Periodic Contention-Free Multiple Access For Broadband Multimedia Powerline Communication Networks

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Abstract— **There is industrial intent to use Powerline Communication (PLC) networks in the home for delivery of multimedia data, with associated challenging quality of service (QoS) requirements. Existing protocols for PLC, for wireless networks, or even for wired networks cannot meet these challenges efficiently. This paper proposes and analyzes a new protocol designed to provide the high QoS needed for delivery of multiple multimedia streams in a PLC environment.**

The proposed protocol, Periodic Contention-Free Multiple Access(PCF/MA), directly addresses the issues of asymmetric communication channel, hidden nodes and near-far effects. The proposed PCF/MA performance is analyzed theoretically and its performance is simulated. The results show that 85Mbps MAC throughput is possible with 100Mbps channel data rate, even when there are hidden nodes in the network. Through mathematical modeling and software simulation for tight bandwidth allocation, such a network can deliver up to 9 MPEG-2 video streams simultaneously without dropping any video frames, compared to 7 video streams using MCSMA/CA (Modified CSMA/CA).

Keywords- Power Line Communication, Reservation, Multimedia Applications, TDMA, CSMA/CA, PCF/MA, Hidden Node, Near-Far Effect Modified CSMA/CA(MCSMA/CA).

I. INTRODUCTION

Recently, broadband communication over Power Line Communication (PLC) networks have attracted much interest in academe and industry, not requires no new wires), but also because almost all electrical devices have to connect to a power outlet eventually. PLC networks make the smart home possible [1].

However, PLC technology is still evolving and many issues remain unsolved. The hostile environment of PLC channels makes reliable data transmission difficult. Much effort is required to ensure data transmission is correct and efficient. The *HomePlug Alliance* has set standards for 14 Mbps class data transmission, namely the HomePlug 1.0 standard. This resulted in a variety of PLC devices for computer-oriented network communications. The performance and reliability of HomePlug 1.0 is comparable to wireless networks using the IEEE 802.11b standard [2]. However, the *HomePlug 1.0* protocol is not suitable for video playback because of its limited network throughput and lack of sufficiently stringent quality of service constraints.

To support multimedia streaming for homes, the *HomePlug Alliance* is now developing the standard for a second generation of PLC devices capable of delivering multiple HDTV streams using newly designed chipsets adhering to the *HomePlug AV* standard, which supports raw data rates up to 200 Mbps. The goal of *HomePlug AV* is to enable PLC devices to deliver some two hours of HDTV video without video frame drops, while simultaneously delivering one or more other data streams of various data rates and traffic types. To achieve the above mentioned goals requires highly efficient and reliable medium access, allowing guaranteed latency and packet loss rate. The efficient cooperation of high speed PLC PHY and MAC protocols becomes important, a feature notably absent from current existing MAC protocols, and are therefore not suitable for *HomePlug AV*.

From our study, we found PLC channels have some unique characteristics:

1. Devices on PLC channel tend to be stationary.

2. PLC network channels tend to be stationary.

3. From network topology point of view, it remains stationary like an ordinary fixed network.

PLC network nodes and channels tend to be stationary [2]. Although channels may be affected by proximate electronic devices for a short period, channel adaptation and power line channel characteristics make the channel remain stationary over long periods. This makes reservation requirements reasonably predictable. Our study also shows that the PLC channel has similar noise characteristics to a wireless network though, from a network topology point of view, it remains stationary like an ordinary fixed network (e.g., Ethernet network).

PLC channels share some characteristics with wireless channels - both of them face hidden node problems, near-far effects and other channel imperfections. However, channel conditions are more severe in PLC channels. To conquer noisy channels, OFDM modulation is used and a tone map is tailored for each new conversation between two devices. PLC channels are asymmetric, which limit the utility of popular hidden node solutions like RTS/CTS.

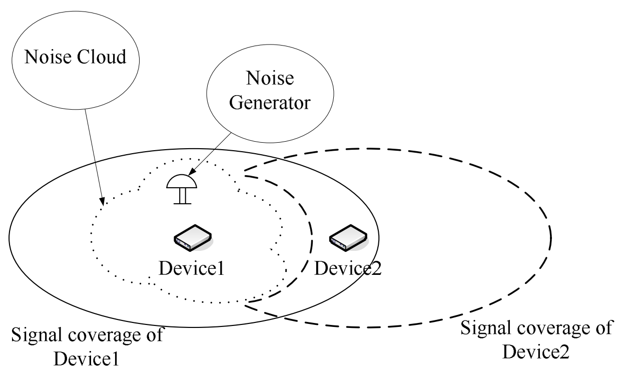

Figure 1. Asymmetric PLC channel caused by nearby noise generator

The asymmetric PLC channel also affects usable protocols that can be used to solve hidden node problems. For example, the RTS/CTS scheme assumes that the communication channel is symmetric such that the virtual carrier sense can be received on all near-by devices.

It is unlikely that simply applying protocols designed for another medium would result in good performance in the PLC environment; the overhead may be too high or the assumptions about noise may be too optimistic for PLC networks.

In the light of PLC's unique characteristics, we propose a new protocol - Periodic Contention-Free Multiple Access (PCF/MA). PCF/MA is an explicit R-ALOHA-like protocol specifically designed for the PLC network - we propose an RTS/CTS-like scheme in the reservation stage to prevent hidden node problems, and a delayed NACK mechanism to conquer the nearfar effect. The reservation can be a persistent reservation (to reduce competition in the reservation stage) or MAC protocol data unit (MPDU) based reservation (to provide flexibility).

Performance of the proposed protocol is evaluated by event driven computer simulation and by mathematical analysis. The simulation results show that 85 Mbps MAC throughput under 100 Mbps channel data rate can be obtained, even when there are hidden nodes in the network. To provide smooth video delivery, we propose a mathematical estimation of the required delay in playback time and the amount of playback buffer with tight bandwidth reservation.

Our simulation shows that an 100Mbps channel can deliver up to 9 MPEG-2 video streams simultaneously without dropping any video frames, however, using a Modified CSMA/CA(MCSMA/CA) in the same environment supports only 7 video streams because of its unfairness, unpredictable behaviors and high overhead.

This paper is organized as follows. A brief survey of existing protocols and the proposed protocol is given in section 2, which is shortened here for lack of space. Section 3 discusses the *PCF/MA* methodology, analysis, performance evaluation and simulation results. The discussion and conclusion are given in section 4.

II. EXISTING PROTOCOLS

Packet contention techniques such as Carrier-Sense Multiple-Access with Collision-Avoidance (CSMA/CA) and ALOHA find widespread use in data communications, including the first generation PLC networks. While they function with little to no coordination, contention results in unpredictable behavior such as unfairness and possibly long delays, which make them unsuitable for delay-sensitive packet delivery.

To solve these problems, one can use packet scheduling or reservation-based methods. Implicit reservations like Packet Reservation Packet Reservation Multiple Access (PRMA) and is a centralized and 'Five-Phase Reservation Protocol" [5] and similar protocols fail to address the issues mentioned above, which makes them unsuitable for high speed PLC.

We propose a new protocol based on an explicit reservation scheme. Robert's reservation scheme and R-TDMA are good candidates; their merit is that a few slots are dedicated for reservation purpose and the rest of them are for data transmission. However, these schemes lack distributed control, hidden-node prevention, and ignore near-far effects, which makes them inappropriate for PLC networks.

Though the power line channel is similar to a wireless channel, there are some unique characteristics specific to the power line channel. Firstly, the characteristics of the PLC channel in a home are in general steady over time rather than dramatically changing as in the wireless channel, i.e., while the attenuation of the signal may be affected by near-by electronics in the short term, from a long term point of view the attenuation is almost stationary [3]. This makes long-term bandwidth scheduling possible. Secondly, the devices in PLC networks are quasi-stationary, i.e., the stations in the PLC network are not constantly moving as are devices in a wireless network, thus the bandwidth fluctuations are much less erratic From our experience, the wireless channel may vary violently because of moving while PLC remains unchanged for a period of time [2]. These two characteristics place PLC networks in a spectrum between Ethernet networks and wireless networks in that they have the properties of a fixed network topology but with much more noise and attenuation.

The asymmetric channel also makes hidden node problems more severe. The devices that cannot hear the RTS/CTS can still affect the on going transmissions. In Fig.2 we depicted one of the common situations in PLC channel.

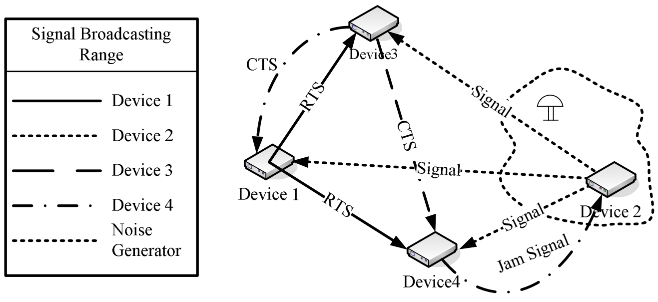

Figure 2. RTS/CTS exchange in an asymmetric PLC network

Although the situation described in Fig.2 is not common, once there is a hidden node in a house, there is always a hidden node since PLC networks has a semi-fixed topology. Without proper solution to the asymmetric PLC channel, most of the devices may fail to response.

Meanwhile, delivering delay-sensitive data streams like HD-Video requires predictable MAC behavior, and contention-based protocols require more effort than contention-free/reservation-based protocols in order to provide the same functionality.

To summarize the above considerations, we propose a new protocol - PCF/MA, as stated below.

III. PROPOSED PCF/MA PROTOCOL

The PCF/MA protocol is a distributed, contention-free protocol that uses a two-way handshake reservation process to establish TDMA slot assignments. The reservation process for a given node only involves nodes within a one hop radius.

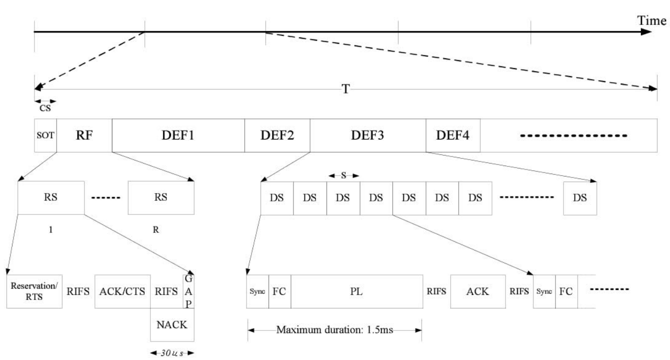

Figure 3. PCF/MA Frame Structure

Fig 3 shows the protocol's frame structure. Time is divided into several TDMA sessions with duration of $T\ \mu s$. Each session is partitioned into a Reservation Frame (RF) and one or more Data Exchange Frame (DEF). Before the RF is a Start of TDMA (SOT) frame issued by all stations on the network that lasts 38.4 μs.[1]

A. Reservation Process

The RF is divided into $R\psi$Reservation Slots (RS). An RS slot serves as a period of time for making a reservation. In each RS, nodes may exchange Reservation Packets (RPs) and ACKs. An RP contains the Source Address (SA), Destination Address (DA), Starting reserved Slot number (SS) and Total reserved Slots (TS) as depicted in Fig. 4.

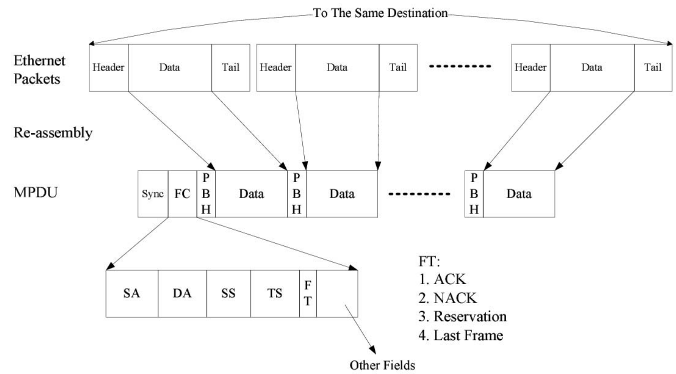

Figure 4. MPDU Process and Format

If a node wants to reserve a DEF, it first listens to the network for at least one TDMA Period. During this period, it monitors network activity and learns the reservations of each station. When the RF begins, it randomly chooses an RS and broadcasts an RP. The destination receives and compares the request with its internal table. If the reservation does not conflict with previous known reservations, the node sends an ACK to the transmitter and completes the reservation process. Other stations in the network also listen and broadcast a NACK signal to jam the possible ACK signal if they detect a conflict. If a collision/NACK happens, the requester waits for next reservation opportunity.

By using a sort of RTS/CTS only in the reservation stage, and with universal veto power, the effects of PLC channel asymmetry are reduced. While internal tables of reservations may not be consistent, this does not matter until a node attempts to reserve some time. At this point, the nodes that know about the conflict inform the offending node using the NACK or delayed NACK mechanism. Use of the delayed NACK approach eliminates the near-far problem for the reservation confirmation.

The data exchange period is divided into $N\psi$data slots (DSs), each with duration of $S\psi\mu s$. A DEF is composed of several DSs. The length of a DEF is decided by the TS field in owner's RP. A DEF always begins at the start of a DS.

If a node successfully reserves a period of time for transmission, it listens and waits until its DEF time (synchronized by the SOT), then starts to transmit *MAC Protocol Data Units (MPDUs)*. If the receiver receives a successful MPDU, it will send an ACK. The sender can continue until the end of its reserved DEF, always leaving sufficient time for the response.

At the end of a transmission, the sender broadcasts a "Last Frame" MPDU to the network. The receiver also broadcasts a "Last Frame" MPDU to mitigate possible hidden node problems and to allow all nodes to update their tables. When a station ungracefully terminates its connection, affected stations (usually the receiver) also broadcast a "Last Frame" MPDU

[1] *The parameters we used in this paper follow those of HomePlug 1.0 as published in [7]*

during the reserved slots to synchronize tables with other stations.

MPDUs combine several Ethernet packets belonging to the same path into a jumbo packet to increase overall efficiency. The original Ethernet packet header and trailer is removed and a new small header called "PHY Block Header" (PBH) containing the sequence number of the original packet is added to indicate the order of the packet. After this process, the original Ethernet packet becomes a new block called a *PHY Block* (PB). The process is depicted in Fig. 4.

Several PBs are then combined into a jumbo packet with a common header to become an MPDU ready for transmission. Based on the current transmission speed, as many Ethernet packets as possible are combined until transmission duration reaches $1.5ms$.

IV. Approximate Performance Analysis and Simulation Results

To calculate the maximum throughput, we assume there are always data to send for each node. We define efficiency as the ratio of time spent on transmitting payload to the total time spent on the whole data exchange process.

The reservation slot time can be obtained by adding a RP duration, two RIFS, an ACK duration and a $4\mu s$ gap which leads to $(72+26+72+26+4)\ \mu s = 200\mu s$. A successful packet transmission requires an MPDU, an ACK and two RIFSs. The total time required for this process is $1624\mu s$ when sender sends a maximum length MPDU. The total DAE slots in a TDMA session can be calculated by $\left\lfloor \frac{T-200R-29}{s} \right\rfloor$ assuming R reservation slots. If there are m transmitters, and the bandwidth is evenly distributed to all transmitters, then a transmitter can have b slots, where

$$b = \frac{\left\lfloor \frac{T-200R-29}{s} \right\rfloor}{m}$$

The total time allowed for transmitting each data stream can be calculated by $b*s$. Since the maximum MPDU has duration of $1.5ms$ and the overhead of a MPDU is $72\mu s$ and there are m nodes, the protocol efficiency E can be calculated by

$$E = \frac{\left\lfloor \frac{\left\lfloor \frac{T-200R-29}{s} \right\rfloor s}{1624m} \right\rfloor 1428m}{T} \tag{1}$$

If we ignore the *floor*($\lfloor\ \rfloor$) operation in Eq. 1, we can obtain the maximum efficiency E_{max} as follows:

$$E_{\max} = 88\% \tag{2}$$

One must note that each DEF starts from the beginning of a DS; if a node does not fully utilize the reserved DS, the efficiency will decrease.

To minimize fixed overhead, a small R is desirable, which may be reasonable since reservations are persistent. However, a small R could make the system unstable when the number of contenders increases.

Lack of space precludes the derivation, but we obtain the desired probability as

$$1-\frac{p}{P} = 1-\frac{n!\sum_{l=0}^{r}\frac{1}{l!}(-1)^{(n-1)}\binom{r}{n-l}(r-(n-l))^{l}}{r^{n}} \tag{3}$$

To verify formula 3, we simulated a constant number of contenders. The simulator simulates one million reservation sessions, and the number of contenders is the same from session to session. The simulator counts the times that at least one contender successfully makes its reservation, which is the condition needed to avoid instability. The simulation results are shown in Fig. 5. From the simulation results, we chose $r = 8$ as a conservative parameter for PCF/MA.

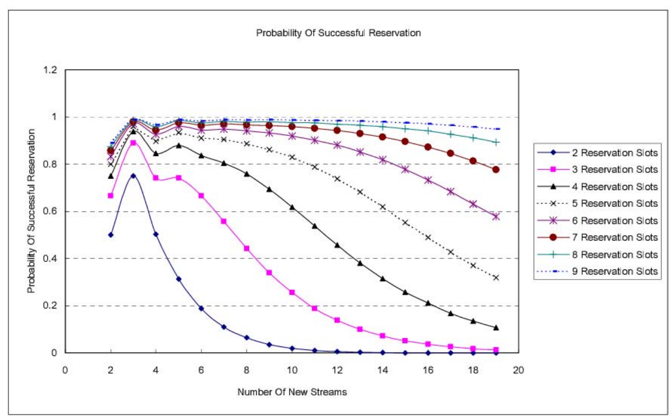

Figure 5. Probability Of Successful Reservation

For comparison, we also modified the CSMA/CA protocol used in 802.11b to a version suitable for PLC. The Modified CSMA/CA (MCSMA/CA) uses the same reservation procedure as in PCF/MA for each MPDU, with MPDU duration limited to 1.5ms.

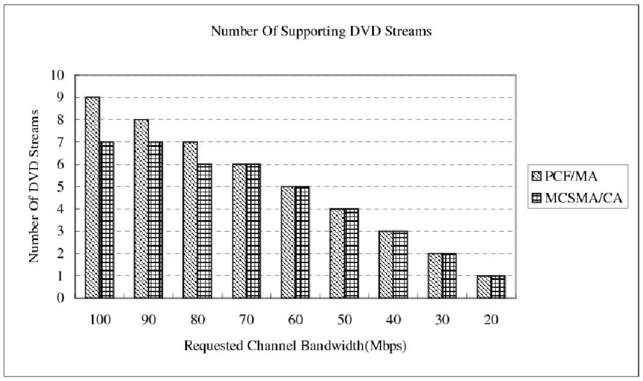

Figure 6. Video Playback Performance Comparisons

An event-driven simulator with *Always On* data streams was used to investigate PCF/MA performance and to compare PCF/MA with MCSMA/CA. The simulation results show that without competition, the MCSMA/CA performs slightly better than PCF/MA (though at worse efficiency). When simulating several DVD streams on the same PLC network, PCF/MA outperforms MCSMA/CA by 28% when the network loading is high (demanded channel bandwidth is higher than 70 Mbps on a 100 Mbps PLC network) as depicted on Fig.6. However, when the network loading is low (demanded channel bandwidth is less than 70 Mbps), the PCF/MA has the same or slightly better performance than MCSMA/CA.

V. CONCLUSION

This paper proposes a new protocol - PCF/MA for high speed PLC networks. To lower overhead caused by contention between MPDUs, we choose a contention-free method. Through simulation, we observed the network efficiency as high as 85% at $T\psi=$ 100. Theoretical analysis found that with eight reservation slots, it can provide a good contention/overhead balance. We also conducted a simulation with constant contenders that verified our analysis. For comparison purposes, we modified the widely used CSMA/CA protocol into a PLC version MCSMA/CA protocol. The simulation results show that PCF/MA protocol has a performance gain of as much as 100% over MCSMA/CA when the $T\psi=$ 100. Our protocol also proved to be able to support more than 200 streams at the same time.

Though the PCF/MA protocol proved to be a high performance protocol, there is much work to be done. Currently, we do not implement priority classes and treat the incoming queue length of the PCF/MA protocol as unlimited. We will address these issues in future publications.

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