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ESACW: An Adaptive Algorithm For Transmission Power Reduction In Wireless Networks

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ABSTRACT

In this paper we propose a new algorithm for reducing the energy dissipation of a wireless ad-hoc network. We first show that the performance and energy dissipation is a function of the probability of packet collision, which can be varied by changing the minimum contention window (CW_{min}) parameter. Then we propose an algorithm, based on the IEEE 802.11 protocol, which can dynamically adjust CW_{min} for better performance and power. Experimental results show that, comparing to the original protocol, the proposed method can save 30% to 60% energy dissipation, and achieve similar or better performance.

Categories and Subject Descriptors: C.2.1[Network Architecture and Design]: Wireless communication

General Terms: Algorithms

Keywords: Wireless ad hoc network, low power, distributed coordination function

1. INTRODUCTION

A wireless ad-hoc network consists of mobile nodes that operate on limited power source such as batteries. To build a reliable wireless network with good survivability, it is important to develop methods for low power wireless communication, such that the lifetime of individual nodes, as well as the lifetime of the entire system, is maximized.

Research work has been done on energy saving techniques at different layers of a wireless network, such as the physical layer, the MAC layer, the network layer, and the transport layer. Authors of [1] proposed a game-theoretic solution to minimize the energy consumption of each link by means of dynamically adapting the modulation level. Reference [2] proposed the Self-Adjusting CW_{min} (SACW) algorithm which can dynamically adjust the initial contention window to decrease the collision probability.[1] The throughput achieved by SACW enhancement is higher than the original IEEE 802.11 and the average energy consumed by one bit transmission is lower than the original IEEE 802.11. However the SACW belongs to distributed algorithm so that it could degrade the fairness as the stations share the media unfairly.

This paper proposes an energy-aware enhancement algorithm based on the original IEEE 802.11 MAC protocol. The remainder of this paper is organized as follows: In the next section, we briefly review the Distributed Coordination Function (DCF) and its performance analysis based on Markov model. We further extend the analysis to find the relations between saturation throughput, energy dissipation as well as media access delay in a wireless network. The detailed algorithm and the experimental results are presented in section 3 and section 4 respectively. Section 5 gives our conclusions.

[1]Though the backoff parameters were fixed in the physical layer in the standard IEEE 802.11 protocol [3], the idea of adaptively setting the backoff window has been recently taken into consideration in the activities of the 802.11e working group.

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2. ENERGY PERFORMANCE TRADEOFFS

2.1 Throughput analysis

We model 802.11 DCF scheme as a discrete-time Markov chain [4]. This model can be employed in all the access mechanism, i.e., basic, RTS/CTS, and hybrid of the former access mechanism. Based on the Markov chain, the probability τ that a station transmits in a randomly chosen time slot can be written as:

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

where $m = \log_2(CW_{max}/CW_{min})$.

The probability that a transmitted packet collides is:

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

where n is the number of the contending stations.The value of τ and p can be solved numerically using (1) and (2).

Let us consider a system in which each packet is transmitted by the means of basic access mechanism. Let P_{tr} be the probability that there is at least one transmission in the considered time slot.

$$P_{tr} = 1 - (1-\tau)^n \quad (3)$$

Let P_s be the probability that a station transmits successfully without collision.

$$P_s = n\tau(1-\tau)^{n-1}/P_{tr} \quad (4)$$

The normalized throughput S can be written as [4]:

$$S = \frac{P_s P_{tr}(E[8l]/R)}{(1-P_{tr}\sigma) + P_s P_{tr} T_s + P_{tr}(1-P_s)T_c} \quad (5)$$

Here R is the channel bit rate. l is the packet payload size in byte. $E[8l]$ is the average payload size. σ is the duration of an empty slot time. T_s is the average length of the time period, during which the packets are transmitted successfully, and T_c is the average length of the time period, during which there are more than one stations transmitting at the same time.

If we denote δ as the propagation delay. T_s and T_c in the basic access case can be written as:

$$\begin{cases} T_s^{bas} = (\text{PHY} + \text{MAC} + E[8l])/R + \text{SIFS} + \delta + \\ \qquad \text{ACK} + \text{DIFS} + \delta \\ T_c^{bas} = (\text{PHY} + \text{MAC} + E[8l^*])/R + \text{DIFS} + \delta \end{cases} \quad (6)$$

where $E[8l^*]$ is the average length of the longest packet payload involved in a collision.

2.2 Analysis of system energy dissipation

In this section we will analyze the transmission energy dissipation of the system. Since p is the collision probability, the probability that a packet transmits successfully after i times of failed transmission can be written as $p^i(1-p)$. Let L_s be the total length of a packet that transmits successfully, and L_c be the total length of a packet that collides with other ongoing packets. L_s and L_c are written as follows:

$$\begin{cases} L_s^{bas} = \text{MAC} + \text{PHY} + E[8l] + \text{ACK} \\ L_c^{bas} = \text{MAC} + \text{PHY} + E[8l^*] \end{cases} \quad (7)$$

Assuming that the channel bit rate R and the transmission power P_{tx} are constant, the transmission energy per bit can be calculated as:

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

where $ShortRT$ is the short frame threshold of retransmission times which is typically set to 7 [3].

2.3 Trade-off between energy and throughput

In this section, we assume that the length of packet is a constant value $l = 1023$ Bytes. We also assume that the system employs frequency hopping spread spectrum (FHSS) PHY layer whose parameters are listed in Table 1.

Table 1: FHSS System Parameters

MAC Header	224 bits	SIFS	28 μs
PHY Header	128 bits	DIFS	128 μs
ACK	112 bits+PHY Header	Propagation Delay	1 μs
RTS	160 bits+PHY Header	Slot Time	50 μs
CTS	112 bits+PHY Header	Channel Bit Rate	1 Mbit/s
Tx. Power	1000mW		

Using the analysis results in Section 2.1, we can obtain the saturation throughput of the basic access mechanism in the case of $n = 5, 10, 20, 50$ and $CW_{min} = 2^4 \sim 2^{12}$. The results are illustrated in Fig. 1. It shows that the throughput highly depends on the value of CW_{min}, and the optimal CW_{min} for the best throughput varies when the number of contending stations in the network varies. The less the contending stations, the smaller is the optimal value of CW_{min}. For example, the optimal value of CW_{min} is 64 when the number of contending stations equals 5, but 256 when the number of contending stations reaches 20. Moreover, for the same CW_{min}, the number of contending stations has great impact on the throughput.

For the same system, we can find the relationship between the system energy consumption and the value of CW_{min} which is illustrated in Fig. 2.

It shows that, when the value of CW_{min} increases, the probability of collision decreases and the times of retransmission attempt decrease. Therefore the average transmission energy decreases. On the other hand, the increase of CW_{min} means that the stations will spend more time in the backoff stage. Therefore the system throughput decreases.

2.4 Analysis of the media access delay

The media access delay is defined as the time from a packet becomes the first in the transmission queue to the successful transmission of its last bit.

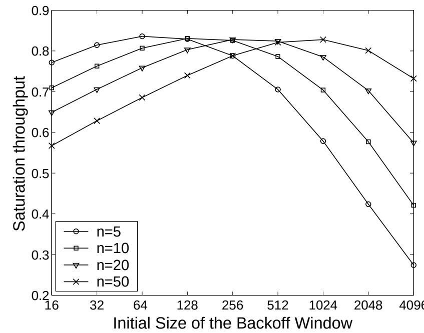

Figure 1: Throughput versus CW_{min} for the basic access mechanism

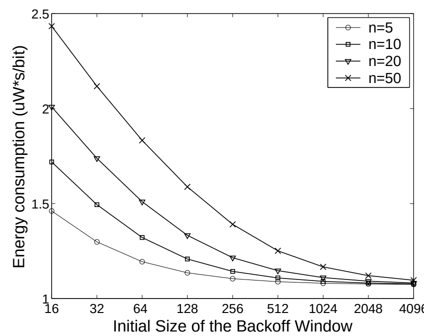

Figure 2: Energy per bit versus CW_{min} for the basic access mechanism

Let B be the media access delay in the number of time slots. If C_{coll} and C_{busy} are the numbers of time slots for which the station experiences collisions and observes busy, respectively. And I is the number of idle time slots that are observed. Then B can be written as:

$$B = I + 1 + C_{coll} + C_{busy} \quad (9)$$

where "1" is added for the successful transmission time slot.

The relation between the conditional collision probability p, B, C_{coll}, and C_{busy} can be written as:

$$\frac{E[C_{coll} + C_{busy}]}{E[B]} = p \quad (10)$$

The value of backoff slots is uniformly chosen in the range $[0, CW_{min}2^i - 1]$ after the station has failed transmission for i times. Therefore, accumulatively, the station will wait for total of $\sum_{j=0}^{i} \frac{CW_{min}2^j - 1}{2}$ time slots on average from the time a packet is ready for transmission to the time of the successful transmission of its first bit, at the $(i+1)^{th}$ attempt.

The probability by which a packet transmits successfully after i^{th} retransmission can be written as $p^i(1-p)$. Then the average value of B can be obtained as:

$$E[B] = \sum_{i=0}^{ShortRT} \{\sum_{j=0}^{i} \frac{CW_{min} * 2^j - 1}{2}\} p^i(1-p) + 1 \quad (11)$$

where "1" is added for the successful transmission slot.

By using equations (9), (10) and (11), the average number of idle slots I can be written as follows:

$$E[I] = \sum_{i=0}^{ShortRT} \frac{(2^{i+1} - 1)CW_{min} - i - 1}{2} p^i(1-p)^2 - p \quad (12)$$

In a transmission period, the average number of collision slots can be calculated:

$$E[C_{coll}] = \sum_{i=1}^{ShortRT} ip^i(1-p) \tag{13}$$

By using equations (10), (11) and (13), we can obtain the average number of busy slots as:

$$E[C_{busy}] = p\{[\sum_{i=0}^{ShortRT} \frac{(2^{i+1}-1)CW_{min}-i-1}{2} p^i(1-p)]+1\} - \sum_{i=1}^{ShortRT} ip^i(1-p) \tag{14}$$

There are two cases for the observed busy slot. One is the successful transmission by other station. In this case, there is one node that transmits data and the remaining stations do not transmit. In the other case, the busy slot is caused by the collision caused by the other stations. We use C_{busy_succ} and C_{busy_coll} to represent the number of time slots for the above two cases. They can be calculated as:

$$\begin{cases} E[C_{busy\_succ}] = E[C_{busy}](1-\tau)^{n-2} \\ E[C_{busy\_coll}] = E[C_{busy}][1-(1-\tau)^{n-2}] \end{cases} \tag{15}$$

The average value of the media access delay can be calculated as:

$$Delay = E[I]\sigma + (E[C_{busy\_succ}]+1)T_s + (E[C_{busy\_coll}] + E[C_{coll}])T_c \tag{16}$$

The media access delay can also be written as the function of the collision probability p if we substitute equations (6), (12), (13), (14) and (15) into equation (16).

2.5 Trade-off between energy and media access delay

By simulating the same system that is described in section 2.3, we can plot the curve of energy dissipation per bit and media access delay versus conditional collision probability p, as shown in Fig. 3. Again, there is a tradeoff between energy dissipation and media access delay. We can see that when the value of p increases, the energy dissipation increases, while the media access delay decreases.

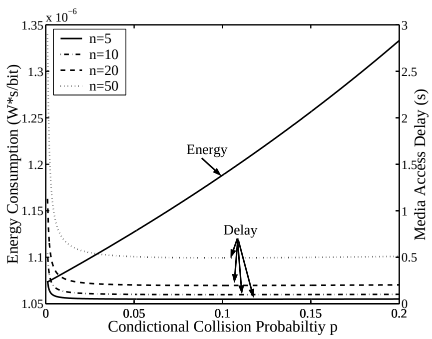

Figure 3: Energy and delay versus conditional collision probability p

To reduce the transmission energy dissipation, we can increase the value of CW_{min} to get a smaller collision probability p. On the other hand, if the delay constraint is stricter, the conditional collision probability p should allow being a bit larger.

3. THE ESACW ALGORITHM

Based on the analysis in the previous section, we know that the conditional collision probability p is an important parameter in an ad-hoc network. We propose a new algorithm called Energy-aware Self Adjusting CW_{min} (ESACW) to enhance the original IEEE 802.11 protocol. ESACW runs at the MAC layer. It dynamically adjusts the CW_{min} according to the collision probability in order to reduce the energy dissipation or achieve better performance. The pseudo code of the ESACW algorithm is shown in Fig. 4.

```
/*Handling the slot S*/
Procedure
Input parameters: S, B, I, C_coll, C_busy
Begin
    switch (the type of S)
    {
        case idle: B++; I++; break;
        case busy: B++; C_busy++; break;
        case collision: B++; C_coll++; break;
        case transmission: B++;
    }
    if (B>1e4 && ((C_busy+C_coll)/B>1.1p' ||
        (C_busy+C_coll)/B<0.9p'))
    {
       k=log2(CW_min);
       if ((C_busy+C_coll)/B>1.1p') then k++;
       if ((C_busy+C_coll)/B<0.9p') then k--;
       CW_min=2^k; CW_max=CW_min*(2^m);
       Create a CW_change_notification package
        P_A containing the information of k;
       Broadcast package P_A;
       Reset B, I, C_coll, C_busy;
    }
End proc

/*Handling the incoming broadcast package P_B*/
Procedure
Input parameters: B, I, C_coll, C_busy, P_B
Begin
... ...
    if (the type of P_B is CW_change_notification)
    {
      reset B, I, C_coll, C_busy;
      extract the k from the package P_B
      CW_min=2^k; CW_max=CW_min*(2^m);
    }
... ...
End proc
```

Figure 4: ESACW Algorithm

The key component in the ESACW is a predefined parameter p' which works as a threshold to limit the conditional collision probability p in the range of $[0.9p', 1.1p']$. If p is not in $[0.9p', 1.1p']$, the stations adjust the value of CW_{min} until p in $[0.9p', 1.1p']$. We can change the value of p' to control the throughput and energy dissipation of the network. The system will consume less transmission energy when the value of p' decreases.

ESACW measures the collision probability instead of calculating this value to reduce computation complexity. By observing the channel, ESACW divides the slot into various types, i.e., busy slot, idle slot, collision slot etc. The collision probability is measured within a moving window of 10000 time slots. Then ESACW compares the p with the p'. If p is larger than $1.1p'$, ESACW doubles the CW_{min} and CW_{max}. If p is smaller than $0.9p'$, ESACW halves the CW_{min} and CW_{max}. Once the CW_{min} and CW_{max} change, ESACW generates a package called CW_change_notification and broadcasts it to other stations for them to update the CW_{min} and CW_{max} to the same values.

4. EXPERIMENTAL RESULTS

Experiments have been carried out in OPNET [5] to compare the performance of algorithms: 1)the original IEEE 802.11, 2)SACW, 3)ESACW. We used four metrics, throughput, energy consumption, delay and fairness in the comparison.

Fairness of the network means that the time for which each station shares the channel is almost the same. Let $Tr(i), 1 \le i \le n$ be the total number of packets which the i^{th} station has transmitted regardless successfully or not in the duration of the simulation. We can define the channel contention fairness as [2]:

$$F = \frac{1}{n}\sum_{i=1}^{n}(\frac{Tr(i)}{\frac{1}{n}\sum_{i=1}^{n}Tr(i)} - 1)^2 \tag{17}$$

A smaller value of F means less fairness in channel contention.

In the original IEEE 802.11 protocol with FHSS PHY layer, the initial contention window is set to 16, i.e., $CW_{min} = 16$. The parameters used in SACW are the same as those used in [2]. We choose two values, 0.02 and 0.08 for p' in ESACW. $p' = 0.02$ means more strict energy constraint. While $p' = 0.08$ means more strict delay constraint. We refer the ESACW with first setting as ESACW0.02 and the ESACW with second setting as ESACW0.08.

Each simulation was performed for duration of 1800 seconds, with the number of stations varies from 5, 10, 20, 30, 40 to 50. Each scenario was simulated for 10 times and the final result is the average over all 10 simulations.

Fig. 5 shows the comparison of the throughput of four simulations. From the figure we can see that: 1). The SACW and ESACW0.08 achieves significantly better throughput than the original protocol and ESACW0.02. 2). When the number of stations increases, the throughput of the original protocol decreases much faster than the ones of SACW and ESACW0.08. 3). Overall, the ESACW0.08 has slightly better throughput than SACW.

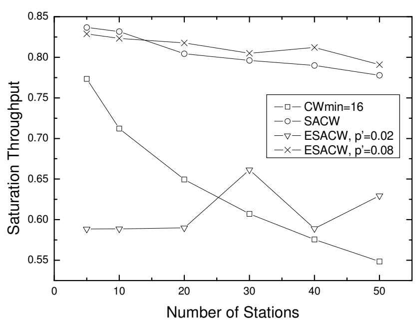

Figure 5: Throughput versus the number of stations

Fig. 6 shows the simulation results of the media access delay versus the number of stations. We can see that the ESACW0.08 achieves the lowest media access delay among all the algorithms.

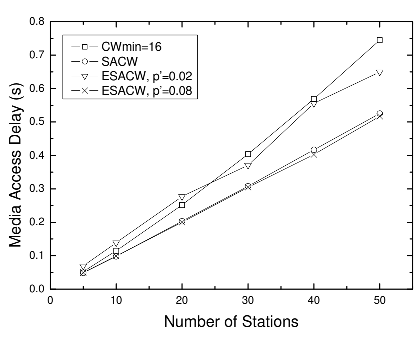

Figure 6: Media access delay versus the number of stations

Fig. 7 shows the curves of the energy dissipation per transmitting one bit data, versus the number of stations. From the results we can see that: 1). The proposed ESACW (ESACW0.08 and ESACW0.02) achieves the lowest energy dissipation in transmission. 2). For ESACW, the average energy dissipation has almost no increase when the number of stations increases. 3). Comparing to the original 802.11 protocol, the ESACW can save from about 30% to 60% of energy.

In the ESACW algorithm, we can set p' to different values for network applications in different environments. For example, we can use a small value of p' for the situation of strict energy constraint. And we can use a larger value of p' for the situation of strict delay constraint.

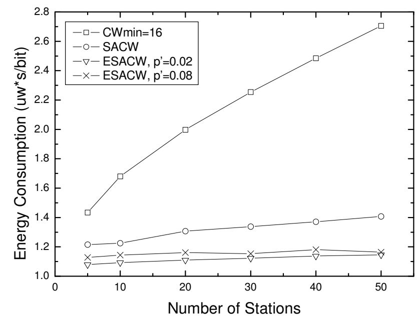

Figure 7: Energy per bit versus the number of stations

Fig. 8 shows the simulation results of the fairness versus the number of stations. Once again, we can see that the proposed ESACW method outperforms the original protocol and the SACW algorithm proposed in [2].

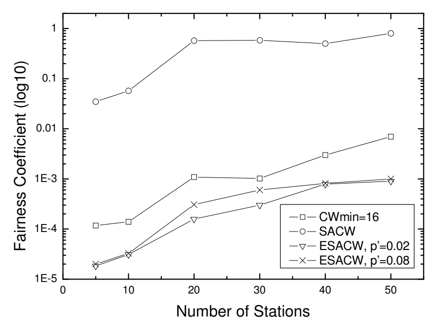

Figure 8: Fairness versus the number of stations

5. CONCLUSION

In this paper, we have shown that the transmission energy dissipation per bit and the media access delay is highly dependent on the conditional collision probability. Based on the relationship, we have proposed an enhancement algorithm ESACW based on the original IEEE 802.11 protocol for ad-hoc networks. The ESACW estimates the conditional collision probability on-the-fly, and dynamically controls the setting of CW_{min} based on the estimate. Experimental results have shown that the proposed ESACW algorithm saves from 30% to 60% transmission energy, comparing to the original IEEE 802.11 protocol.

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