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Novel Congestion Window Control Scheme Based on Differential Game Model over Space Information Networks

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Abstract

The space information network suffers from high delay-bandwidth product and link failure rate which implies that the traditional Slow-Start algorithm in congestion control is not suitable for such networks. Using dynamic non-cooperative game model, this paper proposes a novel congestion window control scheme to improve the network throughput performance via formulating the changing of congestion window. An optimal strategy of congestion window size is obtained by solving the built game model. Simulation results show that the designed scheme can improve the network throughput and reduce the resource waste.

Keywords: Congestion control; Differential game; Space information networks.

1. Introduction

The space information network is a constellation system achieving global coverage. It consists of different kinds of satellites and spacecraft in different orbits. The rapid development of the satellite networks requires the space information network having higher performance [1]. To achieve this end, a key point is to design an optimal congestion control scheme. Network congestion refers to the degradation phenomenon of network performance caused by overload of the network. The objective of the congestion control mechanism is to prevent the network from congestion and to enable its return to normal situation as soon as possible. Therefore, the proposed congestion control scheme has the following steps: detecting, controlling and relieving the network congestion.

Since TCP (Transmission Control Protocol) Tahoe algorithm in [2] was proposed by Van Jacobson, congestion control became a hot network research point. Most traditional congestion control schemes were considered always under the general wireless network environment, so the influence of long delay and high bandwidth for congestion could be ignored. However, high delay-bandwidth product was a feature of the space information network [3], and forms one of the critical factors causing congestion. The Game Theory could build the mathematical model considering the most of the network factors. According to this model, the outcome of congestion control was dynamic. Meanwhile, it is the optimal strategy under the same situation. Each node in the space information network demands higher data transmission efficiency, but the capacity of the network is limited. Therefore, the resource competition among these nodes can be described using non-cooperative differential game [4,5].

In this paper, we pay our attention to the “Slow Start Stage” in traditional congestion control scheme. In this stage, we propose that after congestion has happened, the congestion window size should be continuously reduced while the traditional scheme decreases the congestion window size to 1 immediately. We use non-cooperative differential game as a tool to investigate this point. Firstly, we build a differential

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game model for congestion window considering the degree of congestion reduction caused by data packets loss or link failure. Then we obtain an optimal strategy set through solving the game model to address the problem of congestion control. The optimal strategy set can guide the changing of the congestion window size which can improve the network efficiency.

The following Sections are organized as follows. In Section 2, we present the related works of congestion control. In Section 3, we build a Non-cooperative game model for congestion window size. In Section 4, we solve the built game model and get the optimal strategy for congestion window size setting. Numerical results are shown and discussed in Sections 5 and Section 6 concludes the paper.

2. Related Work

Congestion control techniques have been carried out for decades in traditional IP/TCP internet works [6-9]. Recently, some novel schemes for congestion control in wireless network environments were proposed in [10-13], such as Sensor Networks and Satellite Networks. Dynamic differential game gradually is used to solve network competing problems. In [14,15], authors modeled a differential game according to specific network environment and design requirement, which obtained the optimal scheme through solving Nash equilibrium.

Authors in[7] [8] described an active window management technique by changing the sending rate to improve congestion control and TCP performance. It controlled the queue length of network routers. The losses and retransmissions are the most important reasons of the large energy wasting in this paper. The available network bandwidth determined the sending rate, resulting in the reduction of the energy losses.

In[8] and [9], the authors consider the long delays and high errors over satellite links and proposed a TCP-Cherry congestion control approach. It used supplement data segments to probe the satellite networks for available bandwidth resources. These data segments could not put the network into congestion. Two algorithms Fast-Forward Start and First-Aid Recovery were designed to improve the network efficiency. Because of the similar network environment, we compare the TCP-Cherry approach with our scheme and get the outcome in section 5.

Authors in [10] used a rate-based distributed scheduling algorithm instead of the back-pressure algorithm to achieve low-complexity in multi-hop wireless networks. A new joint congestion control was proposed under a general interference degree model. It obtained a throughput guarantee, and used a novel stochastic method to find the corresponding every flow throughput and the end-to-end delay. The quantity of packets was tightly controlled and the schedule decisions were made without waiting for the packets to totalize.

In [12] the authors used the incoming traffic rate control to solve the congestion collapse in satellite communications systems with broadband multi-beam. It established the mathematical model by a max-min optimization under the constraints of average delay, stableness and beam sharing. Some back-off parameters were introduced to resolve the heterogeneous traffic rates in the satellite communications system.

Multi-packet feedback was used in [13] to guide multiplicative increase, additive increase, and multiplicative decrease (MI-AI-MD) window adaptation. The idle capacity would be utilized faster and acquired relatively steady sending rates by a reasonable rate distribution, even on the networks with high bandwidth delay product. It assumed that the capacity of each link was known by routers.

In [15], in order to design power control problem for deep space exploration, a non-cooperative stochastic differential game model was proposed, in which each node desired to maximize its payoff. It considered the interactions between nodes, and the transmission power of every node in the network could be adjusted effectively. It could construct a route by choosing a suitable node as the relay node according to the environment.

In [16] the authors summarized many host-to-host techniques to resolve several problems with different levels of accuracy and reliability. In different types of network environments such as wired, wireless, high-speed or long-delay, the advantages and disadvantages of corresponding congestion control technique were described in detail.

The traditional congestion control mechanism enters the slow start phase after congestion avoidance phase, and the congestion window size increases from the minimum value. In space information networks, due to the large delay-bandwidth characteristic [17], using the traditional scheme will greatly reduce the network operating efficiency . Furthermore, the space information node is characterised as high-risk, expensive and of relatively short lifetime, and therefore would amount to a waste of resources if the traditional sceme were to be employed. The proposed scheme however, will address these problems.

3. Modeling the System

In traditional TCP congestion control, congestion window size is set to one directly after congestion avoidance stage, and then it uses the Slow Start algorithm to achieve index increasing. Because of the long round-trip time delay in space information network, it needs more time for the Slow Start stage, which makes traditional TCP congestion control scheme an unsuitable candidate for addressing the congestion problem in space information networks. In order to conserve the network resource and improve the operating efficiency, Congestion Window Control algorithm based on game theory (CWGS) is proposed. It focuses on the congestion window decreasing stage as shown in **Fig. 1**. When the network congestion occurs, congestion window size continuously reduces in accordance with certain rules introduced by CWGS. Except for the decreasing stage, our proposed scheme is the same as in traditional TCP congestion control. As shown in **Fig. 1**, the decreasing stage is from the time t_0 of a top threshold value to T.

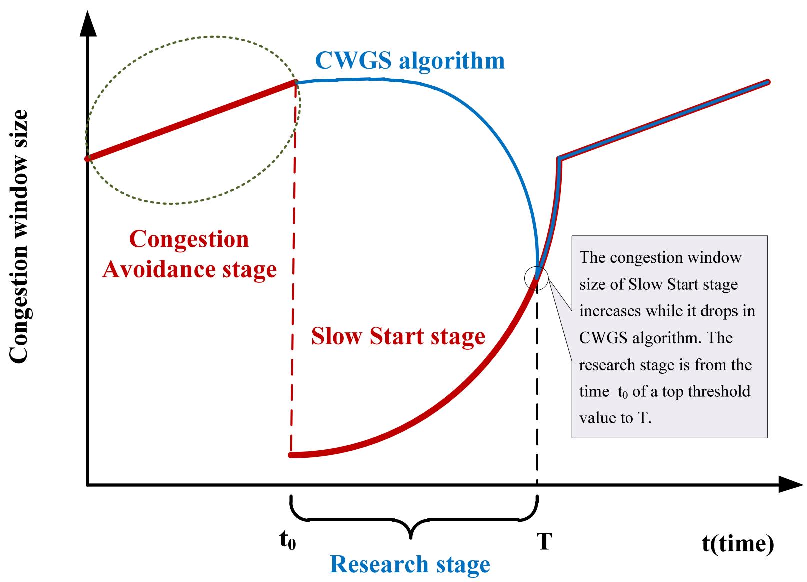

Figure 1. Diagrammatic sketch of the research stage

In our model, the parameters are defined as shown in **Table 1**. The network nodes are denoted as $N\left(N=1,2,\cdots n\right)$ in the game. $w_i\left(t\right)$ $\left(i\in N\right)$ is the congestion window size of node i at time t. SRTT denotes the precision exponential smoothing Round-trip time measured by source; meanwhile BaseRTT denotes the minimum RTT measured by each link. Link service rate is denoted as c_i. $x\left(t\right)$ denotes the amount of congestion data of nodes involved in the game at time t.

Definition 1 Nodes which participate data transmission at the same moment are the Game Players. The Game Strategy is the obtained congestion control window size of each node. The Payoff are the data transmission efficiency of the Game Player node.

Table 1. Parameters table

Parameters	Meaning
$w_i\left(t\right)$	Congestion window size of node i at time t
$x\left(t\right)$	The amount of congestion data of nodes involved in the game at time t.
$r_i\left(t\right)$	The data transmission rate of node i at time t.
$g_i\left[\bullet\right]$	The instantaneous profits of node i at time t.
a_i	*SRTT* of node i.
b_i	*BaseRTT* of node i.
c_i	Link service rate of node i.
t_0	The time of congestion start (Game start time).
T	The time of relieve congestion (Game end time).
α	The factor shows the degree of congestion reduction.
γ	Discount rate.
q	The terminal revenue rate

We build the game model as follows：

With the changing of network congestion status, system throughput correspondingly increases or decreases, so the data transmission rate of node i at time t can be expressed as follows

$$r_i\left(t\right)=\frac{w_i\left(t\right)}{a_i} \tag{1}$$

Considering the situation that all nodes involved in the game effect the profits of node i, we can get the instantaneous profits of this node at time t as follows

$$g_i\left[\bullet\right]=\frac{w_i^2\left(t\right)}{a_i^2\cdot c_i}-x\left(t\right) \tag{2}$$

In space information networks, high link error rate may cause packet loss. The failure of space link can also make transient decrease of congestion degree. It means that *SRTT-BaseRTT* is the estimated value of queuing delay in the current network. The source sends quantity of data ($w_i\left(t\right)$/*SRTT*) per unit time, so in the physical sense, [$w_i\left(t\right)\times$ (*SRTT-BaseRTT*) */SRTT*] can be treated as the estimated value of data queued in the router buffer. Then we can model the network congestion dynamic system as follow

$$\begin{cases} \dfrac{dx\left(t\right)}{dt}=\sum_{i=1}^{N}\dfrac{w_i\left(t\right)(a_i-b_i)}{a_i}-\alpha x\left(t\right) \\ x\left(t_0\right)=x_0 \end{cases} \tag{3}$$

Where $\alpha\ \left(0<\alpha<1\right)$ is a reduction factor. It represents the degree of congestion caused by a variety of reasons in space information networks.

Definition 2 Each node could get terminal revenue $qx\left(T\right)$ at the end of the game. The goal of each node involved in the game wishes maximizing the congestion window size to achieve the optimal data transmission rate, while the consequent congestion problem affects the entire network throughput in turn.

According to the theory proposed in [4], the optimization problem with dynamic non-cooperative game can be modeled as follows:

$$\max_{w_i(t)}\left\{\int_{t_0}^{T}e^{-\gamma(t-t_0)}\left[\frac{w_i^2\left(t\right)}{a_i^2\cdot c_i}-x\left(t\right)\right]dt + e^{-\gamma(T-t_0)}qx\left(T\right)\right\} \tag{4}$$

Where γ is discount rate.

4. Computation of Feedback Nash Equilibrium

In this section, we need to obtain strategy equilibrium for the solution of formula (3) and (4). There are three solution methods for differential game model. The first one is open-loop Nash equilibrium, the second one is closed-loop Nash equilibrium, and the last one is feedback Nash equilibrium. In this section, we will use the last one.

Theorem In space information network, the optimal congestion window size of node i during a slow start stage should be:

$$w_i^* = -\frac{a_ic_i\left(a_i-b_i\right)}{2}\times\left[\left(q+\frac{1}{\alpha+\gamma}\right)e^{(\alpha+\gamma)(t-T)}-\frac{1}{\alpha+\gamma}\right] \tag{5}$$

Where a_i is *SRTT* of node i, b_i is *BaseRTT* of node i, c_i is link service rate of node i, q is a terminal revenue rate, α is the factor shows the degree of congestion reduction, γ is discount rate, T is the time of relieve congestion.

Proof The proof process uses the following theorem [5].

A strategy set $\left\{w_i^*\left(t\right)=\phi_i^*\left(t,x\right),\ i\in N\right\}$ provides a feedback Nash equilibrium solution to the differential game (3)-(4), if there exist continuously differentiable functions $V^i(t,x)$ defined on $\left[t_0,T\right]\times R^m\rightarrow R$, $i\in N$ satisfying the following set of partial differential equations:

$$-V_t^i(t,x) = \max_{w_i}\left\{ e^{-\gamma(t-t_0)}\left[\frac{w_i^2(t)}{a_i^2 \cdot c_i} - x(t)\right] + V_x^i(t,x) \times \left[\sum_{j=1, j\neq i}^{N} \frac{a_i - b_i}{a_i}\phi_j^*(t) + \frac{a_i - b_i}{a_i} w_i(t) - \alpha x(t)\right]\right\} \tag{6}$$

$$V^i(T,x) = e^{-\gamma(T-t_0)} q x(t)\,, \quad i \in N \tag{7}$$

Where $V_t^i(t,x)$ and $V_x^i(t,x)$ are the first-order partial derivatives of $V^i(t,x)$ with respect to t and x respectively. Find the partial derivative for $w_i(t)$ in the formula (6) and make it equal to zero, then we can obtain the following equation:

$$e^{-\gamma(t-t_0)}\frac{2}{a_i^2 c_i} w_i^*(t) + \frac{a_i - b_i}{a_i} V_x^i(t,x) = 0 \tag{8}$$

Performing the indicated maximization in (6) yields:

$$w_i^*(t) = \frac{-\frac{a_i - b_i}{a_i} V_x^i(t,x)}{\frac{2}{a_i^2 c_i} e^{-\gamma(t-t_0)}} = -\frac{a_i c_i (a_i - b_i)}{2} V_x^i(t,x) e^{\gamma(t-t_0)} \tag{9}$$

$A_i(t)$ and $B_i(t)$ are the value functions of node i. It is benefit for the game to get the optimal possible solution. They depend on the quantity of nodes, network conditions, congestion degree and so on.

Upon substituting $w_i^*(t)$ into (6) formula and solving that we obtain the value functions:

$$V^i(t,x) = e^{-\gamma(t-t_0)}\left[A_i(t) x + B_i(t)\right] \tag{10}$$

At time T, we can write

$$V^i(T,x) = e^{-\gamma(T-t_0)}\left[A_i(T) x + B_i(T)\right] \tag{11}$$

Where $A_i(T)$ and $B_i(T)$ depend on the quantity of nodes, network conditions, congestion degree and so on.

Simultaneous equations (7) and (11), we will have the formula (12)

$$\begin{cases} A_i(T) = q \\ B_i(T) = 0 \end{cases} \tag{12}$$

Find the partial derivative for $V^i(t,x)$ with respect to t according to (10) as follows:

$$
\begin{aligned}
V_t^i(t,x) &= (-\gamma) e^{-\gamma(t-t_0)} \left[A_i(t) x + B_i(t) \right] \\
&+ e^{-\gamma(t-t_0)} \left[\frac{dA_i(t)}{dt} x + \frac{dB_i(t)}{t} \right] \\
&= x e^{-\gamma(t-t_0)} \left[-\gamma A_i(t) + \frac{dA_i(t)}{dt} \right] \\
&+ e^{-\gamma(t-t_0)} \left[-\gamma B_i(t) + \frac{dB_i(t)}{dt} \right]
\end{aligned} \tag{13}
$$

Substituting (13) into (6) we can get the formula (14)

$$
\begin{aligned}
-V_t^i(t,x) &= x e^{-\gamma(t-t_0)} \left[\gamma A_i(t) - \frac{dA_i(t)}{dt} \right] \\
&+ e^{-\gamma(t-t_0)} \left[\gamma B_i(t) - \frac{dB_i(t)}{dt} \right]
\end{aligned} \tag{14}
$$

Find the partial derivative for $V^i(t,x)$ with respect to x according to (10) as follows:

$$
V_x^i(t,x) = A_i(t) e^{-\gamma(t-t_0)} \tag{15}
$$

Substituting (9) and (15) into (6), it can be written as

$$
\begin{aligned}
-V_t^i(t,x) &= e^{-\gamma(t-t_0)} \left[-1 - \alpha A_i(t) \right] x + e^{-\gamma(t-t_0)} \\
&\times \left[\frac{c_i (a_i - b_i)^2}{4} A_i^2(t) - \frac{(a_i - b_i)^2}{2} A_i^2(t) \sum_{i=1}^{N} c_i \right]
\end{aligned} \tag{16}
$$

Simultaneous equations (14) and (16), we will have the formula (17)

$$
\begin{aligned}
& x e^{-\gamma(t-t_0)} \left[\gamma A_i(t) - \frac{dA_i(t)}{dt} \right] \\
& + e^{-\gamma(t-t_0)} \left[\gamma B_i(t) - \frac{dB_i(t)}{dt} \right] \\
& = x e^{-\gamma(t-t_0)} \left[-1 - \alpha A_i(t) \right] + e^{-\gamma(t-t_0)} \\
& \times \left[\frac{c_i (a_i - b_i)^2}{4} A_i^2(t) - \frac{(a_i - b_i)^2}{2} A_i^2(t) \sum_{i=1}^{N} c_i \right]
\end{aligned} \tag{17}
$$

To hold the equation (17), $A_i(T)$ and $B_i(T)$ satisfy

$$
\gamma A_i(t) - \frac{dA_i(t)}{dt} = -1 - \alpha A_i(t) \tag{18}
$$

$$
\begin{aligned}
\gamma B_i(t) - \frac{dB_i(t)}{dt} &= \frac{c_i (a_i - b_i)^2}{4} A_i^2(t) \\
&- \frac{(a_i - b_i)^2}{2} A_i^2(t) \sum_{i=1}^{N} c_i
\end{aligned} \tag{19}
$$

Solving differential equation (18), we will have the formula (20)

$$A_i(t)=e^{(\alpha+\gamma)(t-t_0)}\left[\frac{1}{\alpha+\gamma}-\frac{1}{\alpha+\gamma}e^{-(\alpha+\gamma)(t-t_0)}+\tilde{C}\right] \tag{20}$$

Where

$$\tilde{C}=\left(q+\frac{1}{\alpha+\gamma}\right)e^{-(\alpha+\gamma)(T-t_0)}-\frac{1}{\alpha+\gamma} \tag{21}$$

Upon substituting the relevant partial derivatives of $V^i(t,x)$ from (10) into (9) yields the feedback Nash equilibrium strategies

$$w_i^*=-\frac{a_ic_i(a_i-b_i)}{2}\times\left[\left(q+\frac{1}{\alpha+\gamma}\right)e^{(\alpha+\gamma)(t-T)}-\frac{1}{\alpha+\gamma}\right] \tag{22}$$

5. Numerical Simulation and Analysis

In this section, we present the numerical analysis of our built congestion window control scheme. According to the proposed model, we set two numerical simulations. The first simulation will show the proposed scheme's performance under different parameter values. The second simulation will show the influence of our scheme compared with the traditional scheme and the TCP-Cherry approach. The parameters are shown **Table 2**.

Table 2. Simulation parameters setting table

i	q	t (ms)	c_i	a_i (ms)	b_i (ms)	γ	α
1	1	800-900	100	31	30	0.05	0.01
2							
3							

In the first simulation, performance under different parameter values scheme is introduced. The parameter values are the same as in Table 2 except we changing the degree of congestion reduction factor α. It expresses the influence of the congestion window size and the throughput. The values are $\alpha=0.01$, $\alpha=0.02$, $\alpha=0.03$ respectively. The conclusions are shown in Fig. 2 and Fig. 3. **Fig. 2** shows that the congestion window size is smaller with the increase of α and network is more serious. The network throughput during this time interval is shown in **Fig. 3**. The bigger the degree of congestion reduction factor is, the lower the throughput is. The reason for these conclusions is that α denotes the reduction degree of network congestion caused by data loss or link failure. If the congestion window size is relatively reduced, the load on the network will be decrease at the same time interval and it can recover normal situation faster.

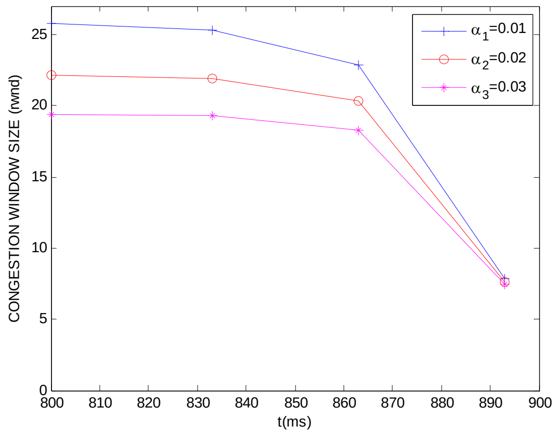

Figure 2. The congestion window size with different value of α in CWGS algorithm

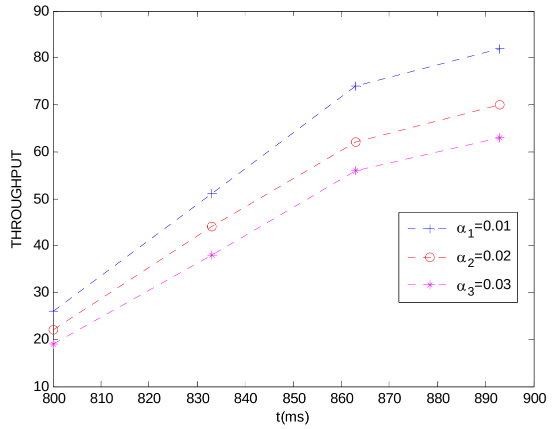

Figure 3. The corresponding throughput with α in **Figure 2**

In the second simulation, we obtain the changes of congestion window size of the three schemes. Fig. 4 shows that the congestion window size is set to one after achieving the top threshold value in traditional Slow Start algorithm, and then it increases exponentially. In TCP-Cherry approach, the congestion window size just reduces to approximately half and then rises rapidly. While our proposed scheme CWGS algorithm decreases exponentially, and then increases exponentially after congestion.

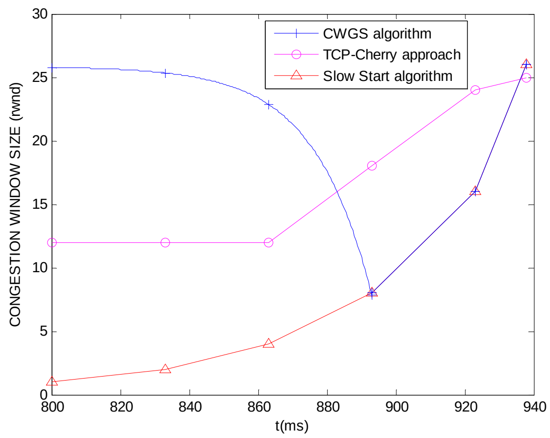

Figure 4. The changes of congestion window size in three schemes

Then we get the corresponding throughput of these three schemes. From Fig. 5 we can see that the CWGS scheme can achieve higher throughput compared with the traditional scheme at the slow start stage and the TCP-Cherry approach. The reason is that the congestion window size being set to one after achieving the top threshold value in traditional scheme is unsuitable which cause the bandwidth lost. The TCP-Cherry approach is not the optimal solution for congestion control in satellite network environment. Our proposed scheme improves the shortcoming of the slow start, and obtain higher throughput than TCP-Cherry.

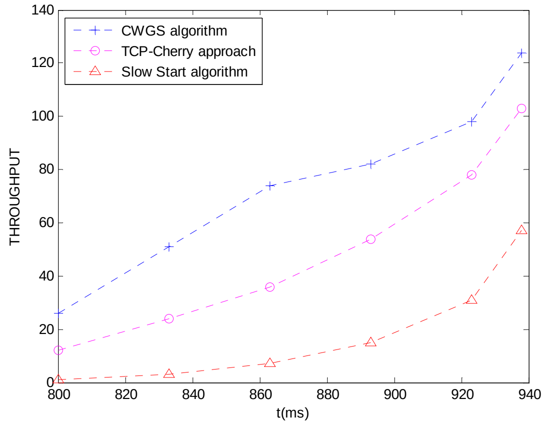

Figure 5. The throughputs implemented by three algorithms.

6. Conclusion

The characteristics of the space information network determine that the conventional traditional control mechanisms cannot be used directly. In this paper, we studied the slow start stage in congestion control. We used non-cooperative differential game to build a model considering the space information network actual environment which suffers from high delay-bandwidth product and link failure rate. Then we turned to feedback Nash equilibrium to solve the built model and obtained the optimal strategy for congestion window size. Lastly, we draw two simulations which showed that our proposed scheme could improve the space information network performance.

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