A CFDP-based Multi-state Model on Ka-band Weather-dependent Channel

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***Abstract*—In this paper, a channel model on transport layer over Ka-band links is proposed, which apparently reflects the characteristics of rain attenuation and equivalent noise temperature from the earth's atmosphere. The proposed model is built on a four-state Markov chain, which considered the different features of various packet types during CCSDS File Delivery Protocol (CFDP) transactions. We provide the exact criterion on how to divide different weather conditions at each state, and give the analytical results on transition probability matrix. In particular, we take Guangzhou in China as an example to find the probability distribution function of rain attenuation, and thus the transition matrix between different states, based on ITU-R rain attenuation model. The simulation results show that, compared with two state channel model, the proposed model could efficiently describe the error characteristics of different packet types during the file delivery, which leads to obvious degradations on CFDP performance.**

Keywords-rain attenuation; equivalent noise temperature; ka-band; CFDP; Markov process

I. INTRODUCTION

Ka-band with largely available frequency bandwidth will greatly increase the capabilities and capacity of the future space networks. Although Ka-band links can bring obvious gains for communication system, it is highly vulnerable to fluctuating weather condition, such as the rainfall. Rainfall not only attenuates the signal power level of the signal at the receiver, but also makes the system noise temperature increased. These two aspects further worsen the signal-to-noise ratio (SNR) and make BERs of the system over long distance increased. On the other hand, high BERs will degrade the reliable delivery on the scientific data, due to frequent retransmissions on the missing data packets.

For file-based scientific data return, CCSDS puts forward CCSDS File Delivery Protocol (CFDP), instead of its terrestrial counterpart (File Transfer Protocol, FTP), which is designed to provide file-based data storage management, store-and-forward relay, and reliable data transfer over space links characterized by large propagation delay and intermittent availability[1]. The CFDP employs Automatic Repeat reQuest (ARQ) retransmission mechanism to file reliable delivery, which is significantly affected by the earth's weather over Ka-band links. In [2], the latency of CFDP over Ka-band is analyzed theoretically, based on a two-state Markov chain channel. This two-state model, denoted by Gilbert-Elliot channel model [3], divides simply the different weather conditions over Ka-band link into two states of "good" and "bad" respectively. Especially, it exploits a large number of atmospheric noise temperature data sampled by DSNs of NASA, from which a threshold is determined to separate two weather states. In [4], a new statistical approach for deep-space communications links design was formulated and optimal link design strategies over Ka-band has been presented by using the atmospheric noise temperature statistics and the ground antenna characteristics to optimize the average data return on the link. A wide-area environment two-state channel model including "ideal state" and "non-ideal state" was proposed in [5], model parameters under three kinds of typical channel environments were fitted by using the statistics method of experimental data. Maruddani et al. [6] evaluated the performance of Ka-band wireless communication system in tropical area by comparing several channel coding schemes.

In the CFDP, PDUs are divided into different types due to their specified roles in the file transfer, with different length. Weather impairments on different types of PDUs over Ka-band links could produce unequal performance degradation, since the PDUs with different length could be lost or received independently at the same BER. Therefore, it is necessary to take the diversified influence of different types of PDUs into account when we model the channel characteristics over Ka-band weather dependent links. In this paper, we attempt to solve this problem by constructing multi-state channel model, in which each state reflects on the individual effects of the different PDUs. This paper has two following novel contributions: a) we built a four-state Markov channel model on transport layer over Ka-band links constructed with rain attenuation and system noise temperature together, which is not considered in the original two-state Gilbert-Elliot channel model. Thus combine the physical characteristics over Ka-band links on transport layer; b) In the model given, we determined the different states of channel by considering specified functions of PDU types of the CFDP, which could exactly characterize the influence on file delivery performance over Ka-band channel.

In Section II, we describe the CFDP file transfer process, and Gilbert-Elliot channel model has been introduced. In Section III, we divide the weather state into several types based on different types of PDUs in the CFDP, and give the derivation of the theoretical formulas, then some simulations is shown to find out the weather-related parameters in this model. The simulation of the delay performance of CFDP under this model with Monte Carlo algorithm, indicating the validity of the model by comparing the channel with others, have been shown in Section IV, followed by conclusions in Section V.

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II. CFDP AND GILBERT-ELLIOT CHANNEL MODEL

A. *Process of CFDP deferred NAK mode transmission*

CFDP has four error control modes to handle the link disruptions and outages frequently encountered in space. In this study, we used the CFDP deferred NAK mode since it is the most generally used form of CFDP for space link [1].

For the CFDP file transfer, each file is divided into multiple protocol data units (PDUs). The sender will send Metadata PDU (MPDU) first, and then send PDUs to the receiver. The end of file PDU (EOF-PDU) is sent at the end of the initial transmission attempt. The receiving entity saves all information about missing data until the EOF is received. It then issues a NAK listing all the PDUs that were not successfully received. Upon the reception of this NAK message, the sender side retransmits the PDUs and the receiver will again responds with NAK messages until all PDUs are received correctly; then, the receiver will send finished message (FIN) to the sender and close the file transmission [7], as shown in Fig. 1.

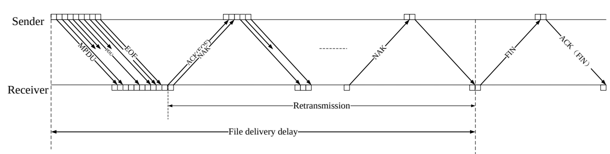


Figure 1. Process of CFDP deferred NAK mode transmission

B. *Gilbert-Elliot Channel*

We define the weather-dependent transport layer channel of CFDP as an erasure channel, which is generally described by Gilbert-Elliot model. There are two weather states in Gilbert-Elliot channel model, "good" and "bad" weather conditions. If it is good weather state, most of the transmitted packets will be received successfully. If not, however, most of the transmitted packets will experience errors due to bad weather condition. Therefore, two different BERs are applying to two different weather conditions. The weather state undergoes stochastic transitions, as shown in Fig. 2, and the transition from one state to another is defined by the transition matrix *P*.

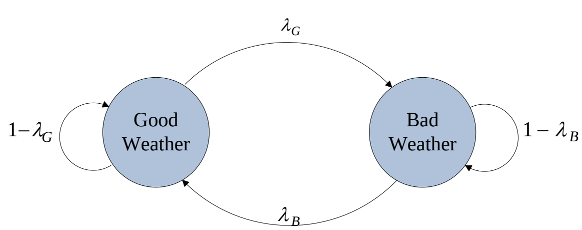


Figure 2. Gilbert-Elliot Channel model

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

We attempt to give the fact that, the performance of the CFDP over two-state weather channel model is worse than that of single-state AWGN channel model, through the comparison between them by Monte-Carlo simulations. The simulation parameters are shown in Table I.

TABLE I. SIMULATION PARAMETERS OF THE COMPARISON

File size	10MB	
The number of simulation	10000	
BERs in two-state weather model	***Good state***	1e-5, 1e-6, 1e-7, 1e-8
	Bad state	1e-3
BERs in single state model	1e-5, 1e-6, 1e-7, 1e-8	

Fig. 3 shows that the average transmission number of the CFDP over two-state weather model is slightly more than that of the single-state model, as a result of taking the bad weather into account. It is indicated that the two-state model could reflect the characteristic of the real weather dependent channel to a small extent. Also, the result of simulation with different combinations of good and bad weather BER pairs: (1e-5, 1e-3), (1e-6, 1e-3), (1e-7, 1e-3), and (1e-8, 1e-3) in two-state model, shows that different pairs produce different average retransmission numbers. It means that, the division criterion of the weather state have a nontrivial effect on the performance of the CFDP.

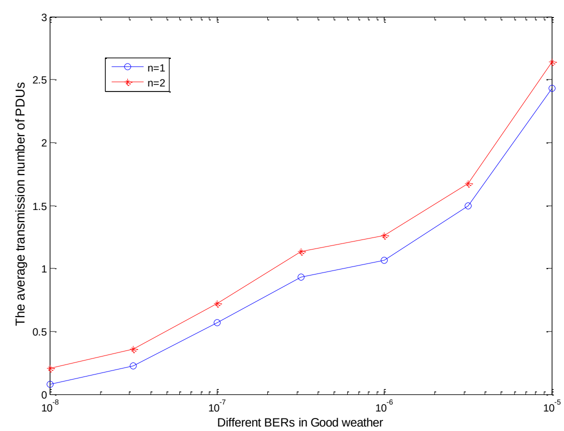


Figure 3. The average numbers of transmissions required under different channel models

Therefore, well-designed criterion of the division is considerably indispensable for the efficiency of the channel model, which could simulate the real channel properly.

III. FOUR-STATE WEATHER CHANNEL MODEL

A. *The method of modeling*

We determined the different states of channel by considering specified functions of PDU types of the CFDP. In the CFDP, different types of PDUs have different lengths and functions [8]. We group the PDUs into three types according to the different lengths. The first type includes

Prompt PDU, ACK PDU, and EOF PDU with the length of approximate 30Bytes; the second type contains Metadata PDU, File data PDU, and Finished PDU with the length of approximate 1024Bytes; another type of PDU is NAK PDU with the variable length, which changes as the number of the lost PDUs during the process of file transport, as shown in Table II.

TABLE II. THE TYPES OF PDUS IN THE CFDP

Types of PDUs	**L_{pdu}(Byte)**
EOF/ACK/PROMPT PDU	30
META/File-data/FIN PDU	1024
NAK	variable

We attempt to include respective possibility of errors occurred in different types of PDUs into the channel model, since the lengths of different types of PDUs (L_{pdu}) have obvious disparity. In this section, we design a multi-state channel model to distinguish the error rate of different types of PDUs, which could combine better with CFDP characteristics than the traditional two-state model. Our proposed weather dependent channel has four state divided by different BERs. The method of modeling is presented in the following way:

We know the relationship between packet error rates P and bit error rates:

$$P = 1-(1-\gamma)^{L_{pdu}} \tag{2}$$

Thus,

$$\gamma = 1-(1-P)^{1/L_{pdu}} \tag{3}$$

The error probability of the first PDU type is very small for its length is very short, and the second PDU type is the longest one, so it will lost when the environment of transmission is bad. We assume that the receive message is right when packet error rates is under 0.01, and the links break off when the packet error rates is above 0.5. So, we take 0.01 and 0.5 as two threshold values. We calculate the upper boundry BERs γ of different PDUs shown in Table III.

TABLE III. THE RELATIONSHIP BETWEEN BERS AND RAIN ATTENUATION

Types of PDU	**Threshold values of packet error rates P**	**Maximum BERs**
EOF/ACK/PROMPT PDU	0.01	4.19e-05
META/File-data/FIN PDU	0.01	1.23e-06
	0.5	8.46e-5

The proposed model contains a good state and three bad ones. Given a good weather state we predetermined, we divided three rainfall states by two BERs threshold in the case of packet error rates is 0.01, We use the BER corresponding to packet error rates is 0.5 as the upper boundary of the BERs. By doing this, we obtain a four weather states of channel model.

In this model, we assume that the transition occurs only between neighboring states since the changing of weather conditions could conforms better to the characteristic of the first order Markov process, as shown in Fig. 4. Let T be the state transmission matrix as shown below, the channel could be represented from a state transmission matrix:

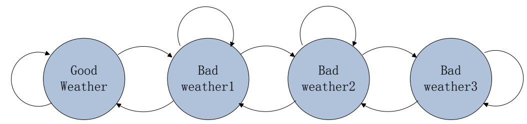


Figure 4. The Four-state weather channel model

$$T = \begin{pmatrix} P_{1,1} & P_{1,2} & 0 & 0 \\ P_{2,1} & P_{2,2} & P_{2,3} & 0 \\ 0 & P_{3,2} & P_{3,3} & P_{3,4} \\ 0 & 0 & P_{4,3} & P_{4,4} \end{pmatrix} \tag{4}$$

B. The calculation on the proposed model parameters

Given BPSK modulation employed in this paper, we have:

$$\gamma = Q(\sqrt{\frac{2\varepsilon_b}{N_o}}) \tag{5}$$

where ε_b is the signal energy of each bit and,

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-t^2/2}dt, \qquad x \ge 0 \tag{6}$$

So, we get:

$$\frac{2\varepsilon_b}{N_0} = (Q^{-1}(\gamma))^2 \tag{7}$$

We used the general antenna gain calculated by follows:

$$G = \eta\frac{4\pi A}{\lambda^2} \tag{8}$$

where λ is the wavelength of the signal, A is the receiving antenna area, and η is the antenna efficiency. For directional antenna, the power density of the destination is:

$$W = \frac{P_s G_s}{4\pi r^2}\ (W/m^2) \tag{9}$$

where r is the distance of transmission, if the effective receiving antenna area is $A\times\eta$, the signal power received at the receiver can be expressed as:

$$P_r^{'} = WA\eta = \frac{P_s G_s A\eta}{4\pi r^2} = \frac{P_s G_s G_r}{L_f} \tag{10}$$

where $L_f=(4\pi r/\lambda)^2$ is the loss of free space.

Here, we consider the rain attenuation to the signal power A_p, and Pr at the receiver is:

$$[P_r]dB = [P_s + G_s + G_t - L_f - A_p]dB \tag{11}$$

The energy of signal at the receiver is:

$$\varepsilon_b = \frac{P_r}{b} \tag{12}$$

where b is bit rates (bit/sec) and we have $N_0=KT$, then according to (7) we have:

$$T = 2 \cdot P / Kb \cdot (Q^{-1}(\gamma))^2 \tag{13}$$

Thus, we get the system noise temperature of earth station T, it is below as in [9]:

$$T_{sys} = \sigma_f T_{Ant} + T_{receiver}(K) \tag{14}$$

where σ_f is the coefficient of coupling, T_{ant} is the equivalent noise temperature in receiving antenna and $T_{receiver}$ is the noise temperature of the receiver.

Having T, we can get T_{ant}:

$$T_{ant} = [T_{sys} - T_{receiver}] / \sigma_f \tag{15}$$

By [10], we have:

$$T_{Ant} = T_m(1-10^{-0.1Ap}) + T_c * 10^{-0.1Ap}(K) \tag{16}$$

where, T_c is cosmic background temperature, usually chosen as 2.7 K. T_m is atmospheric mean radiating temperature (K).

As a result, we obtain

$$A_p = 10 \lg \frac{T_c - T_m}{T_{ant} - T_m} \tag{17}$$

Above formulas give a specific relationship between BERs and rain attenuations corresponding to different types of PDUs. We use these exact values of rain attenuation as the thresholds to divide weather conditions.

We take Guangzhou in China (typical subtropical monsoon climate) as an example in this section, in order to find the PDF of the rain attenuate by using a set of rain data (A_{Ri}, P_i), $i=1,\ldots,N$, which are sampled from the ITU_R rain attenuate model[11,12]. In particular, A_{Ri} is the value of the rain attenuation being exceeded in P_i time in every statistics years, so we have:

$$P_i = prop\{A_i \geq A_{Ri}\}; \quad i = 1,\ldots,N \tag{18}$$

Fig. 5 shows the simulation results of the ITU_R rain attenuation model, and we can find the relationship between A_{Ri} and P_i.

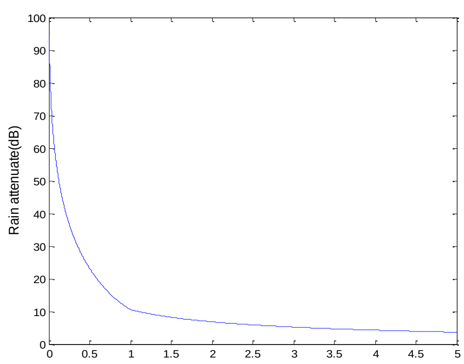


Figure 5. The relationship between rain attenuate and special time percent

Since the rain attenuation follows the logarithmic normal distribution, we can approximate the distribution of rainfall, with its mean and square as that in [13]. The derivation is as below:

$$P = F(\ln A_R) = \int_{\ln A_R}^{\infty} \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-m)^2}{2\sigma^2}\right) dx \tag{19}$$

Similarly:

$$P = Q\left(\frac{\ln A_R - m}{\sigma}\right) = \frac{1}{\sqrt{2\pi}} \int_{\frac{\ln A_R - m}{\sigma}}^{\infty} \exp\left(-\frac{x^2}{2}\right) dx \tag{20}$$

Then, we get:

$$\frac{\ln A_R - m}{\sigma} = Q^{-1}(P) \tag{21}$$

Since mean and square are unknown parameters, we make it as:

$$Q^{-1}(P) = C \cdot \ln A_R + B \tag{22}$$

Where the C and B can be obtained from the linear regression of a set of data known below:

$$(\ln A_{Ri}, Q^{-1}(P_i)), \quad i = 1,\ldots,N \tag{23}$$

Thus, we can get the value of m and σ parameters as:

$$m = -\frac{B}{C}, \quad \sigma = \frac{1}{C} \tag{24}$$

We obtained the value of m and σ parameters by a large number of simulations on linear regression, using the data from the ITU-R model, shown in Fig. 6. As a result, we get the value of mean and square separately: $m= - 1.9020$, $\sigma=1.8950$.

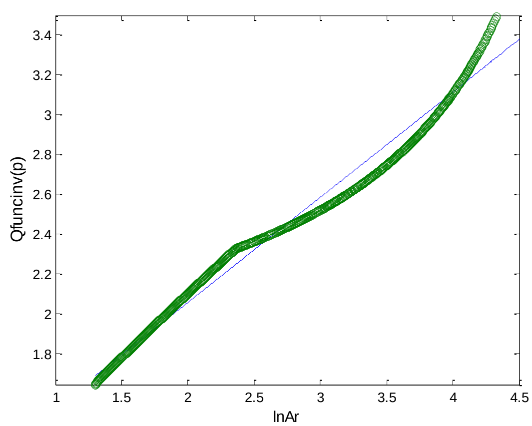
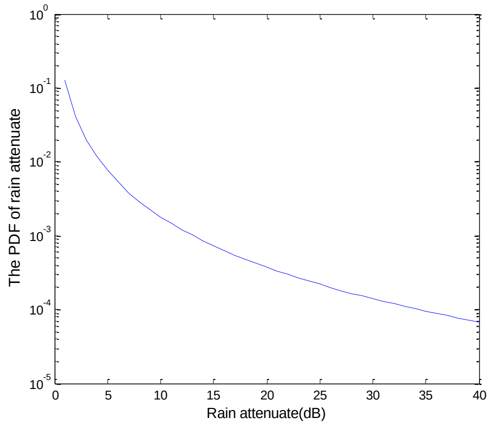


Figure 6. The linear regression of the data from the ITU-R model

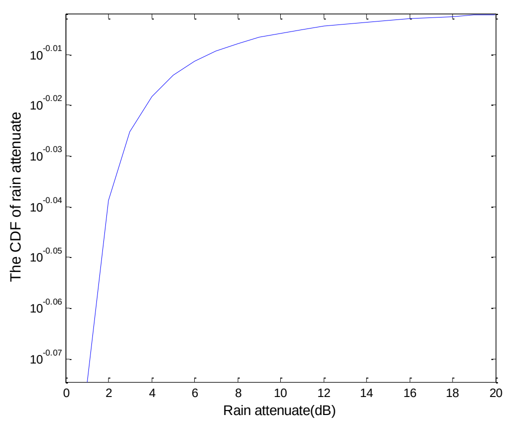
Based on obtained m and σ, we represent the long-term PDF of rain attenuation as follows:

$$P(x) = \begin{cases} \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln x - m)^2}{2\sigma^2}\right) & x > 0 \\ 0 & x \leq 0 \end{cases} \tag{25}$$

The probability distribution function of rain attenuation in Guangzhou is shown in Fig. 7.



(a) The PDU of rain attenuation



(b) The CDF of rain attenuation

Figure 7. The probability distribution of rain attenuation in Guangzhou.

To obtain the state transmission matrix (4), we firstly need to calculate N_k, which is the number of times that attenuation crossed a given threshold l_k in single direction per second. The fade slope f_k is a measure of the time rate of change of attenuation at a given threshold l_k in units of (dB/sec) as defined in [14]. Then, we can calculate N_k approximatively by the multiplication of f_k and the value of PDF at a given threshold l_k in [15]:

$$N_k = f_k \cdot \frac{1}{l_k \sigma\sqrt{2\pi}} \exp(-\frac{(\ln l_k - m)^2}{2\sigma^2}), \quad k > 0 \,\&\, k < K$$

$$N_0 = f_0 \, , k = 0 \tag{26}$$

We also need π_k, which is state probability of the k_{th} state. We approximate the state probability of good weather state to 0.7 in Guangzhou for example, and the probability of the k_{th} state π_k, by long-term probability distribution, is:

$$\begin{aligned}\pi_k &= 0.3 \cdot \int_{l_{k-1}}^{l_k} p_u du \\ &= 0.3 \cdot \int_{l_{k-1}}^{l_k} \frac{1}{u\sigma\sqrt{2\pi}} \exp(-\frac{(\ln u - m)^2}{2\sigma^2}) du\end{aligned} \tag{27}$$

State transition probability $t_{k,k+1}$ is approximated to:

$$t_{k,k+1} \approx N_k / \pi_k \tag{28}$$

Similarly,

$$t_{k,k-1} \approx N_{k-1} / \pi_k \tag{29}$$

Then $t_{k,k}$ is obtained by follows:

$$t_{k,k} = 1 - t_{k,k+1} - t_{k,k-1} \tag{30}$$

According to above formulas, the settings of parameters are shown in Table IV, we take these as example, and the transition matrix we achieved is in Table V.

TABLE IV. THE SETTINGS OF PARAMETERS FOR TRANSITION MATRIX

Latitude	32.24'N	**Longitude**	118.46'E
Frequency(GHz)	20	**Ps(w)**	5
Bit rates(bit/sec)	1M	$\boldsymbol{T_{receiver}}$**(K)**	160
Antenna efficiency	0.65	$\boldsymbol{T_m}$**(K)**	270

TABLE V. THE TRANSITION MATRIX

P	**Good**	**Bad1**	**Bad2**	**Bad3**
Good	0.9886	0.0114	0	0
Bad1	0.0269	0.973	0.0001	0
Bad2	0	0.198	0.492	0.31
Bad3	0	0	0.0604	0.9396

We use the state transmission matrix of the four-state Markov chain to imitate dynamic process of weather states.

IV. SIMULATION AND DISCUSSION

In this section, we evaluate the performance of CFDP under the four-state weather channel model by Monte Carlo simulations.

First, CFDP is evaluated over various BERs with different sizes of files as 1MB, 5MB and 10MB separately in single-state channel. Fig. 8 shows that with the BERs increases, the average retransmission number of PDUs increase significantly. Under the same BER, the average retransmission number of PDUs increases with the size of files. In Fig. 9, the loss of NAK message occurs in the case that BER is more than 1e-5, which indicates the performance of the CFDP is seriously affected by weather conditions, especially bad weather. Therefore, weather effect must be considered in analyzing of the CFDP performance.

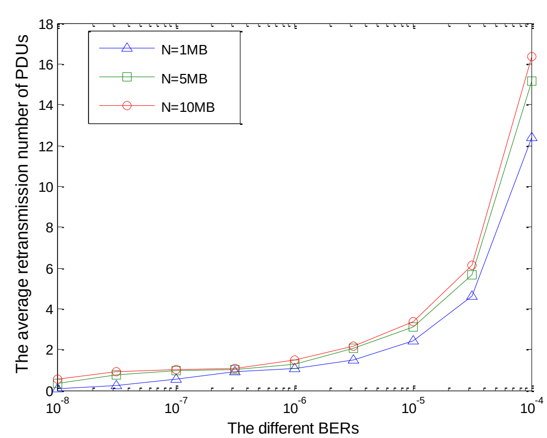


Figure 8. The average retransmission number of PDUs

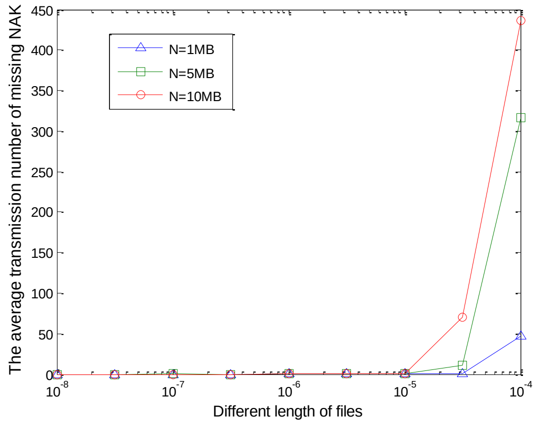


Figure 9. The average number of missing NAK

Fig. 10 shows the comparison of the CFDP performance with different sizes of files over channel models with different weather states *n*, including *n*=1, *n*=2 and *n*=4. The settings of simulations are shown in Table VI.

TABLE VI. THE SIMULATION PARAMETERS

File size(MB)	1, 2, 4, 6, 8, 10, 12	
The times of simulation	10000	
PDU size (Byte)	***long-PDU***	1024
	Short-PDU	30
	NAK	variable
The BERs of channel models	***Single-state***	1e-7
	Two-state model	(1e-7,1e-4)
	Four-state model	(1e-7,4.19e-5,1.23e-6, 1e-4)

We can find that the results of the CFDP performance under the four-state weather model are between that under the two-state model and single-state model. The results have evident decrease on the base of two-state model due to the further revision of weather conditions. It means that the channel we modeled characterizes better the dynamic process of weather conditions.

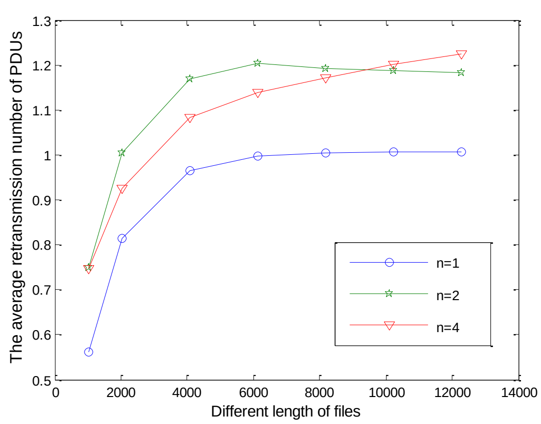
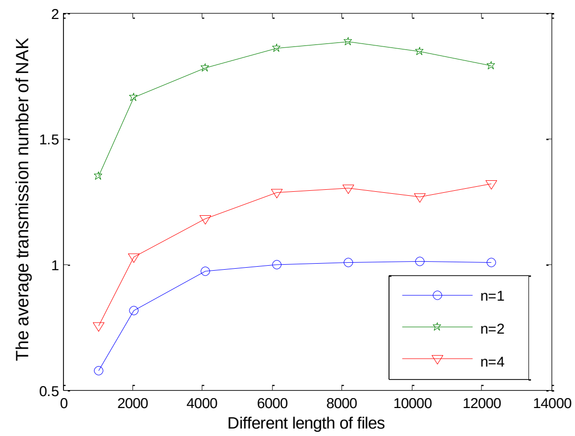
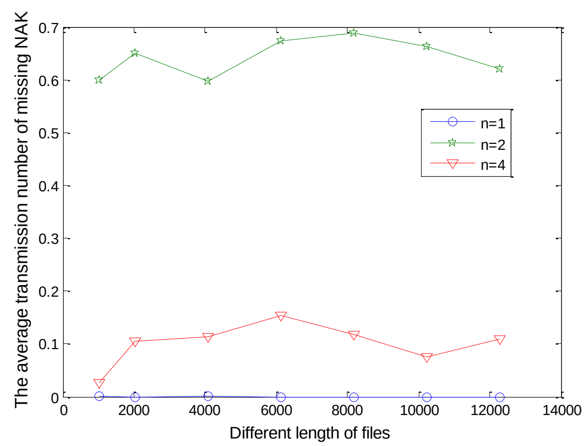


Figure 10. The average retransmission number of PDUs under different channel models

From the channel model, we can get the detailed NAK message which is vital to the whole link. Fig. 11 (a) shows the average transmission number of NAK. And the average number of missing NAK is shown in Fig. 11 (b). Similarly, The result of the four-state weather model has an evident decrease compared with the two-state model. The model could approach to the real channel characteristics more efficiently as a result of the careful revision of weather conditions change.



(a)The average transmission number of NAK



(b) The average transmission number of missing NAK

Figure 11. The performance of transmitted NAK under different channel models.

As a result, the four-state weather channel model gives a accurate description of the detailed dynamic process of weather states, and reflects more efficiently on the impact of weather conditions change on channel performance.

V. CONCLUSION AND FUTURE WORK

In this study, we established the four-state weather channel model on transport layer of CFDP considering the propagation characteristics, including rain attenuation and equivalent noise temperature over Ka-band links. The proposed model could evaluate the performance of CFDP over Ka-band channel model efficiently, by reflecting on the impact of weather conditions into modeling channel. In particular, we design a elaborated-designed division criterion to the weather conditions and divided the weather states by the BERs from the transport layer. The results indicated that the proposed model is more reasonable as it gives realistic results. Moreover, the four-state weather model give a accurate description of the detailed dynamic process of weather states, thus reflects more efficiently on the impact of weather conditions on channel.

Future work should take an emphasis on validation the results with actual measurements, meanwhile, using a high-order Markov chain model in order to accurately simulate weather processes.

VI. ACKNOWLEDGMENT

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