An Optimization Scheme for Energy Efficient Ad-hoc Wireless Networks Operating in Error-prone Channel Conditions

Tsung-Han Lee, Alan Marshall and Bosheng Zhou

***Abstract*—In this paper, a novel dynamic contention window control scheme is presented 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 has a major influence on the probability of collisions and a subsequent impact on DCF performance and on the energy consumed. A new cross-layer approach to alleviating this problem is developed, 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..**

***Index Terms*—ad-hoc networks, power saving, Wireless LANS, channel errors**

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 [2,3,4] of the p-persistent mechanism and binary slotted exponential backoff mechanism for CSMA/CA have identified that parameters such as the CWr,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 [5], 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 [6] and [7] 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 [8]. 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 [9,10]. In addition to reducing energy consumption, transmission power control can potentially be used to improve the spatial reuse of the wireless channel [11]. However, most power control algorithms result in lower throughput [12] 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 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.

Manuscript received March 03, 2009. This work was supported by the National Science Council of Taiwan R.O.C under Grants NSC 97-2218-E-241-003 "The Cross-layer Design for Energy-Conservation in Ad-hoc and Multi-hop Wireless Networks".

Tsung-Han Lee is with the Department of Computer Science and Information Engineering, Hungkuang University, Taichung 433, Taiwan, R.O.C. (phone: 886-988279788; fax: 886-4-26324084; e-mail: th_lee@ sunrise.hk.edu.tw).

Alan Marshall is with the School of Electronics, Electrical Engineering and Computer Science, Queen's University Belfast, Belfast, BT9 5AH UK. (phone: +44 (0)28 9097 4248 / 1789; fax: +44 (0)28 9067 7023; e-mail: a.marshall@ee.qub.ac.uk).

Bosheng Zhou is with the Institute of Electronics, Communications and Information Technology (ECIT), Northern Ireland Science Park, Belfast, BT3 9DT, UK (e-mail: b.zhou@ee.qub.ac.uk).

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, payload length of MPDU, channel condition and number of competing nodes of wireless medium. In [8], 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 and length of MPDU payload 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, we extend the DCWA to a noisy wireless environment. Section 4 describes the simulation results and energy efficiency comparison between DCWA and standard IEEE 802.11. Finally, we conclude the paper in section 5.

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*

When you submit your final version, after your paper has been accepted, prepare it in two-column format, including figures and tables.

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:

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

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.

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

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

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

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.

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

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.

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

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:

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

$P_{r,m,idle}$ 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:

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

$T_{r,m,s}(l)$ 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:

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

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.

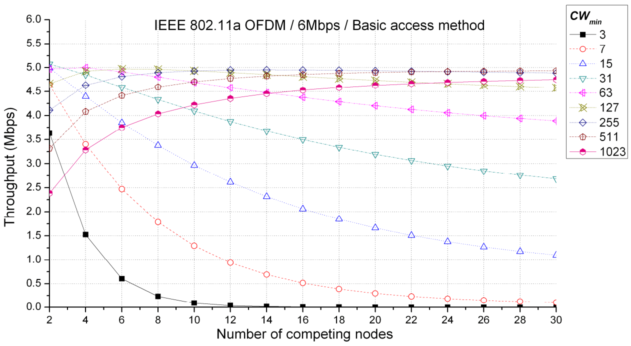

Figure 1, Throughput vs. number of competing nodes using IEEE 802.11a PHY scheme.

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:

$$\frac{dS}{d\tau_m} = 0 \tag{9}$$

$$\frac{dS}{d\tau_m} = \frac{\begin{pmatrix} (n\cdot(1-\tau_m)^{n-1} - n\cdot\tau_m\cdot(n-1)\cdot \\ (1-\tau_m)^{n-2})\cdot f_1(\tau_m) - n\cdot\tau_m\cdot \\ (1-\tau_m)^{n-1}\cdot f_2(\tau_m) \end{pmatrix}}{f_1^2(\tau_m)}\cdot l\cdot 8 \tag{10}$$

Where,

$$\begin{aligned} & f_1(\tau_m) = \sigma_m\cdot(1-\tau_m)^n + T_{r,m,s}(l)\cdot n\cdot\tau_m\cdot \\ & (1-\tau_m)^{n-1} + T_{r,m,c}(l)\cdot \\ & (1-(1-\tau_m)^n - n\cdot\tau_m\cdot(1-\tau_m)^{n-1}) \\ & f_2(\tau_m) = -\sigma_m\cdot n\cdot(1-\tau_m)^{n-1} + \\ & T_{r,m,s}(l)\cdot(n-n^2\tau_m)\cdot(1-\tau_m)^{n-2} + \\ & T_{r,m,c}(l)\cdot n\cdot\tau_m\cdot(n-1)\cdot(1-\tau_m)^{n-2} \end{aligned} \tag{11}$$

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

$$n^2\cdot\tau_m\cdot T_{r,m,c}(l) - n\cdot\tau_m\cdot\sigma_m = n\cdot\sigma_m \tag{12}$$

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

$$\tau_{m,opt} = \frac{\sigma_m}{n\cdot T_{r,m,c}(l) - \sigma_m} \tag{13}$$

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

$$W_{r,m,opt} = \frac{(2-\frac{\sigma_m}{n\cdot T_{r,m,c}(l)-\sigma_m})\cdot(2\cdot(1-\frac{\sigma_m}{n\cdot T_{r,m,c}(l)-\sigma_m})^{n-1}-1)}{\frac{\sigma_m}{n\cdot T_{r,m,c}(l)-\sigma_m}\cdot\left[\begin{array}{l} 2\cdot(1-\frac{\sigma_m}{n\cdot T_{r,m,c}(l)-\sigma_m})^{n-1}-1+ \\ (1-(1-\frac{\sigma_m}{n\cdot T_{r,m,c}(l)-\sigma_m})^{n-1})\cdot \\ (1-(2\cdot(1-\frac{\sigma_m}{n\cdot T_{r,m,c}(l)-\sigma_m})^{n-1})^m) \end{array}\right]} \tag{14}$$

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 [2] 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.

Figure 2 shows the effective throughputs of the *DCWA* in the situation with *n* competing nodes in the carrier sense range. The results show that *DCWA* is able to improve the throughput by eliminating most of the collisions from the competing nodes. On the other hand, the throughput of CSMA/CA is sensitive to the number of competing nodes. Thus the result shows that *DCWA* can efficiently reduce the influence of those collisions in the MAC layer.

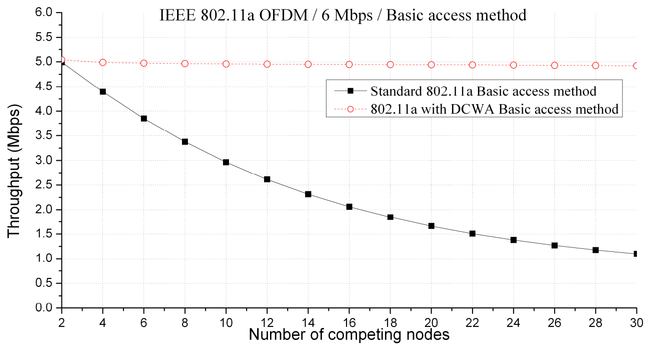

Figure 2, Throughput vs. number of competing nodes using 802.11a OFDM PHY scheme for 6 Mbps

Figure 3 shows the results for the *energy consumption per successfully transmitted Payload bit* for IEEE 802.11a PHY scheme. The result uses the energy model that is presented by the authors in [8]. As can be observed, *DCWA* has much lower energy consumption than standard IEEE 802.11 as the number of competing nodes increases.

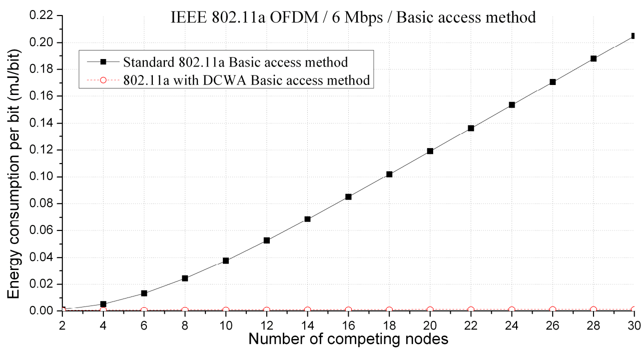

Figure 3, Energy consumption per bit vs. number of competing nodes using 802.11a OFDM PHY scheme for 6 Mbps

ISBN: 978-988-17012-5-1

III. ENHANCING THE DCWA IN A NOISY WIRELESS ENVIRONMENT

The *DCWA* optimizes the contention window size in the MAC layer based on the number of competing nodes.

However this procedure is not efficient when the frame losses are due to a noisy channel condition in the physical layer (PHY). In this situation it is important to study the CSMA/CA behaviour in a noisy channel and compare these results to an ideal channel.

Basically, the frame error rate (FER) is determined by the packet length and the bit error rate (BER), which is related to the received signal-to-noise ratio (SNR), the selected modulation and coding scheme. Here, the BER (denoted by $BER_{r,m,PPDU}$) can be obtained from a Physical Layer Convergence Procedure (PLCP) Protocol Data Unit (PPDU) packet that is sent in transmission rate *r*, PHY scheme *m*. The FER ($FER_{r,m,PPDU}$) [13] is then determined by:

$$FER_{r,m,PPDU} = 1 - \left(1 - BER_{r,m,PPDU}\right)^{N_{PPDU}} \qquad (15)$$

Where, N_{PPDU} is the total number of bits in the received PPDU packet.

In Figures 4 and 5, the results show the impact of frame size on the throughput and energy consumption per bit respectively for various channel conditions. As may be expected, the results show that a larger frame size results in a higher throughput when the channel condition is near ideal, which means a large frame size can significantly improve the data throughput under a good channel condition. However, when the channel is in a bad condition (e.g., BER≥10^{-5}), large frame size degrades the throughput.

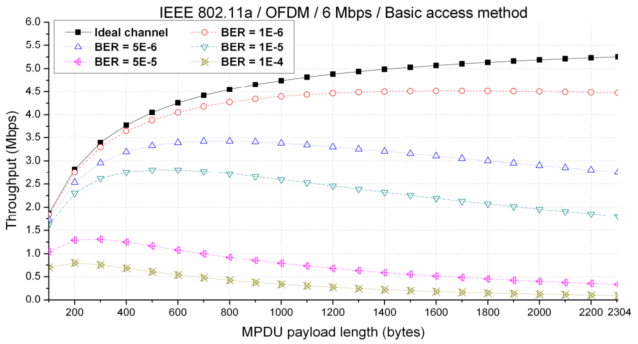

Figure 4, Throughput vs. MPDU payload length using 802.11a OFDM PHY scheme for 6 Mbps in different BER values.

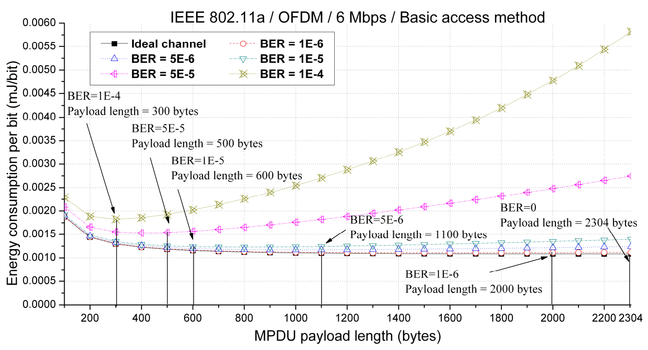

Figure 5, Energy consumption per bit vs. MPDU payload length using 802.11a OFDM PHY scheme for 6 Mbps in different BER values.

The results also show that a trade-off exists between a desire to reduce the MAC/PHY overhead by adopting larger packet sizes, and the need to reduce packet error rates in error-prone environments by using smaller length packets. There is an optimal packet size that maximizes the throughput in different channel conditions (e.g., BER). For an ideal channel, throughput increases with increasing packet length. The optimal MPDU payload length Mopt can be obtained through the analytical model given in [11]. The results shown that, when MPDU payload length $M<M_{opt}$, excessive PHY/MAC overhead in each packet limits the throughput. Otherwise, when $M>M_{opt}$, packet errors limit the throughput (e.g., M_{opt}=600 bytes, when BER = 10^{-5}).

A shorter MPDU payload length is preferred for higher error-prone channels. Therefore, the *DWCA* uses an optimal MPDU payload length at the MAC layer according to the physical channel conditions. Figure 6 shows how the proposed MPDU length (M_{opt}) varies with the channel BER. With this approach throughput can reach the maximal value for any given channel condition.

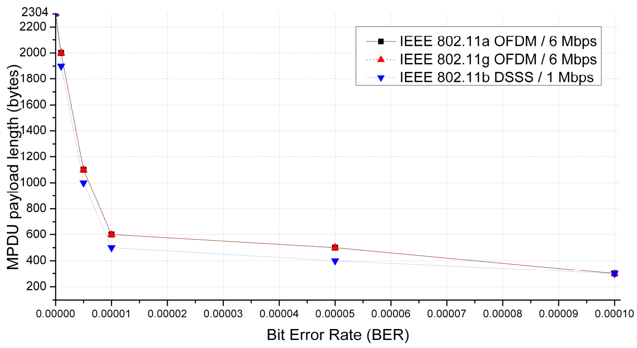

Figure 6, Optimal MPDU (Mopt) payload length at the MAC layer according to the physical channel conditions.

IV. 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 [14].

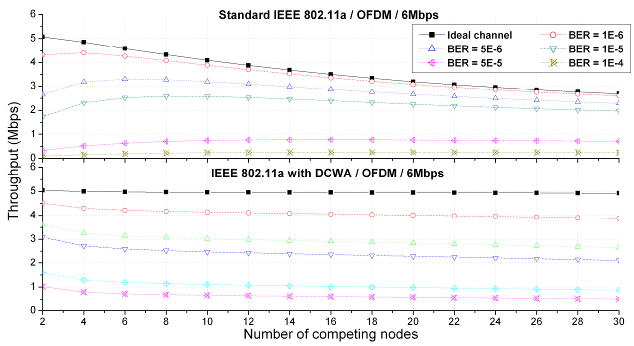

Figure 7, Throughput vs. number of competing nodes (802.11a / 6 Mbps in different BER values).

Figure 7 compares the effective throughput of *DCWA* with the standard IEEE 802.11-based DCF when physical channel conditions are varied. From these results, the throughput of *DCWA* shows a little decrease as the number of competing nodes increase and it is always higher than that of the standard

DCF in both ideal and error-prone channel conditions. For instance, *DCWA* can improve the throughput of the standard DCF by 83.3% under an ideal channel and by up to 117.3% under BER=1E-4 channel condition with up to 30 competing nodes.

Figure 8 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.

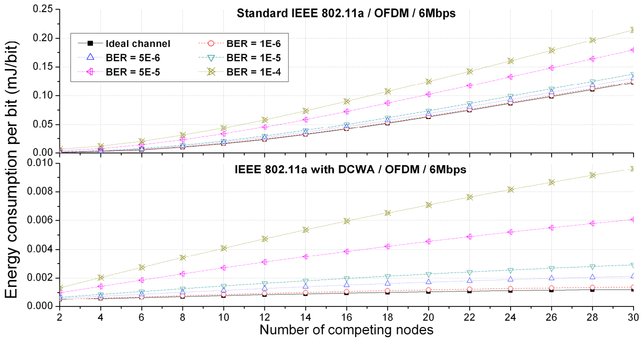

Figure 8, Energy consumption per bit vs. number of competing nodes (802.11a / 6 Mbps in different BER values).

An interesting observation from these results is that the proposed *DCWA* is not only able to eliminate most of the collisions from the channel competition in the MAC layer (Figures 2 and 3), but also reduces the FER by using controllable MPDU payload length which based on physical channel conditions in PHY layer (Figure 7 and 8).

V. Conclusions

In this paper, we presented a control scheme for dynamically varying the contention window and MPDU payload length in ad-hoc wireless networks for both ideal and error-prone channel conditions. The scheme is cross-layer in nature and operates in the MAC and PHY layers. 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 control 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.

References

[1] IEEE 802.11 Work Group, “Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,” ANSI/IEEE Std 802.11, 1999.

[2] F. Calì, M. Conti, and E. Gregori, “Dynamic Tuning of the IEEE 802.11 Protocol to Achieve a Theoretical Throughput Limit,” IEEE/ACM Trans. Networking, vol. 8, no. 6, pp. 785-799, Dec. 2000.

[3] G. Bianchi , “Performance analysis of the IEEE 802.11 distributed coordination function,” IEEE Journal on Selected Areas in Communications, Vol. 18, No. 3, pp. 535 -547, March 2000

[4] Hui Ma, Hewu Li, Peiyun Zhang, Shixin Luo, Cong Yuan,Xing Li,"Dynamic optimization of IEEE 802.11 CSMA/CA based on the Number of Competing Stations," IEEE International Conference on Communications, ICC 2004, vol. 1, pp. 191- 195, June, 2004.

[5] D. Qiao and S. Choi, “Goodput Enhancement of IEEE 802.11a Wireless LAN via Link Adaptation,” Proc. IEEE International Conference on Communications, ICC 2001, vol.7, pp. 1995-2000, June 2001.

[6] Xiaodong Wang, Jun Yin, Dharma P. Agrawal, “Analysis and Optimization of the Energy Efficiency in 802.11 DCF,” MONET Special Issue “Internet Wireless Access: 802.11 and Beyond,” Kluwer Publications, No. 11, pp. 279-286, 2006.

[7] Daji Qiao, Sunghyun Choi, Amit Jain, and Kang G. Shin, “MiSer: An Optimal Low-Energy Transmission Strategy for IEEE 802.11 a/h,” Proc. ACM MobiCom'2003, pp. 161-175, 2003.

[8] Tsung-Han Lee, Alan Marshall and Bosheng Zhou, “Modeling Energy Consumption in error-prone IEEE 802.11-based Wireless Ad-Hoc Networks,” 9th IFIP/IEEE International Conference on Management of Multimedia and Mobile Networks & Services, MMNS 2006, October 25-27 2006, Dublin, Ireland.

[9] Gomez, J., Campbell, A.T., Naghshineh, M. and Bisdikian, C., “Conserving Transmission Power in Wireless Ad Hoc Networks,” in Proceeding of ICNP, pp. 24-34, 2001.

[10] S. Agarwal, S. Krishnamurthy, R. H. Katz, and S. K. Dao, “Distributed Power Control in Ad-hoc Wireless Networks,” Personal, Indoor and Mobile Radio Communications, PIMRC 2001, vol. 2, pp. F-59-F-66, Sep/Oct 2001.

[11] R. Ramanathan, R. Rosales-Hain, “Topology control of multihop wireless networks using transmit power adjustment,” IEEE INFOCOM, 2000, pp. 404-413.

[12] E.-S. Jung and N. H. Vaidya, “A Power Control MAC Protocol for Ad Hoc Networks,” in the Proceeding of the. MOBICOM 2002, vol.1, pp.36–47, September 2002.

[13] Rappaport TS, “Wireless Communications: Principles and Practice,” Prentice Hall, New Jersey, USA, 1996

[14] QualNet simulator, http://www.qualnet.com/.

ISBN: 978-988-17012-5-1