Optimal Time Slot Design in an OFDM-TDMA System over Power-Line Time-Variant Channels

Andrea M. Tonello(1), José Antonio Cortés(2), and Salvatore D'Alessandro(3)
(1,3)DIEGM – Università di Udine, Udine – Italy, e-mail: tonello@uniud.it – salvatore.dalessandro@uniud.it
(2) Departamento de Ingeniería de Comunicaciones – ETSIT – Universidad de Málaga – Spain, e-mail:jaca@ic.uma.es

Abstract—**This paper analyzes the resource allocation problem in an indoor PLC system with a physical (PHY) layer based on OFDM and a medium access control (MAC) scheme with contention and adaptive TDMA regions, similar to the one of the HomePlug AV specification. In particular, this work focuses in the optimization of the TDMA region. By taking into account both the cyclostationary noise and the cyclic variations of the channel response, the optimal time slot duration in a multi-user scenario is determined for various amounts of overhead required by the PHY layer. Hence, the presented results can be used in practical systems to perform a fast real-time time slot length selection and scheduling as a function of the number of active users.**

Keywords—PLC, OFDM, MAC, TDMA,Resource allocation.

I. Introduction

Power line communication (PLC) is becoming one of the most important technologies to enable the in-home delivery of data and multimedia contents. The use of PLC devices allows telecom operators to offer triple play services, which combine telephony, television and Internet access.

PLC channels are frequency selective and time variant. Measurements have shown that they can be modeled as a linear periodically time varying (LPTV) filter with also the presence of additive cyclostationary colored noise [1],[2].

In order to mitigate the frequency selectivity of the channel, the state-of-the-art-systems employ orthogonal frequency division multiplexing (OFDM) as the modulation technique. An attractive feature of OFDM is that it allows practical implementation of the water filling principle by allocating the power across the sub-channels affected by different attenuations due to the channel frequency selectivity.

The quality of service (QoS) required by multimedia contents can be fulfilled with the use of a Hybrid MAC scheme as the one employed in HomePlug AV (HPAV) [3]. HPAV uses a persistent time division multiple access (TDMA) scheme to satisfy the QoS based traffic. While, the best effort traffic is served in a non persistent scheduled region or is left for a contention based region.

Nevertheless, in order to improve the overall PLC system performance, a cross-layer optimization between the physical and the medium access control layers has to be considered. This issue has been previously studied in [4], where the influence of the time slot duration in the performance of an HPAV "like" system is investigated. The differences between our work and the one presented in [4] are the following:

- we take into account the channel response variations, which cause intercarrier and intersymbol interference in the OFDM signal, and not only the cyclostationary noise behavior.
- we provide the optimum time slot duration for different overhead lengths.
- we perform the optimization in a multiuser scenario.
- we propose and evaluate a practical resource allocation procedure using linear programming (LP).

In this paper, we consider a hybrid MAC technique consisting of contention free and contention based regions like the one employed in HPAV. For the contention free region, we propose an algorithm based on LP that allows the computation of the optimal time slot duration and the optimization of the time slots scheduling among the users.

The organization of the paper is as follows. In Section II we describe the PHY layer employed in our simulations. Then, in Section III we present the hybrid MAC model and in Section IV the multi-user resource allocation problem is formulated. However, since this problem is not always solvable, a simplified optimization problem is proposed in Section V. Section VI reports the simulations results and finally in Section **Error! Reference source not found.** the conclusions follow.

II. PHY Layer Description

The PHY layer is based on multicarrier transmission using OFDM with M tones, and a cyclic prefix (CP) length of μ samples. The OFDM symbol duration is equal to $T_0 = NT$ where T is the sampling period and $N = M + \mu$. The channel model consists of an LPTV filter plus additive cyclostationary noise, both obtained with the simulator described in [5]. Denoting by $g_{ch}(nT;iT)$ the channel impulse response at time instant nT to an impulse applied iT time instants before, the received signal can be written as

$$y(nT) = \sum_{i=0}^{L_g-1} x(nT-iT)g_{ch}(nT;iT)+\eta(nT), \qquad (1)$$

where $L_g T$ is the impulse response length, $x(nT)$ is the OFDM transmitted signal, and $\eta(nT)$ is the cyclostationary additive noise. Both, the channel response and the cyclostationary noise have the periodicity of the mains signal (20 ms in Europe).

At the receiver, after symbol synchronization, the CP is discarded and an M-point DFT is computed. The k-th sub-channel output can be written as

$$z^{(k)}\left(\ell T\right) = H^{(k)}(\ell T_0)a^{(k)}\left(\ell T_0\right) + I^{(k)}(\ell T_0) + W^{(k)}(\ell T_0) \quad (2)$$

where $a^{(k)}(\ell T_0)$ is the $\ell - th$ data symbol transmitted on that sub-channel, $H^{(k)}(\ell T_0)$ is the channel frequency response, $W^{(k)}(\ell T_0)$ is the noise contribution and $I^{(k)}(\ell T_0)$ is the intersymbol interference (ISI) plus intercarrier interference (ICI) term. It must be emphasized that these distortion terms arise because of the loss of orthogonality due to both the insufficient CP and to the channel time variations. The latter effect has been traditionally neglected in PLC [4].

In an OFDM system impaired by Gaussian noise and with neither ISI nor ICI, the receiver determines the bit load of each tone from its signal-to-noise ratio (SNR) [8]. Provided that the number of tones is sufficiently high (M>128), the ISI and ICI can be assumed to have a Gaussian distribution. Hence, the bit load can be obtained with the procedure in [8] just by substituting the SNR by a new magnitude that includes the power of the interference term, and that will be referred to as signal-to-noise-plus-interference ratio (SINR). Considering that transmissions are synchronized with the mains and that L OFDM symbols can be fitted into each mains cycle, the symbol index ℓ can be written as $\ell = m + Lr$, where $0 \le m \le L-1$ and $-\infty < r < \infty$. Assuming that all the constellation symbols have the same energy, the power of all the terms in (2) is periodical and the SINR experienced in the k-th sub-channel at the m-th time instant can then be expressed as

$$SINR^{(k)}(mT_0) = \frac{P_U^{(k)}(mT_0)}{P_W^{(k)}(mT_0) + P_I^{(k)}(mT_0)} \quad (3)$$

where

$$P_U^{(k)}(mT_0) = \left|H^{(k)}(mT_0)\right|^2 E\left[\left|a^{(k)}\left(mT_0\right)\right|^2\right]$$

$$P_I^{(k)}(mT_0) = E\left[\left|I^{(k)}\left(mT_0\right)\right|^2\right] \; P_W^{(k)}(mT_0) = E\left[\left|W^{(k)}\left(mT_0\right)\right|^2\right] \quad (4)$$

The receiver estimates the sub-channel SINR during the training phase via reception of known training symbols that are periodically sent by the transmitter. The estimate can be refined or updated using a data decision directed mode during data transmission [6].

III. HYBRID MAC MODEL

We consider a hybrid MAC protocol that uses contention free and contention based regions, similarly to the one employed in HPAV [3]. It can support both the connection oriented traffic and the best effort traffic. Services that require high QoS can be offered using a contention free MAC technique based on TDMA, while best effort traffic can be offered using a contention based scheme as carrier sense multiple access with collision avoidance (CSMA/CA). Similarly to HPAV, we assume to have a node in the network that acts as a central coordinator (CCo). The CCo is responsible to allocate resources by collecting information regarding the network state, i.e., number of users, channel conditions, QoS required from each user request, etc. Once the CCo has collected all the information needed, it dynamically allocates the resources among the users.

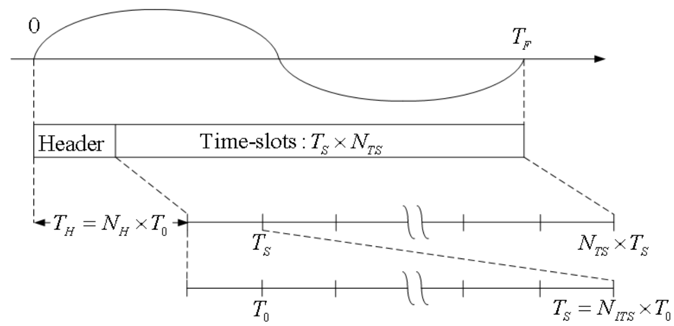


Fig. 1. Frame structure.

We assume the MAC frame to have duration T_F equal to a mains cycle, i.e., $T_F = 20ms$. Fig. 1 depicts the frame structure. The MAC frame is divided into two regions. In the first region, referred to as TDMA sub-frame, centralized TDMA is used. Its duration, T_{TDMA}, depends on the quantity of pending QoS based traffic, and can be expressed as $T_{TDMA} = N_{TDMA}^{MC} T_F$, where N_{TDMA}^{MC} represents an integer number of MAC frames. The TDMA sub-frame comprises a header followed by a number of slots. The header and the slots have a duration equal to an integer number of OFDM symbols duration, i.e., they are equal to $T_H = N_H T_0$, and $T_S = N_{ITS} T_0$.

The MAC frame header carries the following information:

- Time slots duration.
- Scheduling for the time slots. The scheduling is a correspondence between each slot index and the physical address of the node at which that slot has been reserved.
- Number of mains cycles where scheduling is valid.

Each slot carries also some overhead (OH) information that is used by the PHY layer for synchronization and channel estimation algorithms. We assume several scheduling algorithms each comprising a given slot format with a different amount of OH. This is discussed in Section IV.B.

A. Example of Parameters

As an example, we assume transmission parameters similar to the ones used by HPAV. The transmission band is in 0-37.5 MHz with OFDM having 1536 tones. The useful tones are 1066, yielding a useful band in 2-28 MHz. The cyclic prefix duration is equal 6.32 µs. Therefore, the OFDM symbol duration is 47.28 µs. The signal is transmitted with a power spectral density of -50 dBm/Hz.

For simplicity we assume that the contention region is not used. Hence, the number of OFDM symbols in the TDMA sub-frame is equal to 423. We assume a header consisting of 3

OFDM symbols. This results in 420 useful OFDM symbols. The slot duration can vary between a minimum of one OFDM symbol, up to 105 OFDM symbols for a number of nodes (users) N_U equal to 4. If N_U equals 3 then the maximum slot length equals 140 OFDM symbols, while if N_U equals 2 the maximum slot length is 210 OFDM symbols.

IV. MAC PROCEDURES

Before transmission can start, it is necessary to perform resource allocation and scheduling. We focus on the transmission between the CCo and the N_U nodes and, in particular, in the downlink. This can be viewed for example as the scenario where the CCo distributes data coming from internet, e.g., video streaming to different televisions.

Fig. 2 shows the network considered in this work. The uplink and the peer-to-peer connection among nodes can work in a similar way.

The MAC protocol consists of three phases that we refer to as: network state learning, resource allocation, and data exchange. The two first steps have to be performed whenever a new node enters the network or the QoS required by an existing one cannot be fulfilled with the current allocation, e.g. because of a significant channel variation has occurred.

A. Network State Learning

In this phase the CCo learns the network state, e.g., the links condition between it and the nodes, the QoS required by the applications and so on. To accomplish it, the CCo sends training sequences to the users, e.g., the CCo sends known training OFDM symbols modulated using 4-QAM in each carrier. All users estimate the SINR that they experience in each carrier and OFDM symbol in the TDMA sub-frame. Once estimation of the SINR between the CCo and the nodes is accomplished, the nodes can compute bit-loading for all these symbols. The bit-loading map is denoted with $b^{(u,k)}(mT_0)$, and it provides the number of bits that can be transmitted in the $k-th$ carrier to the $u-th$ user if the CCo transmits during the $m-th$ OFDM symbol of the MAC frame.

The bit-loading map is fed back to the CCo by the nodes. It is worth noting that due to the fact that the channel is LPTV with period equal to the mains cycle, each user has to send only the information regarding a mains cycle, i.e., $b^{(u,k)}(mT_0)$ $m=0,...,L-1$. The bit map is computed as follows

$$b^{(u,k)}(mT_0)=\log_2\left(1+\frac{SINR^{(u,k)}(mT_0)}{\Gamma}\right), \quad (5)$$

where $SINR^{(u,k)}(mT_0)$ is the SINR experienced by the $u-th$ user in the $k-th$ carrier during the $m-th$ OFDM symbol of a MAC frame and Γ is the gap factor that takes into account practical coding/modulation constraints [7]-[8]. In our simulations we fix $\Gamma = 9\text{dB}$. The values of $b^{(u,k)}(mT_0)$ are rounded to the nearest constellation available, which in this work are constrained to 2-PAM, 4, 8, 16, 64, 256 and 1024-QAM. Hence, only 3 bits are needed for the bit-loading map of each carrier of an OFDM symbol. Since only 1066 tones are switched on, each user has to send feedback consisting of $3\times1066\times423 \simeq 1.36\text{Mbit}$. By using 4-QAM constellations this requires 319 OFDM symbols, which occupies 75.4% of a MAC frame.

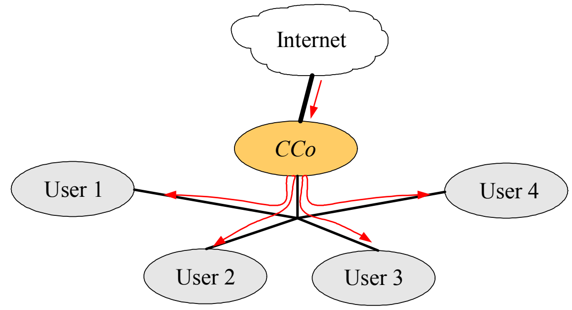


Fig. 2: Network scenario considered in this work.

B. Resource Allocation and Scheduling

Once the CCo has received the bit-loading map from the nodes, it is able to determine the resource allocation and scheduling. We point out that the bit-loading information per OFDM symbol is only required by the CCo to perform the time slot duration optimization. If a fixed time slot length is employed, only the bit-loading map per time slot is needed. This may significantly decreases the amount of feedback information. Moreover, when the CCo has just to compute the slots allocation between the network users, e.g., when a peer to peer communication occurs, it only needs to know the achievable rate $R^{(u)}(mT_0)$ from/to the $u-th$ user during the $m-th$ OFDM symbol of the MAC frame. Clearly, this information is computed using many mains cycles.

As said in Section III, we consider four different scheduling procedures for which a different amount of PHY OH is spent in a slot.

Procedure A. The slot can have length equal to one symbol and each OFDM symbol uses 10% of the number of carriers for OH. In this case, the throughput reached by the CCo for a transmission to the $u-th$ user during the $s-th$ time slot is equal to

$$R_s^{(u)}(N_{ITS})=\frac{N_{ITS}}{T_F}\sum_{k\in K_{ON}}\hat{b}_s^{(u,k)}, \quad (6)$$

where

$$\begin{aligned}\hat{b}_s^{(u,k)} &= \min_m\left\{b^{(u,k)}(sN_{ITS}T_0+mT_0)\right\},\\ s&=0,1,...,N_{TS}-1 \;\; m=0,1,...,N_{ITS}-1,\end{aligned} \quad (7)$$

and K_{ON} is the set of carriers indices employed to transmit useful data (it does not include the ones employed for the overhead). It is worth noting that (7) implies the bit-loading to be invariant in each time slot.

Procedure B. A full OFDM symbol is spent as PHY OH. This choice was described in [9]. In this case we may send in the PHY header the bit map as in HPAV is done. Hence, if the CCo transmits to the *u*-th user during the *s*-th time slot, the throughput is equal to

$$R_s^{(u)}\left(N_{ITS}\right)=\begin{cases}\dfrac{N_{ITS}-1}{T_F}\sum\limits_{k\in K_{ON}}\hat{b}_s^{(u,k)} & N_{ITS}>1 \\ 0 & otherwise\end{cases}, \qquad (8)$$

where K_{ON} indicates the set of used tone indices

Procedure C. As in *Procedure A* but the PHY OH is equal to 10% of the first OFDM symbol in each time slot.

Procedure D. In this case, no PHY OH is present. It is here considered to obtain an upper bound in the performance.

Once the CCo has computed the rate that it would achieve transmitting to each user in each time slot $R_s^{(u)}\left(N_{ITS}\right)$, it has to allocate the slots among the users and, moreover, it has to compute the optimal time slot length. The problem can be viewed as an optimization problem that can be expressed as

$$\max_{\alpha,N_{ITS}}\sum_{u=1}^{N_U}\sum_{s=0}^{N_{TS}-1}\alpha^{(u,s)}R_s^{(u)}\left(N_{ITS}\right)$$

$$\text{subject to}\sum_{u=1}^{N_U}\alpha^{(u,s)}=1,\quad s=0,...,N_{TS}-1,\text{ and} \qquad (9)$$

$$\sum_{s=0}^{N_{TS}-1}\alpha^{(u,s)}R_s^{(u)}\left(N_{ITS}\right)\geq\frac{p^{(u)}}{100}\sum_{s=0}^{N_{TS}-1}R_s^{(u)}\left(N_{ITS}\right),\ u=1,...,N_U$$

where the $\alpha^{(u,s)}$ denote the binary coefficients equal to 1 if slot s is allocated to user *u*, and zero otherwise. $p^{(u)}$ is a weighting factor that denotes the percentage of data rate that the $u-th$ user has to achieve with respect to the one that it would achieve in the corresponding single user scenario. The problem (9) can be solved using integer programming (IP) once N_{ITS} is fixed.

It should be noted that the procedures A-C above are characterized by a different amount of OH. Therefore, they may have an impact on the robustness of the PHY algorithms that dynamically update synchronization and channel estimation. Nevertheless, according to a previous work [6], the considered OH appears to be sufficient. Clearly, procedure C uses the largest OH which however is not required for the PHY algorithms. Further, the transmission in this OH of the bit map from the CCo to the nodes is not necessary since the receiving nodes are already aware of it. Nevertheless, the HPAV system appears to resend the bit map [9].

V. Simplified Optimization Problem

In some cases, IP is not able to provide a solution to (9) in a reasonable computation time. Moreover, it may also happen that the problem is not solvable satisfying the constraints imposed. In these circumstances, some constraints can be iteratively relaxed until IP gives a solution to the problem. Nevertheless, the problem may still be unsolvable in a reasonable time. To simplify the complexity the use of linear programming (LP), once N_{ITS} is fixed, is proposed [10]. That is, for each value of N_{ITS} the coefficients that give the slots allocation are returned via LP followed by rounding the $\alpha^{(u,s)}$ coefficients. The optimal time slot computation can be done computing (9) varying the time slot length, i.e., the number N_{ITS}^{opt} that maximizes the aggregate rate.

It is interesting to note that in some cases the LP followed by rounding the coefficients $\alpha^{(u,s)}$ could give a solution to (9) that doesn't allow all users to transmit. This can happen when the number of time slots that maximizes the aggregate rate N_{ITS}^{opt} is comparable to N_U. To solve this problem the following greedy algorithm can be used:

i. Once N_{ITS}^{opt} has been computed using LP followed by rounding the coefficients, compute $R^{(u)}\left(N_{ITS}^{opt}\right)=\sum_{s=0}^{N_{TS}-1}R_s^{(u)}\left(N_{ITS}^{opt}\right)$ for each user. If for some users $R^{(u)}\left(N_{ITS}^{opt}\right)$ is zero, then decrease N_{ITS}^{opt}.

ii. If N_{ITS}^{opt} is equal to the minimum slot size, then decrease $p^{(u)}$ of one and solve (9) again. Otherwise, go to step i.

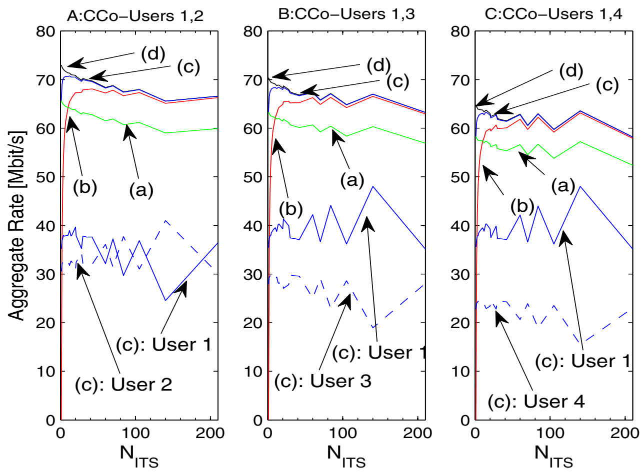
VI. Numerical Results

In this Section we present the simulations results obtained with the solution of (9) using the simplified algorithm based on LP described in Section V. The simulated network is the one showed in Fig. 2, where the data exchange occurs from the CCo to 2, 3 or 4 users. All the combinations CCo-users are considered.

Fig. 3 and Fig. 4 show the aggregate rate for the two-users case obtained using the scheduling procedures described in Section IV.B. It also shows the achieved rate by each user for the scheduling *Procedure C*. Fig. 5 and Fig. 6 show the results for the three and four-users case.

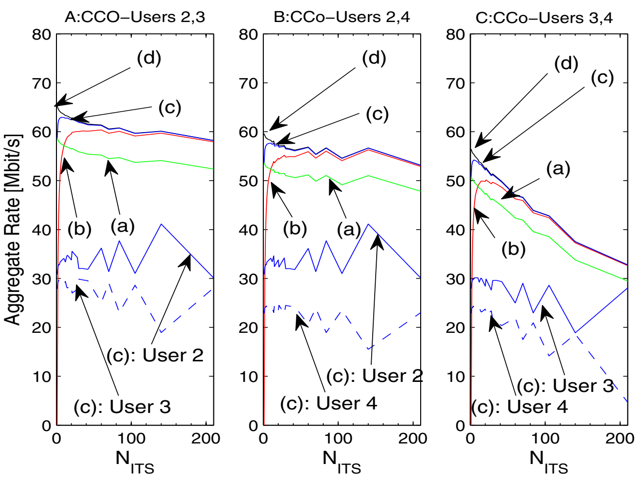
As we can see, the optimal slot duration is always equal to 1 OFDM symbol for the scheduling procedures *A* and *D*. These results are easily explained by noticing that enlarging the time slot always decreases the amount of raw bits transmitted, i.e., without taking into account the OH. This is due to the employed bit-loading procedure presented in (7), which does not adapt the constellation size to the channel changes that may occur during the time slot. Since in procedure *D* there is no OH, increasing the time slot always reduces the bit-rate. In procedure *A* this reduction is even greater because the amount of OH increases proportionately to the time slot duration. It is also worth noting that the performance loss of procedure *B* and, especially *C*, with respect to *D* is quite reduced.

In procedures *B* and *C* a fixed amount of OH per time slot is introduced. Hence, increasing the time slot length reduces the raw bit-rate but, on the other hand, it increases the transmission efficiency, since the percentage of introduced OH decreases. Therefore, the aggregate rate is, in general, a convex function of the slot duration. Clearly, the optimum



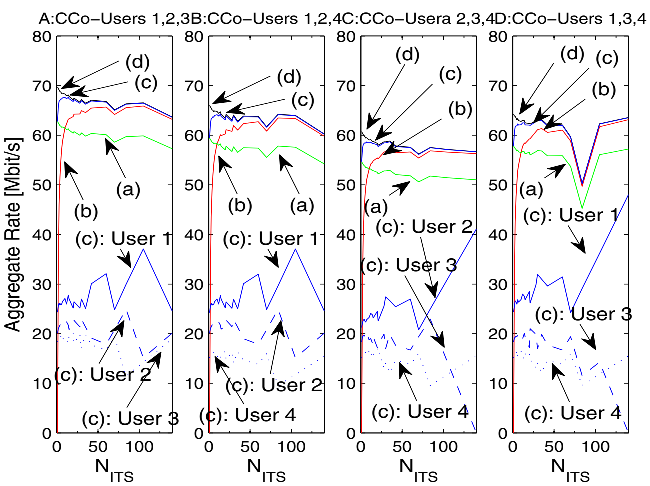
(a): *Procedure A*, (b): *Procedure B*, (c): *Procedure C*, (d): *Procedure D*.

Fig. 3. **Two users scenario**: Aggregate rates for the 4 scheduling *Procedures* and single user rates for the *Procedure C*.



(a): *Procedure A*, (b): *Procedure B*, (c): *Procedure C*, (d): *Procedure D*.

Fig. 4. **Two users scenario**: Aggregate rates for the 4 scheduling *Procedures* and single user rates for the *Procedure C*.

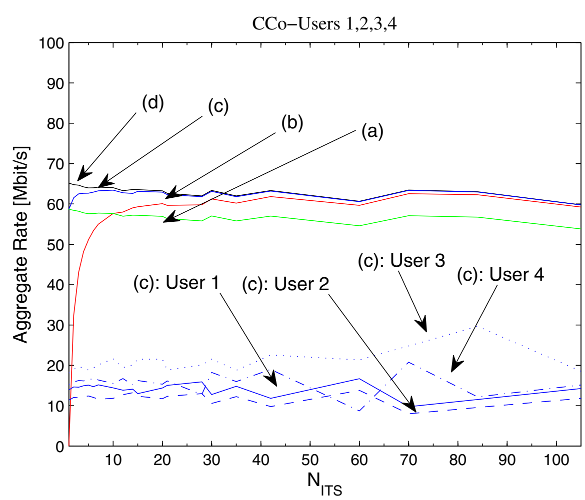


(a): *Procedure A*, (b): *Procedure B*, (c): *Procedure C*, (d): *Procedure D*.

Fig. 5. **Three users scenario**: Aggregate rates for the 4 scheduling *Procedures* and single user rates for the *Procedure C*.

time slot duration depends on the rapidity by which the channel and the noise vary. An example can be observed by comparing results in Fig. 4.A and in Fig. 4.C. In the former one, the characteristics of the involved channels change quite slowly. Hence, the bit-rate loss that occurs because of selecting a longer time slot than the optimum one is quite small. On the other hand, channels involved in the scenario of Fig. 4.C exhibit fast time variations, which leads to a severe performance degradation when the time slot duration is increased over its optimum value.

Table I and Table II list the optimal time slot duration when using procedures *B* and *C,* which are the ones with practical interest, in all the considered scenarios. It can be seen that the optimum values are strongly dependent on the time variation of the involved channels. However, the quite-flat behavior of the aggregate bit-rate curves in Fig. 3 to Fig. 6 indicates that the performance loss that occurs when a fixed time slot duration is employed in all the scenarios is small. This can be corroborated by computing the aggregate bit-rate loss that occurs in each scenario when a non-optimal time slot duration is employed. Fig. 7 and Fig. 8 depict these curves for the two-users and the three-users scenario (the four-users scenario gives similar values). It can be noticed that, in general, 50 OFDM symbols could be a trade-off time slot value when using procedure *B* and 10 OFDM symbols when using procedure *C*. These lenghts lead to aggregate bit-rate loss values smaller than 5%. In practice this loss could be much smaller (it could even be a gain), since employing a fixed time slot length considerably reduces the amount of signaling that the nodes have to transmit to the CCo, as mentioned in Section IV.B.



(a): *Procedure A*, (b): *Procedure B*, (c): *Procedure C*, (d): *Procedure D*.

Fig. 6. **Four users scenario**: Aggregate rates for the 4 scheduling *Procedures* and single user rates for the *Procedure C*.

VII. CONCLUSIONS

This paper has studied the resource allocation problem in an indoor PLC system with a physical layer based on OFDM and a medium access control scheme with an adaptive TDMA region. The presented results have been obtained by taking into account both the cyclostationary noise and the cyclic behavior of the channel response. The optimum time slot duration has been determined in a multi-user scenario for three practical scheduling procedures with different amount of PHY layer OH. It has been shown that although the optimum time slot length is strongly dependent on the speed of the channel time variations, reasonable trade-off values can be selected. The use of these trade-off values avoids the need for computing the optimum time slot in each particular situation, which considerably reduces the amount of feedback information.

Table I. Optimal time slot duration in number of OFDM symbols obtained in the 2-users scenario using *Procedures B* and *C*.

	2-Users Scenario					
	1-2	**1-3**	**1-4**	**2-3**	**2-4**	**3-4**
Proc. B	42	140	140	60	140	21
Proc. C	12	14	140	7	10	5

Table II. Optimal time slot duration in number of OFDM symbols obtained in the 3-users and 4-users scenarios using *Procedures B* and *C*.

	3-Users Scenario				**4-Users Scenario**
	1-2-3	**1-2-4**	**2-3-4**	**1-3-4**	**1-2-3-4**
Proc. B	105	84	35	140	70
Proc. C	14	14	35	140	10

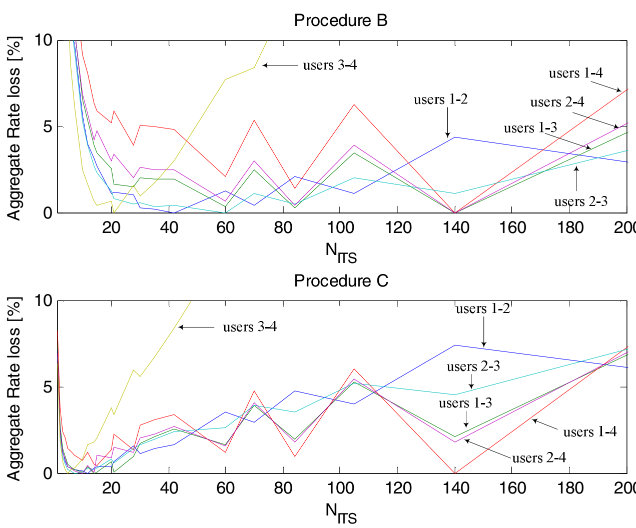


Fig. 7. Aggregate bit-rate loss for the two-users scenario with *Procedure B* and *Procedure C*.

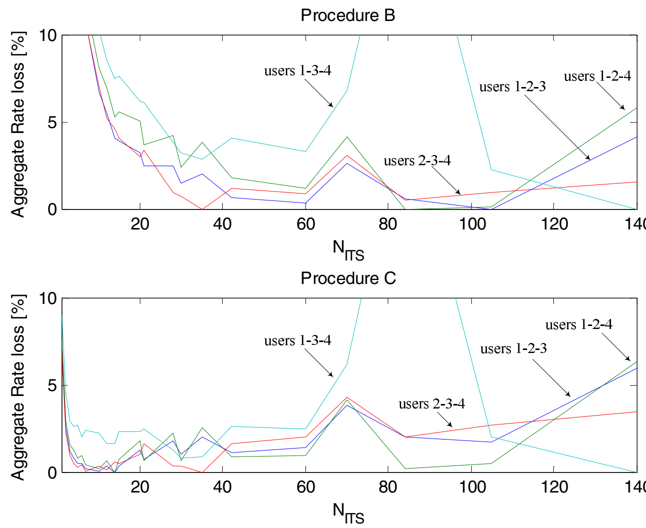


Fig. 8. Aggregate bit-rate loss for the three-users scenario with *Procedure B* and *Procedure C*.

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