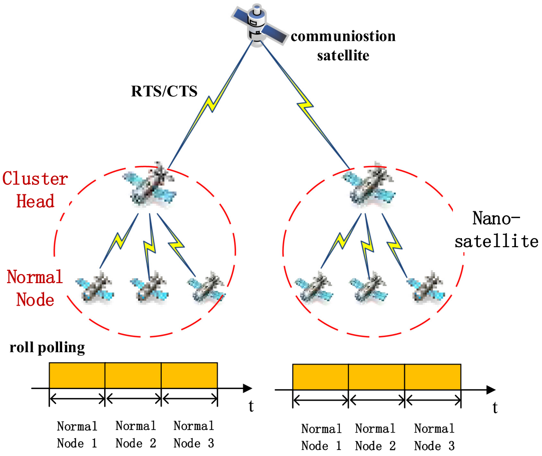

Fig. 3. Cluster head nodes and ordinary nodes access mode

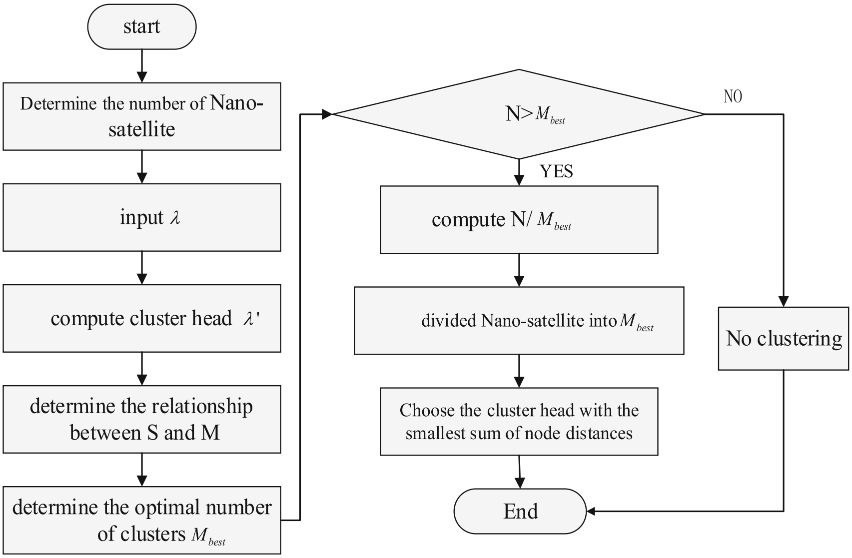

Fig. 4. The specific algorithm process

4 Performance Analysis

4.1 The Arrival Rate

The traffic arrival rate of the cluster head node λ' can be written as:

$$\lambda' = \frac{1}{(\frac{N}{M} - 1) \times (\varepsilon + 2\delta_1) + (\frac{N}{M} - 1)\lambda \times \frac{L}{c}} \tag{3}$$

Among this, λ represents the traffic arrival rate of each satellite, N represents the number of nano-satellites, M represents the number of clusters, ε represents the delay of the cluster head node sending polling frames to the ordinary nodes in the cluster, δ_1 represents the propagation delay from the ordinary node to the cluster head node, and L/c represents data transmission delay.

4.2 The Collision Probability

Since the communication scenario studied in this paper is a space-based information network, when the CSMA/CA protocol is used between clusters, the cluster head nodes cannot listen to each other's state, and can only through RTS/CTS to determine whether the channel is occupied.

As shown in Fig. 5, when station A sends an RTS frame to reserve the channel and waits for the return of the CTS frame, since station B has no listening function, no matter which slot backoff time of station B is completed in the interval between RTS and CTS, station A and station B will collide.

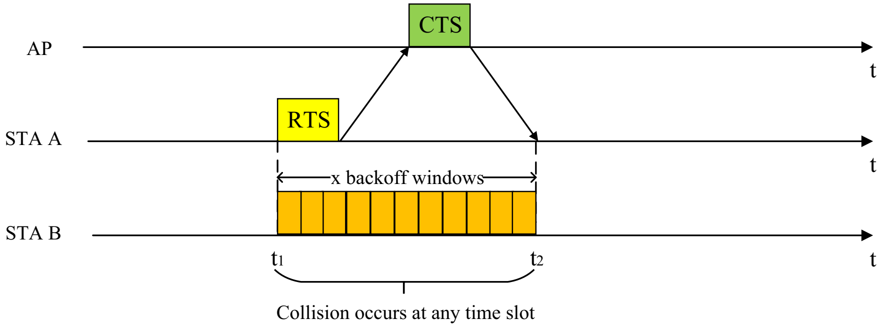

Fig. 5. Data collision slots

The probability of success can be expressed as:

$$1 - p = (1 - \tau)^{x(n-1)} \tag{4}$$

According to the probability of success, the collision probability p is:

$$p = 1 - (1 - \tau)^{x(n-1)} \tag{5}$$

x is the number of time slots included in the interval between RTS and CTS, n is the number of stations, σ is the length of each time slot, δ_2 is the propagation delay, then the value of x is:

$$x = \frac{RTS + CTS + 2\delta_2}{\sigma} \tag{6}$$

4.3 The Time Spent Each State

The probability that at least one packet is being transmitted in a time slot P_{tr} is:

$$P_{tr} = 1 - (1 - \tau)^n \tag{7}$$

Assuming P_s is the probability that is only one packet transmission and the transmission is successful, then P_s is:

$$P_s = \frac{C_n^1 \tau (1 - \tau)^{x(n-1)}}{P_{tr}} = \frac{n\tau (1 - \tau)^{x(n-1)}}{1 - (1 - \tau)^n} \tag{8}$$

Assuming P_{idle} is the probability of channel free, then P_{idle} is:

$$P_{idle} = 1 - P_{tr} = (1 - \tau)^n \tag{9}$$

If the channel is idle, the delay T_{idle} can be written as:

$$T_{idle} = \sigma \tag{10}$$

The probability of successful packet transmission P_{succ} is:

$$P_{succ} = P_{tr} P_s = n\tau (1 - \tau)^{x(n-1)} \tag{11}$$

If there are data packets successfully transmitted in the channel, the delay T_{succ} is represented by:

$$T_{succ} = RTS + SIFS + \delta_2 + CTS + SIFS + \delta_2 + E[P]/c + SIFS + \delta_2 + ACK + \delta_2 \tag{12}$$

The probability of collision of data packets in the channel is:

$$P_{fail} = P_{tr}(1 - P_s) = 1 - (1 - \tau)^n - n\tau (1 - \tau)^{x(n-1)} \tag{13}$$

If the data packets collide in the channel, the time delay T_{fail} is written as:

$$\begin{aligned} T_{fail} &= \frac{1}{2}(RTS + \delta_2) + \frac{1}{2}(RTS + SIFS + CTS + 2\delta_2) \\ &= RTS + \frac{1}{2}(SIFS + CTS + 3\delta_2) \end{aligned} \tag{14}$$

Above all, the expected time spent per state E_s can be written as:

$$\begin{aligned} E_s &= P_{idle}T_{idle} + P_{succ}T_{succ} + P_{fail}T_{fail} \\ &= (1-\tau)^n\sigma + n\tau(1-\tau)^{x(n-1)}(RTS + CTS + E[P] + ACK + 3SIFS + 4\delta_2) \\ &+ \left(1 - (1-\tau)^n - n\tau(1-\tau)^{x(n-1)}\right)\left(RTS + \frac{1}{2}(SIFS + CTS + 3\delta_2)\right) \end{aligned} \tag{15}$$

4.4 System Throughput

Throughput S is the payload transmitted successfully on the channel per time, then S is expressed as the length of the data packet successfully transmitted within the time E_s:

$$S = \frac{P_{succ}E[P]}{E_s} \tag{16}$$

By combining Eqs. (1), (2), (5) and (9), the relationship between the system throughput S and the number of clusters M can be obtained. The number of M when the throughput S is the highest is taken as the optimal cluster number M_{best}.

4.5 The Average Delay

We will compare the performance between non-clustered networks and clustered networks using the average delay (Fig. 6).

Through Eq. (15), we can calculate the average delay T_{ad} of the nano-satellite connecting to the communication satellite and successfully sending the data packet, then the average delay T_{ad} is expressed as:

$$T_{ad} = \frac{L}{\frac{P_{succ}L}{E_s}} = \frac{E_s}{P_{succ}} \tag{17}$$

The average delay of the non-clustered network $T_{not\_cluster}$ is:

$$T_{not\_cluster} = N\lambda \times T_{ad} = N\lambda \times \frac{E_s}{P_{succ}} \tag{18}$$

N represents the number of nano-satellites competing for channel resources, λ represents the traffic arrival rate of nano-satellites.

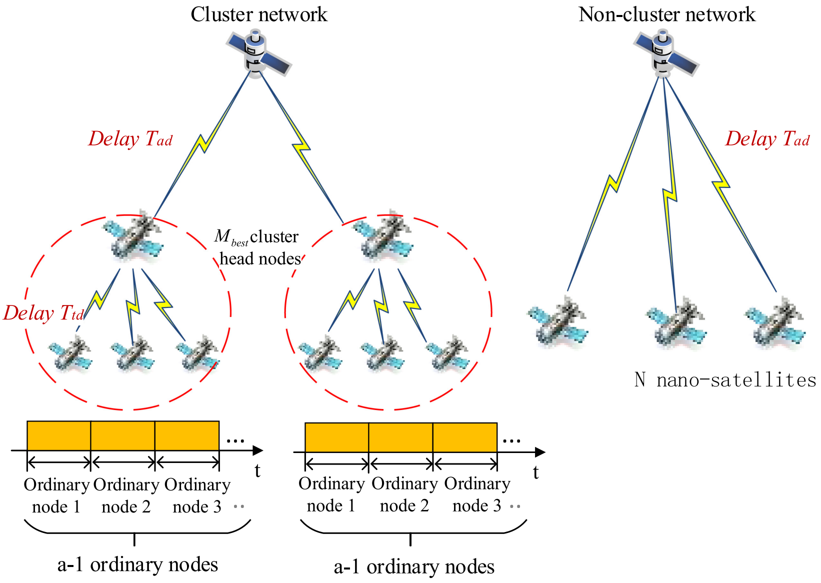

Fig. 6. The average delay of the clustered network and the non-clustered network

The average delay of the clustering network $T_{cluster}$ is:

$$\begin{aligned} T_{cluster} &= M_{best}\lambda' \times (T_{td} + T_{ad}) \\ &= M_{best}\lambda' \times \left(\left(\frac{N}{M_{best}} - 1 \right) \times (\varepsilon + 2\delta_1) + \left(\frac{N}{M_{best}} - 1 \right) \lambda \times \frac{L}{c} + \frac{E_S}{P_{succ}} \right) \end{aligned} \tag{19}$$

5 Simulation and Results Analysis

To verify the performance of the designed nano-satellite network clustering algorithm, this paper with simulations using MATLAB. We compared the average delay of the clustered network and the non-clustered network under different traffic arrival rates. This section first sets up the simulation parameters, then analyzes the performance of the network based on the simulation results (Table 1).

The relationship between the number of clusters and the arrival rate under the conditions of different scales of nano-satellites is shown in Fig. 7. Obviously, the number of clusters increases as the arrival rate or the scale of nano-satellites increases. The number of clusters gradually increases when the arrival rate is low. This is because the load in the network is low, which means the collision probability between clusters is low, and the competition delay is small. The number of clusters increases slowly when the traffic arrival rate is high. This is because the load is high, so the collision probability between clusters is high, and the competition time is prolonged. The selection of the optimal number of clusters aims to balance the polling delay within the

Table 1. Simulation parameter.

Parameter	Value	Parameter	Value
Data packet length	8000 bits	ACK frame length	112 bits
RTS frame length	160 bits	CTS frame length	112 bits
Propagation delay between nano-satellites	0.03 ms	Propagation delay between nano-satellite and communication satellite	1 ms
Back-off window	32	Back-off stage	3
Time slot length	0.8 ms	Traffic arrival rate	(0,1]

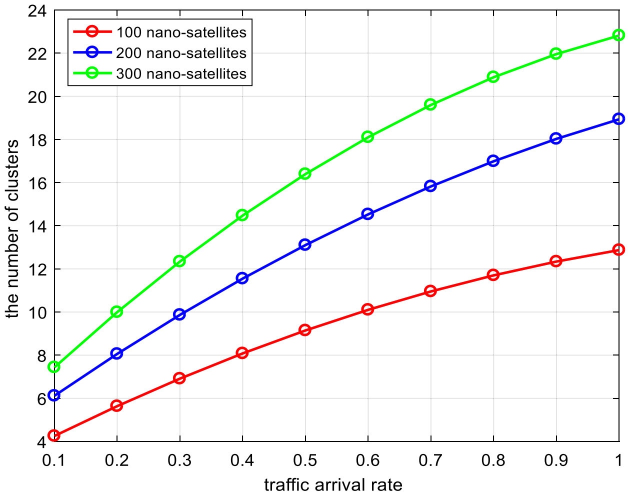

Fig. 7. The relationship between the traffic arrival rate and the number of clusters for different scales of nano-satellites

cluster and the competition delay between clusters, so as to maximize the system throughput and minimize the network delay.

As shown in Fig. 8, it is the relationship between the traffic arrival rate and the number of clusters under the conditions of different link rates.

Figures 9, 10 and 11 show the relationship between the average delay and the arrival rate. As the traffic arrival rate increases, the average delay increases.

Figure 9 shows the relationship between the average delay and the arrival rate of the non-clustered network under the different scales of the nano-satellite. Figure 10 shows the same relationship of the clustered network. It can be seen that as the network scale increases, the average delay also increases due to the probability of node collisions increasing. In general, the larger the scale of the nano-satellite, the more efficient the clustering algorithm is.

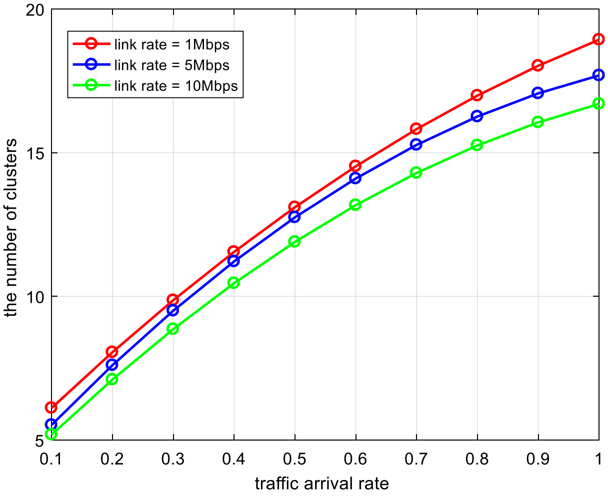

Fig. 8. The relationship between the traffic arrival rate and the number of clusters for different link rate

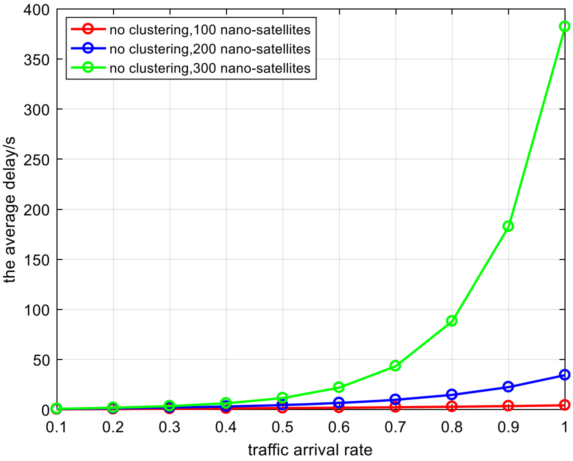

Fig. 9. The relationship between the average delay and the arrival rate for different scales of nano-satellites (non-clustered network)

From Fig. 11 we can see that the delay performance of the clustered network is better than that of the non-clustered network.

In general, the clustering algorithm we designed can effectively reduce the collision probability of nano-satellites and reduce the end-to-end delay.

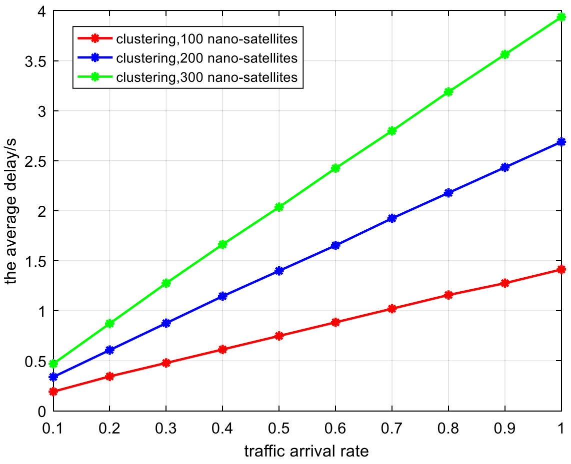

Fig. 10. The relationship between the average delay and the arrival rate for different scales of nano-satellites (clustered network)

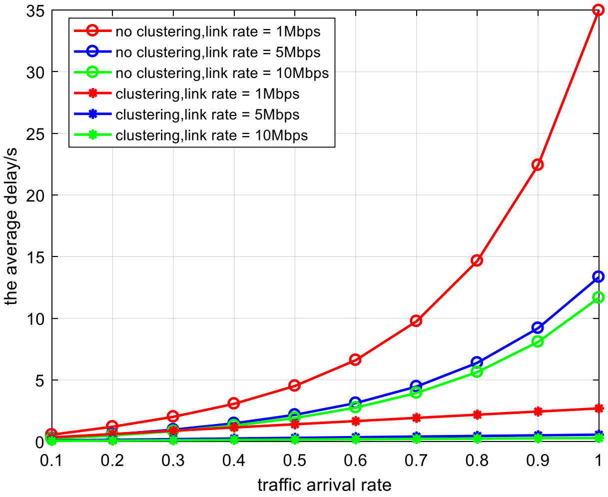

Fig. 11. The relationship between the traffic arrival rate and the average delay for different link rate of the non-clustered and clustered networks

6 Conclusion

A nano-satellite network clustering algorithm based on the optimal number of clusters is designed. We established a random access model of nano-satellites based on a two-dimensional Markov chain, which characterizes the features of satellite network multiple access process without a carrier sensing mechanism. We also deduce the throughput of the nano-satellite network under the access mechanism. To maximize the network throughput, the nano-satellite network clustering algorithm is designed, and the optimal number of clusters is obtained according to the arrival rate, the link rate, and the scale of the nano-satellite. Finally, the performance of non-clustered network and clustered network is compared and analyzed through simulation, and the efficiency of the clustering algorithm is verified. The simulation result shows that the clustered network reduces the average delay and improves the efficiency of information transmission compared with the non-clustered network.

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