Adaptive Contention Window Mechanism for Enhancing Throughput in HomePlug AV Networks

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Abstract—**HomePlug AV (HPAV) is the standard for distribution of Audio/Video content as well as data within the home by using the power line. It uses a hybrid access mechanism that combines TDMA with CSMA/CA for MAC technology. The CSMA/CA protocol in HPAV has two main control knobs that can be used for access control: contention window (CW) size and deferral counter (DC). In this paper, we extensively investigate the impacts of CW and DC on performance through simulations, and propose an adaptive mechanism that adjusts the CW size to enhance the throughput in HPAV MAC. We find that the CW size is more influential on performance compared to the DC. Therefore, to make the network control easier, our proposal uses a default value of DC and adjusts the CW size. Our scheme simply increases the CW size if the network is too busy and decreases it if too idle. We compare the performance of our proposal with those of the standard and other competitive schemes in terms of throughput and fairness. Our simulation and analysis results show that our adaptive CW mechanism performs very well under various scenarios.**

I. INTRODUCTION

Various traditional home appliances are being rapidly replaced by digital value-added ones, and upcoming applications, such as interactive games and voice over IP (VoIP), need communication among the applications. Recently, lots of researches on home networks have concentrated on communication between the applications on multimedia and digital platforms in the local area network environments. In order to provide such connectivity, various home network technologies of wireless and wired have been developed. For wireless solutions, there are IEEE 802.11x wireless local area networks (LANs) [1] and IEEE 802.15.x wireless personal area networks (PANs) [2], which data rates currently vary from 250kbps to 54Mbps. The drawback of the wireless solutions is that overall performance is limited by the interference between other neighboring clients. For wired solutions, there are HomePNA [3] and HomePlug [4], [5], which use existing telephone lines and powerlines, respectively. Because they use already existing lines, the wired solutions are suffering less from the interference problem compared to the wireless solutions. Between the two wired solutions, HomePlug AV (HPAV) is more promising, which has been standardized by HomePlug Powerline Alliance and follows the HomePlug 1.0 standard. While HomePlug 1.0 was designed to distribute the Internet access, HPAV aims at supporting Audio/Video as well as data traffic within the home. HPAV employs the advanced PHY and MAC technologies and provides up to the PHY rate of 150 Mbps. It uses the same MAC protocol of CSMA/CA as HomPlug 1.0.

In [6] and [7], Campista et al. proposed throughput enhancement techniques by simply modifying the collision avoidance algorithm in CSMA/CA. These works focused on throughput rather than fairness. Tripathi et al. in [8] worked on achieving the optimal throughput of HomePlug 1.0 MAC protocol, assuming that every station always knows the exact number of contending stations. As this assumption is unrealistic, the optimal throughput is not achievable in real world. Chung et al. [9] presented a detailed analysis for MAC performance of HomePlug 1.0 by using the Markov Chain model.

In this paper, we propose a scheme that achieves high throughput by adaptively changing each station's CW size without a priori information about the number of contending users. Our proposal simply counts successful transmissions and idle slots for the given beacon interval. When the number of successful transmissions is smaller than a predefined threshold, our scheme changes each station's CW size appropriately. Without requiring any unrealistic assumptions it shows good fairness performance and works well even under heavy loading.

The rest of this paper is organized as follows. In Section II we briefly review the HPAV protocol. Section III explains the numerical analysis background and our proposed scheme. The performance evaluations through numerical analysis and simulations are shown in Section IV, followed by concluding remarks in Section V.

II. HOMEPLUG AV MAC

A. Hybrid Access Control

The HPAV uses a hybrid access mechanism in order to support various type of services. Fig. 1 shows an example of HPAV access mechanism that consists of CSMA/CA and TDMA. TDMA can support some services like VoIP that require strict QoS level by allocating resources periodically. On the other hand, CSMA/CA is suitable for urgent data transfer, control message and best effort service. The HPAV and HomePlug 1.0 use the same protocol of CSMA/CA, so two different versions of HomePlug can communicate with each other.

For the hybrid access control, each HPAV network has a coordinator, named Central Coordinator (CCo). The CCo broadcasts a beacon message periodically that contains some

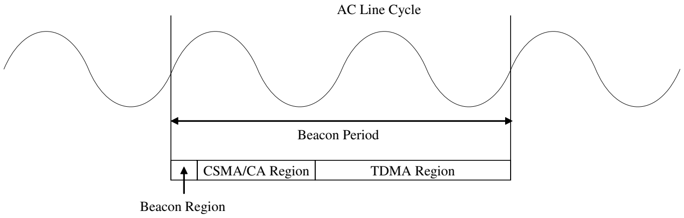

Fig. 1. An Example of HPAV Beacon Period. The Beacon Period is synchronized with AC line cycle and the Beacon Period consists of Beacon Region, CSMA/CA Region and TDMA Region

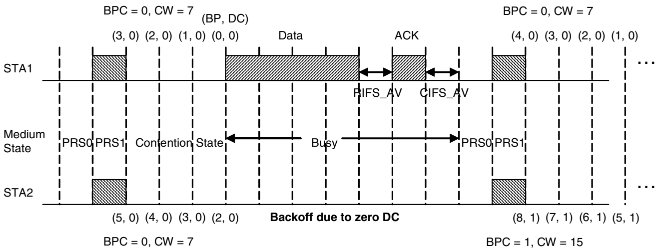

Fig. 2. HomePlug CSMA/CA timing diagram, This figure shows an example of PRP and shows backoff due to DC.

information for access control. Every station in the HPAV network can understand the access mechanism by hearing the beacon. Practically, the CCo generates a beacon every two AC line cycles.[1] The beacon indicates, like a map, when CSMA/CA region and TDMA region start.

B. HomePlug CSMA/CA

HomePlug CSMA/CA[2] is similar to IEEE 802.11 CSMA/CA as both use the binary random backoff algorithm. Differently from IEEE 802.11 CSMA/CA, HomePlug CSMA/CA has Priority Resolution Slot (PRP) and Deferral Counter (DC).

1) PRP: The object of using PRP is to classify priorities among data flows. It consists of two Priority Resolution Slot (PRS), named PRS0 and PRS1. PRP's duration is long enough to detect the medium state, i.e., busy or idle. Thus, HomePlug CSMA/CA can have four kinds of priorities. Each station generates the busy signal and hears the channel until it has the right for transmission according to its own priority. If a station detects the busy signal, it does not enter Contention State, because the busy signal indicates the existence of other higher priority flow. Consequently, stations with the same priority flow can enter the Contention State and contend. The others that have lower priority flows wait until stations with high priority complete their transmissions.

2) DC: The DC is valid during contention while the PRP is valid before contention. When a station has a frame to transmit, it sets the Backoff Procedure Counter (BPC) value to 0, and chooses a random number between 0 and Contention Window (CW) at the given BPC, and sets the Backoff Counter (BC) at the chosen number. If the medium is idle for one slot, each station in Contention State decreases its BC by one, and sends a frame when its BC becomes 0. If a station experiences the transmissions failure, it increases BPC by one and sets BC value at a random number in (0, CW) at the given BPC. Table I shows CW and DC values at each BPC.

TABLE I
CW AND DC AS A FUNCTION OF BPC AND PRIORITY

	High Prioriry		Low Priority	
	CW	DC	CW	DC
BPC = 0	7	0	7	0
BPC = 1	15	1	15	1
BPC = 2	15	3	31	3
BPC $\geq$ 3	31	15	63	15

The DC is a newly introduced parameter, so HomePlug CSMA/CA has three parameters: BPC, CW and DC. The DC prevents the throughput from decreasing induced by collision. Using the DC, each station can perform binary random backoff without collision, which procedures are given as follows. At the beginning of each BPC, each station sets the DC value to a predefined DC value shown in Table I. If the medium is idle for one slot, each station decreases BC by one. If a station has non-zero DC when the medium is busy, it decreases both BC and DC by one. If a station has zero DC when the medium is busy, it performs binary random backoff without transmission. In Fig. 2, STA2 performs binary random backoff without trying to send a frame because its DC is zero and the medium is busy. Consequently, HomePlug CSMA/CA gets similar collision priority to IEEE 802.11 CSMA/CA with lower CW value because it performs binary random backoff without collision.

III. NUMERICAL ANALYSIS REVIEW AND ADAPTIVE CW MECHANISM

IEEE 802.11 CSMA/CA has been analyzed by using the Markov Chain model and assuming saturation condition in [10], and similarly HomePlug CSMA/CA in [9]. In this section, we briefly review the analysis and propose our adaptive CW mechanism.

A. Throughput and Optimal τ Analysis

The Markov Chain model for IEEE 802.11 is a two dimensional chain, however that for HomePlug is a three dimensional chain because HomePlug has one more parameter of DC. τ denotes the probability that a station transmits a frame. From the three-dimensional Markov Chain model [9], the τ is obtained as

$$\tau = \sum_{i=1}^{m} \sum_{j=0}^{M_{i-1}} P_{i,j,0} \tag{1}$$

where m denotes the maximum BPC stage value, M_{i-1} denotes the DC value at the BPC stage i, and $P_{i,j,k}$ denotes the probability that a station is stationary distributed in BPC stage i, DC state j, and BC state k. The transmission probability is

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[1] The AC line cycle is 60 Hz in North America and in Republic of Korea. So, the beacon period is 33.33 msec. In Europe, it is 40 msec as the AC line cycle is 50 Hz.

[2] We use the term of HomePlug CSMA/CA instead of HPAV CSMA/CA because HPAV and HomePlug 1.0 use the same CSMA/CA protocol.

the summation of distribution probability with BC = 0, because a frame is transmitted only when BC is zero. The stationary distribution probability $P_{i,j,k}$ can be found by a numerical method.

The throughput is obtained by

$$S_{sat} = \frac{P_{tr} P_s E[N_{payload}]}{(1-P_{tr})\sigma + P_{tr}(P_s T_s + (1-P_s)T_c)} \tag{2}$$

where P_{tr} denotes probability that there exists at least one transmission in the medium, P_s denotes the probability that a frame transmission is successful, $E[N_{payload}]$ denotes the average size of payload, σ denotes idle slot duration, T_s denotes the average time that the medium is sensed busy due to the successful frame transmission, and T_c denotes the average time that the medium is sensed busy due to collision.

In Bianchi [10], the optimal τ for IEEE 802.11 is expressed as

$$\tau \approx \frac{1}{n\sqrt{T_c^*}} \tag{3}$$

where T_c^* denotes the collision time normalized by slot time. The optimal τ is calculated from (2), so it is also optimal to HomePlug.

B. DC Effect and our Adaptive CW Mechanism

We intuitively discuss the effect of DC on τ and throughput. Decreasing DC by one is the same as deleting one row at HomePlug CSMA/CA Markov Chain model, i.e., decreasing M_{i-1} by one in eq. (1). Reversely, increasing DC by one corresponds to adding one row in the Marchov Chain model. The probability of deleting one row is uniformly distributed in the next BPC. Generally, the CW size at next BPC is double the CW size of the current BPC. So, the probability of decreasing DC is larger than that of increasing DC. Consequently, τ varies in proportion to DC. To observe throughput change with τ variation, we rewrite eq. (2) as

$$\frac{n\tau(1-\tau)^{n-1}}{\sigma(1-\tau)^n + nT_s\tau(1-\tau)^{n-1} + T_c(1-(1-\tau)^n) - nT_c\tau(1-\tau)^{n-1}}. \tag{4}$$

The numerator is a monotonic increasing function of τ and the denominator is a concave function of τ in (0, 1). As it is not possible to describe the tendency clearly, we will investigate the effects of τ on throughput in section IV-C through simulations.

In order to get optimal τ and CW, each station has to know the exact number of contending stations. However, as this assumption is not practical, we are motivated to propose a heuristic adaptive CW algorithm that tries to find a suboptimal CW size in real-time. If each station in the network performs our heuristic algorithm, the estimation of suboptimal CW may be different from station to station. Thus, a centralized approach is more practical in achieving good performance than a distributed approach. Fortunately, the CCo generates the beacon periodically which is assumed robust enough to reach every station within the given logical network. For each beacon period, the CCo collects data such as the number of successful transmissions completed and the number of idle slots past. Then it determines whether the current CW is proper or not, and it increases or decreases the CW size. The CCo inserts the proper CW value into the beacon message and broadcasts it. Every station replaces its current CW with new one. Fig. 3 shows the flow chart of our heuristic adaptive CW adjustment algorithm. The threshold value for the proper number of successful transmissions for a beacon period is set at 10. If the previous beacon period has less than 10 successful transmissions, the CCo check the number of idle slots. If the number of idle slot is smaller than 40, the CCo doubles the CW size. Else if it is larger than 80, then the CCo decreases the CW size by half. Otherwise, the CCo does not change the CW size. Here, the threshold values that we used 10, 40, and 80 are found through simulations.

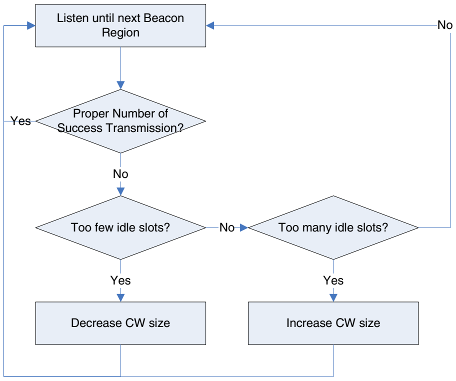

Fig. 3. Flow Chart of Adaptive CW Adjustment Algorithm.

TABLE II
HPAV SYSTEM PARAMETERS USED IN NUMERICAL AND SIMULATION ANALYSIS

Average Payload Size ($E[N_{payload}]$)	46280 bytes
PHY + MAC Header Time	110.48 μsec
PHY Transmission Rate	150.19 Mbps
Beacon Period	33.33 msec
CIFS_AV	100 μsec
RIFS_AV	30.72 μsec
PRS0	35.84 μsec
PRS1	35.84 μsec
σ	35.84 μsec
Response Timeout	140.48 μsec

IV. NUMERICAL ANALYSIS AND SIMULATION RESULTS

In this section, we present numerical and simulation results. Numerical results are obtained from [9], and for simulations we use the event-driven simulator written in C++ language. The parameters used in numerical and simulation analysis are given in Table II. We assume that all flows have the same priority.

A. CW versus Throughput

Fig. 4 plots the throughput versus number of contending stations according to various CWs. The DC is set at the default value of {0, 1, 3, 15}. The lines and points represent analysis results and simulation results, respectively. The results

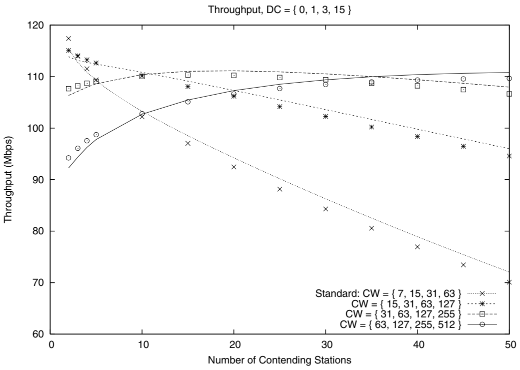

Fig. 4. Throughput considering various CWs versus number of contending stations.

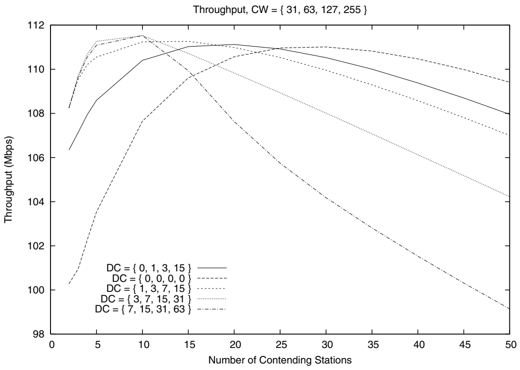

Fig. 6. Throughput for various DCs versus number of contending stations.

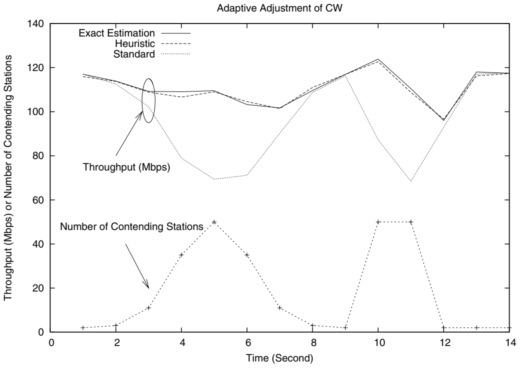

Fig. 5. Comparison of the throughput of our adaptive CW scheme against those of the standard and exact estimating scheme.

show that numerical and simulation results are very close. The throughput in the standard scheme drastically decreases with the number of contending stations. As expected, larger CW results in higher throughput when the load is heavy. We tried four types of CW size and obtained the maximum throughput of 110 Mbps. If we adapt both CW and DC appropriately, we are able to obtain high and stable throughput. However, the throughput increase is not that significant considering the increased complexity. So, we use four types CW patterns for adaptive scheme.

B. Adaptive CW Adjustment

Fig. 5 compares the performance of our adaptive scheme with those of the standard scheme and the exact estimating scheme under time varying number of contending stations. The 'y' axis represents the number of currently active users and the throughput in unit of Mbps. The number of active stations varies between 2 to 50 as the time varies. In the exact estimating scheme, every station is assumed to exactly know the number of contending stations within the network, accordingly being able to set the CW at the optimal value. The standard scheme follows the HPAV standard specification. Surprisingly, the throughput curve of our adaptive scheme is very close to that of the exact estimating scheme.

The standard scheme performs poorly when the network is congested. From 1 to 9 second, we increase and decrease the number of contending stations. Our scheme always achieves more than 100 Mbps of throughput. This means that our algorithm reflects load change adaptively and smoothly. At 10 sec, there is an abrupt change in the number of contending stations from 2 to 50. Still our adaptive scheme shows comparable throughput to the exact estimating scheme. At 12 second, there is a sudden decrease from 50 to 2 in contending stations. The throughput is below 100 Mbps. The reason is that many stations still have large BCs while all stations change their CW values to small values. So at 13 second, the throughput resumes 110 Mbps. Because the sampling period is short, i.e., 1 second, sometimes our adaptive algorithm shows slightly better performance than the exact estimating scheme.

C. DC versus Throughput

Fig. 6 plots the throughput with CW = $\{31, 63, 127, 255\}$ for various DC values according to the number of contending stations n. The case of DC = $\{0, 0, 0, 0\}$ shows the worst performance when the load is light while the cases with larger DC values perform well at light load but badly at the heady load. The solid line represents the performance for the default DC value of $\{0, 1, 3, 15\}$. It shows the maximum throughput around $n = 20$. The throughputs of DC = $\{3, 7, 15, 31\}$ and DC = $\{7, 15, 31, 63\}$ show the similar tendency for $n < 10$. However, as n grows greater than 10, the case of DC = $\{7, 15, 31, 63\}$ performs poorly.

Fig. 7 plots optimal τ for various CWs according to the number of contending stations by using eq. (3). The DC is set at the default value of DC = $\{0, 1, 3, 15\}$. The case of CW = $\{31, 63, 127, 255\}$ has an intersection with optimal τ at $n = 20$, which leads to the maximum throughput as shown in Fig. 6. There is no intersection between the case of CW = $\{7, 15, 31, 63\}$ and optimal τ. With high CW values, which results in good performance for high n, the intersection point moves to the right as expected. This indicates that the throughput can be simply controlled by the CW value only instead of using both the CW and DC values.

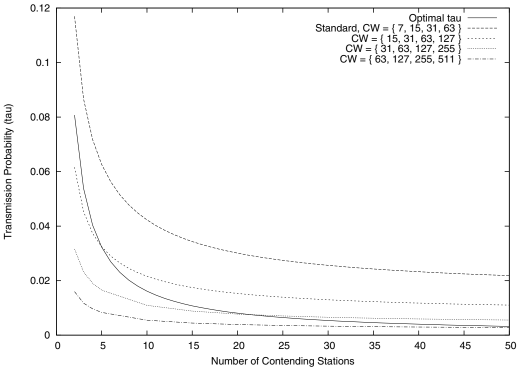

Fig. 7. Optimal τ for various CWs versus number of contending stations.

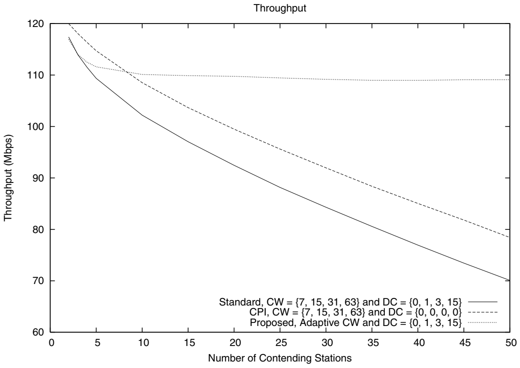

Fig. 8. Throughput Comparison.

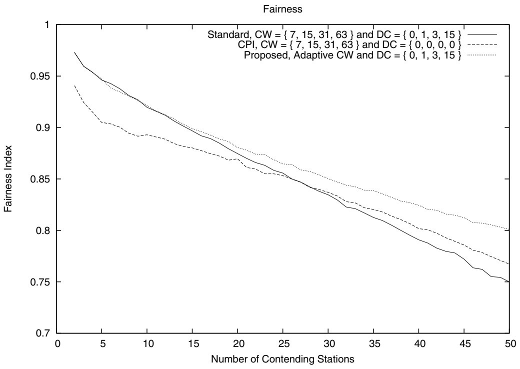

Fig. 9. Fairness Comparison.

D. Comparison with the Competitive Schemes

This section shows the performance comparison results. Campista et al. [6] proposed a throughput enhancement scheme with setting DC = $\{0, 0, 0, 0\}$ and named it Contention window Proactive Increase (CPI). The CPI mechanism avoids collision by increasing the number of times that the backoff procedure is called. Fig. 8 compares the throughputs of the standard, the CPI scheme, and our proposed adaptive CW scheme. The CPI performs always better than the standard and the best under light traffic (i.e., up to $n = 8$). However it shows the same tendency of throughput decrease as the standard with the number of contending stations. Our proposed adaptive CW scheme performs well under any number of contending stations. Fig. 9 shows the fairness performance for one second. We use Jain's fairness index [11] as the fairness metric that is given by

$$fairness = \frac{(\sum_{i=1}^{n} X_i)^2}{n \sum_{i=1}^{n} X_i^2} \qquad (5)$$

where X_i indicates each station's number of successful transmissions for one second. Fairness index of 1 represents perfect fairness. Our scheme improves fairness by about 5 % compared to the CPI scheme that enhances the throughput at the cost of fairness. Overall, our scheme shows good performance in terms of throughput and fairness over almost entire traffic range.

V. CONCLUSION

The CSMA/CA protocol in the HPAV network has two access control parameters of CW and DC. In this paper, we investigated the impacts of these parameters on throughput performance. Through slight extension of existing analysis results and extensive simulations, we found that controlling the CW size adaptively is good enough to achieve good throughput.

By simply counting the number of successful transmission and the number of idle slots that reflects the current load, our adaptive CW scheme adjusts the CW adaptively. It also achieves good fairness. Our scheme is practical and easily implementable because it does not require any unrealistic assumptions.

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