Cross-Layer Designs of Multicarrier NC-PRMA Systems over Powerlines

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Abstract − **We study the performance of Non-Collision Packet Reservation Multiple Access (NC-PRMA) scheme as a MAC protocol for powerline communication networks. A PHY-MAC cross layer design is considered in order to provide Quality of Service (QoS) guarantees for integrated voice, data and video services. System performance is evaluated via simulations in terms of packet dropping probability and mean access delay.**

Keywords − **Cross-layer design, Multiple access, Non-Collision PRMA, powerline networks**

I. INTRODUCTION

Cross-layer protocol designs have recently been studied as an attractive method that can deliver considerable performance improvement in comparison with traditional designs, where each layer in the protocol stack is designed and operated independently. It is an emerging research area, allowing direct communication and information sharing between protocols in adjacent and non-adjacent layers. The exchanged information in cross-layer designs can be about Channel State Information (CSI), estimation of the channel impulse response, signal strength, interference level, physical layer resources such as number of antennas, spatial processing, Quality of Service (QoS) such as throughput, delay, Packet Error Rate (PER) measurement, Bit Error Rate (BER).

In case of wireless networks, collaborative design between the Physical (PHY) and the Medium Access Control (MAC) layer has been analyzed in the literature [1,2]. The PHY layer is responsible for the actual transmission of information bits between the nodes that should communicate. It also controls the rate and power level of transmission. The fundamental unit is bit. The MAC layer is the lower sub-layer of the Data Link layer. It specifies access protocols and it is responsible for allocating bandwidth to users. The fundamental unit is packet. In traditional designs there is a clear frontier between the MAC and the PHY layers and thus, there is no interaction between these two layers. However, in order to design a good MAC protocol, the PHY layer

characteristics are important since data are transmitted in packets, which comprise a series of bits. Thus, incorrect data transmission has an influence on the performance of MAC and higher network layers.

Although separation between PHY and MAC layers is also extremely difficult in case of powerline networks, there are not any proposed PHY-MAC cross-layer schemes in the existing literature to the best of the authors' knowledge. There is strong interaction actually between MAC and PHY layer [3] and thus the efficient cooperation of high speed PLC PHY and MAC protocols becomes important, a feature currently absent from existing MAC protocols [4]. In this paper a "PHY-aware" MAC protocol for powerline networks is proposed, which integrates voice, data and video services and utilizes information provided by the physical layer in order to assign slots to the users. The simulation results show that a satisfactory performance can be achieved by the synergy between physical and MAC layers in a multimedia communication environment.

The paper is organized as follows. The system under study is described in the next section. In Section III the proposed cross-layer cooperation scheme is depicted in detail. In Section IV the simulation results are presented and discussed. Finally, Section V concludes the paper.

II. SYSTEM MODEL

A. MAC Protocol

Networks using reservation MAC protocols are suitable for carrying hybrid traffic (mix of traffic types caused by various services) with variable transmission rates [5]. Moreover, reservation protocols allow realization of various QoS guarantees and ensure near-full network utilization. In case of reservation protocols, the transmission is controlled by a central unit (base station), which is also favourable for realization of an efficient fault management as PLC networks are disturbed by different noise sources.

Packet Reservation Multiple Access (PRMA) is a centralized MAC protocol. It can be viewed as a combination of Time Division Multiple Access (TDMA) and slotted ALOHA protocols and combines random access and reservations. A collision may occur if more than one terminal has permission to send packets in the same available slot. As

the traffic becomes heavily loaded, the PRMA protocol suffers serious performance degradation due to packet collisions.

Several variations of PRMA have been proposed to enhance the performance of the original PRMA protocol. The Non-Collision Packet Reservation Multiple Access (NC-PRMA) protocol is known to be able to transmit packets without any collision. In NC-PRMA, time slots are organized in frames as in PRMA. The difference between PRMA and NC-PRMA is that each frame in NC-PRMA contains also one control slot [6]. The control slot is situated at the beginning of each frame and is further divided into control minislots. Whenever a user has packets to transmit, it sends a request in its own control minislot and in this way collisions are avoided. The base station (BS) has an opportunity to schedule multiple requests received from different users for various services in accordance with the required QoS. Thus, the BS can have a centralized control over the slot allocation policy. If there are idle information slots, the base station assigns randomly an idle slot to the user. In case of voice traffic, users can hold the reservation of a slot until they send every packet of the current spurt in that slot. For non-real time traffic, we assume that the users can hold the reservation of a slot until they finish with the transmission of the arrived packets. Then the slot is released and users send again their requests to the BS when they have a new packet arrival. If there are not any available slots, the contention procedure is repeated as follows: voice users can lose packets if the maximum packet lifetime elapses, so the contention is repeated with the next packet of the talkspurt. On the contrary, data users send a request for a packet until they gain a reservation.

B. Traffic Models

"Triple Play" is a new challenge in powerline communications. Triple Play services consist of voice, data and video and have different requirements in bandwidth, latency, jitter and packet loss. For voice it is important to ensure very low delays since it is the most critical traffic class. For streaming traffic class such as video, a near to continuous video stream is needed.

The voice traffic model can be described as a two state Markov chain, where exponentially distributed talkspurts alternate with exponentially distributed silent gaps. The mean duration of talkspurts is $T_t=1$ sec and for silent gaps $T_g=1.35$ sec [7].

For data packets, the interarrival time and the packet size are geometrically distributed random variables according to simple traffic models described in [8]. We consider a frequent requests scenario, where the mean length of packets is equal to 300 bytes and the mean interarrival time is equal to 0.96 sec.

For the video traffic model, it is assumed that video users create a new packet in every slot according to a Bernoulli experiment with parameter 0.9 [9]. This could be considered a rather simplistic model for video traffic, but our main intention is to examine how the presence of three different traffic scenarios affects the proposed system assuming simple traffic models.

The maximum packet holding time D_{max} is the maximum waiting time for voice packets and is determined by delay constraints on speech communication. When waiting time exceeds D_{max}, the terminal drops the packet and it continues to contend for reservation to send subsequent packets [10]. For delay insensitive services, such as non-real time data packets, there are no severe limits on delay constraints and data packets are never dropped at the MAC, i.e. a negligible dropping probability [7] is assumed.

C. Physical Layer

Power lines provide a hostile environment for communication signals. Orthogonal Frequency Division Multiplexing (OFDM) is very resilient when a communication link suffers from great delay spread [11]. Delay spread is a major problem over power lines [12].

In [13-14] the results of a great measurements campaign are presented. The delay spread is found to be 1.66μsec. In the literature the delay spread fluctuates between 10nsec and 10 μsec. Hence, the channels measured in [13-14] can be considered as severe channels in terms of delay spread.

After the delay spread is determined, the Guard time is set to four times the delay spread i.e. 6.64μsec. The resulted symbol duration is 33.2 μsec and 512 subcarriers are used to transmit data. Each carrier is loaded with bits adaptively in accordance with the channel signal to noise ratio, using a bit loading algorithm [15]. However, flat energy distribution over the subcarriers is used [16].

Obviously, the transmitter must be aware of the channel conditions in order to distribute bits and power to the subcarriers. This implies that several pilot symbols are transmitted on the communications link in order to estimate the subchannels condition. On one hand this is vital for the design of efficient systems, but on the other hand the pilots introduce an extra data load to the system. Thus, a compromise has to be made.

III. CROSS-LAYER COOPERATION SCHEME

Research on cross-layer design involves several research areas such as signal processing, adaptive coding and modulation, channel modelling, traffic modelling, queuing theory, network protocol design and optimization techniques. Channel-aware scheduling strategies are proposed to adaptively transmit data and dynamically assign resources based on CSI. The key idea is to choose these users with better channel conditions in order to transmit packets and thus to ensure a higher performance.

In a typical triple play powerline communications environment three QoS's are required; Voice, data and video. Each has its own probability of error P_{error} demand. Nevertheless, power transmission cannot exceed certain levels imposed by [17] in the frequency region from 1-30MHz. The appropriate amount of power transmission that ensures the probability of error demand depends on the channel conditions between transmitter and receiver, i.e. transfer function conditions and noise level.

The proposed cooperation scheme is rather simple. PHY layer should provide MAC layer with a particular power level in accordance with the individual user's conditions based on measurements and with P_{error} demands. Then MAC decides whether a slot should be assigned to a specific user or the user should wait until the channel conditions are improved and lower transmission power level is needed. The amount of free slots is computed at the beginning of each frame, while the slot allocation procedure takes into account the type of service that each user has to deliver. The MAC allocates slots first to video users since these users have the highest priority. Then, a portion of the free slots can be occupied by contending voice users and the rest by contending data users.

A. Description of the scheme

A powerline communications link between two outlets results in a specific transfer function shape. The power transmission needed to fulfil a certain bit rate on condition that the P_{error} is less than a predetermined level can be easily estimated by using the formulas proposed in [18]. We recall them here for quick reference.

Let K be the number of potential users. Assume that an OFDM system consists of N parallel subcarriers. Each subcarrier is modulated to transmit $R_{k,i}$ bits (k is the user and i is the subcarrier index) and suffers by fading that is different from subchannel to subchannel. Let use the notation $H_{k,i}(f_i)$ to express the subchannel's amplitude and phase influence on the i_{th} subcarrier for the k_{th} user. The parameter $g_{k,i}$ is going to be used often in the remainder of the paper and it expresses the channel to noise ratio at the i_{th} subchannel for the k_{th} user. In fact it summarizes the channel gain and the noise effect per subchannel.

The subchannel to noise ratios are independent from each other as the channel's coherence bandwidth is considered to be smaller than the subcarrier spacing. Moreover, perfect channel estimation is assumed and channel variations are slow and followed accurately by the channel equalizer.

In [18] it is proven that an adaptive OFDM system having $P_{error,k}$=constant, $\forall i \in [1,N]$ aiming to transmit $R_{T,k}$ bits per OFDM symbol needs total transmitting energy equal to $P_{T,k}$ that is given by the following equation:

$$P_{T,k} = \left[2^{\frac{R_{T,k}^{(3)}}{N}} - (\prod_{l=1}^{N} g_{k,l})^{1/N} \cdot \frac{1}{N} \sum_{i=1}^{N} \frac{1}{g_{k,i}} \right] \frac{N \cdot [Q^{-1}(P_{error,k}/4)]^2}{3(\prod_{l=1}^{N} g_{k,l})^{\frac{1}{N}}} \quad (1)$$

The $g_{k,i}(f_i)$, $\forall k \in [1,K]$ and $\forall i \in [1,N]$ originates from measurements.

Using the measured data for fixed total data rate and probability of error (certain requirements for the triple play over PLC) P_T is determined and hence after flat energy distribution $P_{k,i}$ is calculated.

The energy distribution levels for all potential users and for the three error rates are provided to the MAC layer. According to CISPR (Comité International Spécial des Perturbations Radioélectriques) two particular maximum power levels exist in the frequency region of interest: $-104,71dB$ (mW/Hz) for the band 500kHz up to 5MHz and $-100,71dB$ (mW/Hz) for the band 5-30MHz. Users that need to transmit a greater amount of power than the CISPR levels are not allowed to transmit and they should wait for better channel conditions. These power level limits are also in accordance with the Federal Communications Commission (FCC) standard for conducted emissions from Class B information technology equipment [8]. To the best of the authors' knowledge, the CISPR levels are taken into account in a cross-layer design for the first time.

New channel conditions occur for example when a topological change takes place. In general, devices are connected and disconnected from the powerline network frequently, thus changing the network topology. The powerline channel is considered to be quasi-static, so the PHY layer measures the $g_{k,i}(f_i)$ at fixed periods of frames. That means that if a user is not allowed to transmit due to bad channel conditions, then its state will change when a topological change occurs and is detected in a subsequent period of channel measurements.

IV. PERFORMANCE ANALYSIS AND SIMULATIONS RESULTS

In this section, simulation results are presented and discussed. We performed extensive computer simulations in order to evaluate the performance of the proposed scheme. Different traffic scenarios with variable number of voice and data users are considered and the effect of video traffic on system performance is investigated as well.

The system performance is examined in terms of the packet dropping probability P_{drop} for the voice users and of the mean access delay for the data users. Packet dropping probability is defined as the ratio of the number of packets dropped to the total number of packets generated in the simulation run [5]. Speech distortion due to a 1% packet drop is rarely audible and, hence, a packet dropping probability $P_{drop}<0.01$ is considered to be an acceptable level [6]. The mean access delay is defined as the time interval between a new transmission request and the time when a reservation is obtained [7].

It is assumed that each frame contains 20 information slots and that the slot duration is $T_S=10^{-4}$ sec. Based on typical multimedia QoS requirements, we assume that the maximum voice packet lifetime is equal to $D_{max}=10$msec. It is also considered that each OFDM symbol carries from 100 to 200 bits, so the data rate can vary from 3 to 6 Mbps.

In Fig.1 the packet dropping probability for voice users is presented as a function of the number of voice users
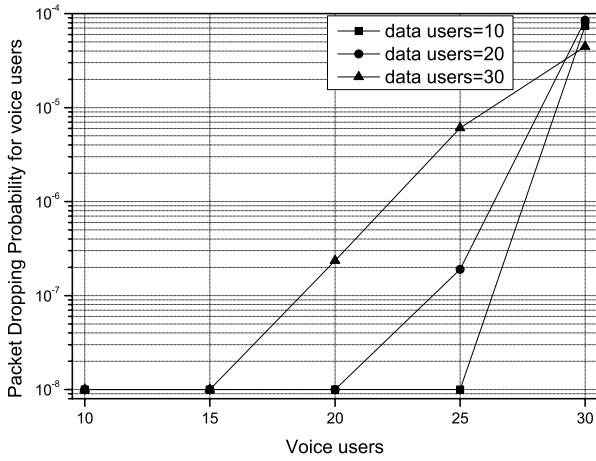
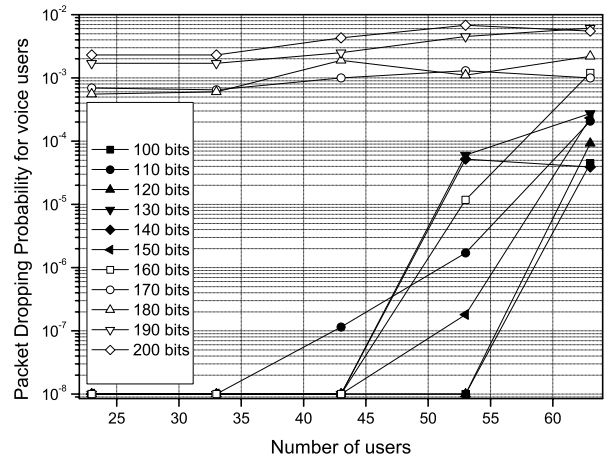Fig.1. Packet Dropping Probability as a function of the voice users parameterized by the number of data users.

Fig.2. Packet Dropping Probability for voice users as a function of the overall number of users parameterized by the number of bits per OFDM symbol.

and different number of data users. The bits per OFDM symbol are equal to 100 and the total number of users is the sum of voice, data and the 3 video users. It can be observed that for constant number of voice users and as the data users increase, the probability that a voice packet will be dropped increases as well in a prospective manner, since the contention procedure becomes harder. Similar behaviour can also be observed for higher data rates.

Fig. 2 presents the packet dropping probability with respect to the overall number of users for the three types of services and for different number of bits per OFDM symbol, i.e. variable data rates. A fixed number of 3 video users is considered in all cases, while the amount of voice users is the same with data users. It can be seen that packet dropping probability deteriorates as the number of users and the number of bits per OFDM symbol increase. However, P_{drop} is always

less than 0.01, which is the maximum acceptable level for voice packet dropping rate.

Fig. 3 and 4 show the mean access delay with respect to the overall number of users for the three types of services and different number of bits per OFDM symbol. The number of video users is again constant and equal to 3 and the amount of voice users is the same with data users. It can be observed that the delay increases when the number of bits per OFDM symbol is more than 150, even if the traffic is low. This is reasonable since more bits per OFDM symbol (higher data rates) can result in deterioration of error probability. In this case, more transmission power is needed in order a user to achieve the required QoS (BER), but this is not allowed by the upper transmission power limit stated by CISPR. Thus, users cannot make a reservation and have to wait until their channel conditions become better, causing in this way higher delays.
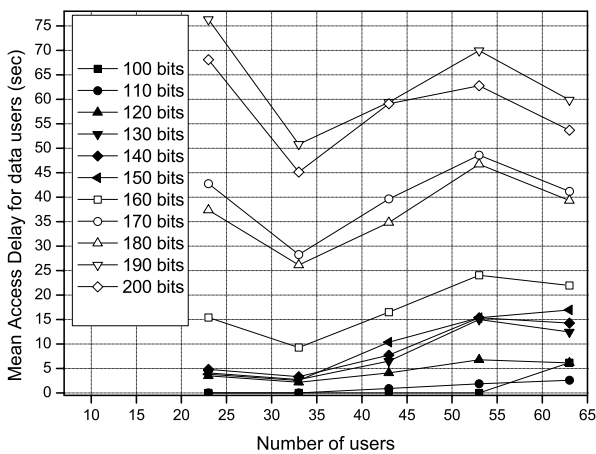

Fig.3 Mean Access Delay for data users as a function of the overall number of users parameterized by the number of bits per OFDM symbol.
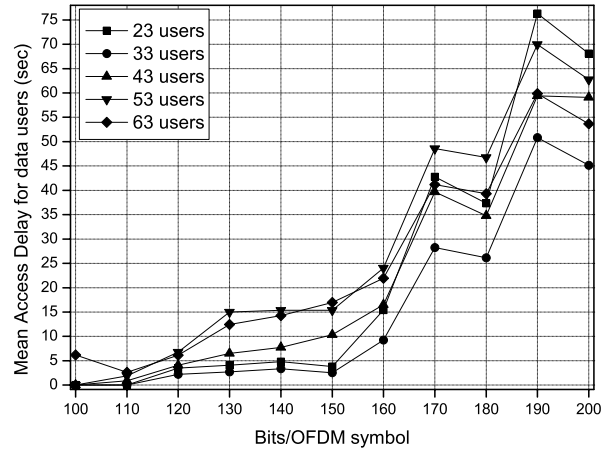

Fig.4. Mean Access Delay for data users as a function of the number of bits per OFDM symbol parameterized by the overall number of users.
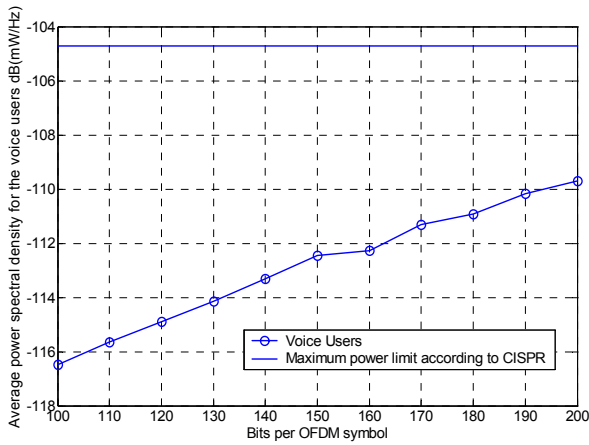
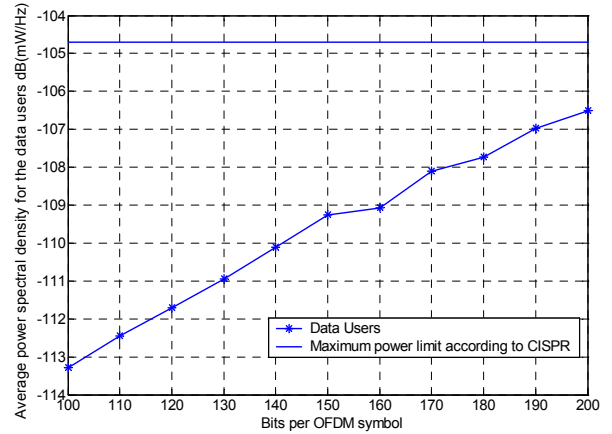Fig. 5. Average transmission power for the voice users and for several data loads.

Fig. 6. Average transmission power for the data users and for several data loads.

Fig. 7 Average transmission power for the video users and for several data loads.

Consequently, there is a tradeoff between data rate and mean access delay.

In figures 5, 6 and 7 the average transmission power is presented for the voice users, the data users and the video users respectively. The CISPR maximum acceptable power level is also presented in the same plot for comparison. The average power is extracted by equation (1) on actual channels. It can be seen that for the specific data loads all users fulfil the power limit on average. The system assures that the Perror of 10^{-3}, 10^{-6} and 10^{-9} are satisfied in all cases for voice, data and video services correspondingly. Moreover, it can be observed that the lowest the probability of error the greater the average transmission power is. Nevertheless, power is kept under the legislation limit. If there was no cross-layer cooperation then arbitrary transmission power would result in CISPR violation.

V. CONCLUSIONS

In this work a cross-layer cooperative design for powerlines is proposed, where the MAC layer exploits information from the PHY layer in order to improve the slot allocation procedure and in this manner to provide reliable services for voice, data and video users. Although there is a lot of further study to be done in the field of cross-layer design for powerline communication networks, the simulation results show that the proposed PHY-MAC cross-layer scheme can be a promising and flexible technique for powerline networks, since it ensures QoS for multimedia services while keeping the transmission power in accordance with the current legislation limits.

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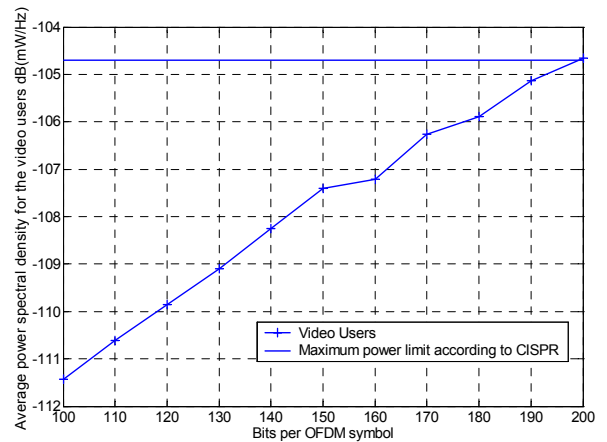[2] Vincent K. N. Lau and Yu-Kwong Kwok, "On the Synergy Between Adaptive Physical Layer and Multiple-Access Control for Integrated Voice and Data Services in a Cellular Wireless Network," IEEE Transactions on Vehicular Technology, Vol. 51, No. 6, Nov. 2002.
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