A Polite Cross-layer Protocol for Contention-based Home Power-line Communications

Aakanksha Chowdhery*, Sumanth Jagannathan*, John M. Cioffi*, Meryem Ouzzif†
*Stanford University, Stanford, CA, USA  †Orange Labs R&D, Lannion, France
achowdhe@stanford.edu, sumanthj@dsl.stanford.edu, cioffi@stanford.edu, meryem.ouzzif@orange-ftgroup.com

Abstract—In typical home power-line communication (PLC) networks using contention-based access methods, providing Quality-of-service (QoS) to high-priority users often comes at the expense of reducing the throughput of low-priority users. This paper proposes a cross-layer protocol which involves interaction between the Physical (PHY) and the Medium-access-control (MAC) layers, for ensuring politeness of the high-priority users toward the low-priority users for uplink transmission in home PLC networks. This protocol modifies the contention-based CSMA protocol of the MAC layer to exploit the cyclostationarity of the noise in home PLC networks. The PLC noise spectrum has been shown in literature to be periodic with the period of AC line cycle. Using this periodicity, the proposed protocol allows longer medium-access times for low-priority users in every AC line cycle, while meeting the high throughput requirements of the high-priority users. The proposed cross-layer protocol, termed Opportunistic CSMA, improves the throughput of the low-priority users by as much as 300% compared to the current CSMA protocols in home PLC networks.

I. INTRODUCTION

Home power-line communication (PLC) networks transmit data over the existing power-line wiring within the home and are a promising alternative for high-quality, multi-stream, entertainment-oriented home networking [1]. Home multimedia applications (HDTV, video-streaming, VoIP etc.) typically require high bandwidths and Quality-of-Service (QoS) support for user satisfaction; for example, HDTV users may require 12-24 Mbps bandwidth, high throughput and stringent delay constraints [2]. Transmission rates of up to 150 Mbps make PLC networks an ideal candidate for the distribution of such home multimedia applications as well as data services. To provide QoS support for the multimedia applications, the MAC layer of the HomePlug AV standard [1] supports a contention-based Carrier-Sense-Multiple-Access (CSMA) protocol that incorporates user priorities. To provide QoS using this CSMA protocol, the users demanding QoS-sensitive applications, such as video-streaming, may be classified as high-priority users, and the users demanding data services, such as web-browsing, may be classified as low-priority users. The high-priority users can be guaranteed high throughputs using such a CSMA protocol with priority.

Several algorithmic variations of the CSMA protocol have been proposed for supporting the QoS constraints of high-priority users and improving the network-throughput in a home network with multiple video users, VoIP, and internet users [3]-[5]. However, the efforts to provide QoS to some high-priority users severely affect the throughput of the low-priority users since most of the resources are allocated to the high-priority users. The collision avoidance algorithm in CSMA protocol has been modified in [3]-[4] to optimize the network-throughput of the HomePlug MAC protocol. The Adaptive Contention Window Increase algorithm [5] achieves the maximum network-throughput while maintaining a throughput difference between priority classes using class-specific optimal contention window size. The algorithms in prior work [3]-[5] have improved the throughput of the high-priority users, but without considering the harm caused to the low-priority users.

For home networks, all applications and services are important without considering the harm caused to the low-priority users. This paper proposes a cross-layer protocol, termed Opportunistic CSMA, for improving the throughput of low-priority users while ensuring high throughput for QoS sensitive high-priority users by exploiting the cyclostationarity of the noise in home PLC networks. Home PLC networks experience cyclostationary noise sources such as the noise generated by electrical appliances connected to the network such as a hair dryer or a light dimmer [6]-[10]. The noise-spectrum is observed to be periodic with the frequency of the power signal (50/60 Hz). The zero-crossings of the AC line cycle typically experience the least noise, while the peaks of the AC line cycle experience the most noise. To provide reliable transmission at all times, a low physical-layer data rate is typically chosen over the entire AC line cycle based on the minimum channel signal-to-noise ratio (SNR), even though the channel SNRs may be significantly better in certain periods. If a higher physical-layer data rate is chosen based on higher value of channel SNR, the transmission may be unreliable when the noise is severe.

The Opportunistic CSMA protocol exploits the cyclostationary nature of the noise by allowing the high-priority users to transmit during the time periods when the channel SNR is high and restricting their access to the medium at other times. Consequently, the high-priority users are allowed to transmit at a higher physical-layer data rate owing to their medium access during higher channel SNR time periods of the AC line cycle. This reduces access time of the high-priority users and provides additional access time to the low-priority users in each AC line cycle, where the access time determines the duration for which the user contends the medium. The additional access time provided by the Opportunistic CSMA protocol thus improves the throughput of low-priority users by as much as 300% while maintaining the throughputs of the high-priority users.
A multi-user multicarrier home PLC network with \( N \) sub-channels and \( U \) users is considered with one transmitter and receiver for each user. Different devices are connected to the power-line network, some of which are user devices and others act as noise sources (Fig. 1). The users are assumed to be synchronized with the power-line cycle, in order to exploit the cyclostationary nature of the power-line channel SNR. Such a model can be applied independently to the uplink and downlink of a home PLC network that employs frequency-division duplexing (FDD). In this paper, only uplink transmission is considered, using bit-loading on 143 tones from 2 to 9 MHz, where the number of tones for uplink is chosen as an example and does not affect the working of the proposed protocol. The protocol works well for any PLC network using FDD to separate uplink and downlink transmission.

The channel transfer function of the connection from each device \( u \) to the gateway on subchannel \( n \) is denoted by \( H^T_{un} \), where the device may be a user or a noise source. For simplicity of notation, we assume that the devices 1 through \( U \) correspond to actual power-line communication devices or users, while the remaining devices \( U + 1 \) through \( U + D \) correspond to different noise sources such as TV, refrigerator, hair-dryer. The number of noise sources is \( D \) for the uplink transmission. The noise variance generated by appliance \( d \) on subchannel \( n \) is \( S^T_{dn} \). The noise sources \( U + 1 \) through \( U + D \) travel through the power-line channel and add at the receiver in the gateway [11]. Assuming that the different noise sources are uncorrelated, the aggregate noise variance at the gateway is

\[
S^T_{tot} = \sum_{d=1}^{D} S^T_{dn} |H^T_{Un+d}|^2. \tag{1}
\]

### III. Algorithms for CSMA Protocol

#### A. CSMA/CA Protocol: Basic Access Method

In a multi-user home PLC network, multiple users share access to the gateway over the same medium using CSMA protocol with Collision Avoidance (CSMA/CA) [1]. Each user contending to transmit a packet senses the channel and gets access to the channel when it is idle. Collision avoidance is achieved using a randomly-chosen backoff Contention Window (CW) before the user starts transmitting, where the value of CW increases exponentially after every collision.

This basic access method of CSMA/CA, which is the same as DCF protocol in IEEE 802.11, does not give priority to any user and is hereafter referred to as Non-PriorityCSMA (NonPrCSMA). There is no waste of resources, such as time or bandwidth, because each user contends only when it has a packet to transmit. However, there is a loss in throughput because of collisions between different users and the waiting times dictated by the random contention periods. It is difficult to provide strict QoS guarantees to high-priority users using NonPrCSMA. Any user having a packet to transmit follows the steps of NonPrCSMA algorithm (Fig. 2), where the AllowedToTransmit() function is always TRUE.

The random backoff algorithm for increasing the CW uses three counters to facilitate its operation: the Backoff Procedure Event Counter (BPC), the Backoff Counter (BC) and the Deferral Counter (DC) [1]. BC keeps track of the random backoff periods. If BC equals zero, the packet transmission attempt will finish in good slots.

The CW is increased by the Backoff Procedure (BPC). NonPrCSMA: If no other high-priority contending. OpCSMA: If high-priority will finish in good slots.

#### B. CSMA protocol with priority classes

The CSMA/CA protocol for Homeplug AV is very similar to CSMA/CA for wireless LAN in IEEE 802.11 [12]. For provision of QoS in HomePlug AV, the user traffic is differentiated into 4 classes: CA0, CA1, CA2 and CA3 in the order of increasing priority. In this paper, the user traffic is classified into 4 classes only: high-priority traffic and low-priority traffic. The higher the priority of the data packet, the earlier it gets to contend for the channel. The CSMA/CA protocol for MAC layer of Homeplug AV uses priority resolution slots or a

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**Fig. 1.** Access to the gateway in a home-PLC network.

**Fig. 2.** Flowchart for Algorithms of the CSMA protocols.
PrCSMA and is hereafter referred to as Priority CSMA (smaller CW for higher priority classes to provide QoS support). When priority resolution slots are used, a low-priority user has to wait until high priority users complete their transmissions (Fig. 2). Alternately, a smaller contention window (CW) can be allocated to the high-priority users when they are contending for the medium to increase the probability that they can access the medium before the low-priority users. In Fig. 2, ChooseCWmin(\cdot) sets a smaller CW for the high-priority user.

C. NonPrCSMA vs. PrCSMA

As the number of users increase in the network, the average throughput of any user remains the same using NonPrCSMA, while the average throughput of high-priority users meets the target throughput, and the average throughput of low-priority users decreases significantly using PrCSMA (Fig. 3), where NonPrCSMA and PrCSMA are discussed in Section III-A and III-B. The simulations consider a network with a single high-priority user and multiple low-priority users. The simulation parameters are the same as those detailed in Section VI. Using NonPrCSMA, a high-priority user with target throughput of 4 Mbps may get only 1 Mbps when there are 8 other low-priority users. PrCSMA, on the other hand, can guarantee 4 Mbps throughput to the high-priority user. However, the penalty in the throughput of low-priority users can be as large as 60%. The average throughput of any low-priority user may decrease from 1 Mbps to 400 kbps in a network using PrCSMA with 1 high-priority user and 8 low-priority users. The performance of the low-priority users must not be penalized so severely to maintain the throughput requirements of the high-priority users.

IV. EXPLOITING CYCLOSTATIONARITY OF PLC

Home PLC networks can exploit the cyclostationary noise characteristics using a cross-layer approach to enhance the performance of the low-priority users while maintaining the throughput requirements of the high-priority users. The major source of noise on the power-line is from electrical appliances connected to the PLC network, which has been confirmed to be cyclostationary in nature ([6]-[10]). The appliance noise is found to be periodic with the AC line cycle because the electrical appliances may turn on/off and may draw power as a function of the AC line cycle. The cyclostationary nature of PLC channel noise may be modeled using a “time mask,” which spans a power-cycle and is multiplied by the PSD of the noise source to give the PLC channel noise. The noise-PSD \( S^n_{\text{tot}} \) described in Section II is actually the stationary PSD for a given time instance. The time mask shows how this PSD varies from one time instant to another within the 20 millisecond power-cycle (50 Hz), and this variation of PSD in time repeats over every power cycle thus capturing the cyclostationarity of the channel. Employing the time mask \( \text{Mask}(t) \), the noise at the Gateway becomes

\[
S^n_{\text{tot}}(t) = \sum_{d=1}^{D} S^n_d(t)|H^n_{U+d}|^2, \quad (2)
\]

where \( S^n_d(t) = S^n_{U} \ast \text{Mask}(t) \). Given the channel transfer functions and the noise at the Gateway, the subchannel signal-to-noise ratio (SNR) of user \( u \) on subchannel \( n \) is expressed as

\[
g^n_u = \frac{|H^n_{U+d}|^2}{S^n_{\text{tot}}}. \quad (3)
\]

The SNR of each subchannel \( n \) exhibits periodicity with AC line cycle because of the cyclostationarity of PLC channel noise. The variation of the subchannel SNR \( g^n_u \) over 20 millisecond power-cycle is shown in Fig. 4. In general, each subchannel can undergo a different variation in SNR over a power-cycle. For simplicity, the time mask is applied equally to all subchannels, i.e., each subchannel decreases or increases in SNR synchronously. However, this model can be easily modified to incorporate a more complicated tonal model for the cyclostationary variation.

The PLC physical layer uses DMT/OFDM modulation for transmission where bit-loading (water-filling) is employed [13]. The physical-layer transmission rate for user \( u \) employing DMT transmission, based on the subchannel SNRs \( g^n_u \), is given by

\[
R_u(t) = \sum_{n=1}^{N} b^n_u(t) = \sum_{n=1}^{N} \beta \left[ \frac{1}{\beta} \log_2 \left( 1 + \frac{\mathcal{E}^{n}_{u} g^n_u}{\Gamma} \right) \right]. \quad (4)
\]

where \( \beta \) is the smallest incremental unit of information that can be transmitted, \( b^n_u \) is the number of bits for user \( u \) on subchannel \( n \), and \( \mathcal{E}^{n}_{u} \) is the energy transmitted on subchannel \( n \). \( \Gamma \) is the SNR gap of the code [13] plus the SNR margin used for protection against unexpected noise, and \( \lfloor \cdot \rfloor \) denotes the rounding down (floor) operation.

To exploit the cyclostationarity of the subchannel SNR, either the physical-layer transmission rate or MAC layer transmission must be a function of the AC line cycle. The physical-layer data rate can be adapted according to the variation in SNR across the AC line cycle if there is sufficient memory and complexity permitted at the modems. For example, the power cycle may be divided into a number of slots, and a bit-loading can be determined for each of these slots [2] to achieve the optimal \( R_u(t) \) as in Eq. (4). However, in practice, the
High-priority users - OpCSMA

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transmission rates, is defined as threshold SNR

The Opportunistic CSMA protocol exploits the cyclostationarity of the noise in home PLC networks for ensuring politeness of the high-priority users toward the low-priority users. This protocol allows the high-priority users to choose a higher physical-layer transmission rate \( R_{\text{thresh}} \) by choosing bit-loading based on the average or median subchannel SNR observed over a time period. If the bit-loading is based on the average or median subchannel SNR observed over a time period, the physical-layer transmission rate constant. This rate is calculated based on a higher level of subchannel SNRs instead of using the worst-case SNRs.

If the bit-loading is based on the average or median subchannel SNR observed over a time period, then it is possible to obtain physical-layer transmission rates higher than the rate when the worst subchannel SNR is used. The higher subchannel SNR, which results in higher physical-layer transmission rates, is defined as threshold SNR \( g^\text{threshold}n \). Table 1 illustrates this by listing the instantaneous data-rate \( R \) as a function of choice of \( g_n \).

- Table 1
  \[
  \begin{array}{cccccc}
  \text{Path # to the gateway} & 1 & 2 & 3 & 4 \\
  \text{\( R_{\text{min}} \) (Mbps) for minimum} g_n & 11.061 & 9.328 & 8.172 & 7.347 \\
  \text{\( R_{\text{med}} \) (Mbps) for median} g_n & 22.288 & 17.913 & 18.896 & 16.510 \\
  \end{array}
  \]

Fig. 4. Variation of SNR over 1 AC line cycle

Fig. 5. Cross-layer Interaction in Opportunistic CSMA.

The bit-loading table based on a threshold subchannel SNR \( g^\text{threshold}n \), which was discussed in Section IV. The high priority access is restricted to the ‘good’ SNR time periods. The low-priority users thus obtain only data access in each AC line cycle, but they must use a physical layer transmission rate \( R_{\text{min}} \) based on the median subchannel SNRs \( g^\text{median}n \). When the high-priority users use bit-loading based on the median subchannel SNR, the division of access times between the high-priority and the low-priority users over an AC line cycle is shown in Fig. 4. The threshold subchannel SNR can be optimally chosen so that high-priority user’s target throughput is achieved. The Opportunistic CSMA protocol thus improves the throughput of the low-priority users by using cross-layer interaction between MAC and PHY layer (Fig. 5) and is hereafter referred to as OpCSMA.

A. The Algorithm for Opportunistic CSMA

The Opportunistic CSMA protocol requires high-priority users to restrict their access at the MAC layer in the ‘bad’ SNR slots. In Fig. 2, all the steps for OpCSMA are same as P-CSMA protocol except for the AllowedToTransmit() function. The AllowedToTransmit() function in OpCSMA returns a TRUE value for CSMA/CA for the high-priority user if the channel SNR is good (above the threshold). For the low-priority users, this function always returns a TRUE value. For simplicity, only two traffic classes have been considered: high-priority and low-priority. However, the algorithm can be easily extended to a larger number of traffic classes using the idea of multiple thresholds.

B. Computing the Gains of Opportunistic CSMA

The MAC layer throughput for each user is defined as the average number of bits transmitted by the user per unit time. This is different from the physical-layer transmission rate, which defines the instantaneous speed at which the bits are transmitted in the physical medium. For random-access protocols like CSMA/CA, the throughput of any user \( u \) is a function of time the user actually accesses the channel, \( T_{\text{access}}(u) \), and physical-layer transmission rate, \( R(u) \). The throughput, \( \eta(u) \), of any user \( u \) can be expressed as

\[
\eta(u) = R(u) \times \frac{T_{\text{access}}(u)}{T_{\text{total}}(u)},
\]

Where \( T_{\text{total}}(u) \) is the total time access to the user.
where $\frac{T_{\text{access}}(u)}{T_{\text{total}}(u)}$ is the fraction of time user $i$ gets access to the channel.

Consider a home PLC network with $N$ low-priority users and 1 high-priority user. For PrCSMA, the same physical layer transmission rate $R_{\text{min}}$ is considered for all the users of Homeplug AV. The access time and throughput for the high-priority user is defined as $T_{\text{HP}}$ and $\eta_{\text{HP}}$, and the access time and throughput for the low-priority user is defined as $T_{\text{LP}}$ and $\eta_{\text{LP}}$. For OpCSMA, the high-priority user transmits at $R_{\text{thresh}}$ and the other users transmit at $R_{\text{min}}$. The medium-access time of the high-priority and low-priority users is defined as $T_{\text{HP,Op}}$ and $T_{\text{LP,Op}}$ percent respectively for OpCSMA. The corresponding throughputs are $\eta_{\text{HP,Op}}$ and $\eta_{\text{LP,Op}}$ respectively.

Suppose a target throughput of $R_{\text{target,HP}}$ is required for meeting QoS of the high-priority user, then both PrCSMA and OpCSMA provide the target throughput to the high-priority user, and this gives $\eta_{\text{HP}} = \eta_{\text{HP,Op}} = R_{\text{target,HP}}$. When the high-priority users use OpCSMA, they lose access time but gain higher physical-layer transmission rate. This results in availability of additional access time for low-priority users. The throughput gain $\eta_{\text{gain,LP}}$ for a low-priority user, because of this additional access time, is given by

$$\eta_{\text{gain,LP}} = \eta_{\text{LP,Op}} - \eta_{\text{LP}} = R_{\text{min}} \times \left( \frac{T_{\text{HP}} - T_{\text{HP,Op}}}{100} \right)$$

$$= R_{\text{min}} \times \left( \frac{\eta_{\text{HP}}}{R_{\text{min}}} - \frac{\eta_{\text{HP,Op}}}{R_{\text{thresh}}} \right). \quad (6)$$

The above computations also allow the gateway to choose optimum threshold SNR $R_{\text{thresh}}$ based on the target throughput for high-priority user and the channel SNR characteristics using Eq. (5).

**VI. SIMULATION RESULTS**

The simulations model the PLC Physical layer (the bit-loading algorithm) in Matlab and the MAC layer in Java. A typical home PLC network is considered with a single high-priority user and an increasing number of low-priority users. For the physical layer, the channel transfer functions are obtained from the measurements provided by the Homeplug Alliance to the ITU G.hn study group [14]. The time mask for modeling the cyclostationarity of the noise is based on Fig. 6(b) in [7] as discussed in Section IV. The minimum physical layer transmission rate is assumed to be 7.2 Mbps for all the users, considering their worst-case subchannel SNRs. For the MAC layer, a single high-priority user is modeled with constant bit-rate (CBR) traffic arrivals, and an increasing number of low-priority users, from 0 to 23, are modeled using Poisson traffic arrivals with a mean inter-arrival time of 3 milliseconds. The packet size is assumed to be 1500 bytes, and the throughput results are averaged over a period of 100 AC line cycles (or 2 sec). The other simulation parameters are summarized in Table II.

Fig. 6 compares the average throughput of low-priority users for NonPrCSMA, PrCSMA, and OpCSMA when the target throughput of the single high-priority user is 4 Mbps. When there are 4 low-priority users in the network, the average throughput of the low-priority user increases from 1.38 Mbps to 2.36 Mbps when OpCSMA is used instead of PrCSMA, and when there are 20 low-priority users, the average throughput of low-priority users increases from 128 kbps to 231 kbps. Thus, a throughput-gain of 80% is achieved for the low-priority users as seen in Fig. 6, while maintaining the 4 Mbps throughput for the high-priority user. The throughput gains, computed using Eq. (6), are same as the throughput gains from simulations if the loss in throughput due to contention is also considered.

As the target throughput for the high-priority user increases from 0 to 12 Mbps, the variation in the average high-priority and low-priority users’ throughput for a network containing 4 low-priority users and 1 high-priority user is shown in Fig. 7. Limited by the contention and physical-layer transmission rates, PrCSMA cannot obtain throughputs above 6 Mbps for the high-priority user. The performance of OpCSMA is compared to PrCSMA for two different SNR thresholds: a median SNR threshold and a SNR threshold corresponding to choosing the 40th percentile of the SNR on each subchannel over the AC line cycle. In both cases, OpCSMA achieves an improvement in the low-priority users’ throughput. When the target throughput of the high-priority user is 4 Mbps, the throughput-improvement for the low-priority user is 80%. However, the median SNR threshold limits the maximum throughput of the high-priority user using PrCSMA to less than 5 Mbps. By lowering the SNR threshold to the 40th percentile level, the throughput of the high-priority user can be increased to the same level as is possible using OpCSMA. At the same time, the gain in low-priority users’ throughput is still very significant, with an improvement of 300% when the target throughput of the high-priority user is 6 Mbps. This figure shows that the threshold SNR can be chosen to span...
the trade-off between achieving a high target throughput for the high-priority user and improving the throughput of the low priority users. For each target throughput for the high priority user, an optimal value for the threshold SNR can be chosen that maximizes the throughput-gain of the low priority users. For example, at the 4 Mbps target throughput, the median SNR (50th percentile) was found to be optimal via simulations.

The throughput-gain of the low-priority users in the proposed OpCSMA protocol depends on the additional access time gained when the high-priority users restrict their access in ‘bad’ SNR periods time. The choice of SNR threshold is based on the high-priority user’s target throughput and the extent of noise-variation across the AC line cycle. For a 22 dB range of noise variation over an AC line cycle (minimum-to-maximum SNR) in Fig. 4, the choice of median subchannel SNR as SNR threshold more than doubles the physical-layer transmission rates, but halves the medium-access time of the high-priority user. This SNR threshold maintains the target throughput of 4 Mbps for high-priority users and gives 50% medium-access time over every AC line cycle to the low-priority users. For a smaller extent of noise variation, i.e. a smaller difference between the minimum and maximum SNR over the AC line cycle, the threshold SNR may be chosen optimally to maintain the trade-off between maintaining high-priority user throughput and improving low-priority user throughput. The proposed system can fall back to using the PrCSMA protocol by simply setting the SNR threshold to the minimum SNR if the extent of noise variation over an AC line cycle is less than 3 dB.

The proposed OpCSMA protocol may incur an additional average delay of half an AC line cycle for the high priority user compared to PrCSMA. This is because over an entire AC line cycle, OpCSMA can achieve the same throughput for the high priority user as PrCSMA. Further modifications to the OpCSMA protocol are possible to ensure that meeting the latency limits of the high priority user is not affected by this extra delay. For example, the OpCSMA protocol may be programmed to fall back to the PrCSMA protocol starting from the last AC line cycle prior to the delay limit. Furthermore, the additional complexity in implementing the Opportunistic CSMA protocol is minimal since the only additional information required by the users is the SNR threshold, which is determined by the gateway based on the traffic scenario.

VII. CONCLUSIONS

A cross-layer approach was presented for ensuring politeness of the high-priority users toward the high-priority users in contention-based home PLC networks. The proposed Opportunistic CSMA protocol exploits the cyclostationarity of the noise in PLC networks to provide as much as 300% improvement in the average throughput of the low-priority users compared to the existing PrCSMA protocol while maintaining the high throughput of the high-priority users. The complexity in implementing the Opportunistic CSMA protocol over the existing protocol is minimal. Using the algorithms proposed in this paper, home network users can enjoy good internet uplink speeds, even if video conferencing or VoIP services are being used, thus enhancing the aggregate user experience.

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