The analysis of IEEE 802.11 DCF protocol based on LEO satellite Wi-Fi network

Wen He¹, Xiaofeng Tao¹, Defeng Ren¹

¹China Academy of Space Technology (Xi’an), China

Abstract. Aiming at the problems of traditional IEEE 802.11 DCF protocol applied to LEO satellite Wi-Fi network, the influence of propagation delay, hidden terminal and user collision on the throughput of MAC layer is fully analysed, and a specific scheme is proposed to adjust the ACK Timeout and the minimum contention window value. The improved two-dimensional Markov model has been used to analyse the DCF protocol throughput theoretically. By using MATLAB simulation, it is verified that the throughput performance is directly related to the transmission probability, and throughput performance is negative correlated with the number of nodes and transmission distance.

1. Introduction

Due to remote locations, sparsely populated areas, and low returns, many rural areas in developing countries in the world have no access to the communication network. They are in short supply of a low-cost solution to network connectivity. In recent years, some people have proposed to combine satellite communications with Wi-Fi technology and utilize LEO satellites to achieve wide-area coverage of Wi-Fi, making Wi-Fi more widely available and more flexible for more users. However, most wireless LANs currently on the market use the IEEE 802.11 standard, and the media access control layer mainly uses Distributed Coordination Function (DCF). However, the LEO satellite Wi-Fi network has the problems of longer propagation delay, hidden terminal, and more user collision. Some technologies of the conventional IEEE 802.11 DCF protocol have shown incompatibility in this network environment, resulting in a drastic throughput reduce [1].

This paper briefly introduces DCF protocol and analyses the existing problems in the LEO satellite Wi-Fi network. According to the characteristics of the LEO satellite channel environment, the corresponding improvements are simply proposed. A modified Markov chain analysis model established. The theoretical analysis results are verified by MATLAB.

2. A brief introduction to DCF protocol

DCF protocol is divided into basic CSMA/CA mode and RTS / CTS mode [2]. The RTS / CTS mode solves the problem of short-range "hidden terminal" by introducing RTS frames and CTS frames.

In the CSMA/CA mode, when the site has data to be transmitted, the busy/free state of the channel must be determined first. Continue to listen when listening to the channel is busy; once idle, and reach the DIFS duration, the data can be sent to the destination node. A random back-off process is performed before sending data, binary exponential back-off algorithm, as shown in Figure 1.
Each node in the retreat process needs to maintain a window parameter. When a node fails to transmit, the contention window of the node will double. When increasing to the maximum, continuous retransmission will keep the maximum value unchanged until the node sends successfully, or the limit of maximum retransmission times is reached, the contention window will be reset to the minimum.

3. The analysis of LEO satellite Wi-Fi MAC protocol
Compared with the quasi-static channel environment of the ground Wi-Fi, the LEO satellite link has a long propagation time and a large area. The direct application of traditional Wi-Fi to the satellite scene can seriously affect the performance of the MAC protocol. Figure 2 shows the LEO satellite Wi-Fi system model used in this study. With LEO satellite as the access point AP, it can realize two-way communication with terrestrial base stations via Wi-Fi. The base station can form an extended terrestrial wireless link with a terminal such as a mobile phone.

3.1. Effect of propagation delay on MAC protocol
802.11 standard uses the Positive Acknowledgment mechanism. All transmitted frames must be acknowledged. The original DCF protocol ACK Timeout is set to 44us, the cell radius does not exceed 1.2km. Relative to the terrestrial Wi-Fi network, the LEO satellite link environment has a long propagation delay. If the ACK Timeout is set too short, it may cause wrong judgment of the transmission situation, which causes the data frame to be retransmitted continuously and may eventually be discarded, thereby reducing the system throughput. Figure 3 shows the interaction of MAC layer data frame in CSMA/CA mode.
Therefore, considering setting a reasonable ACK Timeout based on propagation delay is a better way to improve the system performance. As shown below:

\[ \text{ACK Timeout} = 2 \text{PropTime} + \text{SIFS} + \text{SlotTime} \]  

(1)

3.2. The problem of "hidden terminal"
LEO satellites with orbital altitude of 400km can cover hundreds of thousands of square kilometres. Due to the limited transmitting power of the terrestrial terminals, the terminals that are far apart on the ground can hardly monitor the state of each other, and almost all the terminals become hidden nodes. The RTS / CTS mode is adopted to reduce the adverse effects of "hidden terminals", but it is only suitable for the short-distance indoor environment. In the long-distance link environment, due to the longer propagation delay, and the relatively small value of the slot time, it is possible that other stations receive a station RTS frame before the back-off counter has reached zero, the station will begin data transmission, then there will be collisions, so that the throughput greatly reduced.

Therefore, TDMA can be considered as a basic multiple access method, using a combination of fixed and dynamic scheduling algorithms [3], TDMA access mode for fixed allocation, and contention based CSMA / CA scheme for dynamic allocation. The two will be fused, complement improve each other.

3.3. A serious user conflicts
Due to the LEO satellite-to-ground link environment, the coverage area is large, so the traffic volume is serious. In particular, in the case of hidden terminals, multi-user conflicts will be aggravated. Once a collision occurs, the data frame needs to be retransmitted. However, a longer propagation delay takes longer time and even discards data frames, which seriously affects the system throughput.

Aiming at the shortcomings of DCF protocol, we can improve it from both back-off mechanism algorithm and window parameter [4]. On the one hand, the back-off window algorithm is dynamically adjusted according to the number of active nodes or the network load; on the other hand, \( CW_{\text{min}} \) and \( CW_{\text{max}} \) in the DCF protocol may also be adjusted according to actual network conditions.

The following gives a solution to the problem of "user conflicts".

In a certain transmission period, the number of collision packets \( N_c \) is obtained through the carrier sense retransmission counter, and the number of successful packets \( N_s \) is monitored according to the number of received ACKs. The success rate \( SR \) is defined as the following:

\[ SR = \frac{N_s}{N_c} \]  

(2)

We can determine the network’s busy state by “threshold”.

\[ CW_{\text{min}} = \begin{cases} 0.5CW_{\text{min}}, & \text{SR}>\text{threshold} \\ 2CW_{\text{min}}, & \text{SR}<\text{threshold} \end{cases} \]  

(3)

The algorithm dynamically adjusts the contention window through network conditions to avoid the disadvantages of long delay under light load and high conflict rate under heavy load, and reduce the unfair access between nodes under the BEB algorithm, thereby improving the system throughput.

4. 802.11 DCF Analysis Model of LEO Satellite link
In allusion to the adjustment and optimization of 802.11 DCF protocol, Bianchi first proposed the Markov Chain model [5]. However, the model is proposed for the short-range indoor environment of the ground without considering the propagation delay and hidden terminal problems, and can’t be directly applied to the LEO satellite Wi-Fi link environment. Therefore, this paper presents a modified Markov analysis model for LEO satellite Wi-Fi network based on the literature [6]. The model considers the influence of hidden nodes and long distance.
4.1. Markov Chain model

By Markov state transition diagram can get the following transition probability:

\[ P\{i, j \mid i-1,0\} = \frac{P}{W_i}, \quad i \in [0,m], j \in [0,W_i-1] \]  
(4)

\[ P\{0, j \mid i,0\} = \frac{1-P}{W_0}, \quad i \in [0,m-1], j \in [0,W_0-1] \]  
(5)

\[ P\{i, j \mid i-1,0\} = \frac{P}{W_m}, \quad i \in [m+1,R], j \in [0,W_m-1] \]  
(6)

\[ P\{0, j \mid R,0\} = \frac{1}{W_0}, \quad j \in [0,W_0-1] \]  
(7)

If the active node in the channel is the access point, and the nodes in the ground are visible to each other, when the station detects that the wireless channel is idle and the probability of the back-off counter reduces by 1 is,

\[ p_1 = P\{i, j \mid i, j +1\} = 1 - p, \quad i \in [0,R], j \in [0,W_R-2] \]  
(8)

If the station detects the wireless channel is busy, the probability of its back-off counter frozen is

\[ p_2 = P\{i, j \mid i, j\} = p, \quad i \in [0,R], j \in [0,W_R-1] \]  
(9)

If the active node in the channel is a base station, it is a hidden node with other nodes, and the station can’t detect the busyness of the channel (except the access point AP). Regardless of any situation, the probability of the back-off counter reduces by 1 for each slot time is

\[ p_1 = P\{i, j \mid i, j +1\} = 1, \quad i \in [0,R], j \in [0,W_R-2] \]  
(10)

\[ p_2 = 0 \]  
(11)

Where,

\[ W_i = \min(2W_0 - 1, 2^nW_0 - 1) \]  
(12)

\[ W_0 = CW_{\min} + 1 \]  
(13)

\[ b_{i,j} = \lim_{t \to \infty} P\{s(t) = i, b(t) = j\}, \quad i \in [0,m], j \in [0,W_i-1] \] represents the steady-state distribution probability of Markov chain.

It is assumed that there are n nodes in the LEO satellite Wi-Fi network. The transmission probability \( \tau \) and collision probability \( P \) of each node are the same. A represents an access point...
AP, B represents a terrestrial base station STA(i), and C represents another terrestrial base station STA(j) \( (i \neq j) \). In the LEO satellite Wi-Fi network, due to the long propagation delay and the hidden terminal problem, the collision between nodes may occur between different slottime.

\[
\tau = \frac{1}{1 + p_{\text{RTT}}^{-1} \sum_{r=0}^{R} p_{r}(1 + \frac{W_{r}}{2})} \\
p = 1 - \prod_{c=1, c \neq \text{STA}(i)}^{n} (1 - \mu_{\text{BAC}}) 
\]

\( \mu_{\text{BAC}} \) represents the probability of another base station C colliding with it when a base station B transmits a message to the access point A.

\[
\mu_{\text{BAC}} = \sum_{i=0}^{R} \sum_{j=0}^{W_{i}} b_{X, j} P \{ \lambda_{B, A, C, j} \} 
\]

Where,

\[
P \{ \lambda_{B, A, C, j} \} = N_{\text{BAC}, j} (\prod_{y=1, y \neq B, C}^{n} \sum_{l=0}^{y \cdot W_{l}} b_{y, l, m}) (1 - \sum_{a=0}^{R} \sum_{b=0}^{W_{a}} \min(\frac{j}{W_{a}}, 1)) \cdot b_{C, a, b} 
\]

\[
b_{C, j} = \frac{W_{i} - j}{W_{i}} p_{\tau} \frac{1 - p_{\text{RTT}}^{-1}}{1 - p_{\text{RTT}}^{-1}} 
\]

\[
N_{\text{BAC}, j} = \begin{cases} 1 & \text{int}(NT_{\text{BAC}}) > j \\ \text{int}(NT_{\text{BAC}}) - j & \text{int}(NT_{\text{BAC}}) = j \\ 0 & \text{int}(NT_{\text{BAC}}) < j \end{cases} 
\]

Let \( T_{B, C} \) represent the time interval that another station C occur collision when the station B is transmitting data, just as Figure 5.

\[
T_{B, C} = (t - \delta_{B, C} \cdot t + \delta_{B, C}) 
\]

Where \( \delta_{B, C} \) represents the transmission distance between station B and C.

\[
NT_{\text{BAC}} = \frac{2\delta_{B, C}}{\text{Slot Time}} 
\]

4.2 A calculation of the throughput

The throughput is an important parameter to measure the performance of the network, it refers to the amount of data transmitted successfully in a unit of time. The throughput of this system is defined as

\[
S = \frac{p_{s} p_{n} E[p]}{(1 - p_{n}) \sigma + p_{s} p_{n} T_{s} + p_{n} (1 - p_{s}) T_{c}} 
\]

Where \( p_{n} \) is the probability of at least one transmission in a system slot time, \( p_{s} \) is the probability that only one transmission is transmitted successfully, \( \sigma \) is the length of a slot time, \( T_{s} \) is the
average length that transmit one frame successfully, $T_c$ is the average duration of a transmission collision occurs. It is classified as the conflict length of the sending stations ($T_{c,s}$) and the conflict length of other stations ($T_{c,not-i}$). $E[p]$ is the average payload size of the packets

$$p_r = 1 - (1 - \tau)^n$$ \hspace{1cm} (23)

$$p_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}$$ \hspace{1cm} (24)

In the basic access mode,

$$T_s = H + E[p] + 2 \cdot \text{PropTime} + \text{SIFS} + T_{\text{ACK}} + \text{DIFS}$$ \hspace{1cm} (25)

$$T_c = \frac{\tau}{p_r} T_{c,s} + (1 - \frac{\tau}{p_r}) T_{c,not-i}$$ \hspace{1cm} (26)

$$T_{c,s} = H + E[p] + \text{ACK Timeout} + \text{DIFS}$$ \hspace{1cm} (27)

$$\text{ACK Timeout} = 2 \cdot \text{PropTime} + \text{SIFS} + \sigma$$ \hspace{1cm} (28)

$$T_{c,not-i} = H + E[p] + \text{PropTime} + \text{EIFS}$$ \hspace{1cm} (29)

$$H = \text{PHY} \_ \text{hdr} + \text{MAC} \_ \text{hdr}$$ \hspace{1cm} (30)

By substituting equations (24)-(30) into equation (23), it can be seen that the throughput is determined by the transmission probability. By the differentiation of equation (23) on the transmission probability, it can be seen that the optimal transmission probability for maximizing the throughput depends on the number of active nodes and the transmission distance.

4.3. The simulation verification

In order to verify the relationship between the throughput and the transmission probability, the number of nodes and the transmission distance, the above theoretical analysis results are verified by MATLAB simulation based on the 802.11b protocol standard.

Figure 6. With different transmission distances, the throughput varies with the transmission probability (the number of nodes is 1).
Figure 7. With different transmission distances, the throughput varies with the transmission probability (the number of nodes is 7).

As can be seen from the figure above, the throughput increases with the increase of transmission probability $\tau$ for a single user, and when $\tau$ reaches 0.2, it tends to be stable, and the shorter the transmission distance is, the larger the throughput is. When multi-user, the throughput decreases rapidly with the increase of transmission probability. When $\tau$ approaches 0.6, the throughput tends to zero.

Figure 8. With different number of nodes, the throughput changes with the transmission probability (Transmission distance of 400km).

As can be seen from the figure above, the throughput is not sensitive to the sending probability for a single user. When multi-user, the throughput decreases rapidly with the increase of sending probability, and the more the number of users, the lower the throughput. The simulation results show that in the LEO satellite Wi-Fi network, the throughput is directly related to the transmission probability, and the more the number of users, the longer the transmission distance, the poorer the throughput performance will be.
5. Conclusions
Based on the study of the characteristics of the long propagation, "hidden terminal" and the user conflict of LEO satellite-to-ground link, this paper improves the ACK Timeout and $CW_{\text{min}}$ parameter for the traditional DCF protocol, and a two-dimensional Markov model for LEO satellite link is proposed. The simulation results show that the throughput performance is directly determined by the transmission probability and decreases with the increase of number of users and transmission distance. The follow-up study will propose specific solutions and simulation verification for multi-user wireless communication in the LEO satellite link environment.

References
[1] Wang N 2012 Experimental Study of 2P MAC Protocol in Long Distance Wireless Mesh Networks Tianjin University.
[2] MATTBEW GAST S. 802.11 Wireless Network Authoritative Guide Second Edition. Nanjing: Southeast University Press, 2007.
[3] Tan Fy, Ye L, Yu Fs, Liu Zb 2011 Multiple access protocol with combination of TDMA and CSMA in Ad hoc network Computer Engineering and Design 32(11):3656-3659+3681.
[4] Wang P 2015 Improvement and performance analysis for DCF mechanism in IEEE 802.11 MAC layer Southwest Jiao tong University.
[5] Wang Jj, Li D, Liu Sy 2017 New improved back-off algorithm and simulation for 802.11 DCF Electronic Design Engineering 25(10):148-153.
[6] Simóreigadas F J, Ramoslópez F J, Seoanepascual J 2010 Modeling and Optimizing IEEE 802.11 DCF for Long-Distance Links IEEE Transactions on Mobile Computing 9(6):881-896.