MAC Throughput Analysis of HomePlug 1.0

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***Abstract*— Power line communication technology is one of the most tractable home-networking technologies, because existing power line facilities can be utilized for data communications without deploying any new physical links. Although HomePlug 1.0, the power line communication standard, has undergone field trials and simulations, its analytic model and performance was not presented. In this letter, we analyze the performance of HomePlug 1.0 in terms of saturation throughput.**

***Index Terms*— CSMA/CA, home-networking, HomePlug, saturation throughput.**

I. Introduction

IN SUPPORT of ever increasing demand for connecting various in-home devices, many home-networking technologies have been developed to construct networks in home environments. They can be classified into two categories according to the type of medium, i.e., wireless and wired. IEEE 802.11x wireless local area networks (LAN) [1] and IEEE 802.15.x wireless personal area networks (PAN) [2] are major candidates for wireless home-networking technologies, whose data rate ranges from 20 Kb/s to 54 Mb/s. The most representative wired home-networking technologies are HomePNA [3] and HomePlug [4]. HomePNA uses existing telephone lines as transmission medium and its version 2.0 has been standardized to provide 10 Mb/s transmission rate for up to 25 stations without any hub. HomePlug 1.0 standardized in 2001 is one of the most famous power line communication technologies and it supports up to 14 Mb/s transmission rate using power lines.

Power line communication technologies are promising in the sense that existing power lines can play a role not only as a means to deliver electric power to devices but also as communication medium. Since power lines have been already deployed in home, it is possible to provide data communications promptly without any locational limitation in home. As a medium access control (MAC) mechanism, HomePlug 1.0 extends the random backoff (RB) algorithm of the conventional CSMA/CA used in IEEE 802.11 [5] to avoid collisions between the frames transmitted by stations. Performance of HomePlug 1.0 has been evaluated using simulations in [6]. To our best knowledge, however, mathematical analysis of HomePlug has not been conducted.

In this letter, we propose an analytic model to evaluate performance of HomePlug 1.0 systems. The organization of this letter is as follows. Section II describes the MAC algorithm in HomePlug 1.0. Section III explains our analytic model and evaluates the performance of the MAC algorithm by using the proposed analytic model and simulations. Finally, we conclude in Section IV.

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II. Medium Access Control Scheme

To provide quality of service (QoS) and to resolve collisions efficiently, HomePlug 1.0 adopts two MAC functions, priority resolution and random backoff. The random backoff algorithm of HomePlug 1.0 maintains three counters instead of two counters as in the conventional CSMA/CA. Fig. 1 shows an example of timing sequences for the transmission of frames on the medium. After the transmission of a frame and the reception of a response, there exists a gap called contention interframe space (CIFS) and then a priority resolution period consisting of two priority resolution slots (PRSs), PRS0 and PRS1, follow to resolve priorities among stations. Then, the stations with the highest priority will start random backoff to contend for frame transmissions. If a transmitting station successfully receives a response after response interframe space (RIFS), another new priority resolution period repeats after CIFS.

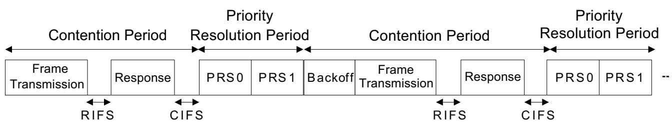

Fig. 1. Example of timing sequences on medium.

A. Priority Resolution

HomePlug 1.0 provides four priorities, CAx, $x = 0, 1, 2,$ and 3. The highest and the lowest priority are indicated by CA3 and CA0, respectively. The priority is determined by the type of a frame to be transmitted. All stations having frames for transmission are required to send or not to send signals in the PRS0 and PRS1 intervals according to the priorities of their frames. Stations with CA0 send no signal in both PRS0 and PRS1 and those with CA1 send signals only in PRS1. Stations with CA3 or CA2 send signals in PRS0. And stations with CA3 send signals in PRS1, but those with CA2 do not.

Those signals in the corresponding PRSs play a role to inform each station's priority to other stations. And the signals in the PRSs can be sensed on the medium to determine which station has the highest priority. By sensing the signals sent by higher priority stations, lower priority stations know the existence of higher priority stations. Based on its priority decision, each station perceives whether its backoff and transmission

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

	Priorities CA3, CA2		Priorities CA1, CA0	
BPC=0	DC=0	CW (W_0)=7	DC=0	CW (W_0)=7
BPC=1	DC=1	CW (W_1)=15	DC=1	CW (W_1)=15
BPC=2	DC=3	CW (W_2)=15	DC=3	CW (W_2)=31
BPC>2	DC=15	CW ($W_3,\ldots$)=31	DC=15	CW ($W_3,\ldots$)=63

can be immediately started or not. Thus, the stations with the highest priority can start random backoff for medium access as described in Section II-B. Stations, other than the highest priority stations, delay their transmissions until higher priority stations finish their transmissions. And then a new priority resolution procedure starts again.

B. Random Backoff Procedure

The backoff algorithm of 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) and the random backoff time, respectively. In HomePlug 1.0, DC is newly introduced to roughly estimate the number of contending stations. Whenever a new frame is in front of the transmission buffer, the value of BPC is initialized as 0 and BC is set to any random value in [0, W_0], where W_0 denotes the initial contention window (CW) size. According to the value of BPC, DC is initialized as in Table I. After BC and DC are updated, BPC immediately increases by one. If a slot is sensed idle, BC is decreased by one while DC is fixed. If a slot is sensed busy, BC and DC are decreased by one. Stations with zero BC can now transmit their frames. Whenever each station experiences a collision, its BPC increases by one until BPC equals to the maximum number of retransmissions. In addition, BPC increases by one when DC is zero and the medium is sensed busy. Then, DC is updated by the value of BPC and BC is newly set to any value in [0, W_{i-1}], where W_{i-1} is the new CW size of BPC i. Thus, the collision probability in the next stage of retransmission may be reduced, because stations can estimate the number of contending stations not only after a collision but also while other stations are transmitting. To effectively resolve collisions, different values of DC and CW are defined as the value of BPC varies (see Table I). Moreover, the value of CW for the frames with CA3 or CA2 is smaller than that for those with CA1 or CA0 to support different delay characteristics for different priorities.

III. THE MATHEMATICAL ANALYSIS

To model and analyze HomePlug 1.0 systems, we assume as follows: there are n stations having frames for transmission; all stations have frames with the same priority; each station has a frame immediately after the successful completion of a frame transmission; collisions are detected when sending stations do not receive ACK from the destination within a given amount of time.

Under these assumptions, the system can be modeled as a tri-dimensional discrete-time Markov chain $(BPC(t), DC(t), BC(t))$, where $BPC(t)$, $DC(t)$, and $BC(t)$ denote the stochastic processes representing the values of BPC, DC and BC at t, respectively. Let the maximum value of BPC be four. Fig. 2 shows the state transition diagram of the Markov chain in HomePlug 1.0, where p_b denotes the probability that the medium is busy and p denotes the probability that a station transmits a frame but it fails due to a collision.

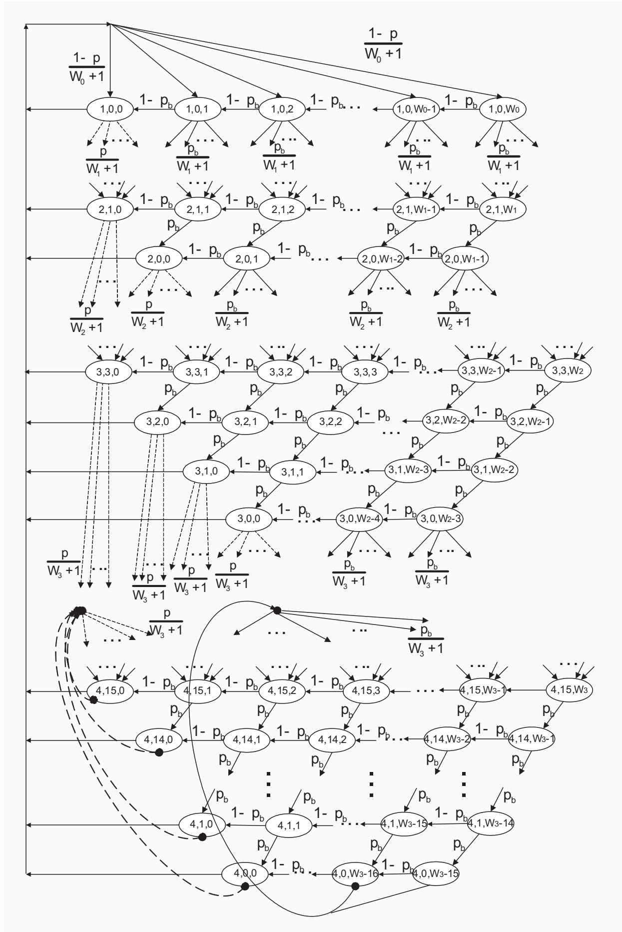

Fig. 2. The state transition diagram of the HomePlug 1.0 system.

The steady state probability $P_{i,j,k}$ that each station stays in state (i,j,k) can be expressed as (1), where W_{i-1} and M_{i-1} denote the size of CW and the maximum value of DC, respectively, at BPC value of i and $p_b = 1-(1-\tau)^{n-1}$ and $p = 1-(1-\tau)^{n-1}$, where τ denotes the probability that a station transmits a frame in a slot.

Since the stations in state $(i,j,0)$ can transmit frames, τ is calculated as

$$\tau = \sum_{i=1}^{4} \sum_{j=0}^{M_{i-1}} P_{i,j,0}. \qquad (2)$$

From (1) and (2), the probability $P_{i,j,k}$ in steady state can be found using a numerical method. To evaluate the performance of the HomePlug 1.0 system, we define MAC saturation throughput as follows:

$$S = \frac{E[Payload]}{E[T_{Req}]}, \qquad (3)$$

where $E[Payload]$ denotes the average payload size of a MAC frame and $E[T_{Req}]$ is the average time required for the

$$P_{i,j,k} = \begin{cases} \frac{(1-p)}{W_0+1}\sum_{h=1}^{4}\sum_{g=0}^{M_{h-1}} P_{h,g,0} & \text{if } i=1,\ j=M_0, \text{ and } k=W_0 \\ \frac{p_b}{W_{i-1}+1}\sum_{h=1}^{W_{i-2}} P_{i-1,0,h} + \frac{p}{W_{i-1}+1}\sum_{g=0}^{M_{i-2}} P_{i-1,g,0} & \text{if } 1<i<4,\ j=M_{i-1}, \text{ and } k=W_{i-1} \\ \frac{p_b}{W_3+1}\{\sum_{h=1}^{W_2} P_{3,0,h} + \sum_{g=1}^{W_3} P_{4,0,g}\} + \frac{p}{W_3+1}\{\sum_{l=0}^{M_2} P_{3,l,0} + \sum_{m=0}^{M_3} P_{4,m,0}\} & \\ & \text{if } i=4,\ j=M_3, \text{ and } k=W_3 \\ \sum_{g=0}^{W_{i-1}-k}(1-p_b)^g P_{i,M_{i-1},W_{i-1}} & \text{if } 1\le i\le 4,\ j=M_{i-1},\ k<W_{i-1} \\ p_b^{M_{i-1}-j} P_{i,M_{i-1},W_{i-1}} & \text{if } 1\le i\le 4,\ j\ne M_{i-1},\ k=W_{i-1}-M_{i-1}+j \\ p_b^{M_{i-1}-j}\sum_{g=0}^{W_{i-1}-k-M_{i-1}+j}\frac{(g+1)\cdots(g+M_{i-1}-j)}{(M_{i-1}-j)!}(1-p_b)^g P_{i,M_{i-1},W_{i-1}} & \\ & \text{if } 1\le i\le 4,\ j\ne M_{i-1},\ k<W_{i-1}-M_{i-1}+j. \end{cases} \quad (1)$$

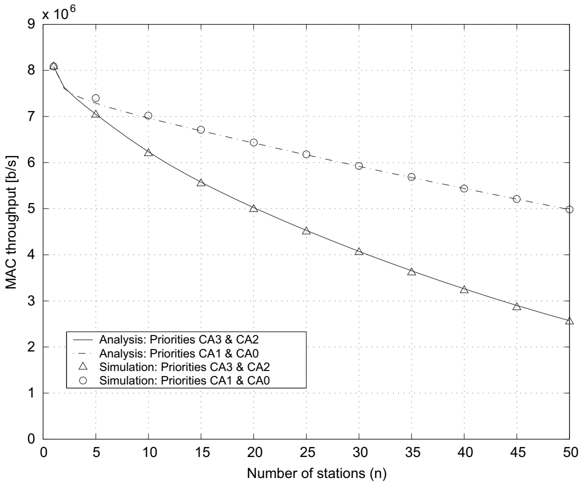

Fig. 3. MAC throughput of HomePlug 1.0.

successful transmission of a frame. $E[T_{Req}]$ can be expressed as

$$E[T_{Req}] = \frac{(1-P_{tr})\sigma + P_{tr}(P_sT_s + (1-P_s)T_c)}{P_sP_{tr}}, \quad (4)$$

where P_{tr} is the probability that at least one station transmits a frame ($P_{tr} = 1-(1-\tau)^n$), P_s is the probability that a station successfully transmits ($P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}}$), T_s is the required time for the successful transmission of a frame ($T_s = PRS0 + PRS1 + T_{fra} + RIFS + T_{res} + CIFS$), and T_c is the wasting time due to the collision of a transmitted frame ($T_c = PRS0 + PRS1 + T_{fra} + CIFS$). And, σ, T_{fra}, and T_{res} denote the duration of an idle slot time, the transmission time of a data frame and its acknowledgment frame, respectively. Finally, replacing the denominator of (3) with (4), the MAC saturation throughput can be obtained as

$$S = \frac{E[Payload]P_sP_{tr}}{(1-P_{tr})\sigma + P_{tr}(P_sT_s + (1-P_s)T_c)}. \quad (5)$$

We consider that the values of CIFS, RIFS, PRS0 and PRS1 are 35.84, 26.0, 35.84, and 35.84 μsec, respectively, and that the duration of an idle slot time σ is 35.84 μsec [4]. In addition, we assume that the size of the payload in a MAC frame is fixed as 1500 Bytes and that the physical channel rate is 14 Mb/s. Then T_{fra} = 1153.5 μsec and T_{res} = 72 μsec [6].

Fig. 3 shows analytic and simulation results of MAC saturation throughput as the number of stations n varies and every frames have the same priority. From the results, the analytic results are very close to the simulation results under the same conditions. As n increases, the MAC throughput decreases, because the probability of collision increases. For a fixed value of n, MAC throughput of the low priority group (CA0 and CA1) is larger than that of the high priority group (CA2 and CA3), since CW of the low priority group is larger than that of the high priority group.

IV. Conclusion

In this letter, we proposed an analytic model of the MAC algorithm in HomePlug 1.0 and evaluated performance. From the analytic and simulation results, the analytic model is shown to be very accurate. In addition, the low priority group demonstrates larger MAC throughput than the high priority group because of larger CW. In general, MAC throughput of the contending stations with the same priority can be improved by increasing the size of CW.

Acknowledgment

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