An Optimal Channel Bonding Strategy for IEEE 802.11be

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Abstract. Although there are a large number of available channels that can be bonded together for data transmission in the next generation WLAN, i.e., IEEE 802.11be protocol, it may cause long data transmission time to transmit large files due to the inefficient channel bonding strategies. This paper proposes an optimal channel bonding strategy based on the optimal stopping theory. Firstly, under the constraint of the number of available channels, the problem of minimizing the transmission time of large files is formulated as an optimal stopping problem, where the time duration of large file transmission is defined as the sum of channel accessing time and data transmission time after successful access into the channel, Secondly, the threshold of successful bonded channel number is derived based on the optimal stopping theory. When the channel access is successful, data transmission is performed if the number of bondable channels is larger than the threshold. Otherwise this data transmission opportunity is dropped and channel competition is resumed. The simulation results show that, compared with the traditional EDCA if access-success then-transmit strategy and the fixed bonding channel number threshold strategy, the data transmission completion time of large file is shortened by more than 40%.

Keywords: Channel bonding · IEEE 802.11be · Optimal stopping theory

1 Introduction

The concept of channel bonding technology is proposed from the IEEE 802.11n standard, the purpose is to improve the transmission rate and throughput. In IEEE 802.11 a/b/g, the bandwidth of each channel is 20 MHz. In IEEE 802.11n, two consecutive 20 MHz sub-channels can be bonded to form a 40 MHz bandwidth channel for data transmission. That is 40 MHz = 20 MHz + 20 MHz. These two channels are defined as a primary channel and a secondary channel, respectively, where the primary channel is mainly used as a broadcast channel to transmit broadcast frames to provide services for wireless connections. In 802.11be, the multi-channel bonding technology has been further developed, supporting the bonding of more adjacent channels (up to 16), and at the same time, the

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primary and secondary channels are no longer distinguished Ref. [1,2]. That is, a node can access any channel, and then bond all other currently idle channels, which further reduces the difficulty of channel bonding and improves the feasibility of channel bonding, but still faces the problem of long and unstable transmission of large files. In the environment of rapid development of network technology, users' requirements for transmitting large files (such as 4k video) become more frequent, so it is necessary to design an effective channel bonding strategy to minimize the total data transmission time of large files.

In view of the existing problems, domestic and foreign scholars have carried out relevant research. Overall, these studies can be divided into two categories: channel bonding and optimal stopping. Sami Khairy et al. studied the performance of distributed and opportunistic multi-channel bonding in IEEE 802.11ac WLAN where existing IEEE 802.11a/b/g users coexist in Ref. [3], and proposed a method for Reduce competition in the network and obtain maximum network throughput. Eng Hwee Ong et al. in Ref. [4] proposed that increasing the bonded channel bandwidth to 160 MHz may not be an effective option, and the throughput no longer increases with increasing bandwidth. Wei Wang et al. proposed for the first time in Ref. [5] a scheme based on adaptive Clear Channel Assessment (CCA) for managing IEEE 802.11 WLAN channel bonding. Compared with the traditional channel bonding scheme and the default CSMA/CA, the throughput is increased by 37% and 46%, respectively. The above studies are all about the channel bonding research before IEEE 802.11ax, but now a channel bonding method suitable for IEEE 802.11be is needed.

In general, the optimal stopping model analysis problem often divides the problem into two parts, profit and cost. Ref. [6–11] The cost is a set of observable random variables $\{C_1, C_2, ...\}$, The cost C and profit Y at each observation may change, when C_n is observed and you choose to stop, you will get a profit Y_n, as shown in Fig. 1:

The purpose of the optimal stopping rule is to obtain the highest net profit, that is, the profit minus all costs. It can be expressed as:

$$\max\left\{Y_n - \sum C_n\right\}$$

Since future benefits and costs are generally unknown, all need to use existing observations to make predictions, and the solution to the optimal stopping rule is expressed as a set of thresholds composed of a series of observable values.

In the field of WLAN, the optimal stopping model has some applications, As applied in Ref. [12], it is applied to the problem of maximizing network throughput in the system model of multi-packet reception (MPR) WLAN with multi-round competition. In Ref. [13], it is used in wireless ad hoc networks to select the next-hop relay selection problem as a sequential decision problem. In Ref. [14], it is applied to consider distributed opportunity scheduling (DOS) in wireless ad hoc networks. However, there are still very few studies on the optimal access timing combined with channel bonding.

The purpose of this study is to propose a more optimized rule based on the channel bonding technology, so that the time required for file transfer is shorter. In IEEE 802.11be channel bonding, each channel can be used as the main channel to access the node, and then bond other idle channels to increase the transmission bandwidth and reduce the transmission time. However, due to the transmission of the node in the channel, etc. the number of idle channels is a random variable, and there may be few available channels after access.

In response to this problem, this article applies the idea of optimal stopping theory, combined with statistical laws, an optimal sending strategy can be obtained, so that file sending can be completed faster. On the premise of assuming that the file transmission speed is proportional to the number of bonded channels; the probability of occurrence of idle time slots in each channel is independently and identically distributed. The strategy in this article adds a judgment after the node accesses the channel to judge whether the current channel status is worth sending. Through analysis of factors such as channel conditions and file size to be sent, the strategy uses the method of minimizing expectations to dynamically obtain a threshold for the minimum number of successfully bonded channels, That is, when the STA accesses the channel, if the number of successfully bonded channels is not less than the threshold, it is selected to send, otherwise it will give up the access and re-compete for the channel to obtain the opportunity to bond more channels. The simulation results show that the file transfer completion time is significantly shortened compared to the traditional access-on-demand and fixed bonded channel number thresholds.

The rest of this paper is organized as follows. Section 2 describes the network topology model and problem modeling of the communication system concerned in this paper. Section 3 carries on the theoretical analysis and derivation of the proposed problem model. Section 4 is the simulation result analysis and error analysis. Section 5 is the summary and outlook.

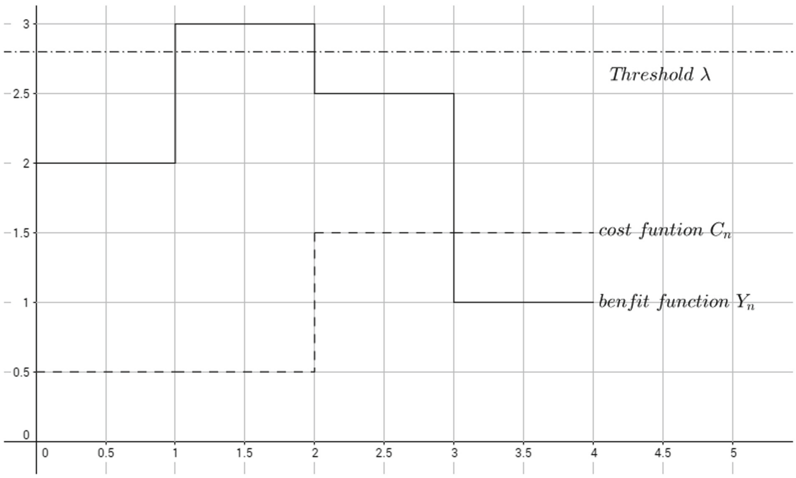

Fig. 1. Schematic diagram of the general optimal stopping model

2 System Model

See Table 1.

Table 1. Symbol notation and meanings

Symbol notation	Symbol meanings
H	Total number of channels
M	Average number of sSTAs in a BSS
h	The number of idle channels cSTA observed
m	The threshold of successful bonded channel number
n	cSTA access channel attempts
x	Number of channels successfully bonded when cSTA accesses
N	Number of access to channels while waiting
A_m	Average waiting time for access channel when threshold is m
S_m	Average sending time when the threshold is m
T_m	The total duration when the threshold is m
λ_m	Maximum file size for threshold m
F	The size of file to be sent
p	Probability of occurrence of free time slots in separate channels
p_h	When observing a channel, the probability that the number of channels that can be bonded is h
$P(m)$	When accessing a channel, the probability that the number of successfully bonded channels is at least m
f	Time required for file transmission on a single channel
s	Transmission rate of a single channel
τ	Probability of sSTA in the channel starting to send
P_{cl}	Probability that cSTA will collide on one of the channels when accessing the channel
P_{ac}	Probability of cSTA accessing the channel
$E[P]$	The average time for each sSTA to send a packet

2.1 Network Topology Model

In order to make the research content of this article more concise, this article will analyze the scene of a basic service set in a wireless local area network. As shown in Fig. 2, The nodes in this basic service set are divided into three categories.

This article divides STAs into two types: sSTA and cSTA, of which sSTAs are traditional STAs, M sSTAs are evenly distributed on H channels, which are regarded as the components of the channel environment in this article, and they are regarded as the background without considered separately when analyzing. And cSTA is a new type of STA using 802.11be. This article will focus on analyzing its behavior (Table 2).

Table 2. The number of each node in the BSS

Nodetype	Number of nodes in a BSS
AP	1
cSTA (STA with Channel bonding capability)	1
sSTA (STA without Channel bonding capability, only working on single channel)	M

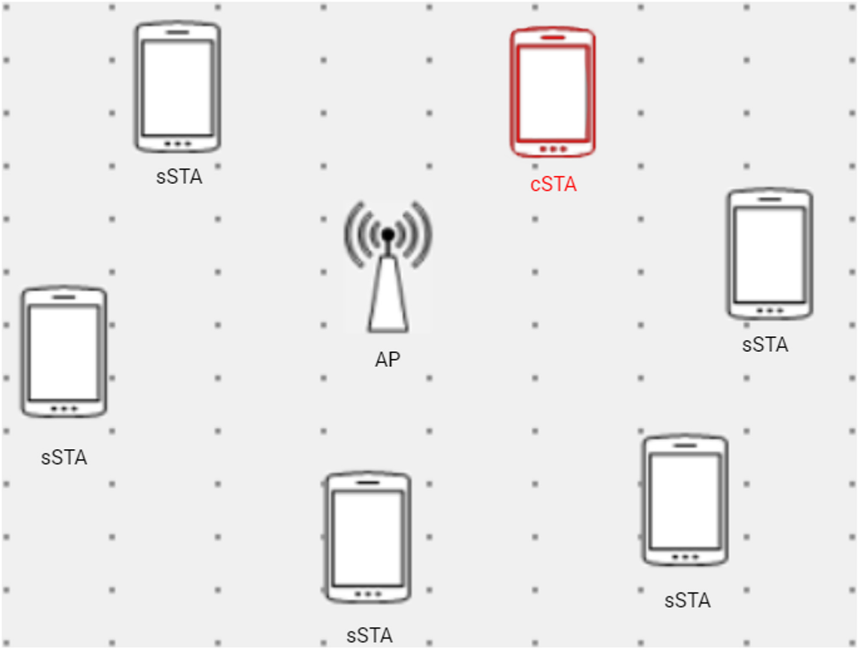

Fig. 2. Schematic diagram of network topology

2.2 Channel Access Method

In the process of accessing the channel, AP and cSTA can bond all current idle channels for transmission after accessing the channel, while traditional sSTAs can only send and receive on a fixed channel, and sSTAs are evenly distributed on all H channels. The specific channel access methods for each node when sending and receiving are as follows.

a) AP and cSTA can work on all H channels, that is.

Send. Data can be send on $m\,(1 \le m \le H)$ channels at the same time, Where m is the number of idle channels when AP/cSTA accesses the channel successfully.

Receive. Data can be received on $m\,(1 \leq m \leq H)$ channels at the same time, Where m is the number of idle channels when AP/cSTA accesses the channel successfully.

b) sSTAs can work on a fixed one of all channels, but cannot bond other idle channels, that is.

Send. Data can only be sent on one channel, which is a fixed working channel for this sSTA, when sSTA access on this channel successfully, data can only be transmitted on this channel.

Receive. Data can only be sent on one channel, which is a fixed working channel for this sSTA, When AP access on this channel successfully, data can only be transmitted on this channel.

But in actual consideration, this article only considers the uplink data transmission scenario, that is, cSTA/sSTA contention access channel for data transmission, and the AP is only responsible for data reception.

2.3 Optimal Stopping Problem Formulation

When cSTA accesses the channel, if there are too few channels available, it can give up the opportunity of this access, re-compete for the channel, and wait for the next access in order to use more channels to obtain a larger transmission bandwidth. It will not start sending until the number of available channels meets its expectations. However, on the one hand, if it wants to wait for more channels to be bonded, more waiting time will definitely need, On the other hand, if it is sent directly after accessing the channel, the file sending time will be very long. The purpose of this article is to give an optimal stopping rule, That is, when accessing the channel, when the number of channels that can be bonded is greater than that, stop waiting, bonding the existing channel to start sending, so as to achieve the minimum total time for cSTA to transfer files.

As with the general optimal stopping problem, in the channel bonding problem, we also need to consider the benefits and costs of the problem, but in fact, The object of the optimal stopping problem is when to stop waiting for the opportunity to access more channels, Once sending starts, no matter how many channels are bonded to send, the final income is consistent, that is, Complete the sending of the file. And the cost of the channel bonding problem only considers the time cost, that is, users want to transmit as quickly as possible. So we divide the time axis into two segments, with the sign of stopping waiting for the opportunity to bond more channels to start sending. As shown in Fig. 3, before the Nth access to the channel and stop waiting, there will be multiple attempts to access the channel, and the time for the nth wait for access to the channel is A_n, Therefore, a set of random variables can be obtained, $\{A_1, A_2, ..., A_N\}$, It follows a geometric distribution $GE\left(1/\left(1-(1-p)^H\right)\right)$, So you can get the waiting time for access to the channel $A = A_1 + A_2 + ... + A_N$, Start sending after stopping waiting. The sending time is a function related to the file size and the number of successfully bonded channels m, the sending time is $S = F/ms$, But the number of successfully bonded channels is a random variable, $m = \{0, 1, .., h\}$, It satisfies the binomial distribution $B(h, p)$, Where h is the number of idle channels found while monitoring the channel, The purpose of the optimal stopping rule is to make the total sending time the shortest, that is, $\min\{A + S\}$, Since this is a random process, this article will use minimization expectations as a criterion for evaluating the optimal stopping.

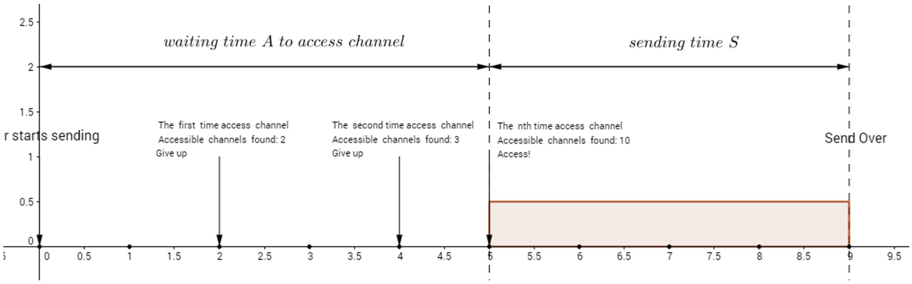

Fig. 3. Schematic diagram of the optimal stopping model in channel bonding

In the channel bonding problem, The only values that can be observed by cSTA are the number of free channels after each access to the channel h and the size of the file to be sent by cSTA F, In addition, it can know the channel idle probability p, and the current number of sSTAs in the BSS M and the number of channels H, Therefore, under the assumptions of this article, the solution of the optimal stopping model in channel bonding will be expressed as: After accessing the channel, the number of successfully bonded free channels x is greater than the threshold m of successfully bonded channels before sending is allowed, The minimum number of successfully bonded channels m is jointly influenced by F, p and the known BSS basic parameters M, H.

3 Optimal Channel Bonding Strategy Derivation

3.1 Channel Analysis

Idle and Busy Situation. According to the assumptions of this article, The channels are independent of each other and do not affect each other, The probability of an idle time slot in all channels is p, According to these conditions, we can get the probability P_{ac} that an accessible slot appears in the channel, that is The probability that each channel is not busy.

$$P_a c = 1 - (1 - p)^H$$

According to the conditional probability formula.

$$P\left(B|A\right)=\frac{P\left(AB\right)}{P\left(A\right)}$$

We can get the probability P_h that the number of available channels is h when cSTA accesses the channel.

$$p_h=\mathrm{C}_H^h\frac{p^h\left(1-p\right)^{H-h}}{P_{ac}}=\mathrm{C}_H^h\frac{p^h\left(1-p\right)^{H-h}}{1-\left(1-p\right)^H} \tag{1}$$

Conflict Situation. After cSTA finds that there are h idle channels, it prepares to access the channel, However, there are only m channels that can be successfully transmitted during access, and cSTA and sSTA conflict on other $(h-m)$ channels, In Bianchi's analysis of DCF Ref. [15], When there are M/H nodes accessing the channel, the channel is idle, busy, and the time used for collision can be expressed as,

$$Idle:\left(1-\tau\right)^{M/H}$$

$$Busy:\left(M/H\right)\cdot\tau\left(1-\tau\right)^{(M/H)-1}\cdot E[P]$$

$$Collision:\left(1-\left(1-\tau\right)^{M/H}\right)+\left(M/H\right)\cdot\tau\left(1-\tau\right)^{(M/H)-1}$$

where $E[P]$ is the average time for each sSTA to send a packet, τ is the probability of a node sending packets in a certain time slot, According to the definition of p as the channel idle probability in this article, the relationship between τ and p can be obtained.

$$p=\frac{\left(1-\tau\right)^{M/H}}{1+\left(E[P]-1\right)\cdot\left(M/H\right)\cdot\tau\left(1-\tau\right)^{(M/H)-1}} \tag{2}$$

Therefore, the collision probability of cSTA on any channel can be obtained.

$$P_{cl}=1-\left(1-\tau\right)^{M/H} \tag{3}$$

Thus, the probability that cSTA will eventually access m channels after finding h idles is,

$$P\left(m|h\right)=\mathrm{C}_h^{h-m}\cdot\left(1-P_{cl}\right)^m P_{cl}^{h-m} \tag{4}$$

3.2 Waiting Time for Access Channel Analysis

According to the assumptions in this article, each time slot on the channel can only have 2 states, accessible or inaccessible, And the probability of an idle slot appearing is p, Therefore, the channel can be regarded as an infinite number of Bernoulli experiments. In the n times Bernoulli experiment, try the kth time to get the first chance of success. In detail, it is expressed as, the probability of the first k−1 times all fail, but the kth success. Therefore, we can use the expectation of geometric distribution $E(X) = 1/p$ to represent the waiting time for the first occurrence of an event.

Take the example that more than channels must be bonded to allow sending. When accessing a channel, the probability that more than m channels are idle is,

$$P(m) = \sum_{i=m}^{H} \sum_{h=i}^{H} p_h \cdot P(i|h) \tag{5}$$

Expressed in Bernoulli's experiment, that is, The probability of being able to access the channel is $P(m)$ and the probability of not being able to access is $1 - P(m)$. Then use the geometric distribution of the expectations to indicate that the average number of attempts to access the channel when more than m channels are idle is.

$$N = \frac{1}{P(m)} = \frac{1}{\sum_{i=m}^{H} \sum_{h=i}^{H} p_h \cdot P(i|h)} \tag{6}$$

Similarly, the time interval between two access channels can be obtained as $1/P_{ac}$, It can be obtained that the average waiting time required for more than m channels to be idle is.

$$A_m = \frac{N}{P_{ac}} = \frac{1}{\left(1 - (1-p)^H\right) \cdot \sum_{i=m}^{H} \sum_{h=i}^{H} p_h \cdot P(i|h)} \tag{7}$$

3.3 Sending Time Analysis

Sending time in this article refers to the time required for file transmission through the bonded channel after the channel has been accessed, Due to the difference in the number of bonded channels, the transmission speed will be different, resulting in different transmission time. If the size of the file to be sent is F, The speed of each individual channel is s, And according to the assumption of this article, the file transfer speed is proportional to the number of bonded channels, Then the transmission time required for bonding m channels can be obtained as F/ms. The stopping rule specifies the minimum number of bonded channels, so the average transmission time is expressed in the desired form. Taking as an example that more than m channels are allowed to be idle, the average transmission time S_m can be obtained as.

$$S_m = \sum_{i=m}^{H} P(i) \cdot \frac{F}{i \cdot s} \tag{8}$$

3.4 Threshold Analysis of the Number of Optimal Stopping Channels

According to the content of the previous two sections, it can be obtained that when the threshold of successful bonded channel number is m, the length of time that cSTA needs to wait for access to the channel and the length of sending files, Therefore, it can be obtained that the total time required by the cSTA when the threshold of successful bonded channel number is m.

$$T_m = A_m + S_m = \frac{1}{\left(1-(1-p)^H\right)\sum_{i=m}^{H}\sum_{h=i}^{H} p_h P\left(i|h\right)} + \sum_{i=m}^{H} P(i)\frac{F}{i \cdot s} \tag{9}$$

Observe the formula (9), F/s is a constant, For convenience, let $f = F/s$, The physical meaning of f is the time required for the file to be transmitted on a single channel, Therefore, the expression for the total time can be written as.

$$T_m = \left(\sum_{i=m}^{H} \frac{p_i}{i}\right) \cdot f + \frac{1}{P_{ac}P(m)} \tag{10}$$

It can be seen that in the case of channel determination (p, H is a constant) and stopping rule determination (m is a constant), The total time T_m required by cSTA is a linear function of f.

Similarly, Expressions of total time can be written when the threshold of successful bonded channel number is $m+1$.

$$T_{m+1} = \left(\sum_{i=m+1}^{H} \frac{p_i}{i}\right) \cdot f + \frac{1}{P_{ac}P(m+1)} \tag{11}$$

Comparing formulas (10) and (11), we can find.

$$\left(\sum_{i=m+1}^{H} \frac{p_i}{i}\right) - \left(\sum_{i=m}^{H} \frac{p_i}{i}\right) = \frac{p_m}{m} > 0$$
$$\frac{1}{P_{ac}P(m)} - \frac{1}{P_{ac}P(m+1)} = \frac{-\sum_{h=m}^{H} p_h \cdot P\left(m|h\right)}{P_{ac}P(m)P(m+1)} < 0$$

So as shown in Fig. 4, There must be an intersection λ_m between T_m and T_{m+1}, Similarly, There must be an intersection λ_m between T_{m+1} and T_{m+2}. Subtract the formulas (10) and (11) to get the expression about the intersection point λ_m.

$$\frac{p_m}{m}\lambda_m = \frac{1}{\left(1-(1-p)^H\right)} \cdot \frac{\sum_{h=m}^{H} p_h \cdot P(m|h)}{P(m)P(m+1)} \quad (12)$$

Simplifying formula (12) can get.

$$\lambda_m = \frac{m \cdot \sum_{h=m}^{H} p_h \cdot P(m|h)}{\left(1-(1-p)^H\right) P(m)P(m+1) \cdot p_m} \quad (13)$$

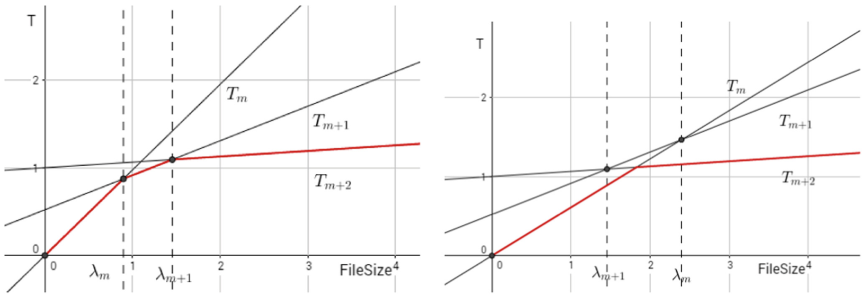

Fig. 4. Schematic diagram of stopping rules m and $m+1$ must have an intersection (Color figure online)

As shown in Fig. 4, the time spent corresponding to the best threshold of successful bonded channel number corresponding to different file sizes is shown by the red line in the figure, It can be clearly seen that there will be 2 situations.

Case 1. As shown in Fig. 4(a) In the case of $\lambda_m < \lambda_{m+1}$, when $f < \lambda_m$, the threshold of successful bonded channel number is m, when $\lambda_m < f < \lambda_{m+1}$, the threshold of successful bonded channel number is $m+1$, when $\lambda_{m+1} > f$, the threshold of successful bonded channel number is $m+2$.

Case 2. As shown in Fig. 4(b) In the case of $\lambda_m > \lambda_{m+1}$, The elapsed time (red line) corresponding to the best successful bonding channel number threshold is not related to T_{m+1}, The file size threshold corresponding to the threshold for switching the best successful bonding channel is the intersection of T_m and T_{m+2}, Therefore, in this case, you can directly delete T_{m+1}

Based on the above analysis, this article will use the following method to solve the optimal successful bonding channel threshold m corresponding to different file sizes.

Algorithm 1. FMT(Find Minimum Threshold) According to the total transmission time of files of different sizes under all fixed thresholds from 1 to H, find the corresponding Number of channels successfully bonded.

Input: H, p, τ, M
Output: $\lambda[]$
Begin proceduce
  $i = 2$
  $rst[] = 0, \lambda[] = 0$ //Initialize to an array of all zeros
  $m = 1 : 1 : H$ //Array 1 to H
  $\lambda[1] = T_{m[1]} \cap T_{m[2]}$ //$\lambda[1]$is the intersection of $T_{m[1]}$ and $T_{m[2]}$, Where T_m is related to H, p, τ, M
  repeat
    set $\lambda[i] = T_{m[i]} \cap T_{m[i+1]}$
    //Determine whether the situation
    if $\lambda[i] < \lambda[i-1]$ **then**
      $m[i+1] = []$ //Delete $T_{m[i+1]}$
    else
      $i = i + 1$
    end if
  until $m[i+1] < H$ //Traverse channel
End proceduce

4 Performance Evaluation

4.1 Simulation Results and Analysis

In the case of different channel busyness (p is different), Compare the performance of different successfully bonded channel threshold m with the optimal stopping rule proposed in this article, cSTA uses different rules to transfer files of different sizes, Perform a simulation analysis of the total time required, and the simulation results are shown in Fig. 5.

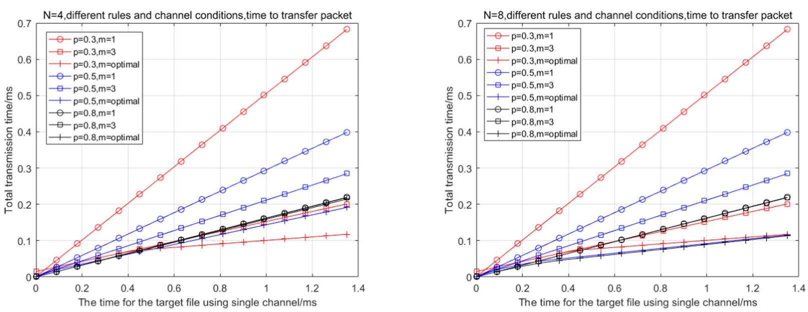

Fig. 5. When $N = 4, 8$, the time chart required to transfer files of different sizes under several stopping rules in different channel conditions

As shown in Fig. 5, the simulation results are consistent with the derivation of the threshold in 3.4, The smaller the threshold of successful bonded channel number, the shorter the time to wait for access to the channel, but the slower the speed of sending files, Therefore, the larger the file to be transmitted, the more suitable it is to wait for more channels to be bonded. On the other hand, the busier the channel, the more time it takes to bond multiple channels.

The optimal stopping rule proposed in this article needs to consider the waiting time and the sending time comprehensively, and select the best threshold for the number of successfully bonded channels according to the file size and the busy state of the channel, so that the sending time of the cSTA is the shortest.

As shown in Fig. 5, when files of the same size are transmitted under various channel conditions, the optimal stopping rule proposed in this article requires the least time compared to rules with fixed thresholds or no thresholds. According to the algorithm proposed in 3.4, we can get the optimal stopping rule for the transmission of files of different sizes under different channel conditions. The specific results are shown in Fig. 6.

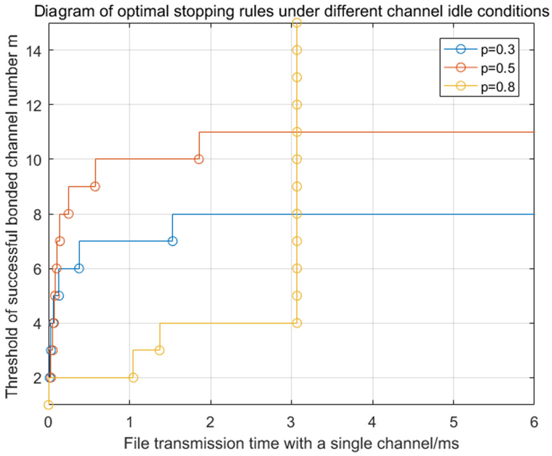

Fig. 6. Diagram of the optimal stopping rules corresponding to different file sizes under different channel conditions

As shown in Fig. 6, under different channel busy conditions, as the file size changes, the threshold m of the number of successfully bonded channels continuously changes. The larger the file to be sent, the greater the threshold m of the number of successfully bonded channels. Among the abnormal results at $p = 0.8$, there are no steps to rise because. Although the channel is idle ($p = 0.8$), the average sending length of sSTA is very short, and the sending frequency is high, The cSTA access probability is extremely high, which is not conducive to bonding too many channels.

4.2 Error Analysis

Since the sending time S_m is a function, When the number of bonded channels is fixed, it will not change, The waiting time A_m for access is a random value, so the error analysis is performed here. As shown in Fig. 7, the absolute error is all within 0.5 time slots. When analyzing the relative error and comparing the absolute error, it can be found that the absolute error is almost 0 when $m = 1, 2$, so the relative error at this time should be discarded, in addition, the relative error is within 1%.

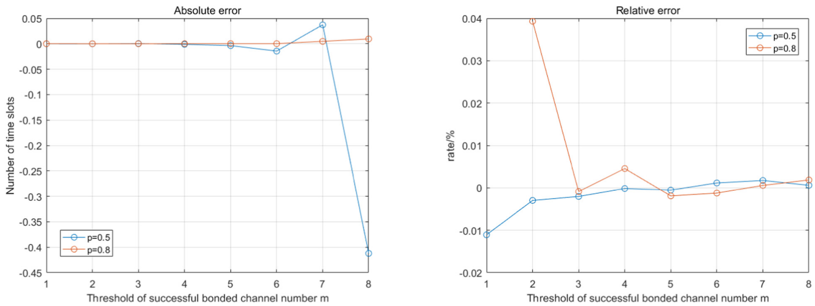

Fig. 7. Error analysis graph of waiting time for access channel

5 Conclusion

This article uses probability and expectation to describe the channel situation and the random behavior of nodes, and then uses the idea of optimal stopping theory to design a channel bonding strategy. That is, before accessing the channel, the node calculates the threshold of the minimum number of bondable channels based on the channel condition and the size of the file to be sent. Then, after the node accesses the channel, it is determined whether the bondable channel is greater than the threshold to determine whether to send. Through simulation, the time taken to transfer files using this channel bonding strategy can be obtained, which is smaller than the traditional channel bonding and fixed threshold channel bonding strategies. Moreover, the error between the simulation and the theoretical results is within 0.5 time slots, so it has a higher reliability.

In the analysis of this article, the channel is assumed to be a very ideal situation, there is no conflict, no impact on each other, and the busyness of each channel is exactly the same, and only one cSTA is considered. This has only a certain reference value for the resolution of practical problems. In one step, we will apply the knowledge of game theory to analyze the behavior of a large number of cSTAs, and analyze the impact of different types of cSTA on the channel. Based on this article, we will find a more general optimal stopping rule.

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