IEEE 802.11 Distributed Coordination Function : Performance Analysis and Protocol Enhancement

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Abstract

According to the analytical model that is used to study the performance evaluation of the IEEE 802.11 Distributed Coordination Function (DCF), we analyze how the size of the initial contention window works on the saturation throughput and the energy consumption. We also provide a new integrate metric to measure both the throughput and the energy consumption. Considering the situation of the constant station number, we preset a optimal CW_{min} *to achieve the maximum performance. On the other hand, we propose a new algorithm called Self Adjusting* $CW_{min}(SACW)$ *for the situation of the time-varying station number. The paper gives the simulation results by means of the new methods and compares them with the original 802.11 protocol.*

1. Introduction

The 802.11 protocol standardize the physical layer (PHY) and medium access control (MAC) for Wireless Local Area Networks (WLAN). There are two fundamental mechanisms to access the medium in IEEE 802.11 protocol [1]. One is point coordination function (PCF). It is a centrally access scheme and utilizes AP to control every node in BSS uniformly.

Another access scheme is DCF. The DCF works with the help of the carrier sense multiple access with collision avoidance (CSMA/CA). Retransmission scheme of collided packets adopts a slotted binary exponential backoff technique. The nodes that use DCF scheme constitute an independent BSS (IBSS) without AP. The IBSS actually is Ad Hoc networks whose feature is self configuration and no fixed infrastructure. The analysis below of this paper focuses on DCF scheme.

The paper is outlined as follows. In the next section, we study the effect of the minimum backoff window on the saturation throughput and energy consumption. The Enhancement on 802.11 protocol and it's simulations are presented in section 3 and section 4 separately. Section 5 gives our conclusion and our future work.

2. The Analysis of The Minimum Backoff Window's Effect on Throughput And Energy Consumption

Several papers [2], [3], [4], [5] have studied the performance evaluation of the IEEE 802.11 DCF. Here the analysis model that we employ in this paper is presented in [5]. It employs a Markov model to analyze the operation of backoff in DCF scheme. Then the saturation throughput is evaluated.

This model can be employed in all the access mechanism, i.e., basic, RTS/CTS, and hybrid of the former access mechanism. By analyzing the Markov chain, probability τ that a station transmits in a randomly chosen slot time is expressed as

$$\tau(p) = \frac{2(1-2p)}{(1-2p)(CW_{min}+1) + p * CW_{min}(1-(2p)^m)} \tag{1}$$

where m is the maximum backoff stage.

The probobility that a transmitted packet collides is:

$$p(\tau) = 1 - (1-\tau)^{n-1} \tag{2}$$

where n is the number of the contending stations.

Solving simultaneously (1) and (2), we can obtain the numerical solution of τ and p. Obviously $\tau, p \in (0,1)$.

Observing (1) and (2), we can learn that p is only dependent on the number of the contending stations n, the maximum backoff stage m and the initial contention backoff window CW_{min}.

[5] shows that the throughput highly depends on CW_{min}, and the optimal value of CW_{min} depends on the number of contending stations in the network. The less the contending stations, the less the optimal value of CW_{min}. Moreover, in the case of the same CW_{min}, the number of contending stations highly impacts on the throughput.

Now we analyze the case of energy consumption. We learn that the p is the probability of a collision seen by a packet being transmitted on the channel. Thus the probability by which a packet transmits successfully after i times of failed transmission can expressed as $p^i(1-p)$. Let L_s be the total length of a packet which transmits successfully, and L_c be the total length of a packet which collides with other ongoing packets. L_s and L_c are written as follows:

$$\begin{cases} L_s^{bas} = \text{MAC header} + \text{PHY header} + E[8l] + \text{ACK} \\ L_c^{bas} = \text{MAC header} + \text{PHY header} + E[8l^*] \end{cases} \tag{3}$$

Here l is the length of the packet in byte. $E[8l]$ is the average length and $E[8l^*]$ is the average length of the longest packet involved in a collision. In this paper $E[8l]$ equals to $E[8l^*]$ because of the constant packet size.

Assuming that the channel bit rate R and the transmission power P_{tx} are constant, the energy that is consumed to

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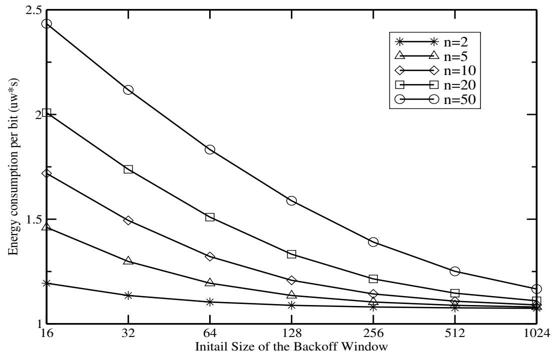

Fig. 1. Energy per bit versus CW_{min} for the basic access mechanism

transmit a bit excluding the overhead is

$$C = \frac{P_{tx} * \sum_{i=0}^{ShortRT} p^i(1-p)(i * L_c^{bas} + L_s^{bas})}{E[8l] * R} \quad (4)$$

where $ShortRT$ is the short frame threshold of retransmission times and is set to 7 typically [1].

Assuming the length of packet is constant equal to 1023 Bytes and $R = 1Mb/s$. We obtain the energy consumption of the basic access mechanism in the case of $n = 2, 5, 10, 20, 50$ and $CW_{min} = 2^4 \sim 2^{10}$. The results are illustrated in Fig. 1. We can learn that the greater the size of CW_{min}, the less the energy consumption per bit. The reason is that with the size of CW_{min} increasing, the probability of collision decreases, and hence the probability of successful transmission increases, thus the times of retransmission decreases, so that the energy consumption per bit decreases.

3. The Enhancement on 802.11 MAC Layer

We can learn that the system performance highly depends on the size of CW_{min} from the above analysis. CW_{min} is set to a constant parameter according to the given PHY layer In IEEE 802.11 protocol. Because of the inflexibility, the throughput of the network can not reach the maximum value in some situations. In this paper, we try to adjust the value of CW_{min} and make it optimal for the system.

We can adopt different value of CW_{min} to get the optimal performance according to different number of the contending stations. Here the performance metric U, which is only scaled by throughput or energy consumption in the past documents, scales both the throughput and energy consumption. U is defined as follows:

$$U(\alpha) = \frac{S}{C^{\alpha}} \quad (5)$$

where S, which was deduced in [5], is the saturation throughput. α is a weight, and $\alpha \geq 0$. When $\alpha = 0$, the integrate metric U equals to the throughput metric S. That is to say that the guideline only consider throughput. If the requirement of the energy consumption is more serious than the one of the throughput, α should be set to a larger value. On the other hand, if the requirement of the throughput is more serious, α should be smaller.

In the reality, the number of stations in the IBSS is either constant or variable. Considering the two situations, we divide the analysis into two parts in the following subsections. One is aimed to the constant number of stations, the other to the variable number of stations.

3.1 The Situation of Constant Station Number

We can choose different CW_{min} according to the different requirements for the throughput and energy consumption. For example, we can set up two (or more) scenarios based on the different requirements to choose the value of CW_{min}. Here two scenarios is set up. In the first one, energy consumption is required more strictly than throughput so that the value of CW_{min} is chosen larger. In the second scenarios, the value of CW_{min} is chosen smaller because throughput is required more strictly than energy consumption.

In order to satisfy the given weight α, the optimal CW_{min}^* can be expressed as

$$CW_{min}^* = \arg \max_{\{CW_{min}\}} U(\alpha) \quad (6)$$

We can know the exact number of the stations in the network so that we can use (6) to calculate the CW_{min}^* corresponding to the optimal U. So that the optimal CW_{min}^* according to different number of the stations are written in a table which is stored in each station. The optimal value can be read directly from the table, instead of recalculating when the number of stations is preknown. Then the stations with optimal CW_{min} can work in the optimal mode to satisfy the given requirement.

3.2 The Situation of Time-varying Station Number

In most of the reality application, the number of stations changes with time. We can use some measures to dynamically evaluate the number of stations in the networks. Then we adjust the value of CW_{min} to reach the optimal performance.

There are three measures to dynamically evaluate the number of stations currently. The first one is probability measurement [6] and the second is called interrupting measurement [7]. However, these two measurements get the relative correct result only when the number of stations is small. When the number of stations reaches 15 or more, the stations number that is estimated has a great deviation from the real one. The last one is presented in [8]. It uses kalman filter to estimate the number of contending stations in the network and it's estimating results are precision. But using kalman filter means a lot of work of signal processing causing more energy to be consumed.

In this paper, a new algorithm, called Self Adjusting CW_{min} (SACW), is proposed to solve the problem. The SACW algorithm need not estimate the number of stations directly. It can adjust the size of CW_{min} based on the times of retransmission. Fig. 2 illustrates the detail of the algorithm. In the algorithm, CW_{min} and CW_{max} is expressed as cw_min and cw_max separately.

```
if (transmission failed && W=cw_min)
{
  retx_count++;
  succtx_count <- 0;
  if (retx_count>=double_cw_min_thresh(cw_min))
  {
  retx_count <- 0;
  double cw_min and cw_max
  }
}
elseif (transmission succeeded && W=cw_min)
{
  retx_count <- 0;
  succtx_count++;
  if (succtx_count >= halve_cw_min_thresh(cw_min))
  {
  succtx_count <- 0;
  halve cw_min and cw_max
  }
}
```

Fig. 2. The Self Adjusting CW_{min} algorithm

The initial value of the retx_ count and succtx_ count is set to 0. Here retx_ count records the times of the transmission which is failed in the first attempt (i.e., the contention windows equals to the cw_ min). That is to say that when the packet is failed to transmit in the first attempt, the value of retx_ count increases by 1. The value of retx_ count is set to 0 as long as the packet is transmitted in its first attempt. When retx_ count is greater than the double_ cw_ min_ thresh(cw_ min) which is preestablished, cw_ min and cw_ max will double.

The parameter succtx_ count records the times of the transmission which is successful in the very first attempt. When succtx_ count is greater than the value of halve_ cw_ thresh(cw_ min), cw_ min and cw_ max will decrease by half.

Fairness is the special feature of medium-sharing technique. Fairness of the contention means that the time for which each station shares the channel is almost the same. When the SACW algorithm is adopted, double_ cw_ min_ thresh(cw_ min) and halve_ cw_ min_ thresh(cw_ min) are supposed to be set properly. Otherwise, CW_{min} in some stations will be bigger, and the other will be smaller. As the result of it ,the station contention for the channel become unfair. Obviously the stations with smaller cw_ min can access the channel more longer than the ones with bigger cw_ min, and the former can transmit more packets in the saturated transmission environment. This unfairness should be avoided.

We introduce a parameter F in order to scale the fairness of the channel contention. Let $Tr(i), 1 \leq i \leq n$ be the total number of packets which the i-th station have transmitted regardless successfully or not in the interval $[0, T]$. In particular, T is it's duration time in the simulation. Then

$$F = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{Tr(i)}{\frac{1}{n}\sum_{i=1}^{n} Tr(i)} - 1\right)^2 \tag{7}$$

The greater the parameter F, the more unfair the channel contention.

4. Simulation Results

We use OPNET, an event driven simulation tool, to model and simulate the network performance. The simulation is divided into two parts. The first one is aimed to the situation of constant number of stations. The second is aimed to the one of the SACW algorithm.

4.1 The Case of Constant Number of Stations

The simulation is based on IEEE 802.11 protocol with FHSS. The channel bit rate R is set to 1Mb/s. The length of packet is set to 1023 Bytes and the maximum index of backoff m is set to 6. We use (5) to obtain the different CW_{min} according to different weight α. Then we use the obtained CW_{min} to simulate. The different random seed is adopted in each simulation. Each scenario is simulated for 10 times. The result is the mean value of each simulations. The duration of each simulation is set to 300 seconds.

Table I shows the α's impact on the saturation throughput and energy consumption when the number of stations is 10. We can see that the analysis value and simulation result are almost the same. It shows that the analysis model proposed in section 2 is quite correct. Different α causes different optimal CW_{min} and hence the saturation throughput and energy consumption are different. When $\alpha = 0$, we can obtain the highest saturation throughput but not the lowest energy consumption. CW_{min} becomes bigger with greater α, and so both the energy consumption and the saturation throughput reach lower value. We can adjust the value of α to satisfy both the saturation throughput and the energy consumption basing on different specific scenarios.

TABLE I

PERFORMANCE VERSUS α FOR 10-STATION MODEL

Performance		Original, CWmin=16	α=0, CWmin=128	α=1, CWmin=256	α=2, CWmin=512
Saturation throughput	Analysis	0.7094	0.8306	0.8259	0.7862
	Simulation	0.7098	0.8243	0.8217	0.7827
Energy per bit	Analysis	1.7188	1.2080	1.1429	1.1083
	Simulation	1.6914	1.2101	1.1425	1.1080

There is not the fairness problem which is introduced in section 3 in the situation of constant number of stations because the value of CW_{min} is preset and will not change adaptively.

4.2 The simulation of the SACW

We can change the presetting parameters, such as double_ cw_ min_ thresh(cw_ min) and halve_ cw_ min_ thresh(cw_ min), to control the throughput and energy consumption of the network. Moreover we will consider the fairness of the channel contention. The optimal values for the parameters of SACW algorithm, which are listed in table II, are determined after we have simulated a lot of experimental scenarios with a variety of parameters.

In the original 802.11 protocol with FHSS PHY layer, the initial contention window is set to 16, i.e., $CW_{min} = 16$.

Each simulation lasts for 300 seconds, with the number of stations chosen to be 5, 10, 20, 30, 40 or 50. Each result is

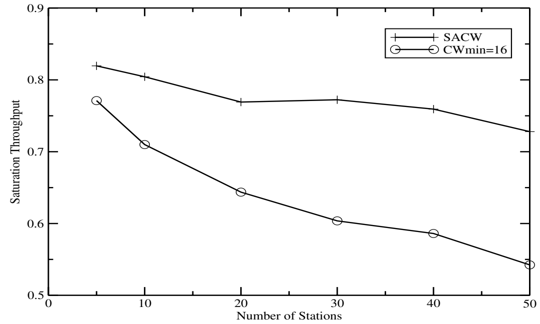

Fig. 3. Throughput versus the station number

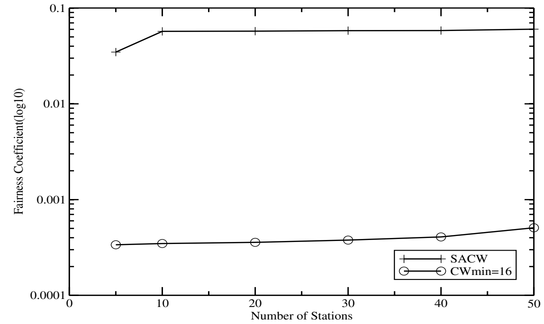

Fig. 5. Fairness versus the station number

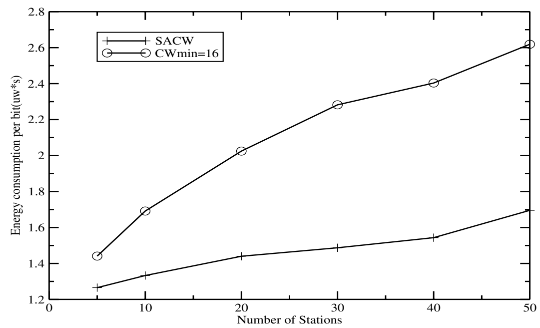

Fig. 4. Energy per bit versus the station number

obtained from the average of 10 simulation runs.

Fig. 3 and 4 shows the throughput and energy consumption separately with different number of stations. In Fig. 3, the throughput curve of original 802.11 protocol declines more sharply than the one of the SACW. While the energy per bit curve of original 802.11 ascends more sharply than the one of the SACW.

We can learn the less the throughput is obtained and the more energy per bit is consumed in both the SACW algorithm and original 802.11 protocol if the number of stations is more. However, the falling range of saturation throughput in the SACW is much less smaller than the one in original 802.11 protocol and the increasing range of energy consumption in the SACW is less than the one in original 802.11 protocol. For example, if the station number equals to 50, the saturation throughput will increase by 34.2% and energy consumption will decrease by 35.5% when the SACW is employed.

But the SACW algorithm has a little flaw, see Fig. 5, that the fairness is little poorer than the one employed the original 802.11 protocol. Because the SACW algorithm can not guarantee that the size of CW_{min} in each stations is the same in any time. Obviously if a station with bigger CW_{min}, it obtained the channel for a longer time. However, the fairness coefficient of SACW is relative small and can be accepted in most of the reality applications.

TABLE II
PARAMETERS OF THE SACW

cw_ min	15	31	63	127	≥ 255
double_ cw_ min _ thresh(cw_ min)	3	4	5	6	7
halve_ cw_ min_ thresh(cw_ min)	30	30	30	30	30

5. Conclusion

In this paper, we have presented an integrate metric U to weigh both the throughput and the energy consumption. We also proposed two kinds of method to obtain the optimal value for U according to the condition of constant station number and the one of time-varying station number separately. The method for condition of constant station number is realized with the help of looking up a prestablished table which stores the value CW_{min} for optimal U basing on the given scenario. While for the situation of time-varying station number, SACW algorithm was proposed. We can get to a conclusion that the two methods outperform the original 802.11 protocol which physical layer adopts FHSS (the same to DSSS obviously).

Future work consists of integrating the ideas with throughput, minimum-energy transmission protocols.

References

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