An efficient channel condition aware proportional fairness resource allocation for powerline communications

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An Efficient Channel Condition Aware Proportional Fairness Resource Allocation For Powerline Communications

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***Abstract*—Powerline communications (PLC) become a viable local area network (LAN) solution for in-home networks. We are witnessing a growing number of in-home devices and services using PLC systems. In this paper, the resource allocation problem with peak BER constraint is investigated in multiuser context. A new proportional fairness resource allocation algorithm which takes into account the channel conditions is proposed for the downlink. This algorithm is based on linear precoded OFDM (LP-OFDM) which enables reliable high bit rate transmission under peak BER constraint. The algorithm tries to maximize the overall throughput of the system under different users required bit rate constraints. Simulations are run over PLC channels and it is shown that proposed algorithms under peak BER constraint give better performance than classical proportional fairness algorithms. In addition, the linear precoding technique brings significant data rate gain and reduces the number of unsatisfied users.**

	Objective	**Advantage**	**Disadvantage**
Max sum capacity	$\max \sum_{u=1}^{U} R_u$	Best sum capacity	No data rate proportionality among users
Max minimum user's capacity	$\max \min_u R_u$	Equal user data rate	Inflexible user data rates distribution
Max weighted sum capacity	$\max \sum_{u=1}^{U} w_u R_u$	Data rate fairness adjustable by varying weights	No guarantee for meeting proportional user data

TABLE I
RATE MAXIMIZATION STRATEGIES [3].

I. INTRODUCTION

Powerline communication basic concept is to transmit information and electricity simultaneously along electricity lines as an alternative to constructing dedicated communications infrastructure. Although PLC has been in operation for decades as a narrowband system carrying only small amounts of data, it has become more significant in recent years due significant advances achieved in terms of modulation and signal processing schemes which enable its use for broadband communications. PLC systems can then be utilized to provide a wide variety of applications. These applications can include multimedia services such as video and audio conferencing, online training, news and software distribution, database replication, home automation and surveillance. Hence, there is a need to share the resources (bandwidth, energy, data rate) between devices and services. The third work package (WP3) of the FP7 OMEGA (Home Gigabit Networks) project targets this goal. This European project is devoted to develop innovations in transmission technology and convergence layer for wireless i.e., LAN, ultra wide band (UWB), 60 GHz systems, visible light communication systems and PLC systems [1], [2].

The powerline channel exhibits multipaths caused by reflections on the discontinuities of the network and offers impulse responses that can be assumed as quasi-static. These two main features encourage the use of robust communication systems for the former and the exploitation of the knowledge of the channel state information (CSI) at the transmitter side for the latter. In the literature, the resource allocation issue in orthogonal frequency division multiple (OFDM) has been studied in single and multiuser contexts. The adaptive OFDM based communication systems adapt the transmission to the channel conditions individually for each subcarrier, by means of so called bit-loading. The number of bits on each subcarrier depends on the signal-to-noise ratio (SNR) of the subcarrier and the error rate constraint approximated by the normalized SNR (also known as SNR gap). These systems do not fully exploit the allocated power spectral density (PSD) in PLC context [4], [5], [6]. For mutual exploitation of residual energies, it has been proposed to add a linear precoding component to classical OFDM. LP-OFDM is a combination of multi-carrier and spread spectrum techniques also known as MC-SS techniques. This technique has shown very good performances in difficult environments and brings a significant increase in bit rate compared to classical OFDM systems [4], [5], [6].

Under satisfaction of the different QoS requirements (rate, delay, error probability, etc.), bits, energies and subcarriers have to be allocated to different users in order to optimize the expected goal. Table I gives the different rate maximization strategies in multiuser context [7], [8], [9]. R_u is the data rate a user u gets. In this paper, the maximum weighted sum capacity problem under peak bit error constraint (BER) is considered for the downlink in PLC systems. As in power constraint, a

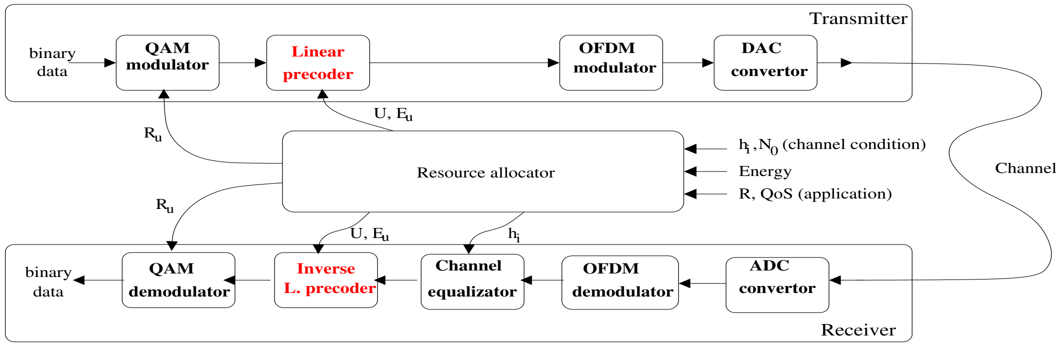

Fig. 1. LP-OFDM system transmitter-receiver model.

peak constraint is defined in opposition to average constraint [12]. The peak power constraint is the PSD constraint where the power is limited for each subcarrier. In the case of BER, this constraint is applied to each bit. In [7], each user receives a weight according to his required bit rate. This weight does not take into account the user channel conditions and this may lead to no guarantee for meeting proportional user data rate (table I). In [10], each user receives a number of subcarriers that is the ratio of its required bit rate to the number of bits computed with its average channel gain. The users required bit rate will be decreased when the power constraint is too low to meet users required bit rate.

In addition, the aforementioned algorithms try to maximize the different bit rate goals under peak BER constraint. This peak BER constraint is taken into account in the bit rate calculation by the signal-to-noise ratio (SNR) gap [14], which is variable for different modulation orders. In a general approach and in [7], [10], it is assumed a constant SNR gap value for all modulation order. This assumption may lead in some losses in the final bit rate. In [6], [11], the proposed bit-loading algorithms try to maximize the overall PLC throughput under a peak BER constraint where the SNR gap remains variable for different modulation orders. In these proposed algorithms, the idea is to iteratively allocates bits until satisfaction of the peak BER constraint. Besides giving good results, their computational complexity is still rather high at low SNR values. What is needed is an algorithm that accurately determines the final bit allocation in a low computational complexity fashion.

In this paper, the peak BER constraint optimization problem is investigated and an efficient bit-loading algorithm is proposed. This algorithm dynamically allocates subcarrier, bit and energy based on the linear precoding technique. It is also extended to multiuser context and a new channel condition aware proportional fairness (CCAPF) algorithm is proposed. This algorithm tries first to satisfy users required bit rate when it is possible and then tries to maximize the overall bit rate.

This paper is organized as follows. Section II presents the studied systems and the optimization problem. Section III gives the proposed peak BER constraint bit-loading algorithm, which is extended to multiuser context for the channel condition aware proportional fairness algorithm in section IV. The performances of the proposed algorithms are given in section V over PLC channels. Finally, section VI concludes the paper.

II. System model and problem formulation

A. Linear precoded OFDM systems

As previously stated, LP-OFDM results from the combination of multi-carrier modulation and spread spectrum. In our study, the LP component is not used to share access between users, as code division multiplex access (CDMA) does, but is used to multiplex different data symbols of a given user. The merging process consists in connecting a set of subcarriers with precoding sequences to mutually exploit their energies. This set of subcarriers is called block in the following and the subcarriers are not necessary adjacent. Each block is precoded using one orthogonal Hadamard matrix. The number of blocks is defined as the ratio of total number of subcarriers N to the precoding sequence length L. The classical OFDM system is obtained for $L = 1$. If judiciously done, each resulting set holds an equivalent SNR such that the total supported throughput is greater than the sum of the individual throughputs supported by each subcarrier taken separately. Fig. 1 gives the LP-OFDM transmitter-receiver model.

B. Rate adaptive optimization problem

When trying to maximize the bit rate under the peak BER constraint $\widehat{ber}$, the optimization problem for a block S of L subcarriers in a single user case is [4], [5]

$$\begin{cases} \max\limits_{C,E_c} R_S = \max\limits_{C,E_c} \sum\limits_{c=0}^{C-1} R_c \\ \text{with } R_c = \log_2\left(1 + \dfrac{E_c}{\Gamma_c N_0} \dfrac{L^2}{\sum\limits_{n\in S} \dfrac{1}{|H_n|^2}}\right) \\ \text{subject to, } \quad \sum\limits_{c=0}^{C-1} E_c \leq E \\ \qquad \dfrac{4}{R_c} Q\left(\sqrt{3\Gamma_c}\right) \leq \widehat{ber}\,. \end{cases} \tag{1}$$

The adaptive parameters are the precoding sequence length L, the energies E_c allocated to each sequence and the number of precoding sequences C within each block. There is an interdependency between the allocated bit R_c to precoding sequence c and the SNR gap Γ_c given by

$$\Gamma_c = \frac{1}{3}\left(Q^{-1}\left(\frac{R_c \times \widehat{ber}}{4}\right)\right)^2 , \tag{2}$$

where Q^{-1} is the inverse of the well-known Q-function given by

$$Q(\alpha) = \frac{1}{\sqrt{2\pi}}\int_{\alpha}^{+\infty} e^{-\frac{x^2}{2}} dx \tag{3}$$

The symbol error rate (SER) is then variable for each modulation order and is approximated by $\widehat{ser} \approx R_c \times \widehat{ber}$. For simplicity, it is assumed in [15] a constant SER value for all modulation orders that is $\widehat{ser} \approx 2 \times \widehat{ber}$ for $R_c \geq 2$. Therefore Γ_c becomes constant and is

$$\Gamma_c = \Gamma = \frac{1}{3}\left(Q^{-1}\left(\widehat{ser}\right)\right)^2 = \frac{1}{3}\left(Q^{-1}\left(\frac{\widehat{ber}}{2}\right)\right)^2 , \; \forall R_c \geq 2 \tag{4}$$

Hence, we understand intuitively that this assomption leads in some losses in bit rate because the peak BER constraint $\widehat{ber}$ for R_c bits is reduced to $2 \times \widehat{ber}/R_c$. For a constant SNR gap Γ, the BER constraint in problem (1) is eliminated. In this context, it has been proven that, over the block S of L subcarriers, the optimum achieved bit rate under PSD constraint and with zero forcing receiver is [4]

$$R_S = L \times \log_2\left(1 + \frac{E}{\Gamma N_0}\frac{L}{\sum\limits_{n\in S}\frac{1}{|H_n|^2}}\right), \tag{5}$$

and $R_c = R_S/L$.

III. Proposed bit-loading algorithm with peak BER constraint

In this section, we try to maximize the overall throughput under peak BER constraint per subcarrier. For a peak BER constraint, Γ is no more constant for the modulation orders and bit-loading algorithms have to be performed with variable SNR gap Γ_c for each modulation order R_c. In [6], [11] and [13], it has been proposed bit-loading algorithms trying to solve this problem. The main idea in these algorithms is to iteratively allocate the bit to subcarriers or blocks of subcarriers until the satisfaction of peak BER constraint. In this paper, an efficient bit-loading algorithm with peak BER constraint is proposed for LP-OFDM in a single user context and is extended to multiuser context in the following section. The main idea is to predefine the sum of inverse channel gains within a block S which is needed to transmit R_S bits. From (5), the needed sum of inverse channel gains (NSICG) is derived as

$$\text{NSICG}_c = \frac{E}{\Gamma_c N_0}\frac{L}{(2^{\overline{R_c}} - 1)} , \tag{6}$$

when assuming the same modulation order $\overline{R_c}$ for all subcarriers within the block S, and Γ_c is computed using (2). Let $\overline{R_c} = \lfloor R_S/L \rfloor$ for the block S of L subcarriers, therefore $\overline{R_c} \leq R_S/L < \overline{R_c} + 1$ and then, as NSICG is a decreasing function of the modulation order $\overline{R_c}$

$$\frac{E}{\Gamma_c N_0}\frac{L}{(2^{\overline{R_c}} - 1)} \leq \frac{E}{\Gamma N_0}\frac{L}{(2^{\frac{R_S}{L}} - 1)} < \frac{E}{\Gamma_{c+1} N_0}\frac{L}{(2^{\overline{R_c}+1} - 1)} , \tag{7}$$

where $\Gamma_{c+1} \leq \Gamma \leq \Gamma_c$. From (5), we derive

$$\text{NSICG}_c \leq \sum_{n\in S}\frac{1}{|H_n|^2} < \text{NSICG}_{c+1} . \tag{8}$$

Hence, for the block S, the achieved bit rate is computed from (5) setting $\Gamma = \Gamma_c$. For real systems, the bit rate achieved by an adaptive LP-OFDM system using discrete modulation is maximized if, on block S, $\overline{R_c}$ bits are allocated to precoding sequence c, and $\overline{R_c}$ is [6]

$$\overline{R_c} = \begin{cases} \lfloor R_S/L \rfloor + 1 & (1 \leq i \leq n_c) , \\ \lfloor R_S/L \rfloor & (n_c < i \leq L) , \end{cases} \tag{9}$$

where

$$n_c = \left\lfloor \frac{L\left(2^{R_S/L} - 2^{\lfloor R_S/L \rfloor}\right)}{\left(2^{\lfloor R_S/L \rfloor + 1} - 1\right)\frac{\Gamma_{c+1}}{\Gamma_c} - \left(2^{\lfloor R_S/L \rfloor} - 1\right)} \right\rfloor . \tag{10}$$

Then, the achievable bit rate $\overline{R_S}$, is

$$\overline{R_S} = n_c \times (\lfloor R_S/L \rfloor + 1) + (L - n_c) \times \lfloor R_S/L \rfloor \tag{11}$$

Each precoding sequence energy contribution in the total energy of the given block, is

$$E_c = (2^{\overline{R_c}} - 1)\frac{\Gamma_c N_0}{L^2}\sum_{n\in S}\frac{1}{|H_n|^2} , \tag{12}$$

which satisfies

$$\sum_c E_c \leq E \tag{13}$$

The bit-loading algorithm for a block S of L subcarriers is given below

for each modulation order $\overline{R_c}$, ($\overline{R_c} = 2, \cdots, \overline{R_{cmax}}$) **do**
    compute Γ_c from (2)
    compute NSICG_c from (6) and store it in a look-up table
end for
for the block S **do**
    compute $s = \sum_{n\in S} 1/|H_n|^2$
    if $s < \text{NSICG}_c$ **then**
        $\overline{R_c} = \overline{R_{cmax}}$ for all c
    else
        find $\overline{R_c}$ as $\text{NSICG}_c \leq s < \text{NSICG}_{c+1}$
        compute R_S using (5) and setting $\Gamma = \Gamma_c$
        compute n_c, $\overline{R_c}$
    end if
end for

This algorithm is much simpler to implement, since no convergence iterations are required, but simply a look-up table in order to store, for each allowable modulation order R_c, the required Γ_c and NSICG_c to guarantee a target peak BER. For multi block systems, the aforementioned bit-loading algorithm is applied for each block. Subcarriers that maximize the overall throughput are then chosen. It has been proven that choosing the best available subcarriers for each block maximizes the system throughput [4].

IV. Proposed channel condition aware proportional fairness algorithm

In multiuser context, B blocks of subcarriers are distributed among users. A proportional fairness resource allocation scheme is considered where the overall bit rate is maximized under satisfaction of users minimum bit rate requirements

$$\begin{cases} \max\limits_{S_b} \sum\limits_{u=1}^{U} R_u = \max\limits_{S_b} \sum\limits_{u=1}^{U}\sum\limits_{b=1}^{B} s_{u,b} \times R^u_{S_b} \\ \text{where } R^u_{S_b} = L \times \log_2 \left(1 + \dfrac{E}{\Gamma N_0} \dfrac{L}{\sum\limits_{n \in S_b} \dfrac{1}{|H_{u,n}|^2}}\right) \\ \text{and } s_{u,b} = 1 \text{ if } u \text{ uses the block } b, \text{ else } 0 \\ \text{subject to } R_u \geq \widehat{R_u} \end{cases} \quad (14)$$

Due to PSD constraint in PLC systems, all users have the same peak power constraint E on each subcarrier. For simplicity, it is assumed that all users utilize the same precoding sequence length L. The minimum required bit rate $\widehat{R_u}$ is converted into a weight for each user

$$r_u = \frac{\widehat{R_u}}{\sum_{v=1}^{U} \widehat{R_v}} . \quad (15)$$

In [7], a proportional fairness (PF) algorithm is proposed to solve this problem where each user receives a weight $\phi_u = r_u$ according to his bit rate requirement. When extending PF algorithm to blocks, each user will receive $B^i_u = \lfloor \phi_u \times B \rfloor$ blocks of subcarriers. This allocated numbers of blocks do not take into account users channel conditions. Namely, a user u with bad channel conditions may need more blocks of subcarriers than B^i_u or a user v with good channel conditions may need less blocks than B^i_v. As a result, there is no guarantee for meeting proportional user data rate. In this paper, a channel condition aware proportional fairness (CCAPF) is proposed. This algorithm is applied in LP-OFDM context and users channel conditions are taken into account when allocating blocks of subcarriers. Consequently, the user who reaches his required bit rate will not receive additional blocks and the unallocated blocks will be redistributed among unsatisfied users. Unlike, the max-min user capacity scheme (table I), flexibility is introduced when redistributing the unallocated blocks. Therefore, a unsatisfied user who has very bad channel conditions will not receive additional blocks and the more capable user will receive additional blocks.

In [10], it is assumed that each user experiences the same channel gain $\overline{h_u}$ over all subcarriers, and $\overline{h_u} = \text{mean}_n |H_{u,n}|^2$. Therefore, the number of bits per block $\overline{R^u_S}$ can be estimated using (5) for each user. Hence, a unsatisfied user u who has achieved R_u bit rate right now, needs about

$$B^2_u = \left\lfloor \left(\widehat{R_u} - R_u\right) / R^u_S \right\rfloor \quad (16)$$

blocks to be satisfied. The following algorithm tries to allocate blocks among users in order to satisfy their required bit rate. In the initialization step, each user receives one block of subcarriers. In [7], there is no priority among users but in the proposed algorithm, a priority is introduced among users according to their channel capacities. The more the user channel capacity, the lesser its priority.

initialize $R_u = 0$, $B_u = 0$, $\Omega = \{1, 2, \cdots, U\}$
compute $\overline{h_u}$ and $\overline{R^u_S}$
sort users according to $\overline{h_u}$
for each sorted user u **do**
    compute R^u_S where S is its L best available subcarriers
    $R_u = R_u + R^u_S$, $B_u = B_u + 1$,
    if $B_u = B^i_u$ or $\widehat{R_u} \leq R_u$ **then**
        $\Omega = \Omega - \{u\}$
    end if
end for
while Ω is not empty **do**
    find $u^* = \arg\min_{u \in \Omega} R_u / \phi_u$
    compute $R^{u^*}_S$ where S is its L best available subcarriers
    $R_{u^*} = R_{u^*} + R^{u^*}_S$, $B_{u^*} = B_{u^*} + 1$,
    if $B_{u^*} = B^i_{u^*}$ or $\widehat{R_{u^*}} \leq R_{u^*}$ **then**
        $\Omega = \Omega - \{u\}$
    end if
end while

At this step, there are $B^r = B - \sum_{b=1}^{B} B_u$ unallocated blocks. These blocks are redistributed when it is possible to unsatisfied users. For each unsatisfied user v, B^2_v is computed and if $B^2_v > B^r$, user v will not receive additional blocks. Else, user v will receive the maximum number of blocks which allows to satisfy its required bit rate.

After this stage, if there are unallocated blocks, the maximum sum capacity (table I) algorithm is performed. Thus, the best user on each block receives this block.

V. Simulation results

In this section, we present simulation results for the proposed algorithms. The generated signal is composed of $N = 1160$ subcarriers transmitted in the band 1–30 MHz. Perfect synchronization and channel estimation are assumed. A high background noise level of -110 dBm/Hz is assumed and the signal is transmitted with respect to a flat PSD of -50 dBm/Hz. The maximum number of bits per symbol is limited to 15. The multipath channel models of the various in-home measured channels for PLC given in [16] are used. In [16], PLC channels are classified into 9 classes according to their capacities, and a model of transfer function is associated

Class	Channel model
1	$-80 + 30 \times \cos\left(\frac{f}{5.5.10^7} - 0.5\right)$
2	$-43 + 25 \times \exp\left(-\frac{f}{3.10^6}\right) - \frac{15}{10^8} f$
3	$-38 + 25 \times \exp\left(-\frac{f}{3.10^6}\right) - \frac{14}{10^8} f$
4	$-32 + 20 \times \exp\left(-\frac{f}{3.10^6}\right) - \frac{15}{10^8} f$
5	$-27 + 17 \times \exp\left(-\frac{f}{3.10^6}\right) - \frac{15}{10^8} f$
6	$-38 + 17 \times \cos\left(\frac{f}{7.10^7}\right)$
7	$-32 + 17 \times \cos\left(\frac{f}{7.10^7}\right)$
8	$-20 + 9 \times \cos\left(\frac{f}{7.10^7}\right)$
9	$-13 + 17 \times \cos\left(\frac{f}{4.5.10^7} - 0.5\right)$

TABLE II
TRANSFER FUNCTION CHANNEL MODEL BY CLASS.

to each class (table II). The higher the channel class number, the better its channel conditions.

In a first step, we analyse the impact of peak BER constraint bit-loading with variable SNR gap. First simulations are run over the class 5 channel. The single user case allows to compare the bit-loading algorithms with constant SNR gap (PF algorithm defined in [7]) and variable SNR gap (proposed CCAPF algorithms). Results are given for a peak target BER of 10^{-5}. Fig. 2 depicts the achieved bit rates for proposed CCAPF algorithms and the PF algorithm. The difference between the CCAPF ($L = 1$) and PF algorithms shows the better performance of bit-loading with variable SNR gap than bit-loading with constant SNR gap. The CCAPF ($L = 8$) algorithm curve also shows that the linear precoding component brings an additional bit rate. In addition, at class 5 channel reference gain, the CCAPF ($L = 8$) algorithm brings 4.5% of bit rate gain compared to the CCAPF ($L = 1$), and the CCAPF ($L = 1$) algorithm brings 3.4% of bit rate gain compared to classical PF algorithm. The reason for the better performance of the LP-OFDM system is explained in Fig. 3, where the used energy per subcarrier are compared for different algorithms. To highlight the energy distribution, these subcarriers are sorted in descending order. The used energy is the minimal required energy allowing the transmission of the

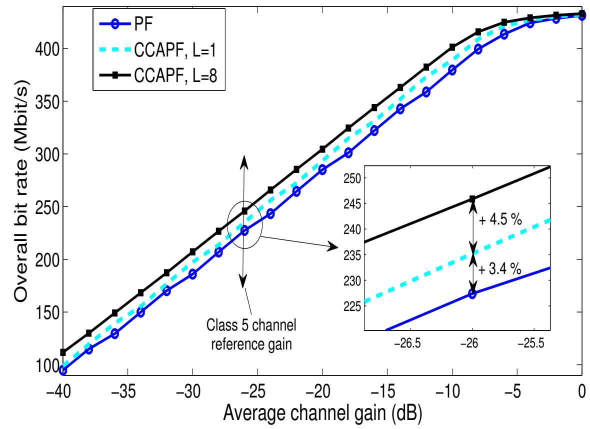

Fig. 2. Achieved bit rates for constant and variable SNR gap for class 5 channel.

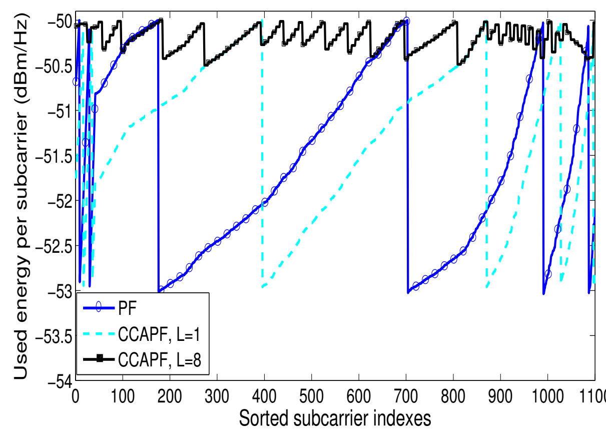

Fig. 3. Energy distribution for class 5 channel, channel gain is equal to -26 dB.

maximum data rate. Jump positions in curves correspond to the change in modulation orders. It is clear that the classical OFDM bit-loading algorithms in PF and CCAPF ($L = 1$) systems are not fully exploiting the available energy on each subcarrier due to discrete modulation orders. The used energy of both systems are similar and the gap between the curves are due to different constraints (peak BER (variable SNR gap) and constant SNR gap). The precoding component accumulates the unused energies of a given block of subcarriers to transmit additional bits. The adaptive LP-OFDM bit-loading in CCAPF ($L = 8$) system utilizes more efficiently the PSD limit.

In the second step, the new bit-loading algorithm with peak BER constraint is extended to multiuser context. To maximize the overall bit rate under satisfaction of different user bit rate requirements, the proposed linear precoding based channel condition aware proportional fairness algorithm is performed for 9 users. The principle of redistributing blocks of subcarriers is directly applied to PF algorithm and this algorithm is called "Modified PF". In addition, it is considered that all users have the same peak BER constraint of 10^{-5} and each

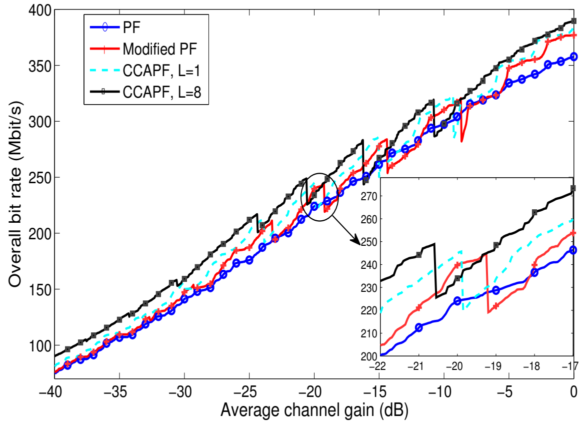

Fig. 4. Achieved overall bit rate for 9 users.

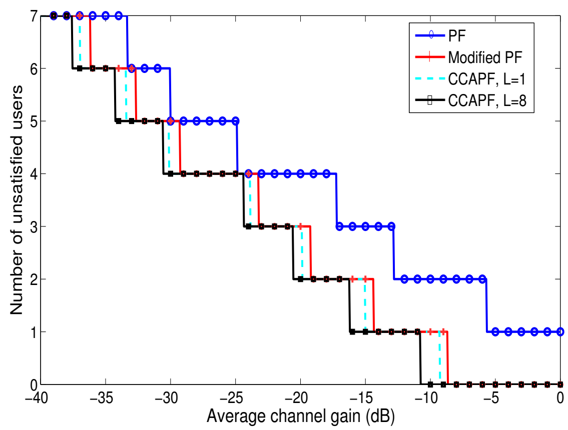

Fig. 5. Number of unsatisfied users for different average channel gain.

user experiences one different channel class and the required minimum bit rate is 20 Mbit/s for all users. Fig. 4 and Fig. 5 gives respectively the comparisons of the achieved bit rate and the number of unsatisfied users. The "Modified PF" gives more overall bit rate than PF algorithm and reduces the number of unsatisfied users. This result shows the performance of blocks redistribution. In addition, the new peak BER constraint algorithms bring best performances in term of overall bit rate and number of unsatisfied users. The difference between the "Modified PF" and the CCAPF algorithms confirms the result highlighted in the first simulation step. The jump positions in their curves show the effect of redistribution of blocks, where bit rate is reallocated to a user who can satisfy his required bit rate. One jump position is zoomed out in Fig. 4, and there are gaps between the "Modified PF" and the CCAPF algorithms. These gaps explain what is shown in Fig. 5 where CCAPF ($L = 8$) algorithm gives lesser unsatisfied users than CCAPF ($L = 1$) algorithm, which gives lesser unsatisfied users than "Modified PF". The PF algorithm gives more unsatisfied users because a user become satisfied when his channel conditions allow him and there is no effort from best users to "help" worst users.

VI. Conclusion

In this paper, the resource allocation problem with peak BER constraint has been investigated in multiuser context for powerline communications. An efficient bit-loading algorithm has been proposed and extended to multiuser context. A channel condition aware proportional fairness resource allocation has been also presented. It has been shown through simulations that the proposed peak BER constraint method combined with linear precoding technique offers better performances and guarantees for more users to meet their required bit rate than classical proportional fairness algorithm.

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