Contention Window based Parameter Selection to Improve Powerline MAC Efficiency for Large Number of Users

Kartikeya Tripathi, Jong-Dae Lee, Haniph Latchman
and Janise McNair
Electrical and Computer Engineering
University of Florida
Gainesville, Florida, USA

Srinivas Katar
Intellon Corporation
Ocala, Florida, USA

Abstract—**Power line based communication systems (PLC) are emerging as strong contenders in the home and personal environments. Their advantages of high data rates, no additional wiring and easy scalability make them very attractive for deployment in local area networks and broadband power line (BPL) Internet access. Effective use of the powerline bandwidth requires robust physical and medium access control (MAC) protocols to mitigate the harsh conditions of the powerline channel, as well as the capability to support prioritized multimedia traffic. Home Plug 1.0 is the most commonly used technology for powerline communication. HomePlug 1.0 uses carrier sense multiple access/collision avoidance (CSMA/CA) to provide a maximum MAC data rate of 8 Mbps. Just as in 802.11, the throughput performance of this scheme becomes critical when the number of users increases, as in BPL. In this paper, a modification in the medium access control protocol of Home Plug 1.0 is proposed, to make it a constant contention window based scheme. This modification is shown to significantly enhance the MAC performance under saturation conditions. An analytical and simulation framework is used to tune the modified protocol for best performance, under the assumption that the number of active stations is known or can be reliably estimated.**

Keywords-Medium Access Control (MAC), Powerline Communications (PLC), CSMA/CA, Saturation Throughput

I. INTRODUCTION

With the emergence of affordable and portable devices for home, entertainment and personal use, it is natural that the next step would be to get them to communicate with each other on a multimedia and digital platform in the local area network environment of a home or small office/home office. Affordable broadband Internet communication to residential customers is now available via cable modem and various forms of digital subscriber lines (DSL). While it is a simple matter to use a 10/100 Base-T network hub to link several computers in a single room or in a small office environment, it is much more challenging to provide network connections in several rooms in a typical home [1][2]. Another approach is to deploy an IEEE 802.11 [3] wireless local area network (WLAN) with wireless modems in each device connecting to one or more wireless hubs (infrastructure-based) or to each other (ad-hoc based). The wireless option is certainly viable (with data rates now up to 54 Mbps), except for the fact that a dedicated wired infrastructure connecting multiple access points is required to cover the entire home. Power lines, being ubiquitously deployed as a wire-line network for carrying electrical power, are then the obvious choice as the medium for communication amongst the plethora of home-based and personal devices like PDAs and MP3 players. They offer the convenience of already being there, and having outlets in almost all locations in a household for easy access. Further, devices can easily obtain electric power if they are deployed on PLC systems, while wireless mobile devices rely on batteries and have difficulty in maintaining continuous electric power. HomePlug 1.0 [4], standardized in 2001, is one of the most popular powerline communication technologies, and it supports up to 14 Mbps transmission rate using power lines.

The PLC systems, however, are not free of problems. The powerline communication channel can be notorious due to electric noise and interference, as well as channel variability depending on the appliances that are in use from time to time. Even then, with the support of advanced modulation and channel coding techniques, e.g. Orthogonal Frequency Division Multiplexing (OFDM) and Forward Error Correction (FEC) [5], the present version of the HomePlug 1.0 has been shown to out-perform the traditional IEEE 802.11a/b in many field tests of connectivity, throughput and link stability [6].

The MAC of HomePlug 1.0 is CSMA/CA based and extends the random backoff algorithm of IEEE 802.11 [3]. Analytical performance evaluation and enhancements of 802.11 MAC has been extensively carried out in [7] [8] [9] [10] [12]. Based on that body of work, Jung et el [11] worked out a detailed analysis for the MAC performance of HomePlug 1.0. In the present paper, a modification in the medium access control protocol of Home Plug 1.0 is proposed, to make it a constant contention window based scheme. This modification is shown to significantly enhance the MAC performance under saturation conditions. An analytical and simulation framework is used to tune the modified protocol for best performance, under the assumption that the number of active stations is known. The rest of the paper is organized as follows: section II gives an outline of the MAC protocol used in HomePlug 1.0. Section III presents the modification of the standard protocol that makes it a constant contention window scheme, and its analytical model. In section IV, the resulting theoretical bound of the MAC efficiency is evaluated, and the constant contention window size is parameterized. Section V gives numerical results, and section VI gives some concluding remarks.

II. HOMEPLUG 1.0 MAC

The MAC for HomePlug 1.0 has two components: Priority Resolution and Random Backoff.

A. *Priority Resolution*

In HomePlug 1.0, quality of service (QoS) is provided by differentiating user traffic into 4 priority levels: CA0, CA1, CA2 and CA3. The first two are lower priority traffic, and CA2 and CA3 have higher priorities. The higher the priority of the data packet, the earlier it gets to contend for the channel. Before channel contention begins, HomePlug 1.0 arranges for the resolution of the priorities of contending traffic by introducing two priority resolution slots (PRSs), PRS0 and PRS1. All stations having frames to transmit send signals in these slots, in accordance with the priorities of their data. Stations with CA3 data can send signals in PRS0 and PRS1. Stations with CA2 data can send signals in PRS0. Stations with CA1 data can send signals in PRS1. Stations with CA0 data can not send signals in either of these slots. The two PRSs inform all the stations of the priorities of other stations hopeful of contending for the channel, and those with lower priorities defer to those with higher priorities. Once the stations that will be in the contention are decided, they begin their random backoff procedures. This is shown in figure 1. The station that wins the contention transmits its data, and the response is received after a time equal to Response Interframe Space (RFIS) has elapsed. After the response of a successful transmission is received, the next priority resolution session begins after Contention Interframe Space (CIFS).

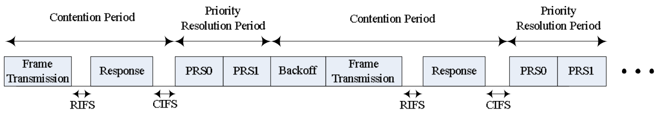

Figure 1. Sequence of events in HomePlug 1.0 MAC

B. *Random Backoff*

The backoff algorithm of HomePlug 1.0 is different from that of IEEE 802.11 in that HomePlug 1.0 uses three counters: backoff procedure counter (BPC), deferral counter (DC) and backoff counter (BC). BPC and BC represent the number of retransmissions (backoff stage, corresponding to the s value in 802.11 [7]) and the random backoff time (corresponding to the b value in 802.11 [7]), respectively. In HomePlug 1.0, DC is newly introduced to roughly estimate the number of contending stations. Every station starts its contention for the channel by initializing the value of BPC to 0, and choosing BC randomly between 0 and CW_0-1, where CW_0 denotes the initial contention window (CW) size. The value of DC is set depending on the value of BPC: every time BPC changes, DC (and BC) are updated with respect to table I. If a slot is sensed idle and BC is not zero yet, BC is decreased by one while DC and BPC are fixed (if BC becomes zero, the station transmits). If a slot is sensed busy, both BC and DC are decreased by one at the end of that busy slot. If DC then becomes less than zero, the BPC is updated to the next higher value, and both DC and BC are reinitialized according to the new BPC value (table I). In that case, BC is chosen randomly from 0 to CW_i-1, where CW_i is the new CW for BPC *i.* The same happens in the case of a collision also. In case of a success, the BPC is set to its minimum value, and DC and BPC are set accordingly.

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

	Priorities CA3, CA2		Priorities CA1, CA0	
BPC = 0	DC = 0	CW(W_0)= 8	DC = 0	CW(W_0)= 8
BPC = 1	DC = 1	CW(W_1)= 16	DC = 1	CW(W_1)= 16
BPC = 2	DC = 3	CW(W_2)= 16	DC = 3	CW(W_2)= 32
BPC > 2	DC = 15	CW($W_{3,..}$)= 32	DC = 15	CW($W_{3,\ldots}$)= 64

III. CONSTANT CONTENTION WINDOW MAC

The standard HomePlug 1.0 back off algorithm is tailored for networks with small number of stations. In networks with large number of stations, such as may be encountered in BPL applications, the collision overhead drastically reduces the MAC efficiency. To overcome this problem, we propose a new back off scheme that uses and adapts the contention window size based on the number of contending stations in the network. Furthermore, the BPC value is kept constant under all circumstances. So, rather than changing the CW every time BPC is updated at the end of a collision or success or when DC reaches a negative value, the station reverts to the same value of CW (hence called W) to draw the next BC from. Since the value of DC is also updated with BPC, it is reset to the same value, hence called λ, every time BPC is reset.

A. *Mathematical analysis*

A homogeneous, bi-dimensional Markov chain is used to model the above described system. Each state comprises the current values of DC and BC for the node under consideration. The Markov Chain is in discrete time, in that the state of the system is observed at the beginning of every slot. Since collisions and successful transmissions also begin at the start of a slot, the time spent in these, which is more than an actual slot time, can be embedded into the time of Markov Chain. Figure 2 shows the state transmission diagram of the Markov Chain for a node in the modified HomePlug 1.0. Here, p_i represents the probability that a node finds the medium idle at current time slot. The analysis is carried out for n stations of equal priority under saturation conditions.

$\Pi(i,j)$ is used to represent the steady state probability that the node has a DC value of i and BC value of j. For the given Markov Chain, the stationary distribution can be found from the following two recursive equations:

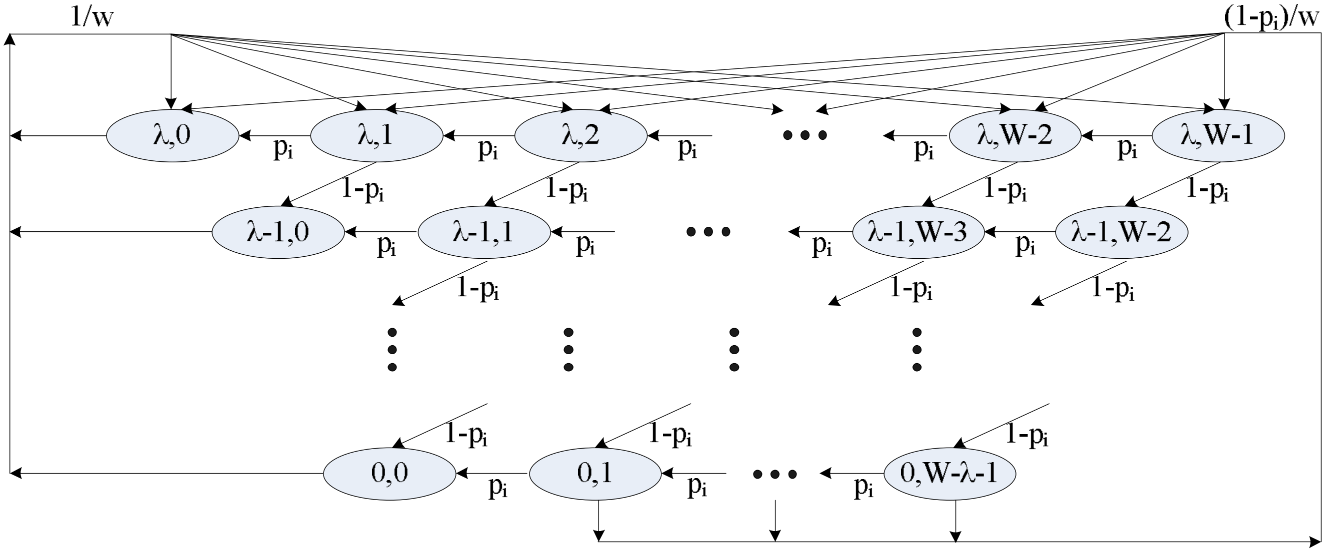

Figure 2. State Space representation of Markov Chain Model for Constant Contention Window based HomePlug 1.0

$$\Pi(\beta, W-\lambda-i_\beta) = (1-p_i)\sum_{j_\beta=1}^{\beta+i_\beta} p_i^{j_\beta-1}\,\Pi(\beta+1, W-\lambda-i_\beta+j_\beta) \tag{1}$$

for $i_\beta = 1-\beta, 2-\beta, \ldots W-\lambda$, and $\beta = 0, 1, \ldots \lambda-1$

and

$$\Pi(\lambda, W-\lambda-i_\lambda) = \Pi(\lambda, W-1)\sum_{j_\lambda=0}^{\lambda+i_\lambda-1} p_i^{j_\lambda} \tag{2}$$

for $i_\lambda = 1-\lambda, 2-\lambda, \ldots W-\lambda$

The probability p_0 that a node will transmit in any randomly chosen slot of time is given by

$$p_0 = \sum_{i=0}^{\lambda} \Pi(i, 0) \tag{3}$$

Since p_i is the probability that the node under consideration finds the medium idle, it is related to p_0 through the following equation:

$$p_i = (1-p_0)^{n-1} \tag{4}$$

Solving these equations numerically, the value of p_0 corresponding to n, W and λ can be found. This can be used to calculate the MAC efficiency for the modified HomePlug 1.0. Specifically, the probabilities that a randomly chosen time slot will experience, respectively, a successful transmission, an idle passage and a collision are:

$$\begin{aligned} P_S &= np_0(1-p_0)^{n-1} \\ P_I &= (1-p_0)^n \\ P_C &= 1-P_S-P_I \end{aligned} \tag{5}$$

The MAC efficiency, η, can then be expressed in terms of P_S, P_I, P_C and slot time T_I, time for successful transmission T_S (inclusive of data time T_{Data} response time and RIFS), and time for a collision T_C. If the collision time and successful transmission time are considered constant, and if the time for priority resolution is not considered, the relation becomes

$$\eta = \frac{P_S T_{Data}}{P_S T_S + P_C T_C + P_I T_I} \tag{6}$$

In section V, it is shown that the MAC efficiency found from this mathematical analysis matches exactly that from simulation of the constant contention window based HomePlug 1.0.

IV. CONTENTION WINDOW PARAMETERIZATION

Note that the expression for MAC efficiency in (6) is a function of p_0. To maximize the MAC efficiency, this expression can be differentiated with respect to p_0 to get the optimal value p_0, called $p_{0,opt}$. For n stations, we get

$$T_I\left(P_S\frac{dP_I}{dp_0} - P_I\frac{dP_S}{dp_0}\right) + T_C\left(P_S\frac{dP_C}{dp_0} - P_C\frac{dP_S}{dp_0}\right) = 0 \tag{7}$$

which gives

$$1-\frac{T_C}{T_I} = \frac{1-np_{0,opt}}{(1-p_{0,opt})^n} \tag{8}$$

It is now possible, using (1), (2), (3), (4) and $p_{0,opt}$ found above, to parameterize W and λ to values that will give the best performance for the modified MAC running for a given number of stations. In the next section, the numerical results to these effects are presented.

V. NUMERICAL RESULTS

A discrete event simulation was written for generating results for the modified HomePlug 1.0 MAC, and to compare them with those of the standard protocol. Figure 3 shows the agreement between the analytical and simulation results for the MAC efficiency of the constant contention window based HomePlug 1.0 protocol. Results are shown for two different cases of values of W, λ is fixed at 7. Notice that for a constant λ, the performance gets better as W increases.

Figure 4 shows the solution of (8) for varying number of stations. Many cases of T_I and T_C are shown. Note that (8) is agnostic to the underlying backoff scheme. The result shown would be the same for 802.11 and standard HomePlug 1.0 for the same values of T_I and T_C. The rest of the analysis is carried out for values of T_I and T_C equaling 20 micro-seconds and 800 micro-seconds respectively (i.e. collisions last for 40 slots).

Using equations (1), (2), (3), and (4), the values of p_0 can be obtained as a function of W and λ for a given number of stations. Figure 5 shows the results for n = 5.

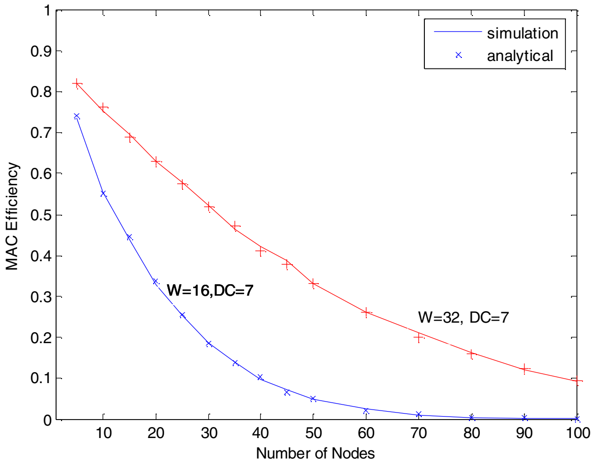

Figure 3. Comparison of analytical and simulation based performance of constant contention window based HomePlug 1.0

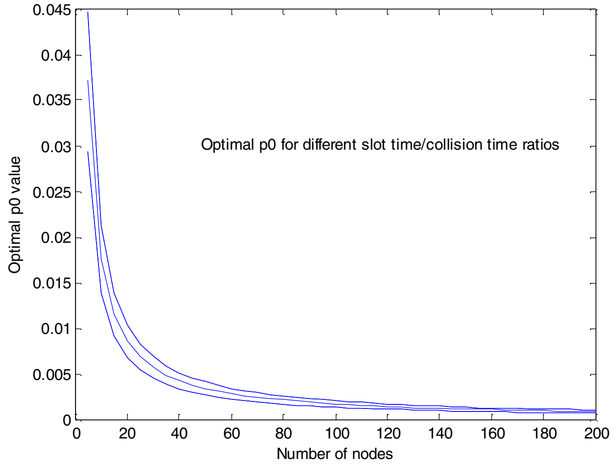

Figure 4. Optimal p0 value as a function of number of stations; the different curves correspond to varying T_I/T_C ratios

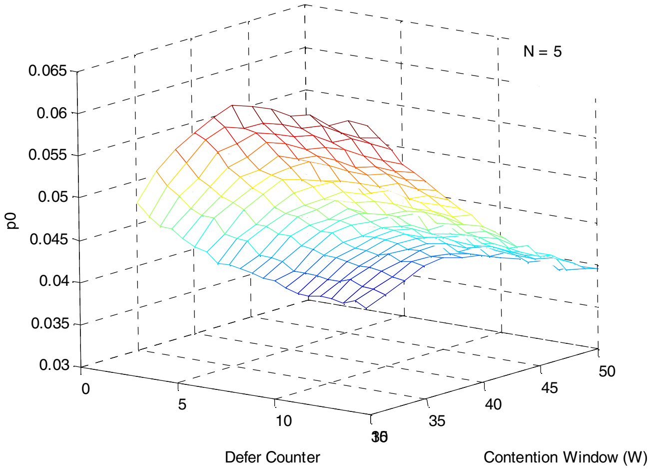

Figure 5. p0 as a function of W and λ for 5 stations

For figure 5, W is varied from 30 to 50, and λ from 3 to 15. It is possible to search through this mesh for those values of W and λ that give $p_{0,opt}$ for that number of stations. Note that there can be more than one combination of W and λ that give $p_{0,opt}$. E.g., for n = 5, $p_{0,opt}$ is 0.0446. This corresponds to $W = 34$ and $\lambda = 3$, and $W = 44$ and $\lambda = 15$.

Performing a search for W and λ, as in figure 5, for a varying number of stations, yields figure 6. Results are shown for $\lambda = 3$ and $\lambda = 15$. In both cases, the W value that gives the optimal p_0 is a linear function of the number of stations. In fact, the slope of the best linear fit doesn't change with λ, only the intercept does.

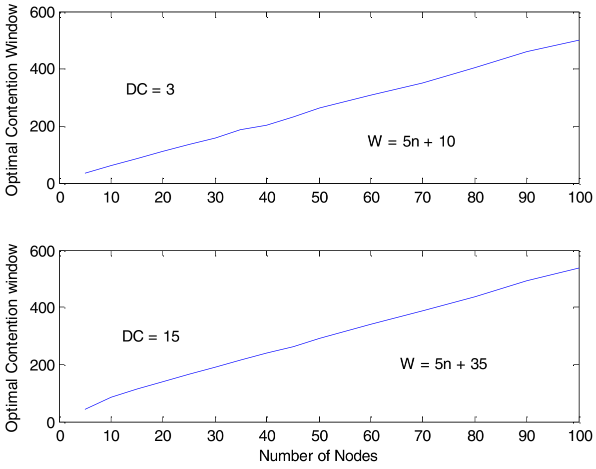

Figure 6. Variation of W that gives optimal p_0 as a function of number of stations, for two values of λ

Using results of figure 6, W can be parameterized as a function of number of active stations. Note that both cases in figure 6 will produce the same value of $p_{0,opt}$ for a given number of stations. Figure 7 reports the enhancement in MAC efficiency when optimal constant contention window, as a function of n, is deployed in the modified HomePlug MAC.

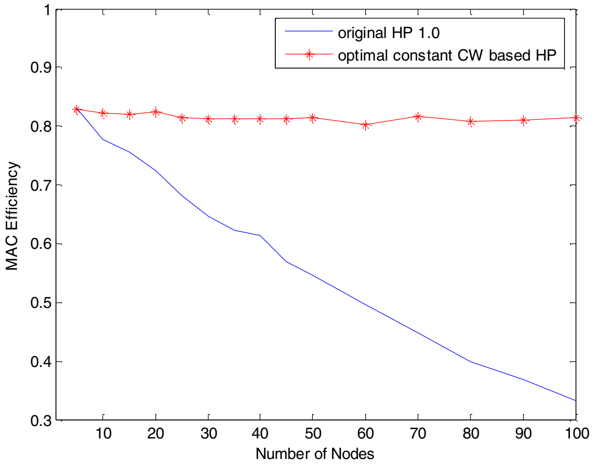

Figure 7. Comparison of performance of standard HomePlug 1.0 MAC and constant CW based MAC with optimal window sizes

VI. CONCLUSION

In this paper, a modification to the standard HomePlug 1.0 MAC protocol has been proposed, to make it a constant contention window based scheme. An analytical framework based on Markov Chains is developed for modeling this modified protocol under saturation conditions, and is proven to accurately match the actual performance of the system. It is shown that the performance can be substantially enhanced if the variables of the modified system (the contention window and defer counter) are parameterized in terms of the number of active stations. This parameterization emerges to be linear, which, when implemented, produces superior results. If the number of stations can be estimated at run time, the modified protocol can be dynamically tuned to provide optimal performance.

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