Analysis on Node-by-Node Delay Performance of CCSDS File Delivery Protocol Based on the Stochastic Network Calculus

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***Abstract*—CCSDS File Delivery Protocol is an important protocol providing reliable delivery services for space communications. In this paper, a periodical service curve model for CCSDS file delivery protocol of deferred negative acknowledgement with Fractional Brownian Motion (FBM) as arrival model of spatial data service flow is established. Meanwhile, numerical analysis upon delay bounds, throughput and bit error rate of deferred negative acknowledgement CCSDS protocol are derived by using stochastic network calculus under different self-similar parameters, which will provide reference for the cutting application of CCSDS file delivery protocol in sky-earth integrated information network.**

Keywords—Stochastic Network Calculus;CCSDS File Delivery Protocol; Delay Bound

I. INTRODUCTION

Established in 1982, Consultative Committee for Space Data System (hereinafter referred to as CCSDS) is an international authority on technologies of space data system. CCSDS formulated a set of more perfect protocol system upon space communication against the development of space network, which consists of the following components from bottom to top: Physical Layer, Data Link Layer, Network Layer, Transport Layer, and Application Layer. Wherein, each layer contains several protocols available for combination, for example, there are mainly SCPS-SP (SCPS Security Protocol), SCPS-TP (SCPS Transmission Protocol), and CFDP (CCSDS File Delivery Protocol) in Transport Layer. Shown as in Figure 1for the reference model of CCSDS space-communication protocol system[1], CFDP features with reliable node-to-node transmission mechanism, which acquires reliability without lower protocols and thus satisfies the reliability requirement upon delivery service of space communication. Based on different transmission time of Negative Acknowledgement Information (herein after referred to as NAK), there are four types of CFDP delivery modes: Immediate NAK, Deferred NAK, Prompted NAK, and Asynchronous NAK [2-4]. The paper focused on Deferred NAK CFDP as researching target.

Stochastic Network Calculus is a set of theory arising in recent years used to analyze the quality assurance of network service. There are two core concepts of the theory: Stochastic Arrive Curve (abbr. SAC) and Stochastic Service Curve (abbr. SSC). Wherein, SAC describes the features of arrived data flow, and SSC describes the service features of data flow, both of which are widely applied to network performance analysis [5-7]. Reference [7] explained the method of modeling to self-similar services with the help of stochastic network calculus. Reference[8]introduced the way of modeling to 802.11 protocol service process of Vehicle Ad Hoc Network (VANET) by stochastic network calculus. Against the delay performance of CFDP protocol, References [2-4]analyzed the influence of bit error and file size to the average file transferring time of CFDP protocol. Reference [2] researched the relationship between bit error and the probability distribution of CFDP protocol delay. The paper researched node-to-node delay performance of deferred NAK CFDP protocol with stochastic network calculus, analyzed the influence to the reliability and throughput of CFDP transmission service from self-similarity and bit error of space network flow.

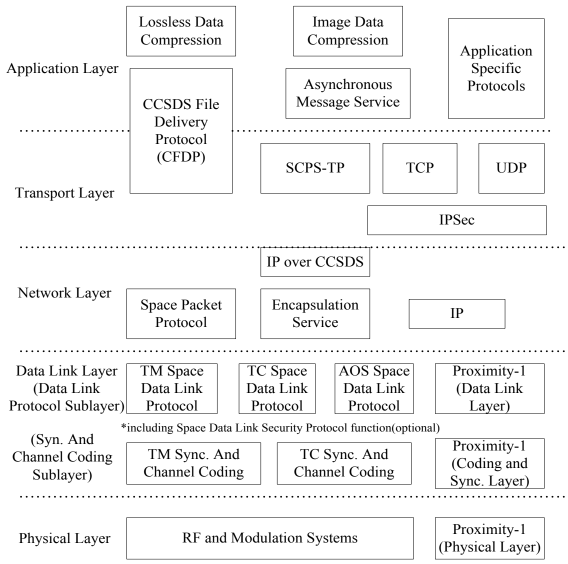

Fig. 1. Architecture of CCSDS Space Communication Protocol

Section Ⅱ of the paper introduces basic theory of stochastic network calculus and the transmission process of deferred NAK CFDP protocol. Section Ⅲ establishes a periodical service model of deferred NAK CFDP protocol, and derives the delay bounds and throughput of CFDP with combination to arrival model of self-similar traffic flow. Section Ⅳ derives the influences to delay bounds and throughput from different parameters via numerical analysis. The last paragraph draws a conclusion to the full text.

II. SYSTEM MODEL

A. Deferred Acknowledge Type of CFDP Protocol

The concept of *Transaction* is introduced into CFDP, and there is no handshake process[2, 3] during the initiation of transaction. Every time when file is transferring, the transmitting end will create a transaction and allocate a transaction ID number to it, packaged into Protocol Data Unit (abbr. PDU) together with other information.

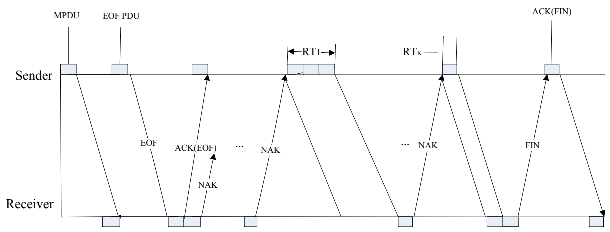

Fig. 2. Deferred NAK Mode Transmission

Working procedure of CFDP deferred NAK transmission[3] is shown as Figure 2:

(1) First of all, transmitting end will send MPDU (Meta Data PDU) containing name, size, source, target ID of file and other information to receiving end, and immediately transmit data PDU.

(2) PDU will perform retransmission request only after receiving end receives correct EOF (End of File).

(3) Receiving end will count the total PDUs amount previously lost by EOF PDU.

(4) Receiving end will send ACK (EOF) after receiving correct EOF PDU and send a retransmission request NAK that contains lost PDUs information. At the same time, receiving end starts a NAK timer, and lost PDUs records will be checked when the timer expires. If lost PDUs still exist, NAK will be sent again according to new recording information with a new timer started.

(5) Transmitting end will request for retransmitting PDUs according to NAK requirements after receiving ACK (EOF).

(6) Receiving end will send a FIN PDU after confirming that all the PDUs have been successfully received.

(7) Transmitting end returns a ACK (FIN) after receiving FIN PDU, and shuts down the transaction. Receiving end will also shut down the transaction after receiving ACK (FIN).

B. Stochastic Network Calculus

Definition 1: Non-negative Wide-sense Increasing Function

For every function $a(\bullet)$, there holds

$$Q = \{a(\bullet) : \forall 0 \le x \le y, 0 \le a(x) \le a(y)\}$$

and for any function $a \in Q$,we set $a(x) = 0, \forall x < 0$.

Definition 2: Non-negative Wide-sense Decreasing Function

For every function $a(\bullet)$, there holds

$$\bar{Q} = \{a(\bullet) : \forall 0 \le x \le y, 0 \le a(y) \le a(x)\}$$

and for any function $a \in \bar{Q}$, there is $a(x) = 1, \forall x < 0$.

Arrival process and departure process of system model are respectively defined as actual value accumulation function $A(0,t)$ and $D(0,t)$, which relatively symbols the data volume are arrived and departed from the system within time interval $(0,t]$. Both $A(0,t)$ and $D(0,t)$ are non-negative wide-sense increasing functions, and there is $A(s,t) = A(0,t) - A(0,s)$ and $D(s,t) = D(0,t) - D(0,s)$.

Within time $t > 0$, data flow delay is :

$$d(t) = \inf\{\tau \ge 0 : A(0,t) \le D(0,t+\tau)\}. \tag{1}$$

Defined function $S(s,t)$ indicates accumulated service volume of system in time interval $(s,t]$. Decide departure process $D(0,t)$ of system via $A(0,t)$ and $S(s,t)$, wherein,

$$D(0,t) \ge inf_{\tau\in[0,t]}\{A(0,\tau) + S(\tau,t)\}.$$

Based on stationarity, when $s \ge 0$, distribution of $A(s,s+t)$ and $A(0,t)$ are same. Moment generating function (abbr. MGF) of Defined function $A(0,t)$

$$M_A(\theta,t) = \mathrm{E}[e^{\theta A(0,t)}]. \tag{2}$$

Set $\bar{M}_S(\theta,t) = M_S(-\theta,t)$ for symbol unification.

Definition 3:*v.b.c* Stochastic Arrival Curve

If there is a stochastic arrival curve $\alpha \in Q$ of communication data flow A and accompanying to bound function $f \in \bar{Q}$, then for all the $0 \le s \le t$ and $\forall x \ge 0$, there is:

$$P\{sup_{0\le s\le t}\{A(s,t) - \alpha(t-s)\} > x\} \le f(x). \tag{3}$$

Thus α is the *v.b.c* stochastic arrival curve of communication data flow A, which is noted as $A(t) \sim_{vb} < f, \alpha >$.

Definition 4: weak stochastic arrival curve

If service node S has a stochastic service curve$\beta \in Ϙ$ and accompanied bound function $g \in \bar{Ϙ}$, when $\forall t \geq 0$, and $\forall t \geq 0$, there is:

$$P\{A \otimes \beta(t) - A^*(t) > x\} \leq g(x). \quad (4)$$

Then β is the weak stochastic arrival curve of node S, which is noted as$S \sim_{ws} < g, \beta >$.

Theorem 1: Stochastic Delay Bound

Presume input flow of a service system is A, when there is *v.b.c* stochastic arrival curve$A \sim_{vb} < f, \alpha >$ during arrival process of input flow, and the system provides weak stochastic arrival curve $S \sim_{ws} < g, \beta >$, then the system delay $D\ (t)$ on time *t* is:

$$P\{D(t) > x\} \leq f \otimes g(inf_{s \geq 0}[\beta(s) - \alpha(s - x)]), \quad (5)$$

wherein $t \geq 0$, $x \geq 0$.

III. Performance Analysis

A. Flow Model

Fractional BrownianMotion (abbr. FBM) is a self-similar service flow model widely accepted. Characteristics of FMB is manifested on Hurst parameter via which we could understand whether the service flow processes long-range dependency. When $H \in (0.5,1)$, FBM has long-range dependency[7].

Definition 5: Description to an arrival $A(t)$by FBM is:

$$A(t) = \lambda t + \sqrt{a\lambda} Z_H(t). \quad (6)$$

wherein, the average arriving rate of FBM $\lambda > 0$, α is the variance. $Z_H(t)$ is a standard FBM process.

Then there is *v.b.c* stochastic arrival curve $A \sim_{vb} < f, \alpha >$ about arriving process $A(t)$, wherein,

$$\begin{cases} \alpha(t) = rt \\ f(x) = \exp(\frac{1}{-2a\lambda}\left(\frac{r-\lambda}{H}\right)^{2H}\left(\frac{x}{1-H}\right)^{2-2H}) \end{cases}. \quad (7)$$

B. Service Model

Make following presumptions to Transaction before analyzing the deferred NAK mode service process:

(1) Each PDU has same size, transmitting time, and probability of transmission failure[2, 3];

(2) NAKs as retransmission request also have same size, transmitting time, and probability of transmission failure[2, 3];

(3) Error events of PDUs occurring in links are mutually independent[3];

(4) Ignore the transmission time of EOF PDU and ACK (EOF)[2, 3].

Set EOF timer as $2T_{prop}$ and NAK timer as $2T_{prop} + RT_k$ during service process analysis, wherein RT_k is the time need for PDUs retransmission in k-th NAK record. Analysis upon retransmission stage is divided into two sections, i.e. the first transmission stage and overall retransmission stage[3], shown as Figure 3. Symbol definitions adopted in the analysis are listed in TABLE Ⅰ.

TABLE I. Symbol Definition

Symbol	value
PDU number of each file, N	{1000}
Bit error rate, P_{bit}	$\{10^{-5},10^{-4}\}$
PDU error rate, P_{ef}	$\{10^{-2},10^{-1}\}$
NAK error rate, P_{er}	$\{10^{-4},10^{-3}\}$
i-th PDU retransmission, H_i	
Maximum retransmission times, H_M	{3,5}
Unidirectional transmission time, (T_{prop} /s)	{0.12}
Transmission time of single PDU, (T_{PDU}/s)	{0.005}

From above presumptions, H_i confirms to geometric distribution, and $H_M = \max\{H_1, H_2, H_3, \cdots, H_N\}$. Since the exact value of H_M is hard to obtain, if the completeness of file is between 95% and 99.9%, we assume that the transaction is deemed completed.

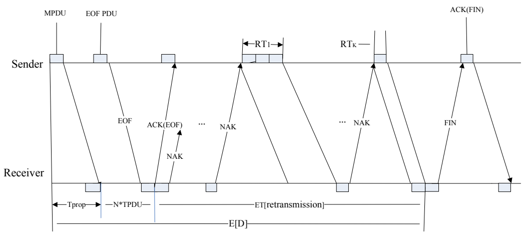

Fig. 3. Time Expectation of Transaction

Time expectation of the first retransmission stage is:

$$\sum_{i=1}^{\infty}\left[i * \left(2T_{prop} + RT_1\right)\right]P_{er}^{i-1}(1 - P_{er}) = \frac{2T_{prop} + RT_1}{1-P_{er}}. \quad (8)$$

Time expectation of the entire retransmission stage is:

$$E\left(\sum_{i=1}^{H_M}\frac{2T_{prop} + RT_i}{1-P_{er}}\right) = \frac{[E(H_M)]*2T_{p}}{1-P_{er}} + \frac{E[\sum_{i=1}^{H_M} RT_i]}{1-P_{er}}. \quad (9)$$

wherein,

$$E\left(\sum_{i=1}^{H_M} RT_i\right) = \sum_{i=1}^{H_M} E(RT_i) = (N * P_{ef} * T_{PDU})(\frac{1}{1-P_{ef}}),$$

$$E(H_M) = \sum_{i=1}^{\infty}[1 - (1 - P_{ef}^i)^N]. \quad (10)$$

From above derivation, the time expectation of first stage can be expresses as:

$$E[D] = T_{prop} + N * T_{PDU} + \frac{[E(H_M)]*2T_{prop}}{1-P_{er}} + \frac{N*P_{ef}*T_{PDU}}{(1-P_{er})(1-P_{ef})}. \quad (11)$$

Since the size of each transaction file is same, set model against the transmission process of deferred CFDP protocol via a periodical service process, wherein, the period is the time expectation$E[D]$of a transaction.

For $\forall t \geq 0$ and$\forall \theta > 0$, the MFG[8] of service process is,

$$\bar{M}_S(\theta,t) = e^{-\theta\delta\left\lfloor\frac{t}{E[D]}\right\rfloor}[1+(\frac{t}{E[D]}-\left\lfloor\frac{t}{E[D]}\right\rfloor)(e^{-\theta\delta}-1). \quad (12)$$

Then for service process $S(t)$ with weak stochastic service curve $S\sim_{ws} <g,\beta>$, wherein,

$$\begin{cases}\beta(t) = t\cdot\left\{\frac{\delta}{t}\cdot\left\lfloor\frac{t}{E[D]}\right\rfloor-\frac{1}{\theta t}log\left[1+(\frac{t}{E[D]}-\left\lfloor\frac{t}{E[D]}\right\rfloor)(e^{-\theta\delta}-1)\right]\right\} \\ g(x)=e^{-\theta x}\end{cases} \quad .(13)$$

C. Performance Analysis

According to the above analysis, we got the Arrival process $A(t)$ with a *v.b.c* stochastic arrival curve $\sim_{vb} <f,\alpha>$,

wherein,

$$\begin{cases}\alpha(t)=rt \\ f(x)=\exp(\frac{1}{-2a\lambda}\left(\frac{r-\lambda}{H}\right)^{2H}\left(\frac{x}{1-H}\right)^{2-2H})\end{cases}. \quad (14)$$

At the same time, service process $S(t)$ has weak stochastic service curve $S\sim_{ws} <g,\beta>$, wherein,

$$\begin{cases}\beta(t) = t\cdot\left\{\frac{\delta}{t}\cdot\left\lfloor\frac{t}{E[D]}\right\rfloor-\frac{1}{\theta t}log\left[1+(\frac{t}{E[D]}-\left\lfloor\frac{t}{E[D]}\right\rfloor)(e^{-\theta\delta}-1)\right]\right\} \\ g(x)=e^{-\theta x}\end{cases} \quad . (15)$$

Combining Theorem 1,

$$\begin{aligned}&\{D(t)>x\}\le f\otimes g\left(\inf_{s\ge0}\left[\beta(s)-\alpha(s-x)\right]\right) \\ &=\inf_{0\le u\le x}\left\{f\left(\inf_{s\ge0}\{\beta(s)-\alpha(s-x)-u\}\right)+g(u)\right\} \\ &=f\left(\inf_{s\ge0}\left[\beta(s+x)-\alpha(s)\right]\right)+g(x) \\ &=f(\beta(x))+g(x) \\ &=exp(\frac{1}{-2a\lambda}(\frac{r-\lambda}{H})^{2H} \\ &(\frac{x\cdot\{\frac{\delta}{x}\left\lfloor\frac{x}{E[D]}\right\rfloor-\frac{1}{\theta x}\log[1+(\frac{x}{E[D]}-\left\lfloor\frac{x}{E[D]}\right\rfloor)(e^{-\theta\delta}-1)]\}}{1-H})^{2-2H}+e^{-\theta x}.\end{aligned} \quad (16)$$

From service curve of service process $S(t)$, it is derived that throughput[6] of the process is:

$$\beta(\theta,t)=\frac{\delta}{t}\cdot\left\lfloor\frac{t}{E[D]}\right\rfloor-\frac{1}{\theta t}log\left[1+(\frac{t}{E[D]}-\left\lfloor\frac{t}{E[D]}\right\rfloor)(e^{-\theta\delta}-1)\right]. \quad (17)$$

IV. Numeric Results

This section analyzed the influence of different parameters upon delay bound and throughput. For convenience, probability of random variables violating bound constrain is abbreviated as violation probability.

A. Delay Bounds and Similar Parameters

This sub-section analyzed the relationship between file transmission delay and violation probability when the similar parameter $H\in(0.5,1)$. From Figure 4, we can derive that, accompanying the increasing of similar parameter H, violation probabilities of same delay are increasing, vice versa. When the value of H exceeds 0.7, delay and violation probability increase rapidly, because the larger similar parameter is, the bigger burstsize of FBM service flow is. It is proven by numeric analysis that the intensification of correlative self-similarity characteristics of space data service flow will increase deferred NAK CFDP delay.

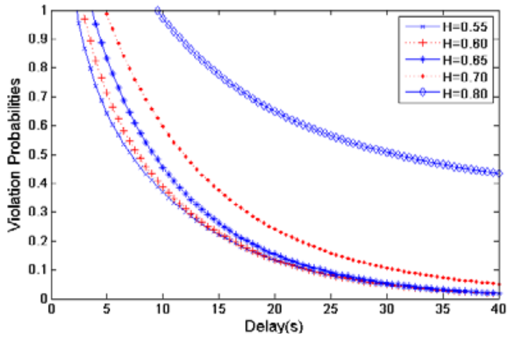

Fig. 4. Delay Bound and Self-similar Parameters

B. Delay Bound and Bit Error Rate

This sub-section analyzed the delay bound of file transmission of CFDP protocol under different bit errors P_{bit}. From Figure 5, it is discovered that accompanying with increasing of P_{bit}, violation probability of same delay is also increasing. This proves that bit error rate which reduces NAK CFDP transmission mechanism will increase the reliability of data transmission. Similarly, delays with same violation probability are also increasing, which indicates that bit error rate reducing NAK CFDP transmission mechanism promotes delay performance of the protocol.

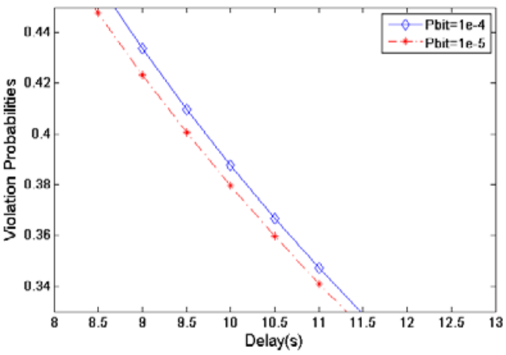

Fig. 5. Delay Bounds and Bit Error Rate

C. Throughput and Bit Error Rate

This sub-section analyzed the relationship between bit error rate P_{bit} and CFDP protocol throughput.

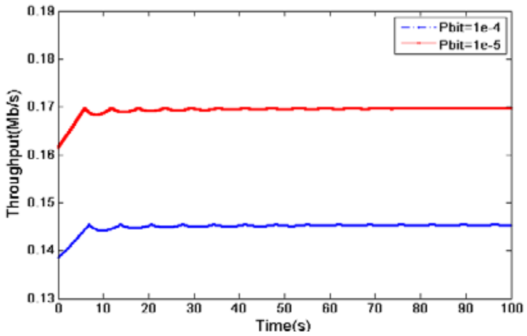

Fig. 6. Throughput and Bit Error Rate

Figure 6 indicates that, when bit error P_{bit} is 10^{-5}, deferred NAK CFDP protocol throughput is obviously higher than that of 10^{-4}. Experiments show that, throughput ofdeferred NAK CFDP protocol increases when bit error rate P_{bit} is reducing, which benefits file transmission.

V. CONCLUSION

In order to analyze delay performance of deferred type CFDP protocol, the paper analyzed the interrelationships between self-similar parameter H, file transmission delay bound, throughput and bit error using stochastic network calculus theory after establishing periodical service model established with Fractional Brownian Motion as arrival model. Through numeric analysis, we can derive that increase of correlative self-similarity of space data service flow will increase delay and reduce error bit of deferred NAK CFDP protocol, which promotes the reliability of data transmission and protocol delay performance. The analyzing result provides a reference for CFDP cutting application in sky-earth integrated information network.

ACKNOWLEDGMENT

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