A Weather-forecasting Improved CFDP over Ka-band Channel

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***Abstract*—A novel file delivery scheme over a Ka-band channel is proposed, which is heavily dependent on weather around the earth's atmosphere. The proposed scheme based on CFDP is designed to resist the influence of weather conditions by the weather-forecasting. In this work, the condition-forecasting model that the weather sequence is forecasted through the first two states is constructed, demonstrated by the theoretical analysis and furthermore, implement of forecasting algorithm is also carefully researched and designed. Simulating results show that the file delivery time of selection-waiting CFDP with weather-forecasting is reduced effectively compared with traditional CFDP.**

Keywords-Ka-band; weather-forecasting; CFDP; file delivery time; NAK

I. INTRODUCTION

As a result of long round trip times and frequent packet errors, the CFDP (CCSDS File Delivery Protocol) for deep-space communications was proposed by the CCSDS (Consultative Committee for Space Data Systems) [1][2]. On the one hand, deeper space exploration, further probing, and even larger amount of data transferred, not only lead to more and more CFDP retransmissions, but also increases of the file transfer delay; thus, the validity of the data transmission was seriously affected. On the other hand, as the Ka-band is strongly influenced by weather conditions, CFDP has no relevant functions to resist the state's high error rate of bad weather. Although Ka-band links can be available to a large range of bandwidth, which will greatly increase the capabilities and capacity of the future space networks, yet they are highly vulnerable to fluctuations in weather, such as the rainfall. In this paper, the selection-waiting CFDP in order to meet the change of Ka-band weather conditions is proposed due to the original CFDP was highly improved in that the file transfer delay was decreased efficiently.

Some works had been done in order to improve the performance of CFDP by researchers. In [3], an automatic repeat-request (ARQ) scheme of the Consultative Committee for Space Data Systems file-delivery protocol for the single-hop file-transfer operation was presented, and the CFDP performance was in detail analysed in [4-7], which came down to the cislunar, geo-stationary Earth orbit (GEO) and low Earth orbit (LEO) link environments.

A novel file delivery mechanism over a Ka-band channel is proposed in this paper, which is heavily dependent on weather of the earth.

This paper is organized in the following way. Firstly, the related works of our study are briefly explained, which contain deferred NAK CFDP transmission mechanism and Gilbert-Elliot channel. Secondly, the weather-forecasting algorithm is thoroughly demonstrated. Thirdly, the selection-waiting CFDP is designed and the simulation of the novel file delivery mechanism is illustrated and satisfied results are gained.

II. PROBLEM FORMULATION

The Deferred NAK CFDP Transmission Mechanism is produced in the background that TCP/IP uses less efficiently in space communication, but the CFDP is a transmission protocol for the application layer [3]. Then CCSDS proposed four different ways for NAK in CFDP; they are Immediate NAK, Prompted NAK, Asynchronous NAK and Deferred NAK. In this paper, we take Deferred NAK CFDP as an example of analysis simplicity. As is shown in Figure 1, when file transmission states, the object file is divided into a set of protocol data units (PDUs) before being sent. At the first "spurt", the sending entity of CFDP core procedure issues all PDUs of file in order. As soon as the EOF PDU is received correctly, the receiving entity acknowledges it with ACK (EOF) and then checks the integrality and validity of object file by file information contained in the Meta PDU. Those sequence numbers of missing PDUs are listed and reported back to sending entity by a NAK message. According to the information in NAK, sending entity initiates the second "spurt" consisted of the PDUs required by receiving entity, and so on. Once all of object file PDUs are received successfully, the receiving entity returns back a FIN PDU to the sending entity, which requires an acknowledgement with ACK (FIN). When ACK (FIN) is successfully delivered to the receiving entity, this transmission is finished and closed.

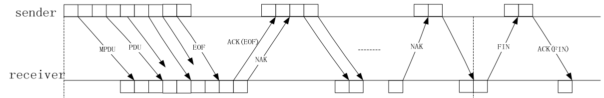

Figure 1. Two error state AWGN channel Gilbert-Elliot model

In the study of channel model, according to the Gilbert-Elliot channel [8], a variation of the additive white Gaussian noise (AWGN) channel is used to model different bit error rate (BER) in each weather state. This type of

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channel, called the Gilbert-Elliot (GE) channel [8], has two weather states, a good and a bad weather state, which are separated by the threshold value. During good weather conditions, most of the transmitted packets will be received successfully, during bad weather conditions, however, most of the transmitted packets will generate some errors due to the high noise temperature at receiver. Therefore, two different BERs are applied to each good and bad weather state. In our new model, we define the relatively high BER value for the bad weather state and relatively low BER value for the good weather state.

To capture the weather correlation, the Gilbert-Elliot channel with two weather states are shown in Figure 2. The transition from one state to another state is defined by the transition matrix *P*, which completely characterizes the channel behavior. In this model, the current state is determined by the previous state, and the λ_G and λ_B are the transition probabilities from good to bad and from bad to good state, respectively.

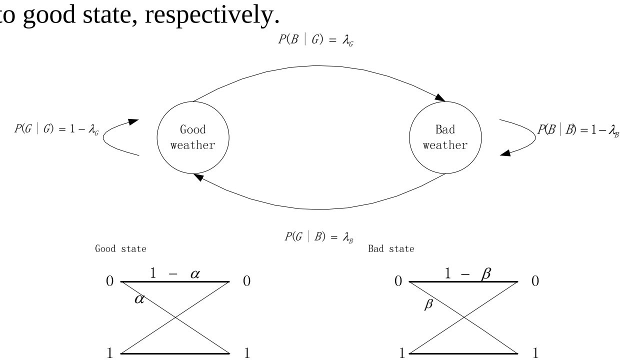

Figure 2. Gilbert-Elliot channel

Then the transition matrix is

$$P = \begin{bmatrix} P(G/G) & P(B/G) \\ P(G/B) & P(B/B) \end{bmatrix} = \begin{bmatrix} 1-\lambda_G & \lambda_G \\ \lambda_B & 1-\lambda_B \end{bmatrix} \quad (1)$$

The difference of the file transfer delay between Gilbert-Elliot (GE) channel and AWGN channel is illustrated in Figure 3, which depicts MRO (Mars Reconnassance Orbiter) sending files using the CFDP over Ka-band. Under the same condition (files are at most 10MB in size and transmission rate is 200kb/s) the simulation was carried out and the result was compared. Figure 3 shows that the file transfer delay over GE channel is longer than AWGN. It is said that the performance of CFDP is poor over Gilbert-Elliot channel. As a result, it is necessary to improve the CFDP over Ka-band.

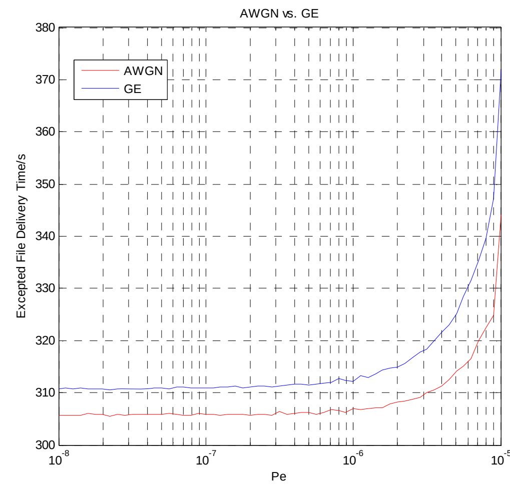

Figure 3. The file transfer delay over Gilbert-Elliot channel and AWGN channel

III. WEATHER-FORECASTING ALGORITHM

A. Condition-forecasting Model and Assumption

It is known that the one-way packet transmission time is $T = 20\,\mathrm{min}$. Mars sends data packets to the earth, and then the earth returns the control commands to the Mars. The time spent in this process is $2T$. We consider the bit-error-rate of the receiver (P_e) as threshold, when $P_e < 10^{-5}$, we believe that the weather state is good. Otherwise, it is bad.

$$\begin{cases} P < P_e, \text{good state} \\ P > P_e, \text{bad state} \end{cases} \quad (2)$$

As is shown in Figure 4, assume that the initial channel state is good ('1'), we can forecast the next state according to the Ka-band channel model. Then, we forecast the third state due to the first two states. While forecasting the fourth state, the true value of the third can be determined because of the NAK feedback mechanism. We set the third state as the new initial state to predict the next two states. In this way, the so-called two-step forecast is carried out.

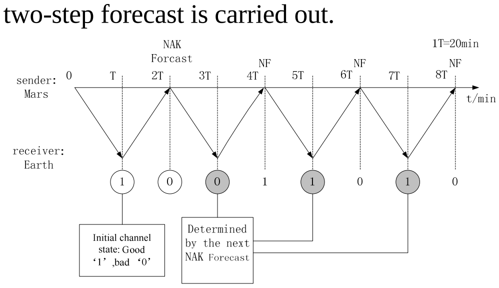

Figure 4. State of channel forecasting theory according to Ka-band

Step 1, When the file starts to transmit, the receiver record**s** the error rate every time when the file reach**es** the earth. According to the error rate at this moment, the receiver can estimate the weather condition: a good state denoted by 1 and a bad state denoted by 0.

Step 2, condition-forecasting model is worked by the written '0' or '1' into the received words of the NAK, and the sender could get this weather condition when the NAK reaches Mars.

Step 3, when the sender receives the NAK with the value '1', it judges that the weather condition is good, otherwise bad, as is shown in Figure 5.

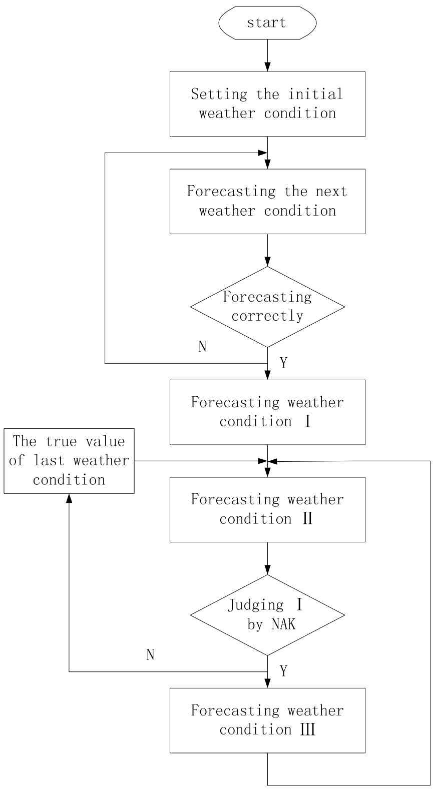

Figure 5. The condition-forecast flow chart

B. Error Analysis

According to the GE channel model mentioned above, the steady probability can be attained when the probability of good weather is P_G and that of bad is P_B. If the initial state is bad('0'), one-step prediction error probability is

$$P_{e0} = 2\lambda_B(1 - \lambda_B) \tag{3}$$

Similarly, when the initial state is good ('1'), one-step prediction error probability is

$$P_{e1} = 2\lambda_G(1 - \lambda_G) \tag{4}$$

So, the sum of the one-step prediction probability is

$$P_{error} = P_B \cdot P_{e0} + P_G \cdot P_{e1} \tag{5}$$

The two-step state transition matrix is

$$P^2 = \begin{bmatrix} (1-\lambda_G)^2 + \lambda_G\lambda_B & 2\lambda_G - \lambda_G^2 - \lambda_G\lambda_B \\ 2\lambda_B - \lambda_B^2 - \lambda_G\lambda_B & (1-\lambda_B)^2 + \lambda_G\lambda_B \end{bmatrix} \tag{6}$$

Similarly, two-step prediction probability is

$$\begin{aligned} P'_{error} &= P_B \cdot 2(2\lambda_B - \lambda_B^2 - \lambda_G\lambda_B)[(1-\lambda_B)^2 + \lambda_G\lambda_B] \\ &+ P_G \cdot 2[(1-\lambda_G)^2 + \lambda_G\lambda_B](2\lambda_G - \lambda_G^2 - \lambda_G\lambda_B) \end{aligned} \tag{7}$$

C. Implement of the Forecasting Algorithm

CFDP NAK [2] packet format originally has reserved 3-bit (as shown in Figure 6). The reserved words can be used to carry the value of the initial state of the two-step prediction. Selecting the first reserved word, when the initial state is good, the value '1' will be written, otherwise we will write '0'.

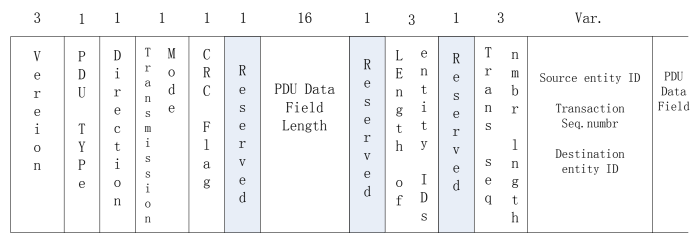

Figure 6. Fixed PDU header of CFDP

IV. DESIGN OF SELECTION-WAITING CFDP

According to the analysis of the predictive model about the Ka-band channel, the selection-waiting CFDP mechanism is chosen to overcome shortcomings in the light of the change of the weather conditions (as is shown in Figure 7).

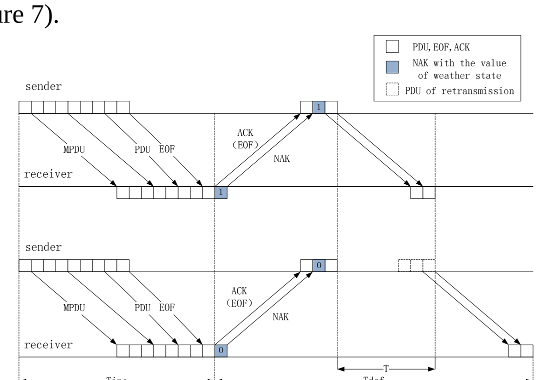

Figure 7. Selection-waiting CFDP transmission mechanism

TABLE Ⅰ NOTATION

Symbol	Definition
W	Total File Delivery Time

T	Once-Waiting Time
T_{prop}	One-way propagation delay
T_{inc}	Transmission Detection Time at First Time
T_{def}	Time of Retransmission
P_e	Bit Error Rate
P_{ePDU}	Pocket-loss-rate of PDU
P_{eEOF}	Pocket-loss-rate of EOF
L_{PDU}	Length of PDU
$T_{ACK(EOF)}$	Transmission Time of ACK(EOF)

Based on the tow-step forecasting of NAK, when the channel condition is good, the sender transmits the file to the receiver normally. However, when the channel is bad, the sender will make the following judgments: (1) if the time of the file-transmission time>T(20min), it will wait for the time value of T, and then transmit sequentially；(2) if the time of the file-transmission time<T, it transmits the file directly.

The relationship between the pocket-loss-rate of PDU and the bit error rate is

$$P_{ePDU} = 1 - (1 - P_e)^{L_{PDU}} \tag{8}$$

The pocket-loss-rate of the EOF is

$$P_{eEOF} = 1 - (1 - P_e)^{L_{EOF}} \tag{9}$$

The time value of the EOF timer is set as

$$time\_EOF = 2T_{prop} + T_{ACK(EOF)} \tag{10}$$

The mathematical expectation of the transmission of EOF is

$$E(EOF) = \frac{P_{ePDU}(2T_{prop} + T_{EOF} + T_{ACK(EOF)})}{1 - P_{ePDU}} + T_{prop} + T_{EOF} \tag{11}$$

We can get the Transmission Detection Time at first time is

$$\begin{aligned} T_{inc} &= NT_{PDU} + E(EOF) + T_{ACK(EOF)} \\ &= NT_{PDU} + \frac{P_{ePDU}(2T_{prop} + T_{EOF} + T_{ACK(EOF)})}{1 - P_{ePDU}} \\ &\quad + T_{prop} + T_{EOF} + T_{ACK(EOF)} \end{aligned} \tag{12}$$

The time value of NAK is

$$time\_NAK_i = 2T_{prop} + R_i \tag{13}$$

and，

$$E(\sum_{i=1}^{M_N} R_i) = NT_{PDU}(\frac{1}{1 - P_{ePDU}} - 1) \tag{14}$$

$$E(M_N) = 1 + \sum_{m=1}^{\infty}[1 - (1 - P_{ePDU}^m)^N] \tag{15}$$

The time of retransmission at ith time is

$$T_{def_i} = \begin{cases} n_i \cdot T_{pdu} + 2 \cdot T_{prop}, good\_weather \\ n_i \cdot T_{pdu} + 2 \cdot T_{prop} + T, bad\_weather \end{cases} \tag{16}$$

So the time of retransmission is

$$T_{def} = \sum_{i=1}^{M_N} T_{def_i} \tag{17}$$

And the total of file delivery time is

$$W = T_{inc} + T_{def} \tag{18}$$

V. Simulation and Discussion

The Earth-to-Mars communication is taken as an example to testify the rationality of selection-waiting CFDP proposed in this paper. Some experiments parameters are shown in Table Ⅱ and Table Ⅲ.

TABLE Ⅱ PARAMETERS IN SIMULATION

Parameters	Parameters Descriptions	Value
P_e	Bit-error-rate of Direct Point-to-point Communication Between Mars and Earth	10^{-4}、10^{-5}、10^{-6}、10^{-7}、10^{-8}
Tx(kb/s)	Transmission Rate	200
N	Number of PDUs	10^5、$2*10^5$...
L_{pdu}(Kbyte)	Length of PDU	2
d(km)	The Distance between Mars and Earth	4×10^8

TABLE Ⅲ VALUE OF TRANSITION MATRIX

transition probability	**Sampling by averaging**	**Sampling by choosing the max**	**Sampling by choosing the min**
P(G/G)	0.9773	0.9656	0.9853
P(B/G)	0.0227	0.0344	0.0147
P(G/B)	0.1667	0.1618	0.1799
P(B/B)	0.8333	0.8382	0.8201

Figure 8 compares the performance of selection-waiting CFDP and traditional CFDP as the numbers of PDU varies from $1x10^5$ to $1x10^6$ under different bit error rates. The results show that the file delivery time of both selection-waiting CFDP and the traditional CFDP increases in line ratio as the number of PDU increase. Apparently, as the bit-error-rate decreases, the file delivery times both increase based on two CFDPs. In Figure 8, the performance of CFDP with weather-forecasting mechanism is better than that of the Gilbert-Elliot channel. It is said that Selection-waiting CFDP could reduce approximately $5x10^3$s time at least, compared with the traditional CFDP. As the result, it means that Selection-waiting CFDP is more applicable than that of the traditional CFDP in the space communication over Ka-band heavily influenced by the weather conditions, which is significant for cutting down the transmission time for long-distance space communication links such as the Earth-to-Mars communication.

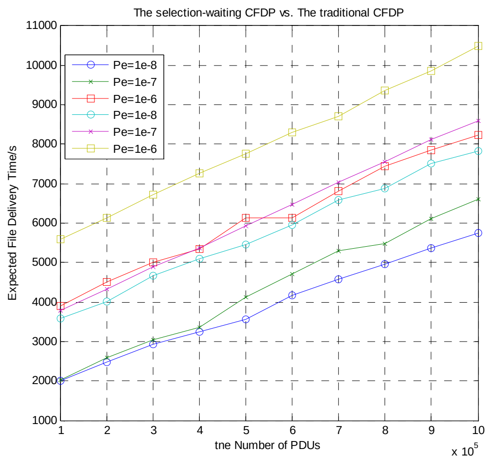

Figure 8. The file delivery time of the selection-waiting CFDP vs. The traditional CFDP under the different bit-error-rates

We choose the transition matrix which is sampling by averaging in above simulation. In fact, the transition probability from good to bad states can be derived by 1/(average duration of good weather) and the transition probability from bad to good state is 1/(average duration of bad weather). The transition probabilities of different sampling methods with the threshold of *20K*,are shown in the Table Ⅲ. These transition probabilities will be used for simulating weather patterns.

VI. CONCLUSION

In this study, the weather-forecasting algorithm is presented to evaluate the CFDP performance under good and bad weather conditions, and a novel file delivery protocol, inserting the weather-forecasting algorithm into traditional direct point-to-point link, is proposed. Based on the condition-forecasting model eatablished, comprehensive experiments are carried out and discussed under different conditions of parameters involved in the proposed protocol. Results indicate that the proposed protocol perform much better than that of the traditional Deferred NAK CFDP in terms of file delivery time.

Further work will consider the selection of transmission rate into the performance of the proposed protocol over Ka-band. And another algorithm about the perception of channel will be proposed and will be compared with the protocol proposed in this work.

VII. ACKNOWLEDGMENT

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