2010 Fourth International Conference on Genetic and Evolutionary Computing

An Energy Efficient Cross-layer Design by Using the Contention Window Optimization Scheme for Ad-hoc Wireless Networks Operating in Error-prone Channel Conditions

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Abstract

A novel dynamic contention window control scheme is presented in this paper to improve the performance and energy efficiency of IEEE 802.11-based CSMA/CA DCF wireless networks operating in ad-hoc mode. The number of competing nodes in physical carrier sense systems is one of the major impact on DCF performance and on the energy consumed. A new approach in presented in this paperis using a cross-layer framework to alleviating the problem in both MAC and PHY layers, which attempts to improve the performance and energy efficiency by controlling the contention window size in the MAC layer according to the number of competing nodes, and the length of the MPDU (MAC Protocol Data Unit) payload according to the physical channel condition in the PHY layer.

Key words: ad-hoc networks, energy conservation, error-prone channel conditions, contention window

I. INTRODUCTION

In the IEEE 802.11 standards [1], the Distributed Coordination Function (DCF) based on CSMA/CA with binary slotted exponential backoff, is the fundamental access method used to support asynchronous data transfer. However, the performance of this protocol deteriorates with an increase in the number of competing nodes trying to simultaneously send frames over the shared medium. Previous analytical models [2] of the *p*-persistent mechanism and binary slotted exponential backoff mechanism for CSMA/CA have identified that parameters such as the $CW_{r,m,min}$ (minimum Contention Window) and the number of competing nodes in the carrier sense range, have a major influence on the protocol's performance. It is impossible to maintain high performance using fixed protocol parameters under different channel conditions (e.g. traffic loads and bit error rate). Therefore, the ideal CSMA/CA protocol should not only be simple and effective, but also dynamically adjust its parameters to the change in physical channel conditions. However, all the above models have focused on enhancing the performance without consideration of any physical channel contention.

The energy efficiency of DCF is analyzed in [3], by considering both the collisions and the retransmissions caused by packet errors. However the effect of packet collisions probability due to the variable number of competing nodes in the carrier sense range is not considered. In [4], the energy consumption models presented do consider the effect of transmission errors, but the performance models address the effect of errors in data frames only (i.e. signaling and control frames are not considered). Previous work by the authors has described an energy model for the case where the network operates with a variable number of competing nodes under both ideal and error-prone channel conditions [5]. According to this energy model, the degradation in throughput, delay, and energy efficiency due to transmission errors can be determined.

One important approach to reducing the energy consumed in an ad-hoc network is to change the power levels of transmissions to that required to be received by the destination and no more. This is normally performed as an iterative process whereby the transmitted power level is adjusted based on feedback from the receiver [6]. In addition to reducing energy consumption, transmission power control can potentially be used to improve the spatial reuse of the wireless channel [7]. However, most power control algorithms result in lower throughput [8] because they reduce the power level of transmissions which causes the transmitted packets to become more sensitive to physical channel conditions, such as noise or interference from hidden nodes. The reduced signal power can then results in more energy consumed due to packet re-transmissions.

In an error-prone channel, packet transmission failures between a pair of wireless nodes may be due to signal losses as well as packet collisions. Thus when a receiver detects an erroneous packet, this packet is automatically rejected. Accordingly, the sender

978-0-7695-4281-2/10 $26.00 © 2010 IEEE
DOI 10.1109/ICGEC.2010.132

assumes that packet loss is because of a collision and takes measures to avoid further collision in the network by doubling its contention window size. This is obviously sub-optimal; the contention window should not be simply increased to avoid collisions when packet loss is due to a noisy channel condition.

Therefore, a novel dynamic contention window control scheme has been developed to optimize the energy efficiency and performance of IEEE 802.11 DCF wireless networks. The proposed scheme uses different factors that affect the energy consumption of the 802.11 DCF MAC and PHY layers. These factors include the selected PHY scheme, transmission rate, channel condition and number of competing nodes of wireless medium. In [5], an analytical model of the energy consumption in IEEE 802.11-based DCF networks was introduced. In this paper, all the factors used in this model are employed in a control scheme that dynamically varies the contention window for 802.11-based DCF wireless networks.

The rest of the paper is organized as follows. In section 2 we present the dynamic contention window algorithm (*DCWA*) for IEEE-based CSMA/CA under ideal channel conditions. In section 3 describes the simulation results and energy efficiency comparison between *DCWA* and standard IEEE 802.11. Finally, we conclude the paper in section 4.

II. DYNAMIC CONTENTION WINDOW ALGORITHM (DCWA) FOR IEEE 802.11-BASED CSMA/CA UNDER THE IDEAL CHANNEL CONDITIONS

The proposed scheme (*DCWA*, Dynamic Contention Window algorithm) minimizes the communication energy consumption in 802.11-based DCF systems by combining dynamic contention window control with adaptive MPDU payload length. The main idea of *DCWA* is to measure and estimate the average collision probability, and from this the transmitter determines the most energy efficient contention window size and transmits an optimal MPDU payload length for each data frame based on channel conditions.

A. Average Collision Probability

A method to detect the wireless network traffic loads and the number of competing nodes is necessary. In the IEEE 802.11 MAC protocol with DCF, the assumption is that all radios are identical, use single channel and omni-directional antennas. Consider a fixed number of n contending nodes. The collision probability $P_{r,m,collision}$ is the probability that in a time slot at least one of the n-1 remaining nodes transmits [8]. This is given by:

$$p_{r,m,collision} = 1-(1-\tau_m)^{n-1} \quad (1)$$

From equation (1), τ_m is the probability that a node transmits in a slot time, n active nodes contend to access the medium and each node has transmission probability τ_m.

$$\tau_m = 1-\sqrt[n-1]{1-P_{r,m,avg}} \quad (2)$$

Where $P_{r,m,avg}$ is the average probability of collision for the selected transmission r and PHY scheme m. The average probability of collision is used to estimate the number of competing nodes in the medium. A regular update period T is used to estimate the current probability of collision. The instantaneous probability of collision $P_{r,m,curr}$ at the k^{th} update period T is measured as

$$\rho^k_{r,m,curr} = \frac{Nc}{Ns} \quad (3)$$

Where N_c is the number of collisions and N_s is the number of packets sent during the k^{th} update period T. Equation (4) shows the estimated average collision probability.

$$P_{r,m,avg} = P^k_{r,m,avg} = \varepsilon \times \rho^{k-1}_{r,m,avg} + (1-\varepsilon)\times \rho^k_{r,m,curr} \quad (4)$$
$$\varepsilon \in [0..1]$$

B. Optimal Contention Window Size

Based on the above analysis, the optimal contention window is based on the number of competing nodes can be obtained.

We define $P_{r,m,tr}$ as the probability in a slot time at least one or more transmissions. n active nodes contend to access the medium and each node has transmission probability τ_m.

$$P_{r,m,tr} = 1-(1-\tau_m)^n \quad (5)$$

If a transmission is successful, it implies that only one node is transmitting and no other nodes can transmit, conditioned on the fact that at least one station is using the channel. During this slot time, the probability of successful transmission $P_{r,m,s}$ is:

$$p_{r,m,s} = \frac{n\tau_m(1-\tau_m)^{n-1}}{p_{r,m,tr}} = \frac{n\tau_m(1-\tau_m)^{n-1}}{1-(1-\tau_m)^n} \quad (6)$$

$P_{r,m,idle}$ is the average number of idle time slots for the selected transmission rate r and PHY scheme m between two consecutive busy periods in the cycles. Since for each idle timeslot, the probability of packet transmission is $P_{r,m,tr}$, the $P_{r,m,idle}$ can be expressed as:

$$P_{r,m,idle} = (1-\tau_m)^n \quad (7)$$

$T_{r,m,s}(l)$ is the duration of a successful transmission for the selected transmission rate r, PHY scheme m and MAC payload size l. The probability of a successful transmission is $P_{r,m,s}$. A collision period for the selected transmission rate r, PHY scheme m and MAC payload size l is $T_{r,m,c}(l)$. The probability that a collision occurs between any number of nodes in the system is $(1-P_{r,m,s})$. Throughput is defined as the fraction of time that the channel is used to successfully transmit payload bits. Therefore, throughput S can be expressed as:

$$S = \frac{P_{r,m,s} \cdot P_{r,m,tr} \cdot l \cdot 8}{\begin{pmatrix} P_{r,m,idle} \cdot \sigma_m + P_{r,m,s} \cdot P_{r,m,tr} \cdot T_{r,m,s}(l) + \\ P_{r,m,tr} \cdot (1 - p_{r,m,s}) \cdot T_{r,m,c}(l) \end{pmatrix}} \qquad (8)$$

The throughput of DCF can be obtained from equation (8) by given any number of competing nodes. Figure 1 shows that when a small contention window (e.g. $CW_{r,m,min}$=3) is used, the throughput drops after only a small number of competing nodes. However, a larger $CW_{r,m,min}$ will improve the throughput of an individual node in a saturated network when the number of competing nodes is increased. Figure 1 also shows that a larger $CW_{r,m,min}$ will improve the throughput of an individual node in a saturated 802.11 CSMA/CA network when the number of competing nodes is increased. This highlights the ineffectiveness of a static contention window size in resolving a variable number of competing nodes in a CSMA/CA system.

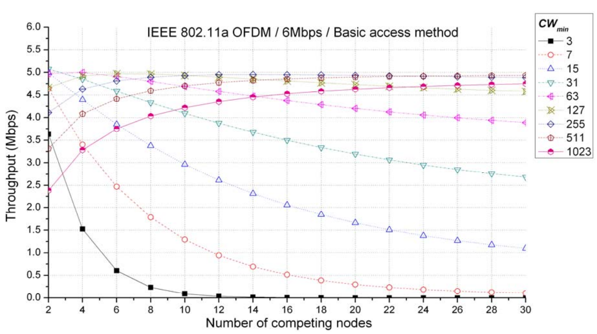

Figure 1, Throughput vs. number of competing nodes using IEEE 802.11a PHY scheme.

For a given number of competing nodes, different $CW_{r,m,min}$ sizes results in different throughput, access delay and the energy consumption. The derivative of equation (2) with respect to τ_m, and imposing it equal to 0, equation (8) is obtained as follows:

$$\frac{dS}{d\tau_m} = 0 \qquad (9)$$

$$\frac{dS}{d\tau_m} = \frac{\begin{pmatrix} (n \cdot (1-\tau_m)^{n-1} - n \cdot \tau_m \cdot (n-1) \cdot \\ (1-\tau_m)^{n-2}) \cdot f_1(\tau_m) - n \cdot \tau_m \cdot \\ (1-\tau_m)^{n-1} \cdot f_2(\tau_m) \end{pmatrix}}{f_1^2(\tau_m)} \cdot l \cdot 8$$

(10)

Where,

$$f_1(\tau_m) = \sigma_m \cdot (1-\tau_m)^n + T_{r,m,s}(l) \cdot n \cdot \tau_m \cdot (1-\tau_m)^{n-1} + T_{r,m,c}(l) \cdot (1-(1-\tau_m)^n - n \cdot \tau_m \cdot (1-\tau_m)^{n-1})$$

$$f_2(\tau_m) = -\sigma_m \cdot n \cdot (1-\tau_m)^{n-1} + T_{r,m,s}(l) \cdot (n - n^2\tau_m) \cdot (1-\tau_m)^{n-2} + T_{r,m,c}(l) \cdot n \cdot \tau_m \cdot (n-1) \cdot (1-\tau_m)^{n-2}$$

(11)

From equation (11), $(1-\tau_m)^{n-1} \approx 1$. Thus, equation (12) can be obtained as follows:

$$n^2 \cdot \tau_m \cdot T_{r,m,c}(l) - n \cdot \tau_m \cdot \sigma_m = n \cdot \sigma_m$$

(12)

Thus, the optimal probability that a node transmits in a slot time $\tau_{m,opt}$ can be obtained as,

$$\tau_{m,opt} = \frac{\sigma_m}{n \cdot T_{r,m,c}(l) - \sigma_m}$$

(13)

Finally, the optimal contention window size $W_{r,m,opt}$, depends on the number of competing nodes n for the selected transmission rate r and the PHY scheme m, and can be determined by

$$W_{r,m,opt} = \frac{(2 - \frac{\sigma_m}{n \cdot T_{r,m,c}(l) - \sigma_m}) \cdot (2 \cdot (1 - \frac{\sigma_m}{n \cdot T_{r,m,c}(l) - \sigma_m})^{n-1} - 1)}{\frac{\sigma_m}{n \cdot T_{r,m,c}(l) - \sigma_m} \cdot \begin{bmatrix} 2 \cdot (1 - \frac{\sigma_m}{n \cdot T_{r,m,c}(l) - \sigma_m})^{n-1} - 1 + \\ (1 - (1 - \frac{\sigma_m}{n \cdot T_{r,m,c}(l) - \sigma_m})^{n-1}) \cdot \\ (1 - (2 \cdot (1 - \frac{\sigma_m}{n \cdot T_{r,m,c}(l) - \sigma_m})^{n-1})^m) \end{bmatrix}} \qquad (14)$$

Equation (14) presents the optimal contention window size ($W_{r,mopt}$) so that the throughput can approach its maximum value at a particular number of competing nodes. This result is very similar conclusion with *Cali's* research [9] of the *p*-persistent CSMA/CA, which proposes dynamically tuning the transmission probability during each slot for every node according to the measured number of competing nodes.

III. Simulation Results and Discussion

In this section, simulation results are presented for the channel throughput, access delay and energy consumption between the standard IEEE 802.11-based and 802.11 using DCWA enhance mechanism in both ideal and error-prone channel conditions. A simulation environment was developed using the Qualnet developing library [10].

Figure 2 shows the effective energy conservation of the *DCWA* in the situation with *n* competing nodes in both ideal and error-prone channel conditions. The results show that *DCWA* has lower energy consumption per bit than standard IEEE 802.11 as the number of competing nodes increases in each of the three PHY schemes. The results also show that the energy consumption of *DCWA* is always directly proportional to the number of competing nodes.

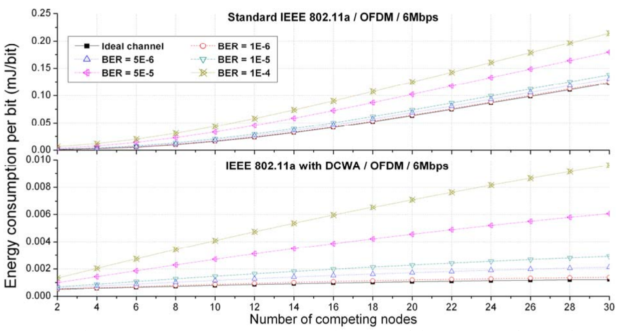

Figure 2, Energy consumption per bit vs. number of competing nodes (802.11a / 6 Mbps in different BER values).

An interesting observation from these results is that the proposed *DCWA* is able to eliminate most of the collisions from the channel competition in the MAC layer.

IV. CONCLUSIONS

In this paper, we presented a control scheme for dynamically varying the contention window in ad-hoc wireless networks for both ideal and error-prone channel conditions. The scheme attempts to optimize the number of nodes competing in the MAC layer, as well as the MPDU payload length of the transmitted frame according to the PHY layer channel condition.

The simulation results show that the proposed scheme can not only achieve a higher throughput than the standard IEEE 802.11 DCF, but it can also improve the energy efficiency of packet transmission under a dynamically varying number of competing nodes in both ideal and error-prone channel conditions. This paper describes research that is applied in the PHY and MAC layers. In principle these algorithms can be implemented as modifications to all 802.11a/b/g PHY schemes though a dynamic contention window controls mechanism. An interesting area of future research will be to extend the cross-layer approach to provide further MAC/PHY parameters for multi-hop wireless routing information such as AODV and DSR to optimize multi-hop routing protocol capacity.

ACKNOWLEDGMENT

This work was supported by a research grant from Taichung University of Education, Taiwan.

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