# Adaptive Spread Spectrum Multicarrier Multiple Access over Wirelines

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***Abstract*— In this paper, we investigate the dynamic resource allocation adapted to spread spectrum multicarrier multiple access (SS-MC-MA) systems in a multiuser power line communication (PLC) context. The developed adaptive system is valid for uplink, downlink, as well as for indoor and outdoor communications. The studied SS-MC-MA system is based on classical multicarrier modulation like DMT, combined with a spread-spectrum (SS) component used to multiplex several information symbols of a given user over the same subcarriers. The multiple access task is carried out using a frequency division multiple access (FDMA) approach so that each user is assigned one or more subcarrier sets. The number of subcarriers in each set is given by the spreading code length as in classical SS-MC-MA systems usually studied in the wireless context. We derive herein a new loading algorithm that dynamically handles the system configuration in order to maximize the data throughput. The algorithm consists in an adaptive subcarrier, code, bit and energy assignment algorithm. Power spectral density constraint due to spectral mask specifications is considered as well as finite order modulations. In that case, it is shown that SS-MC-MA combined with the proposed loading algorithm achieves higher throughput than DMT in a multiuser PLC context. Because of the finite granularity of the modulations, some residual energy is indeed wasted on each subcarrier of the DMT spectrum. The combining of a spreading component with digital multitone (DMT) allows to merge these amounts of energy so that one or more additional bits can be transmitted in each subcarrier subset leading to significant throughput gain. Simulations have been run over measured PLC channel responses and highlight that the proposed system is all the more interesting than the SNR is low.**

***Index Terms*— Dynamic resource allocation, bit loading, power line communications (PLC), multiaccess communications, spread-spectrum multicarrier multiple access (SS-MC-MA).**

## I. Introduction

WITH the increasing ubiquity of the Internet, the demand for high data rate communications over the access network has been growing rapidly. Permanent necessity for additional transmission capacities on the so-called "last-mile" has motivated the study of new telecommunication networks and new transmission technologies. A promising possibility is then offered by power line communications (PLC) using the power supply grids for communications.

However, power distribution networks have not been designed for communication purposes and do not present a favorable transmission medium. The most crucial properties of the PLC transmission channel are deep fades caused by multipaths, frequency-dependent cable losses, as well as unfavorable noise conditions [1], [2]. PLC systems have moreover to manage point-to-multipoint multiuser communications. To cope with the impairments of such a hostile channel, PLC systems have to apply robust and efficient modulation techniques such as spread spectrum (SS) and multicarrier (MC) schemes [3]. In particular, recent investigations have focused on orthogonal frequency division multiplexing (OFDM) and code division multiple access (CDMA) systems [4]–[7]. On the other hand, various combinations of both schemes (MC-SS), like multicarrier CDMA (MC-CDMA), have been introduced since 1993 [8], [9]. MC-SS schemes have shown very good performances in the case of multiuser communications in difficult environments and are today proposed for beyond 3G mobile cellular systems [10], [11]. These hybrid techniques have also been investigated in recent studies in the digital subscriber line (DSL) context [12], and represent as well potential solutions for PLC [13].

On the other hand, it turns out that the PLC channel exhibits long-time variations due to the various devices that are switched on/off in the network [14]. A simple approach is then to consider the PLC channel as invariant for periods of time that are long compared to symbol durations. This quasi-static behavior encourages the use of adaptive modulation schemes that require the knowledge of the instantaneous channel state information (CSI) at the transmitter side. Practically, the symmetric property of the transfer function of the PLC channel can be helpful for that purpose [15]. Note however that there also exist periodic variations of the input impedances of the loads connected to the network that translate into short-time variations of the transfer function [16]. This behavior must in fact be incorporated in the CSI which needs to be refreshed preiodically. Some studies have advantageously applied loading principles to spread spectrum systems [17], [18], but among the existing adaptive schemes, digital multitone (DMT) used for DSL communications is the most popular. Like OFDM, DMT is based on multicarrier modulation but historically comes from the DSL community and is usually combined with bit loading techniques

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assuming CSI at the transmitter. DMT carries out energy and bit distribution across the subcarriers yielding significant performance improvements as demonstrated in many papers [19]–[21]. In a multiuser environment, adaptive sharing of the spectrum can moreover be carried out and leads to performance increase compared to classical static sharing methods such as time and frequency division multiple access (TDMA, FDMA) [22], [23].

In the PLC context, the most limiting factor is given by electromagnetic compatibility specifications. Standards generally specify admissible spectral masks that give rise to a power spectral density (PSD) constraint, sometimes called peak-energy limited constraint. PSD limitations can severely affect the data throughput of a DMT system [24], [25], when classical algorithms that only consider the total transmit power as a constraint are applied. Even with algorithms adapted to PSD constraint, some amount of energy is wasted on each subcarrier due to the finite granularity of constellations [26]. In this paper, we will show that adding a spreading component in the frequency domain of a multicarrier system allows to exploit the energy resource more efficiently. It will be highlighted that the spreading process is indeed capable to pool the energy available on each subcarrier of a given subset so that the transmission of one or more additional bits is possible. In order to focus on the contribution of the spreading process, channel coding is not considered. In this paper, we thus propose to apply an adaptive loading algorithm to a particular version of MC-SS schemes, commonly referred to as spread spectrum multicarrier multiple access (SS-MC-MA) [27] which can be classified as particular linearly precoded DMT.

As it will be detailed in the paper, SS-MC-MA is a multicarrier modulation that combines SS and FDMA. The FDMA component is based on the transmission of several subsets of subcarriers in parallel, each subset being exclusively assigned to a specific user. The SS component allows each user to multiplex several symbols within the same subset by spreading them in the frequency domain. Different spreading sequences can be associated to different modulation orders and different transmit power levels. We actually propose to adapt these quantities according to the channel knowledge. Moreover, an adaptive subcarrier distribution is also considered to efficiently share the spectrum resource among the users. This work then results in a subcarrier, code, bit and energy allocation algorithm, based on the channel instantaneous fading characteristics of *all* users. Perfect knowledge of these characteristics at the transmitter side is assumed in the paper. Since each user is assigned its own subset of subcarriers, the problem formulation strictly holds in both uplink and downlink transmissions. The proposed scheme can also be applied either to indoor or outdoor PLC networks.

The paper is organized as follows. In section II, the structure of the new adaptive SS-MC-MA system is presented and related to the DMT approach. In order to keep this paper clear, the whole system will be studied in three steps, corresponding to three systems, studied from the most simple to the most complex. In section III, we derive the capacity expressions of the different systems. An optimal code, bit and energy algorithm for the single block and single user system is then proposed in section IV. In section V, we extend the results of section IV to the cases of the multiple block systems with one and several users. Suboptimal but practical algorithms are hereby introduced. In section VI, simulation results are then presented over measured PLC channel responses and compared to those obtained with the classical DMT system. It is shown that the adaptive SS-MC-MA system combined with the proposed loading algorithm achieves higher throughput than the DMT system. Finally, we conclude in section VII.

## II. SS-MC-MA system descriptions

In order to give better understanding of the issues involved, we introduce three SS-MC-MA systems, A, B, and C. System A consists in a single user single block transmission system, system B consists in a single user multiple block transmission system, and system C is the multiple user multiple block system proposed herein. Throughout the paper, we mean by "block" a set of subcarriers bound with the same spreading codes. We emphasize that the very aim is to exploit system C for power line communications, but the two other systems will provide allocation algorithms that will be adapted to the final solution.

### *A. System A: single user and single block case*

The first system assumes the transmission of a single subcarrier block owned by a single user. As shown in Fig. 1, the signal generation is based on the combination of spread spectrum and multicarrier schemes and a specific loading algorithm handles the dynamic configuration of the whole system. The $K_1$ incoming symbols of the only active user, *i.e.* user 1 in Fig. 1, are generated using $2^q$ quadrature amplitude modulation (QAM) constellations. A spreading code matrix $\boldsymbol{C} = (c_{l,k})_{0<l\leq L\,,\,0<k\leq K_1}$ is then applied to the obtained complex symbol vector $\boldsymbol{S}_1 = [s_1, \cdots, s_{K_1}]^T$, which means that each symbol is multiplied by a specific code sequence and added with each other. These spreading codes are orthogonal codes extracted from the Hadamard matrix[1] of size $L \times L$, and the number of used codes is such that $K_1 \leq L$. Moreover, a certain amount of energy $E_k$ is assigned to each code sequence, or equivalently to each complex symbol $s_k$. Each chip of the resulting spread symbol is then transmitted in parallel over a subset of $L$ subcarriers among the $N$ available subcarriers of the multicarrier spectrum, which implies $L \leq N$. It is important to keep in mind that the subcarrier block is not necessarily composed of adjacent subcarriers and that a subcarrier distribution step has to be processed before multicarrier modulation (Fig. 1). In the following, we denote $\mathcal{H} = \{1, \cdots, N\}$ the set of the available subcarriers. System A actually consists of an adaptive multicarrier

[1] This matrix is not derived from the only Sylvester construction, and $L$ can then be equal to all multiple of 4.

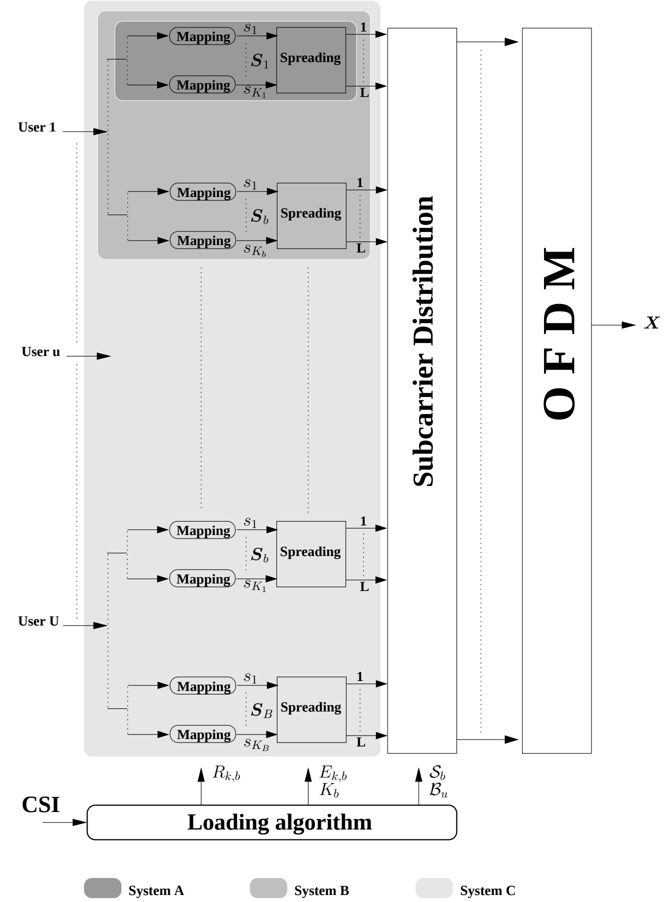


Fig. 1. Schematic representation of the SS-MC-MA systems

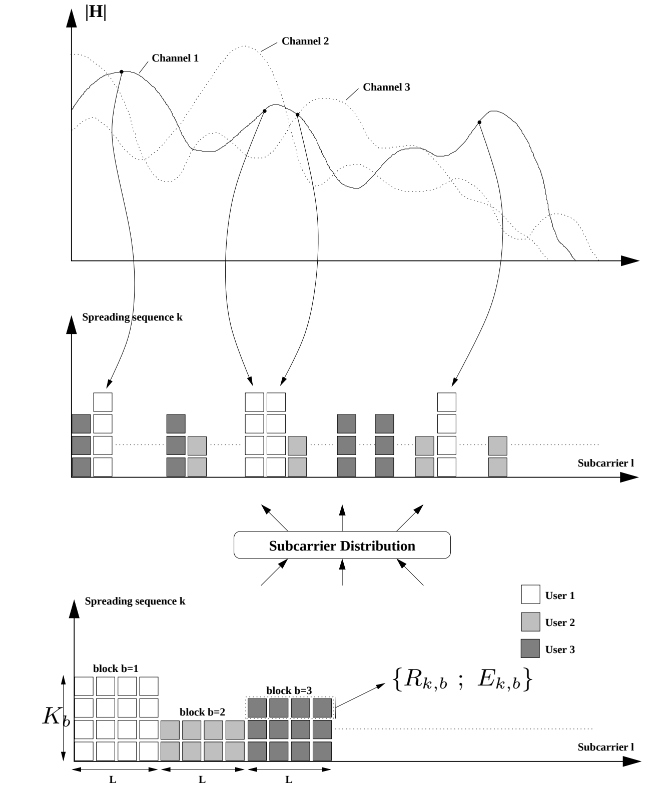


Fig. 2. Exemple of subcarrier distribution and allocation result with the proposed adaptive SS-MC-MC system for $L = 4$

modulation applied to a CDMA signal. The knowledge of $R_k$, $E_k$ and the subcarrier assignment procedure are provided by the loading algorithm. The transmitted signal $\boldsymbol{X}^{(\mathrm{A})}$ can finally be written

$$\boldsymbol{X}^{(\mathrm{A})} = \boldsymbol{F}\boldsymbol{\Pi}(\mathcal{P})\ \boldsymbol{C}(\mathcal{P})\ \boldsymbol{E}(\mathcal{P})\ \boldsymbol{S}_1(\mathcal{P})\ , \tag{1}$$

where $\mathcal{P}$ is the allocation policy followed by the loading algorithm, $\boldsymbol{E}$ is the $K_1 \times K_1$ diagonal matrix whose terms convey the energy assigned to each complex symbol $s_k$, $\boldsymbol{\Pi}$ is a permutation matrix of size $N \times L$ which performs the subcarrier distribution, and $\boldsymbol{F}$ is the Fourier matrix of size $N \times N$. The multicarrier component is assumed to be adapted to the channel, which implies that the channel can be modeled by a single complex coefficient per subcarrier [8].

### B. System B: single user and multiple block case

Contrary to system A, system B allows the active user to transmit its data over several blocks of subcarriers. System B is then the multiple block extension of system A as evident from Fig. 1. The system supports $B = \lfloor \frac{N}{L} \rfloor$ blocks of spread symbols transmitted in parallel over $B$ subsets $\mathcal{S}_b$ of $L$ subcarriers, where $\lfloor \cdot \rfloor$ denotes the integer part. As in system A, the subcarriers of a given subset are not necessarily adjacent. The transmitted chips are frequency interleaved across the multicarrier spectrum, following the subcarrier distribution policy. The codes within a given block can differ in energy and modulation orders, and the number of codes can be different from one block to another, depending on the loading algorithm outputs. We denote $K_b$ the number of spreading codes used on subset $\mathcal{S}_b$, $E_{k,b}$ the amount of energy assigned to the $k$th code of subset $\mathcal{S}_b$, and $R_{k,b}$ the modulation order associated to that code. The transmitted signal $\boldsymbol{X}^{(\mathrm{B})}$ is then

$$\boldsymbol{X}^{(\mathrm{B})} = \sum_{b=1}^{B} \boldsymbol{X}_b^{(\mathrm{A})}\ , \tag{2}$$

where $\boldsymbol{X}_b^{(\mathrm{A})}$ corresponds to the symbol generated by system A when subcarrier block $\mathcal{S}_b$ is used. Note that with $L = 1$, and thus with $B = N$, system B amounts to DMT.

### C. System C: multiple user and multiple block case

System C is the herein proposed system for power line communications. The extension of system B to multiple user case yields system C. As shown in Fig. 1, several users have to share the subcarrier set $\mathcal{H}$ to transmit their data. Multiple access is managed following an FDMA approach, which is a fundamental feature of the SS-MC-MA scheme. To ensure FDMA, the different subsets $\mathcal{S}_b$ must be mutually exclusive, and each user $u$ must exclusively transmit its data on the subsets that have been assigned to him. Hence, the SS component is not used to handle multiple access among users as in the well-known MC-CDMA scheme but instead to multiplex different symbols of the same user on different subcarriers. Fig. 2 illustrates the spectrum sharing of system C. Point-to-multipoint or multipoint-to-point communications must be considered here, and there are as many channel links as active users (Fig. 2). The subcarrier distribution is carried out taking into account the different channel frequency responses as it will be detailed later on. As evident from the example taken in Fig. 2, note that the number of blocks per user is not necessarily the same, and each block of each user can get different modulation orders, number of codes, and amount of energy. All of these parameters are handled by the loading algorithm.

The obtained signal for system C writes

$$\boldsymbol{X}^{(\mathrm{C})} = \sum_{u=1}^{U} \boldsymbol{X}_u^{(\mathrm{B})} , \tag{3}$$

where $\boldsymbol{X}_u^{(\mathrm{B})}$ is the symbol generated by system B when the subcarrier blocks belonging to user $u$ are used. Note that taking $L = 1$ leads to a multiuser DMT system. Hence, the proposed system consists in the generalization of DMT to the use of a frequency spreading component.

## III. Capacity considerations

In this section, we aim at computing the SS-MC-MA system capacity in order to solve the multiuser allocation problem. Along the article, DMT will be considered as the reference system and its capacity will be reminded herein for comparison purposes. Moreover, power spectral density constraint corresponding to power mask specifications will be assumed for both systems.

### A. System A

As always in this paper, system A is considered at first. Let us then assume a single user transmission over a subset $\mathcal{S}_1$ of $L$ subcarriers. After multicarrier demodulation with guard interval removal, zero forcing (ZF) channel correction, and despreading, the received signal carried by the $k$th code is [11]

$$y_k = L s_k + \sum_{l \in \mathcal{S}_1} c_{l,k} \frac{z_l}{h_l} , \tag{4}$$

where $h_l$ is the frequency channel coefficient that belongs to the selected subset $\mathcal{S}_1$ and $z_l$ is the corresponding sample of complex background noise assumed to be Gaussian and white whith variance $N_0$. We suppose a simple receiver structure where each symbol $y_k$ is estimated independently. Thus, the total system capacity is the sum of the system capacities associated with each code $k$. The per-symbol capacity of system A using ZF detection is then

$$\mathcal{C}^{(\mathrm{A})} = \sum_{k=1}^{K_1} \mathcal{C}_k = \sum_{k=1}^{K_1} \log_2 \left( 1 + \frac{\Big(\mathrm{E}\left[y_k\right]\Big)^2}{\mathrm{var}\left[y_k\right]} \right) , \tag{5}$$

where $\Big(\mathrm{E}\left[y_k\right]\Big)^2 = L^2 E_k$ and $\mathrm{var}\left[y_k\right] = \sum_{l \in \mathcal{S}_1} \frac{N_0}{|h_l|^2}$. Then, it comes

$$\mathcal{C}^{(\mathrm{A})} = \sum_{k=1}^{K_1} \log_2 \left( 1 + \frac{L^2}{\sum_{l \in \mathcal{S}_1} \frac{1}{|h_l|^2}} \frac{E_k}{N_0} \right) , \tag{6}$$

and the PSD constraint is expressed as $\sum_{k=1}^{K_1} E_k \leq E$, i.e. the sum of the energies allocated to the different codes transmitted within a given bandwidth must remain under the amount of energy allowed for that bandwidth. Considering the same subset $\mathcal{S}_1$, the capacity of the DMT system writes

$$\mathcal{C}^{(\mathrm{DMT})} = \sum_{l \in \mathcal{S}_1} \log_2 \left( 1 + |h_l|^2 \frac{E}{N_0} \right) , \tag{7}$$

which is the sum of the $L$ capacities per subcarrier.

### B. System B

Let us now consider multiple block transmission over several subsets $\mathcal{S}_b$, $b \in [1, \cdots, B]$ as mentioned for system B. Each received block being processed independently at the receiver side, the capacity of the whole system is then the sum of the system capacities $\mathcal{C}_b^{(\mathrm{A})}$ of each subset $\mathcal{S}_b$ given by (6). This yields

$$\begin{aligned} \mathcal{C}^{(\mathrm{B})} &= \sum_{b=1}^{B} \mathcal{C}_b^{(\mathrm{A})} \\ &= \sum_{b=1}^{B} \sum_{k=1}^{K_b} \log_2 \left( 1 + \frac{L^2}{\sum_{l \in \mathcal{S}_b} \frac{1}{|h_l|^2}} \frac{E_{k,b}}{N_0} \right) . \end{aligned} \tag{8}$$

Following the same analysis, the DMT system capacity is expressed over the same subcarriers using $L = 1$, $K_b = 1$ and $B = N$. When both systems use the same sets of subcarriers it can be shown that $\mathcal{C}^{(\mathrm{DMT})} \geq \mathcal{C}^{(\mathrm{B})}$ for $L > 1$. This result is intuitively expected since DMT allows to achieve maximal capacity whereas system B is not able to, owing to the use of ZF as a detection scheme. Note that equality is obtained for flat fading channels. However, it will be shown that the inequality no more holds when finite order modulations are used.

### C. System C

The capacity of system C is easy to derive from (8), since the blocks of each user are demodulated separately. Hence, expression given by (8) can then be rewritten as

$$\mathcal{C}^{(\mathrm{C})} = \sum_{u=1}^{U} \sum_{b \in \mathcal{B}_u} \sum_{k=1}^{K_b} \log_2 \left( 1 + \frac{L^2}{\sum_{l \in \mathcal{S}_b} \frac{1}{|h_{l,u}|^2}} \frac{E_{k,b}}{N_0} \right) , \tag{9}$$

where $h_{l,u}$ denotes the channel gain of user $u$'s subcarrier $l$ and $\mathcal{B}_u$ is the set of indices $b$ such that subsets $\mathcal{S}_b$ belong to user $u$. As previously stated, the DMT system capacity considering the same subcarriers is expressed using $L = 1$ and also leads to $\mathcal{C}^{(\mathrm{C})} \leq \mathcal{C}^{(\mathrm{DMT})}$ for $L > 1$.

## IV. Single block bit loading

In this part we focus on the optimization of system A. In order to work on reliable throughput rather than capacity bound, a convenient quantity called the signal to noise ratio gap $\Gamma$, sometimes called the *normalized SNR*, is introduced. This gap is a measure of the loss introduced by the QAM with respect to theoretically optimum capacity [19]. With channel coding, the SNR gap is modified to include the coding gain [19]. We also consider another quantity called the noise margin $\gamma$ which is an additional gap. With these two quantities, the throughput achieved with system A, can from (6) be expressed

$$R^{(\mathrm{A})} = \sum_{k=1}^{K_1} R_k = \sum_{k=1}^{K_1} \log_2\left(1 + \frac{1}{\gamma\Gamma} \frac{L^2}{\sum_{l\in\mathcal{S}_1} \frac{1}{|h_l|^2}} \frac{E_k}{N_0}\right), \quad (10)$$

and the DMT throughput is

$$R^{(\mathrm{DMT})} = \sum_{l\in\mathcal{S}_1} R_l = \sum_{l\in\mathcal{S}_1} \log_2\left(1 + \frac{1}{\gamma\Gamma}|h_l|^2 \frac{E}{N_0}\right). \quad (11)$$

Assuming perfect channel state information at the transmitter side, system A optimization can be carried out using (10). Two possible optimization policies can be considered: either the throughput is maximized for a given noise margin $\gamma$, or the noise margin is maximized for a target throughput $R$. Each of these optimization policies results in a so-called *loading algorithm*, which consists in a subcarrier, code, bit, and energy allocation procedure. In this paper, we focus on the throughput maximization with noise margin $\gamma = 1$. In the sequel, $x^*$ will denote optimality of $x$ and $\bar{x}$ will be used to stress the finite granularity assumption used on $x$. Besides, as we only consider single block transmission in this section, subscript $b$ that denotes the block number will be omitted.

### A. Infinite granularity

Let us first investigate the throughput maximization in the case of infinite granularity of the constellations, *i.e.* when $R \in \mathbb{R}$, and with $\gamma = 1$. Constraining the transmit PSD to remain under a given level, the related problem can be formulated as follows

$$(P): \quad \max_{\mathcal{S},K,E_k} \sum_{k=1}^{K} \log_2\left(1 + \frac{1}{\Gamma} \frac{L^2}{\sum_{l\in\mathcal{S}} \frac{1}{|h_l|^2}} \frac{E_k}{N_0}\right) \quad (12)$$

$$\text{subject to} \begin{cases} \text{(C1a)} & \mathcal{S} \subset \mathcal{H} \\ \text{(C2a)} & K \leq L \\ \text{(C3a)} & \sum_{k=1}^{K} E_k \leq E \end{cases}$$

Constraint (C2a) is due to the use of orthogonal spreading sequences and constraint (C3a) is the PSD constraint. To solve $(P)$, we have to choose the number $K$ of codes, the rates $R_k$ and the energies $E_k$ per code, and to select the $L$ subcarriers of subset $\mathcal{S}$ under constraints (C1a), (C2a), and (C3a). Assuming at first that $\mathcal{S}$ is given, the solution to $(P)$ can simply be derived following the Lagrange optimization procedure, which yields the following proposition.

*Proposition 1:* Over a given subset $\mathcal{S}$, the throughput of system A under PSD constraint is maximal for $E_k^* = E/K$ and $K = L$. The optimal achieved throughput is then

$$R^* = L\log_2\left(1 + \frac{1}{\Gamma} \frac{L}{\sum_{l\in\mathcal{S}} \frac{1}{|h_l|^2}} \frac{E}{N_0}\right). \quad (13)$$

Proposition 1 simply says that system A reaches maximum throughput at full load and for an equal sharing of energy among the codes. Likewise, it follows immediately that the total throughput has also to be equally distributed among the $L$ codes, *i.e.* $\forall k$, $R_k^* = R^*/L$. Hence, the throughput maximization problem leads to a very simple solution which consists in achieving a uniform bit and energy distribution among the codes. This allocation policy is intuitively applied in most of MC-SS combined systems.

The best subcarrier subset $\mathcal{S}^*$ must now be found to complete the optimization problem. From (13), the optimal subset selection is obtained basically invoking that $f(x) = \ln(1+1/x)$ is a decreasing function for $x > 0$. This leads to the following proposition

*Proposition 2:* The optimal subcarrier subset $\mathcal{S}^*$ that maximizes the throughput (13) is such that $\forall l \in \mathcal{S}^*$, $\forall l' \notin \mathcal{S}^*$, $|h_l| \geq |h_{l'}|$.

Proposition 2 says that the $L$ subcarriers of system A must be selected among the "best" ones, meaning by best subcarriers the subcarriers with the highest power gains $|h_i|^2$. Hence, both propositions give a fairly simple procedure to the throughput maximization task when no constraint on the constellation granularity is considered.

### B. Finite granularity

If we now consider the use of discrete modulations, the maximization problem gets a bit trickier. The bit rates are constrained to be integer and theoretical throughput $R^*$ can not be achieved. Furthermore, each expected $R_k^*$ may not be a multiple of $L$, which prevents from uniformly distributing bits among the codes as wanted by Proposition 1. The maximization problem $(P)$ must then be restated taking into account the integer constraint. Note that the finite granularity assumption still holds with channel coding, even if the bit rates can become non-integer. Based on the intuitive idea that bits should be distributed among the codes as uniformly as possible, the following theorem gives the optimal loading solution to the stated problem. This result represents one of the major contributions of the paper.

*Theorem 1:* Let $\mathcal{R}$ be the bit allocation policy. Under PSD constraint and assuming finite granularity of rates, the achievable throughput is maximal when $\mathcal{R}$ assigns $\lfloor R^*/L \rfloor + 1$ bits to $\lfloor L(2^{R^*/L - \lfloor R^*/L \rfloor} - 1) \rfloor$ codes and $\lfloor R^*/L \rfloor$ bits to $L - \lfloor L(2^{R^*/L - \lfloor R^*/L \rfloor} - 1) \rfloor$ codes.

*Proof:* From Proposition 1, $R^*$ is the maximal achievable throughput of the system. We have to distribute $\lfloor R^* \rfloor$ bits *at most* among the $L$ available codes, so that each code receives an integer number of bits, *and* that the related energy cost meets the PSD constraint. Let us write $R^* = p + qL$, with $q = \lfloor R^*/L \rfloor$. If $p = 0$ the proof is obvious and $q$ bits are assigned to each code. Otherwise, a potential solution is to assign $q$ bits to each code and to distribute $n$ bits among the $p$ remaining bits to $n$ codes. As we *a priori* do not know if the $\lfloor R^* \rfloor$ bits can be allocated while verifying the PSD constraint, $n$ is such that $n \in [0; \lfloor p \rfloor]$. Hence, $n$ codes receive $q+1$ bits and $L-n$ codes receive $q$ bits. Let denote $\mathcal{R}^*$ such an allocation policy. We have (i) to prove that $\mathcal{R}^*$ costs minimum energy for a given $n$, and (ii) to find the largest $n$ with respect to the PSD constraint.

Let us first prove (i). From (10), the energy cost expresses

$$\sum_{k=1}^{L} E_k = \frac{1}{\alpha} \sum_{k=1}^{L} (2^{R_k} - 1), \qquad (14)$$

with $\alpha = L^2 / \sum_{l \in \mathcal{S}} \frac{N_0 \Gamma}{|h_l|^2}$. Hence, the proof amounts to demonstrate that $\mathcal{R}^*$ minimizes $\sum_{k=1}^{L} 2^{R_k}$. Therefore, for any allocation policy $\mathcal{R}$, we define function $f(\mathcal{R}) = \sum_{k=1}^{L} 2^{R_k}$ with $R_k$ given by $\mathcal{R}$. Without loss of generality, suppose that the bits are initially allocated with respect to $\mathcal{R}^*$ and let us show that any bit exchange leads to a higher energy spent, *i.e.* $f(\mathcal{R}) - f(\mathcal{R}^*) > 0 \; \forall \mathcal{R}$. We firstly consider the allocation policy defined by the bit exchange $R_i = q \mapsto q + a$ and $R_j = q \mapsto q - a$ for some $i, j$ and $a > 1$. We have

$$\begin{aligned} f(\mathcal{R}) - f(\mathcal{R}^*) &= n 2^{q+1} + (L - n - 2) 2^q + 2^{q+a} \\ &\quad + 2^{q-a} - n 2^{q+1} - (L-n) 2^q \\ &= 2^{q-a} \left( 2^{a+1} (2^{a-1} - 1) + 1 \right) . \end{aligned} \qquad (15)$$

Since $a > 1$, $f(\mathcal{R}) - f(\mathcal{R}^*) > 0$. Following the same analysis for the three cases

$$\begin{cases} R_i = q & \mapsto q + a \\ R_j = q + 1 \mapsto q + 1 - a \end{cases}, \begin{cases} R_i = q + 1 \mapsto q + 1 + a \\ R_j = q & \mapsto q - a \end{cases}$$

$$\text{and} \quad \begin{cases} R_i = q + 1 \mapsto q + 1 + a \\ R_j = q + 1 \mapsto q + 1 - a \end{cases}$$

leads to the same conclusion. Then, the allocation policy $\mathcal{R}^*$ minimizes $f$, and thus minimizes the energy spent $\sum_{k=1}^{L} E_k$, which proves (i).

Let us now solve (ii). This consists in finding the largest $n$ such that $\sum_{k=1}^{L} E_k \leq E$, which amounts to solve the following inequalities

$$\begin{aligned} E - \sum_{k=1}^{L} E_k = &\frac{L}{\alpha} \left( 2^{R^*/L} - 1 \right) - \frac{n}{\alpha} \left( 2^{\lfloor R^*/L \rfloor + 1} - 1 \right) \\ &- \frac{L-n}{\alpha} \left( 2^{\lfloor R^*/L \rfloor} - 1 \right) \geq 0 , \end{aligned} \qquad (16)$$

$$\begin{aligned} E - \sum_{k=1}^{L} E_k = &\frac{L}{\alpha} \left( 2^{R^*/L} - 1 \right) - \frac{n+1}{\alpha} \left( 2^{\lfloor R^*/L \rfloor + 1} - 1 \right) \\ &- \frac{L-(n+1)}{\alpha} \left( 2^{\lfloor R^*/L \rfloor} - 1 \right) < 0 . \end{aligned} \qquad (17)$$

This leads to $n \leq L(2^{R^*/L - \lfloor R^*/L \rfloor} - 1)$, and to $n + 1 > L(2^{R^*/L - \lfloor R^*/L \rfloor} - 1)$. Hence the largest $n$ is $\lfloor L(2^{R^*/L - \lfloor R^*/L \rfloor} - 1) \rfloor$. This solves (ii), and completes the proof. ■

Theorem 1 gives the closed form solution to the optimal bit allocation problem when finite granularity is assumed. The maximal achieved throughput, denoted $\bar{R}^*$, then expresses

$$\begin{aligned} \bar{R}^* = &\left( \lfloor L(2^{R^*/L - \lfloor R^*/L \rfloor} - 1) \rfloor \right) \left( \lfloor R^*/L \rfloor + 1 \right) \\ &+ \left( L - \lfloor L(2^{R^*/L - \lfloor R^*/L \rfloor} - 1) \rfloor \right) \left( \lfloor R^*/L \rfloor \right) \end{aligned} \qquad (18)$$

Note that $\bar{R}^* \leq R^*$ and equality is obtained when $\frac{R^*}{L} \in \mathbb{N}$. If we have $R^* < L$, then some codes will not receive any bit, and the number of codes used will be $K = L - \lfloor L(2^{R^*/L - \lfloor R^*/L \rfloor} - 1) \rfloor$. The bit distribution can finally be computed from $\bar{R}_k^*$ using (10) with $\gamma = 1$,

$$\bar{E}_k^* = \frac{\Gamma}{L^2} \sum_{l \in \mathcal{S}} \frac{N_0}{|h_l|^2} \left( 2^{\bar{R}_k^*} - 1 \right). \qquad (19)$$

Concerning the subset choice, it is straightforward that the optimal subset $\mathcal{S}^*$ given by Proposition 2 in the case of infinite granularity is also optimal when finite granularity is assumed, since we can express $\bar{R}^* = f(R^*)$ where $f$ is an increasing function. However, as $f$ is non bijective, Proposition 2 gives a sufficient but not necessary condition to the subset selection in the finite granularity case. Consequently, there exists a set of subcarrier subsets $\bar{\mathcal{S}}^*$ for which the optimal throughput $\bar{R}^*$ can be reached. For $R_k \in \mathbb{N}$, Proposition 2 can then be restated as follows. The proof is obtained using (13) and (19).

*Proposition 3:* Let $\bar{\mathcal{W}}^*$ be the set of the subcarrier subsets $\bar{\mathcal{S}}^*$ for which system A can achieve maximal throughput $\bar{R}^*$. $\forall \bar{\mathcal{S}}^* \subset \bar{\mathcal{W}}^*$, we have

$$\sum_{l \in \mathcal{S}^*} \frac{1}{|h_l|^2} \leq \sum_{l \in \bar{\mathcal{S}}^*} \frac{1}{|h_l|^2} \leq \frac{L^2}{\Gamma N_0} \frac{E}{\sum_{k=1}^{L} (2^{\bar{R}_k^*} - 1)} . \qquad (20)$$

One can check that $\mathcal{S}^* \subset \bar{\mathcal{W}}^*$ and equalities in Proposition 3 are obtained when $\bar{R}^* = R^*$. The left term of the inequality corresponds to the subset made up of the best subcarriers and leads to the lowest energy spent, while the right term is obtained for a subset that leads to the highest energy spent, that is when the system reaches the PSD level limit.

Eventually, Theorem 1, Proposition 3 and (19) give the allocation procedure that maximizes the throughput of system A. The algorithm is described in Fig. 3. Note that we propose to select the best subcarriers to form subset $\bar{\mathcal{S}}^*$, which corresponds to the case of minimal energy spent. Hence, we equivalently use $\bar{\mathcal{S}}^*$ or $\mathcal{S}^*$. The algorithm requires low computations resource since only two values $\bar{E}_k$ and $\bar{R}_k$ must be found.

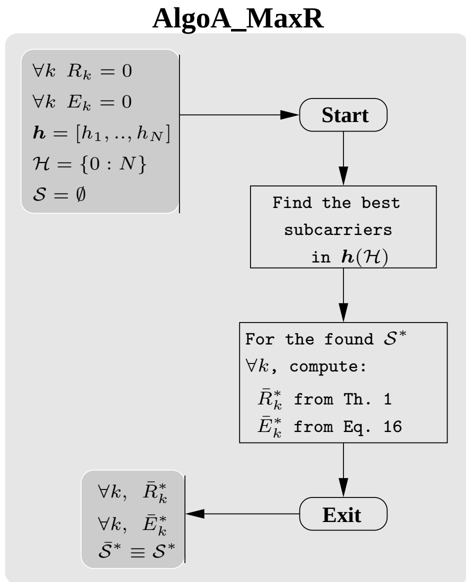


Fig. 3. Rate maximization algorithm of the single block system

Concerning DMT, throughput maximization is fairly simple under PSD constraint and consists in allocating maximum rate $\lfloor R_l \rfloor$ given by (11) to each subcarrier $l$ of the selected subset.

## V. Multiple block bit loading

The previous propositions and theorems give the solution to the throughput maximization problem in the case of the single block single user SS-MC-MA system, *i.e.* system A. In the knowledge of those results, we are now ready to investigate the case of the other two systems. The optimal solution to the subcarrier distribution task will be studied in the infinite granularity case, and then exploited to provide suboptimal but practical loading algorithms in the finite granularity case.

### A. Single user case

Let us first study the bit allocation algorithm for system B. Taking into account the noise gap $\Gamma$ the achievable throughput expresses from (8)

$$\begin{aligned} R^{(\mathrm{B})} &= \sum_{b=1}^{B} R_b \\ &= \sum_{b=1}^{B} \sum_{k=1}^{K_b} \log_2 \left( 1 + \frac{1}{\Gamma} \frac{L^2}{\sum_{l \in \mathcal{S}_b} \frac{1}{|h_l|^2}} \frac{E_{k,b}}{N_0} \right), \end{aligned} \quad (21)$$

where $R_b$ is the achieved rate on subset $\mathcal{S}_b$. The maximization problem can then be formulated,

$$(P): \quad \max_{\mathcal{S}_b, K_b, E_{k,b}} \sum_{b=1}^{B} R_b$$

$$\text{subject to} \begin{cases} \text{(C1b)} & \forall b \ \mathcal{S}_b \subset \mathcal{H} \ \text{ and } \forall b \neq b' \ \mathcal{S}_b \cap \mathcal{S}'_b = \emptyset \\ \text{(C2b)} & \forall b \ K_b \leq L \\ \text{(C3b)} & \forall b \ \sum_{k=1}^{K_b} E_{k,b} \leq E \end{cases}$$

Considering infinite granularity, $(P)$ can immediately be restated exploiting Proposition 1

$$(P): \quad \max_{\mathcal{S}_b} \sum_{b=1}^{B} R_b^* \quad \text{subject to (C1b).} \qquad (22)$$

where $R_b^*$ is the optimal achieved rate on subset $\mathcal{S}_b$ from Proposition 1. Hence, only the subset allocation has still to be optimized, which is the purpose of the following proposition.

*Proposition 4:* The optimal subcarrier subsets $\mathcal{S}_b^*$ that maximize the throughput are such that $\forall b \neq b', \forall l \subset \mathcal{S}_b^*, \forall l' \subset \mathcal{S}_{b'}^*, |h_l| \geq |h_{l'}|$.

*Proof:* We have basically to show that any subcarrier swapping between two subsets $\mathcal{S}_b^*$ and $\mathcal{S}_{b'}^*$ given by the proposition leads to a rate loss. This is done using simple derivative study of a sum of logarithm functions. ■

Proposition 4 is the immediate generalization of Proposition 2 to the case of multiple blocks. A practical solution to make use of Proposition 4 is to sort the subcarriers in ascending (or descending) order of power gain.

If the finite granularity case is considered, problem $(P)$ becomes:

$$(P): \quad \max_{\mathcal{S}_b} \sum_{b=1}^{B} \bar{R}_b^* \quad \text{subject to (C1b),} \qquad (23)$$

using the optimal loading policy derived in Theorem 1. As highlighted by our discussion about Proposition 3, the subset choice $\bar{\mathcal{S}}_b^*$ that guarantees an achieved rate $\bar{R}_b^*$ is not unique. Applying Proposition 4 in the finite granularity case actually results in a suboptimal solution to $(P)$. Some good subcarriers could indeed be spared on subset $\mathcal{S}_b^*$ and be re-allocated to another subset $\mathcal{S}_{b'}^*$ in order to increase the rate $\bar{R}_{b'}^*$ without modifying $\bar{R}_b^*$. The optimal subset choice would consist in finding the subcarriers that fully exploit the PSD in each subset $\mathcal{S}_b^*$, that is to say the subcarriers yielding the second equality in (20). This optimal solution could be obtained following a subcarrier swapping approach after the initial subcarrier distribution given by Proposition 4. The resulting rate gain would however not be sufficiently high to compensate for the complexity increase of such a solution[2]. Therefore, we will directly exploit Proposition 4 to select the subsets in system B. Hence, the obtained algorithm is suboptimal in

[2]The maximum rate gain is actually less than one bit per block, *i.e.* the total rate gain $\Delta_R$ is such as $\Delta_R < \frac{N}{L}$.

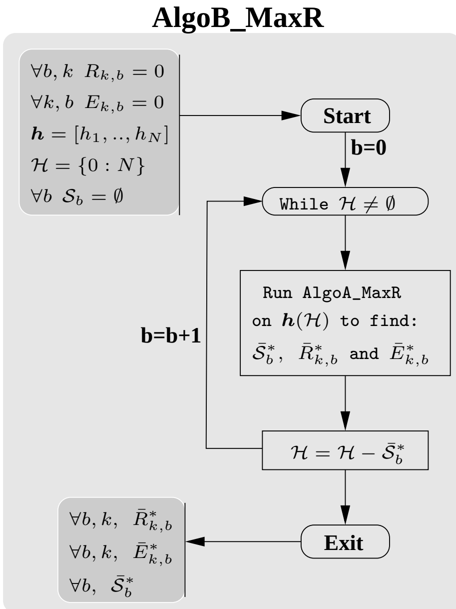


Fig. 4. Rate maximization algorithm of the single user multiple block system

the sense that the subcarrier allocation procedure is suboptimal. Nevertheless, the bit and energy loading procedure remains optimal for the selected subsets.

The structure of the algorithm is presented in Fig. 4. It simply consists in iteratively running the algorithm proposed for system A until the whole set of available subcarriers is exploited. At each iteration, a new subset is formed with the best remaining subcarriers, and the optimal bit and energy loading procedure of system A is carried out. The subcarriers can be sorted at the beginning of the algorithm to easy the selection of the good subcarriers at each iteration. Finally, it is worth noting that the proposed algorithm can also be exploited with DMT since system B is equivalent to DMT when $L = 1$.

### B. Multiple user case

Let us finally investigate the whole allocation loading task. Let us denote $R_u$ the rate assigned to user $u$. The aim of the multiple user throughput maximization algorithm is to maximize each individual throughput $R_u$ rather than to maximize the total throughput of the system. This can be formulated as:

$$(P): \quad \max_{\{\mathcal{B}_u,\ \mathcal{S}_b\},\ K_b,\ E_{k,b}} \quad \min_{u} \ R_u \ , \quad \text{subject to} \begin{cases} \text{(C1b)}, & \text{(C2b)},\ \text{(C3b)}, \\ \text{(C4b)}, & \forall u \ \mathcal{B}_u \subset \{1, \cdots, B\} \\ & \text{and } \forall u \neq u',\ \mathcal{B}_u \cap \mathcal{B}_{u'} = \emptyset \end{cases} \tag{24}$$

with $R_u = \sum_{b \subset \mathcal{B}_u} R_b$. Constraint (C4b) ensures that the users can neither share the same subset nor share the same subcarriers and thus guarantees FDMA. Considering Theorem 1, the problem reduces to the max-min problem

$$(P): \quad \max_{\{\mathcal{B}_u,\ \mathcal{S}_b\}} \ \min_{u} \sum_{b \subset \mathcal{B}_u} \bar{R}_b^* \quad \text{subject to (C1b) and (C4b).} \tag{25}$$

The optimization problem essentially consists in finding and assigning the different subsets so that each user can transmit a number of bits as high as possible. This is actually a complex combinatorial optimization problem. To find the optimal solution, $(P)$ should be formulated into a standard convex optimization problem. However, the resulting algorithm would require an intensive computation due to the recursive nature of solving a convex optimization problem. This is why a greedy approach is eventually used, which leads to a suboptimal but fairly simple solution. Basically, it consists in iteratively assigning one block of best subcarriers to the user that has the lowest instantaneous rate. As an FDMA approach is carried out, allocating bits to a subcarrier prevents other users from using that subcarrier. This dependency is the very reason of the suboptimality of *any* greedy algorithm [28]. Nevertheless, we will see in simulations that the proposed scheme offers very satisfying results.

The algorithm is presented in Fig. 5. As mentioned in the figure, the algorithm is composed of three main stages. The initialization stage computes, for each user, the maximal rate achieved if a single user multiple block communication is considered, *i.e.* if system B is employed by each user independently. Therefore, the throughput maximization algorithm of system B is run. This step is useful to establish in which order the $U$ first subsets have to be allocated to the users. The so-obtained priority order is used in the second stage to assign a first block of subcarriers to each user. The user with the smallest computed rate $\bar{R}_u^*$ is considered at first, then the second smallest, and so on. The subcarriers are selected among the best ones to provide the highest rate to each user. The throughput maximization algorithm of system A is thus exploited. At the end of this stage, each user owns one block of subcarriers and in the final stage, the iterative process corresponding to the greedy approach is run. At each iteration, the user with the smallest rate $R_u$ is selected and is assigned a new subset $\mathcal{S}_b$ which leads to the highest increase of its rate, which is handled by system A's maximum throughput algorithm. The algorithm ends when no more subcarriers are available.

Note finally that, when $L = 1$, the proposed algorithm can be applied to multiple user DMT systems. The subcarrier distribution strategy is then very close to that proposed in [23] except that some priority order is considered in the initialization stage and that the SNR gap is taken into account in our algorithm.

## VI. Simulation results

In this section, we will present simulation results for the proposed adaptive SS-MC-MA scheme and we will compare the performance of the new scheme with the performance of DMT, *i.e.* when $L = 1$. The generated

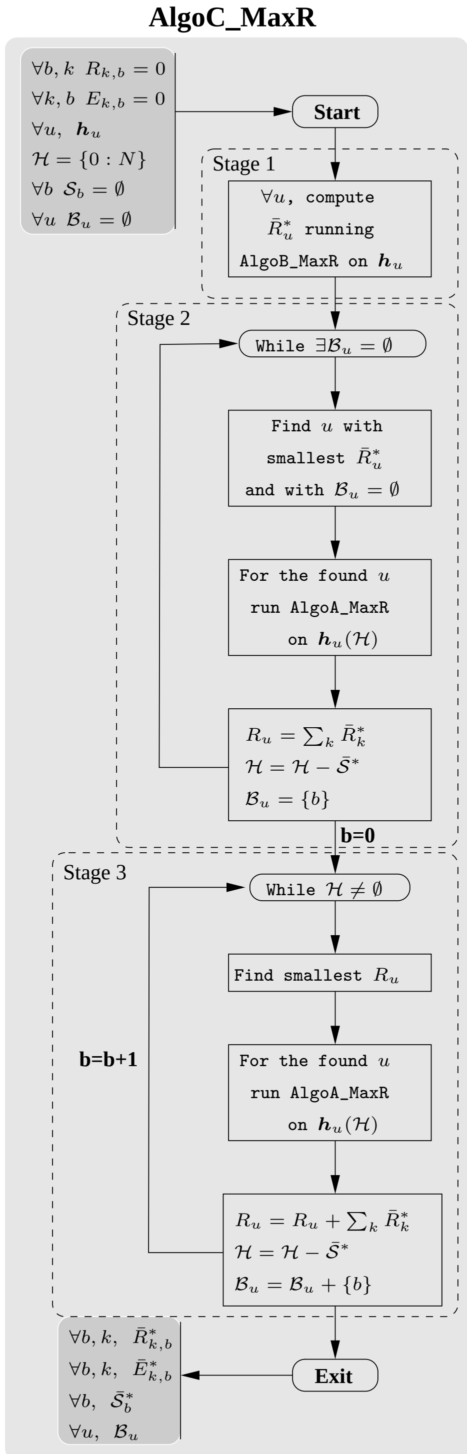


Fig. 5. Rate maximization algorithm of the proposed SS-MC-MA system

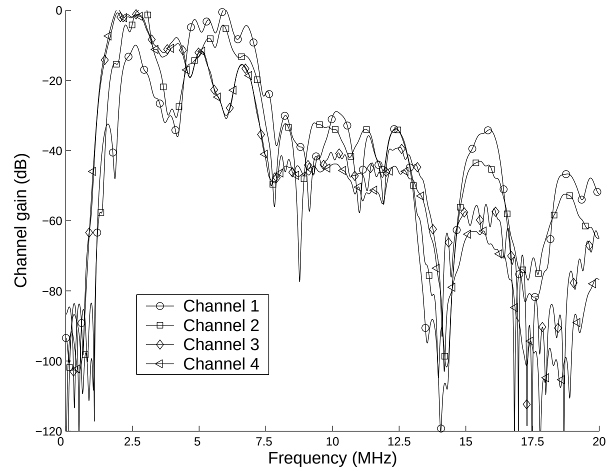


Fig. 6. Examples of normalized measured PLC channel responses

SS-MC-MA signal is composed of $N = 2048$ subcarriers transmitted in the band $[0 - 20]$ MHz. The subcarrier spacing equals 9.765 kHz and a long enough cyclic prefix is used to overcome intersymbol interference [29]. We assume that the synchronization and channel estimation tasks have successfully been treated. We use power line channel responses, displayed in Fig 6, that have been measured in an outdoor residential network by the French power company *Electricité de France* (EDF). We apply the proposed algorithms to the case of a 4-user communication over these channels. We assume a background noise level of $-110$ dBm/Hz and the signal is transmitted with respect to a flat PSD of $-30$ dBm/Hz. We consider that $2^q$-ary QAM are employed with $q = [2 : 15]$ as in DSL specifications. Results are given for a target SER of $10^{-3}$ corresponding to an SNR gap $\Gamma = 6$ dB without channel coding.

Fig. 7 shows the achieved average rates per user versus the average channel gain $G = \frac{1}{N}\sum_n |h_n|^2$ which conveys the attenuation experienced by the signal through the channel. Rates are expressed in bit per multicarrier symbol (bit/symb). The corresponding SNR is then given by $SNR = -30 + G_{dB} + 110$. The system performance is presented for a spreading factor $L = 64$ with SS-MC-MA and for $L = 1$ with DMT, in the case of infinite and finite granularity. As expected from section III, achieved rates are slightly higher with DMT when granularity is infinite, since DMT represents the optimal solution. In the finite granularity case however, both schemes achieve lower throughputs, which is due to the combined effect of the PSD constraint and discrete modulation requirements. Nevertheless, SS-MC-MA exhibits the lowest throughput loss and performs closer to the infinite granularity upper-bound than DMT when the channel gain is low. Note that a saturation floor is reached for high channel gains corresponding to high SNR. This is simply due to the modulation order limitation. In that case, the PSD constraint is no more preponderant, which explains that both schemes perform very close to each other.

In order to emphasize the behavior differences between SS-MC-MA and DMT, the same results are presented in Fig. 8 relatively to the DMT performance with infinite granularity denoted as the reference curve. It is then highlighted that SS-MC-MA outperforms DMT. Furthermore, it is worth noting that the SS-MC-MA system is all the more interesting than the channel gain is low, *i.e.* the reception SNR is low. For instance, at an average

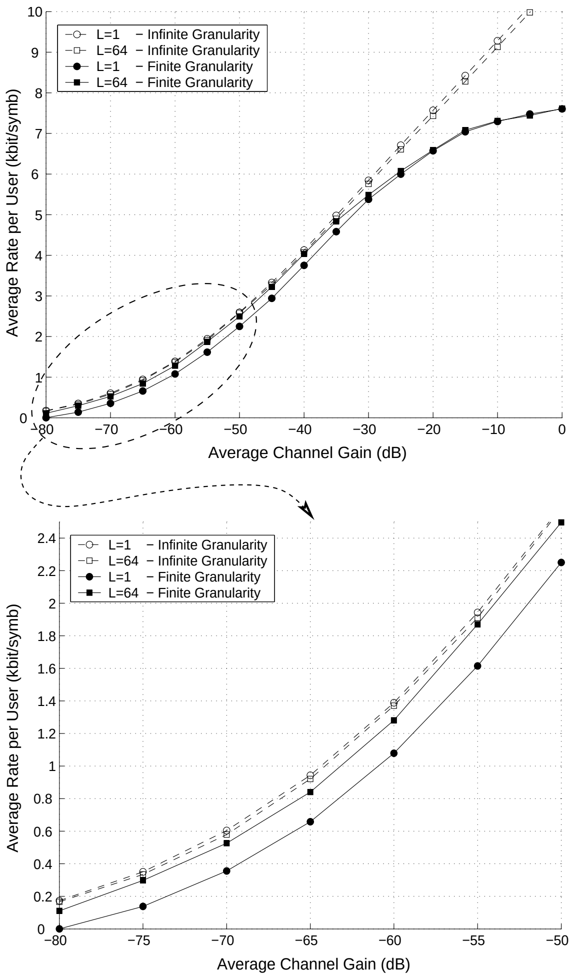


Fig. 7. Achieved throughputs for the proposed algorithm with infinite granularity (IG) and finite granularity (FG) versus average channel gain

channel gain of -70 dB, the throughput loss with finite granularity is less than 15% with SS-MC-MA while it is around 40% with DMT. The important conclusion is that the spreading function can improve rate allocation when discrete constellations are used under PSD constraint. The reason is that the DMT is not able to exploit the total amount of energy available on each subcarrier in the case of PSD constraint and finite order modulations, while the spreading component of SS-MC-MA allows the subcarriers of a same subset to pool their energy to transmit one or more additional bits. SS-MC-MA gives rise to significant throughput gains, especially when the total throughput is low. It is interesting to note that SS-MC-MA can almost transmit 65% of the achievable rate at a channel gain of -80 dB, corresponding to SNR=0 dB, while DMT can not transmit any more rate in the same conditions. Hence, we conclude that the proposed system can especially be advantageously exploited for poor SNR. This is equivalent to claim that the spreading component allows to ensure reliable communications over long lines. The proposed system can then be used in order to increase the range

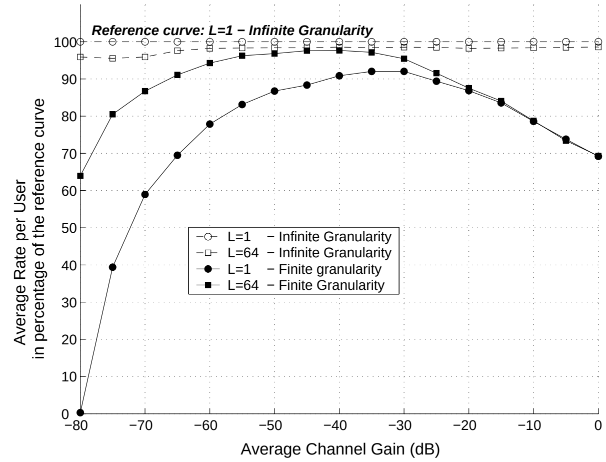


Fig. 8. Achieved throughputs for the proposed algorithm evaluated in percentage of the reference system: Lc=1 with infinite granularity

of PLC systems.

Fig. 9 exhibits the rates achieved by each user for several spreading factors and for a channel gain of $-60$ dB. It clearly appears that results are improved when $L > 1$, which validates the benefit of the spreading component. For a spreading factor of 16 for example, SS-MC-MA can transmit 1260 bits per symbol and for each of the 4 users, while DMT only offers 960 bits per symbol and per user, which represents a throughput gain of 34%. The corresponding total throughput is around 49,2 Mbps for SS-MC-MA and 37,6 Mbps for DMT, within a bandwidth of 20 MHz. The rate gain saturates from a certain spreading factor and the system is more efficient in assigning equal rates to users when $L$ remains not to large. The rate dispersal is due to the spectrum sharing policy of the proposed algorithm. Due to the greedy approach, the subcarrier distribution efficiency depends on the subcarrier block size, or more precisely on ratio $L/N$. It can actually be shown that if $L \ll N$, then individual rates converge to the same value. Thus, there is a trade-off in the spreading factor choice. On one hand, the spreading factor has to be sufficiently large to significantly increase the throughput, and on the other hand, the spreading factor has to be restrained to a relatively small value to ensure uniformly distributed rates among users. Recall that such imperfection is only due to the sub-optimality of the subcarrier sharing method used herein, which could be improved by a subcarrier swapping approach. Eventually, a spreading factor between 16 and 32 turns out to be the best trade-off.

## VII. Conclusion

In this paper, we proposed an adaptive SS-MC-MA system suitable to backward and forward links of PLC networks. We introduced a novel loading algorithm that handles the subcarrier, code, bit and energy resource distribution among the active users of the system. We focus on the system throughput maximization constrained to PSD limitations and finite order modulations. We derived the optimal solution in the case of single user and single

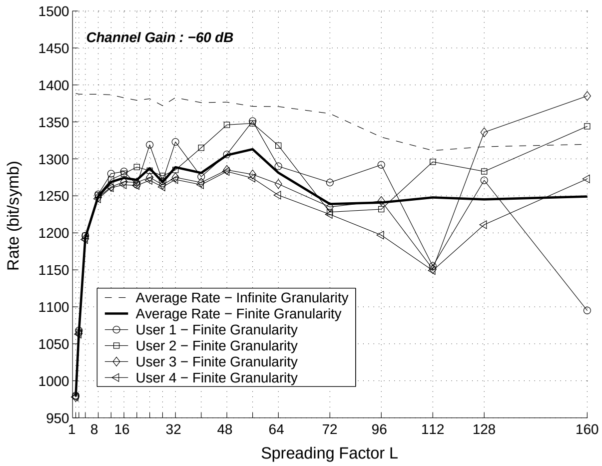


Fig. 9. Achieved throughputs versus code length for an average gain of -60 dB

block transmissions and proposed a simple algorithm in the case of multiple user and multiple block transmissions. In the latter algorithm, the subcarrier distribution strategy is based on a greedy approach which represents a suboptimal but practical solution to the stated problem.

We analyzed the performance of the new system and compared the results to those obtained with the DMT system. It was highlighted that DMT is equivalent to the proposed SS-MC-MA system with $L = 1$. The spreading component was shown to provide throughput gain especially for low channel gains. This behavior was explained by the energy gathering capability of SS-MC-MA within each subcarrier block. Contrary to DMT, the proposed system can exploit the residual energy conveyed by each subcarrier because of the finite granularity of the QAM modulations. These algorithms can be straightforwardly exploited to compare both systems with channel coding, i.e. using specific code/signal-constellation pairs. We can expect that SS-MC-MA will then keep its advantage but that the bit rate difference will be reduced. Furthermore, we can note that spreading component leads to a very low increase of the complexity. The additional cost is then limited.

We also investigated how the rate distribution among users was influenced by the spreading factor. It was shown that SS-MC-MA was all the more efficient in equally distributing rates than the spreading factor was small. Eventually, it raised a trade-off concerning the spreading factor choice. On one hand, the spreading factor has to be sufficiently large to increase the throughput, and on the other hand, it has to remain relatively small to ensure uniformly distributed rates. For well-chosen spreading factors, we then concluded that the proposed adaptive system was able to transmit higher rates than DMT. The proposed results thus demonstrated that SS-MC-MA could improve the range of PLC systems.

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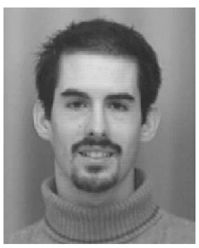

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