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***Abstract*—Power-line communications (PLC) is recognized as an alternative technology for delivering broadband services in home and small-office environments. Multicarrier modulation is one of the most effective solutions for combating the imperfections of the power-line channel. One of the technical challenges in increasing the potentiality of PLC technology is the utilization of the available spectrum when different users compete for the available resources. Due to the frequency and time-varying characteristics of the power-line network, the various users experience different channel conditions, thus the application of efficient resource allocation will increase the overall network performance. This paper addresses the problem of subchannel and power allocation for indoor PLC networks with multiple links employing power spectral density limitations, and presents an efficient multiuser loading algorithm. The proposed solution encounters both uplink and downlink traffic, guarantees a set of minimum data rates to all users, and allocates the available resources with fairness according to the channel quality of each link. We demonstrate the performance of the proposed algorithm using an illustrative example of a typical indoor network and we examine its effectiveness under various channel conditions.**

***Index Terms*—Bandwidth optimization, bit-loading, fading channels, indoor power-line network, multicarrier communications, multiuser resource allocation, power-line communications.**

I. Introduction

POWER-LINE COMMUNICATIONS (PLC) receive increasing interest as a potential solution for delivering broadband services over the power grid [1]. Due to the wide availability of the power-line medium, PLC is considered as a promising technology for in-building networking [2] as well as for the last mile access [3]. Recent results based on theoretical analysis and field tests report a competitive performance of emerging PLC solutions for inhome networking compared with other candidate technologies [4], [5]. One technical challenge in increasing the potentiality of the PLC technology is the utilization of the available spectrum. Due to its primary and original use of conveying electrical power, the power-line medium is a harsh environment for data transmission. In particular, the low-voltage power-line channel is a frequency selective fading channel with time-varying characteristics and suffers from colored and impulsive noise generated by electrical appliances and external sources [6]. In addition, the power-line channel response depends on the network's topology and loading conditions [7]. The use of advanced signal processing and efficient coding techniques is necessary in order to compensate the restrictions of the power-line channel imperfections [8], [9].

The utilization of the power-line medium is investigated from many aspects, like efficient signal transmission and medium access control [1]. Multicarrier-modulation (MCM) techniques have shown enhanced system performance in combating the multipath fading and intersymbol-interference (ISI) characteristics of the power-line channel [10]. MCM studies over PLC networks mainly focus on orthogonal frequency-division multiplexing (OFDM) techniques, that decompose the available bandwidth into orthogonal narrowband subchannels. One of the crucial issues in OFDM transmission is the allocation of the power resources to the available subchannels. This task is accomplished by an appropriate bit-loading algorithm. When the communicating devices are aware of the channel state information (CSI), optimum power allocation is possible by assigning different number of bits in each subcarrier according to the signal-to-noise ratio (SNR) of each subchannel [11]. OFDM is particulary suitable for frequency selective channels, such as the power-line channel, and enables efficient spectrum utilization by zeroing tones, which either are in deep fades or are reserved due to regulatory issues [12]. Moreover, the experience gained in other well-established wireless and wired applications that employ multicarrier transmission, such as 802.11 in wireless local-area networks (WLANs) [13] and digital subscriber lines (DSL) [14], has given rise in the investigation of various techniques of multiuser OFDM under the particular characteristics of the PLC environment [15]–[17].

This paper addresses the problem of resources allocation management in OFDM power-line networks consisting of multiple bidirectional point-to-point links between data communications devices and a central networking device. In particular, we consider the indoor low-voltage power-line network, where the PLC devices are connected at various termination points (power sockets). Fig. 1 shows an illustrative example of an inhome PLC network, where several user devices establish bidirectional links with a central device, the PLC gateway. The latter acts as the network's management unit and as the interface with the backbone communications infrastructure that provides Internet connectivity via a high-speed broadband link [e.g., asymmetric digital subscriber line (ADSL)]. Thus, the PLC gateway routes the local data traffic to the Internet or to the user terminals [4]. Each link in the PLC network generally experiences different channel conditions, which are subject to

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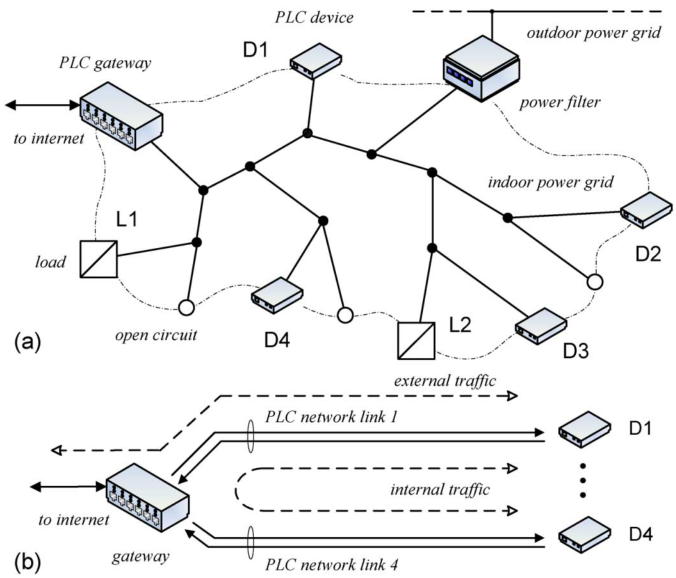

Fig. 1. General example of indoor PLC network infrastructure: (a) power grid and (b) communications topology.

change as the network's loading changes [7] (e.g., different loads are plugged in (out of) the network). Therefore, under a given network loading, several subchannels may become unsuitable for transmission for some links, but suitable for other links. This situation is known as multiuser diversity and stems from channel diversity. The problem under investigation is the allocation of the available bandwidth and power resources to the different users in the context of frequency-division multiple-access (FDMA). FDMA imposes that each subchannel is assigned to one user only and to one direction of transmission, either in the downlink (from the gateway to user devices), or in the uplink (from user devices to the gateway), that is, all users share the same medium and transmit in specific nonoverlapping frequency bands.

Recently, a lot of effort has been devoted to adaptive multiuser loading techniques in FDMA multicarrier systems [15]–[22]. Multiuser resource allocation is a constraint optimization problem and, generally, it is treated either in the downlink or in the uplink. There are two basic classes of multiuser loading problems based on the optimization objective, namely rate adaptive and margin adaptive. The rate adaptive objective is the maximization of the sum of user rates subject to overall power constraints [18], while the margin adaptive objective is the minimization of the total power given a set of user data rates [19]. In the latter case, the solution exists only if the requested target rates can be supported. Since, the PLC channel conditions exhibit significant variations as the network's loading changes, the *a priori* definition of a guaranteed high target-rate set for all links is not possible. Therefore, the strategy of maximizing the overall network rate subject to a minimum rate requirement for each user seems more appropriate for the indoor PLC environment.

Maximizing the sum of rates imposes that each subchannel is assigned to the user with the best channel quality [18]. Such an allocation rule may penalize the users with poor or even moderate channel conditions, thus a fairness issue is raised. The problem in [20] aims in maximizing the worst rate in the network. The max–min strategy results in similar user rates; thus, it is not appropriate when different rates are requested (e.g., for supporting different types of services), while generally it results in lower overall network rate by suppressing the capacity of users with high channel quality. In [21] and [22], the requirement for proportional fairness in the achievable user rates is formulated subject to a set of nonlinear constraints and suboptimum solutions are provided. In [23], the concept of balanced capacity is proposed; however, the allocation problem is not FDMA, rather it considers the multiuser capacity region achieved with successive message decoding and cancellation at each receiver.

In this work, we investigate the problem of multiuser resource allocation for ODFM indoor PLC networks including both downlink and uplink, subject to a common power spectral density (PSD) mask constraint. Assuming L active PLC devices in Fig. 1, we have L downstream and L upstream links. Due to the frequency and time-varying nature of the indoor power-line channel, a fixed downlink–uplink subchannel assignment may be insufficient to support the total downstream and upstream traffic requirements. Therefore, efficient subchannel allocation for both directions of transmission is necessary in order to increase the overall network performance. The proposed resource allocation management aims to provide a set of minimum data rates for all links and to allocate the remaining resources with fairness according to the quality of each link. In order to examine the resource allocation issues, we formulate the multiuser loading problem as a constraint optimization problem, where the objective is the maximization of the total network rate and the constraints are properly defined in order to encounter the above targets. In this paper, we present a low-complexity suboptimum solution based on a round robin allocation scheme with user priorities that provides joint subcarrier and power allocation.

Section II presents the multiple access channel environment of the indoor PLC network using an indicative power grid topology and addresses the requirement for fair resource allocation for both upstream and downstream links. Section III formulates the multiuser loading problem, discusses the relation between channel quality and proportional rate fairness, and also examines the minimum data rate strategy. Section IV describes the new discrete multiuser loading algorithm, while Section V provides numerical results that demonstrate the performance and the effectiveness of the proposed algorithm for different network loading scenarios.

II. Indoor PLC Multiaccess Channel

Fig. 2 shows an indicative topology of an indoor PLC network, where the power grid consists of several interconnected cable sections; the numbers in brackets give the length of each section in meters. There are 14 termination points (outlets), denoted as T_i ($i = 1, \ldots, 14$). At T_6, an appropriate coupling power filter with constant impedance is connected between the PLC network under consideration and the rest of the power grid. In our example, we consider the central networking device at T_1 and data communications devices at termination points $\mathrm{T}_{2,7,8,10,13}$. In such a network, the channel response between

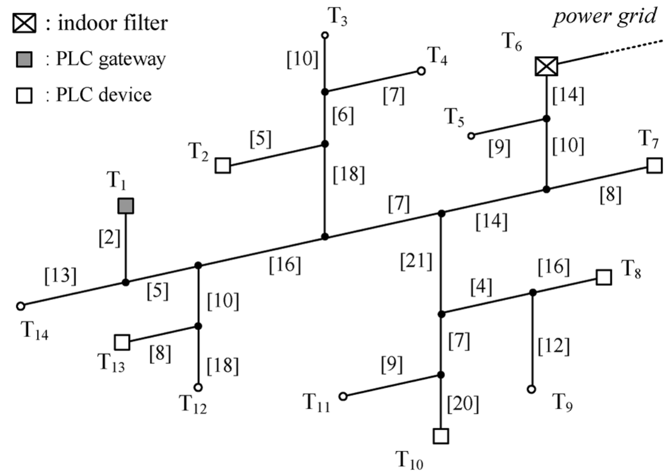

Fig. 2. Example topology of an indoor PLC network.

any two termination points depends on the topology, the cables characteristics, and the network loading conditions according to the different loads [7].

Fig. 3 shows the upper and lowerbounds of the channel-response variation of links T_1-T_7, T_1-T_8, and T_1-T_{13} in the frequency range of 1–11 MHz for the loading scenarios of Table I. We considered the VVF ($2 \times \phi 1.6$-mm) wiring cable and a $100\angle 0$ impedance for the PLC devices. From the channel-response envelope curves (solid lines), we observe that in all frequency bands, the channel gain of each link displays significant variations depending on the network loading conditions. For illustrative purposes, Fig. 3 also includes the channel response of each link for the loading scenarios 1 and 3 of Table I (dashed lines). We observe that the spectral characteristics of each link may change significantly for different network loading (e.g., the deep fades of link T_1-T_8 appear in different frequency bands for scenarios 1 and 3). Fig. 3 also shows that the links have different channel quality; they display different attenuation levels for the same loading conditions (e.g., links T_1-T_8 and T_1-T_{13} present a mean attenuation level difference of 16 dB for loading scenario 1). This behavior depends on the relative distance between the communicating devices, the network topology, and the loading conditions. Similar results are also obtained for links T_1-T_2 and T_1-T_{10}.

In such a frequency-selective environment, efficient resource allocation is necessary in order to maximize the overall network performance. As several links experience poorer channel quality than others, it is important to impose fairness constraints and to ensure a minimum rate for each user. Moreover, due to the time-varying behavior of the power-line channel, the *a priori* definition of a downstream–upstream bandwidth assignment is not possible; proper subchannel allocation according to the network channel conditions is necessary for both directions of transmission; otherwise, severe performance degradation may be reported for the links displaying deep fading characteristics. Thus, the proposed resource-management strategy encounters both upstream and downstream links and aims to satisfy the following requirements:

- to provide a set of minimum data rates to all active links in the network;

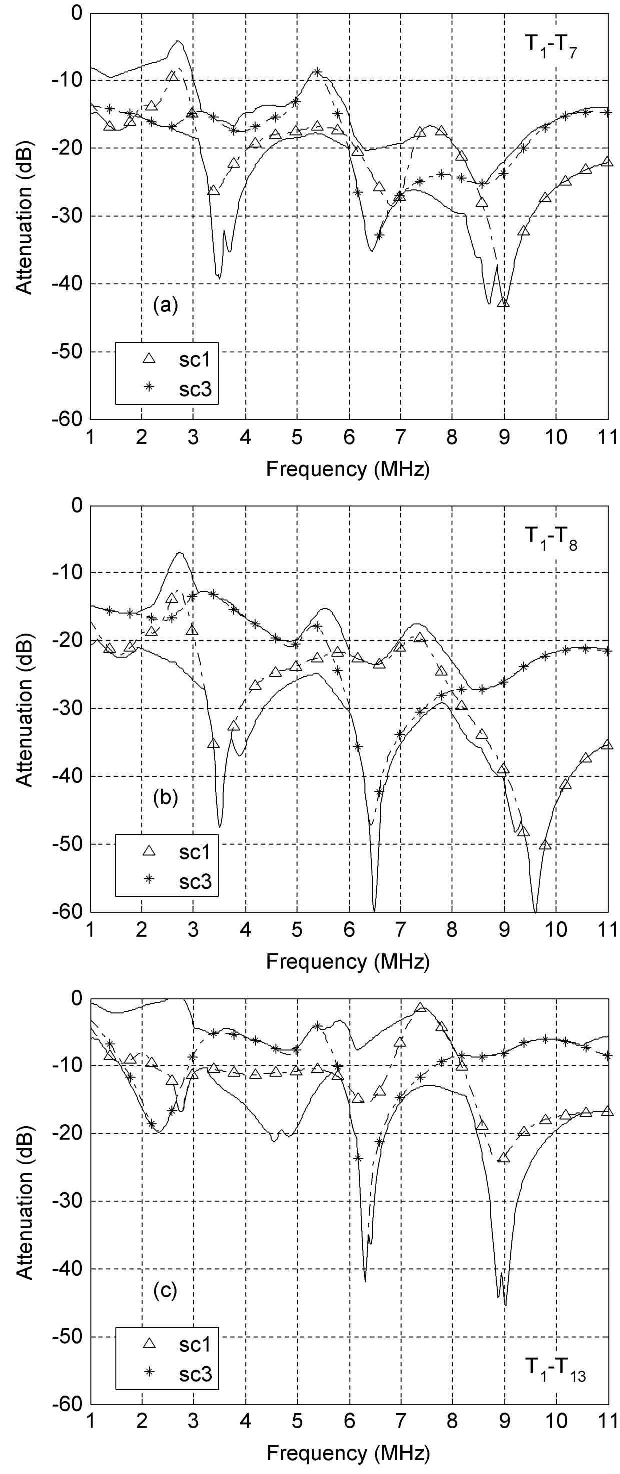

Fig. 3. Channel gain variation for the loading scenarios of Table I.

- to provide fairness in the allocation of the remaining resources according to the channel quality of each link.

In order to examine several network traffic configurations between downstream and upstream, we introduce the downlink-to-uplink data rate ratio β, which is the same for all bidirectional links. For applications with symmetric data traffic $\beta = 1$. However, when asymmetric data traffic is considered, such as Internet access, video streaming, etc., the value of β can vary

TABLE I
LOADING SCENARIOS (SC) FOR THE INDOOR PLC NETWORK IN FIG. 2 (∞ DENOTES OPEN CIRCUIT)

	sc1	sc2	sc3	sc4	sc5	sc6	sc7	sc8	sc9	sc10
T_4	∞	$30\angle-90$	∞	$30\angle-90$	∞	$10\angle-90$	∞	$10\angle-90$	$20\angle-90$	$20\angle-90$
T_5	∞	∞	$20\angle-90$	$20\angle-90$	$30\angle-90$	$30\angle-90$	∞	∞	$10\angle-90$	$10\angle-90$
T_7	∞	∞	$10\angle-90$	∞	$20\angle-90$	$20\angle-90$	$20\angle-90$	$10\angle-90$	$30\angle-90$	$30\angle-90$
T_{10}	∞	∞	$10\angle-90$	$10\angle-90$	∞	∞	$20\angle-90$	∞	$20\angle-90$	$20\angle-90$
T_{12}	∞	$20\angle-90$	∞	$20\angle-90$	$30\angle-90$	$30\angle-90$	∞	∞	∞	∞
T_{14}	∞	$20\angle-90$	∞	∞	$10\angle-90$	∞	$30\angle-90$	$10\angle-90$	∞	$10\angle-90$

according to the type of services (e.g., ADSL provides asymmetric data traffic configurations with downstream-to-upstream rate ratio up to 9 : 1 [24]). The total data traffic in the network of Fig. 1 consists of internal traffic, which corresponds to the data exchanged between the PLC devices and can be considered symmetric, and external traffic, which is the incoming/outgoing data traffic from/to the backbone network and it is asymmetric. The external data traffic is usually the dominant traffic in the indoor PLC network.

Hereafter, we assume that the PLC gateway knows the CSI (i.e., the subchannel gain-to-noise ratio values), of all active links in the network. Therefore, the multiuser loading algorithm is executed at the network management and control unit of the PLC gateway and the results are transmitted to all PLC devices. Although the channel frequency response of a link may change as the network's loading changes, this is a slow time-varying process. Therefore, the following analysis is based on the channel conditions of a given loading scenario. If performance degradation is reported due to channel changes, the PLC gateway adapts the resource allocation to the new conditions in order to maintain high network performance.

III. MULTIUSER RESOURCE ALLOCATION PROBLEM

Let L be the number of active PLC devices in the network and N be the number of available subchannels. According to the FDMA rule, each subchannel is allocated to a single link between a PLC device and the PLC gateway, either for downstream or for upstream transmission. Therefore, each bidirectional link consists of two independent users and the available bandwidth and power resources have to be allocated to $K = 2L$ users. Let $\Omega = \{1, 2, \dots, N\}$ denote the set of subchannels and $S = \{1, 2, \dots, K\}$ denote the set of all users, where the pair identifiers $(k, k+L)$, for $k = 1, \dots, L$, correspond to the same bidirectional link between the kth PLC device and the PLC gateway, and indicate the downstream and upstream of that link, respectively.

For each user $k \in S$, we denote as $g_{k,n} = |H_{k,n}|^2/N_{k,n}$ the channel gain-to-noise ratio of subchannel n, where $H_{k,n}$ is the channel frequency response and $N_{k,n}$ is the total noise power. Let $p_{k,n}$ denote the power allocated to subchannel n of user k, and $\bar{p}$ denote the PSD mask (i.e., $p_{k,n} \leq \bar{p}, \forall k, n$). Assuming quadrature amplitude modulation (QAM), the number of bits in subchannel n of user k is $r_{k,n} = \log_2(1 + (p_{k,n} \cdot g_{k,n})/\Gamma)$, where Γ is the SNR gap and depends on the target probability of error, the applied coding, and a system margin, which reflects immunity with respect to the SNR degradation [11]. If $r_{\max}$ is the number of bits that correspond to the maximum constellation size, the bit allocation of each user is upperbounded by $\bar{r}_{k,n} = \min(\log_2(1 + (\bar{p} \cdot g_{k,n})/\Gamma), r_{\max})$ bits in each subchannel. Since we can assign each subchannel to one user only, we define the subchannel allocation matrix $\mathbf{A} = [a_{k,n}]_{K\times N}$, where $a_{k,n} = 1$, when subchannel n is allocated to user k; otherwise, $a_{k,n} = 0$. Therefore, the total rate (in bits per OFDM symbol) of user k is $R_k = \sum_{n=1}^{N} a_{k,n} \cdot r_{k,n}$, while the downlink-to-uplink data ratio condition imposes that $R_k/R_{k+L} = \beta$, $\forall k = 1, \dots, L$. We also denote as D_k the minimum rate that has to be provided to user k.

In [21], the requirement for fairness in the achievable user rates is formulated via a set of nonlinear constraints, $R_1 : R_2 : \dots : R_K = \gamma_1 : \gamma_2 : \dots : \gamma_K$, where $\{\gamma_k\}_{k=1}^{K}$ are constant values that determine the proportional rate fairness for all users. In the presented analysis, the issue of fairness on the achievable data rates is related with the channel conditions of each user, thus the constants $\{\gamma_k\}_{k=1}^{K}$ are not associated with user priorities, rather they are defined according to the channel quality of each user. Moreover, in our case, the downstream-to-upstream rate ratio requirement implies a restriction on the definition of the fairness constraints for the downlink and uplink users. Since $R_k/R_{k+L} = \beta$ for $k = 1, \dots, L$, it follows that the constants $\{\gamma_k\}_{k=1}^{K}$ should also satisfy $\gamma_k/\gamma_{k+L} = \beta$ for $k = 1, \dots, L$. Details on the definition of the $\{\gamma_k\}_{k=1}^{K}$ are provided below.

The multiuser loading problem considered in this paper is formulated by

$$\begin{aligned}
&\max_{r_{k,n}, a_{k,n}} \sum_{k=1}^{K}\sum_{n=1}^{N} a_{k,n} \cdot r_{k,n} \\
&\text{subject to} \sum\nolimits_{n=1}^{N} a_{k,n} \cdot r_{k,n} \geq D_k, \quad \forall k \in S \\
&\qquad 0 \leq r_{k,n} \leq \bar{r}_{k,n}, \quad \forall k, n \\
&\qquad \sum\nolimits_{k=1}^{K} a_{k,n} \leq 1, \quad \forall n \in \Omega \\
&\qquad R_1 : R_2 : \dots : R_K = \gamma_1 : \gamma_2 : \dots : \gamma_K. \qquad (1)
\end{aligned}$$

The first constraint indicates the minimum data rate that has to be satisfied for each user, while the second constraint indicates the upper-bound of any admissible bit allocation. The third constraint imposes the FDMA rule; the inequality encounters the case when a subchannel displays very low SNR for all users and thus it cannot support any data rate. The last constraint imposes the requirement for proportional rate fairness, where $\gamma_k = \beta \cdot \gamma_{k+L}$ for $k = 1, \dots, L$; note that the constraint includes both downstream and upstream users. In (1), we assume that the power budget in both directions of transmission is sufficient (i.e., all PLC devices are able to transmit at the maximum PSD level in all subchannels in order to increase their data rates).

A. Channel Quality and Proportional Rate Fairness

The values of $\{\gamma_k\}_{k=1}^K$ are defined according to the requirement for proportional user rates. In this paper, the fairness on the achievable user rates is related with the channel quality of each link. Therefore, a reasonable and practical assumption is to associate the channel quality of each user with the total rate achieved in single-user communications (i.e., when the user utilizes all available bandwidth and power resources). We denote the single-user rate of user k as $R'_k = \sum_{n=1}^N \bar{r}_{k,n}$. The subchannel gain-to-noise ratio values of downlink and uplink are generally different, thus $R'_k \neq R'_{k+L}$. Since $\gamma_{k+L} = \gamma_k/\beta$ for $k = 1, \ldots, L$, if we set $\gamma_k = R'_k$ for $k = 1, \ldots, L$, then $\gamma_{k+L} = R'_k/\beta$. Therefore, the last constraint in (1) becomes $R_1 : \ldots : R_L : R_{L+1} : \ldots : R_K = R'_1 : \ldots : R'_L : R'_1/\beta : \ldots : R'_L/\beta$. According to the above relation, we request that the users are allocated rates with proportional fairness to the downlink single-user rates.

In real communications systems, the number of bits in each subchannel is restricted to integer values: $r_{k,n} \in \mathbb{Z}_+$, and thus, $\bar{r}_{k,n} = \min(\lfloor \log_2(1 + (\bar{p} \cdot g_{k,n})/\Gamma) \rfloor, r_{\max})$. In this case, the proportional rate constraint is satisfied approximately; for any practical multiuser loading with integer bit allocation, the resulting fairness ratios R_k/γ_k have different values and their variance indicates the level of convergence to a global fairness value. When a large number of resources is available, an efficient bit allocation algorithm should provide near equal fairness ratios. The resource allocation method presented in Section IV is a suboptimum solution of (1) that provides integer bit allocation based on a low-complexity algorithm. Hereafter, we denote ρ_k as the fairness ratio of user k, where $\rho_k = R_k/R'_k$ and $\rho_{k+L} = R_{k+L}/(\beta^{-1} \cdot R'_k)$ for the downstream and upstream users, respectively.

B. Minimum Data-Rate Strategy

In order to obtain a feasible solution in (1), the definition of the minimum rates should be consistent with the downstream-to-upstream rate ratio and proportional rate constraints. Regarding the latter, the following two strategies are considered. One approach is to request a minimum user rate, which is a percentage α of the single-user rate (i.e., $D_k = \alpha \cdot R'_k$), while the other approach is to specify the same minimum rate for all users. In general, R'_k represents the quality of the link; therefore, the proportional minimum rate strategy provides a minimum QoS that is determined by the channel quality of each user. The constant minimum rate strategy provides the same minimum data rate to all users; however, it reduces the total rate of the high-quality users and, thus, the overall network rate, since more resources are allocated to the users with poor channel conditions in order to meet the data-rate constraint. Both minimum rate strategies are investigated in the numerical results section. The downstream-to-upstream rate ratio constraint is satisfied by initially determining the minimum data rates D_k for $k = 1, \ldots, L$ for the downlink and then setting $D_{k+L} = D_k/\beta$ for the uplink.

C. Network Resource Management

In the next section, the multiuser loading problem in (1) is solved using a suboptimum low-complexity algorithm that satisfies two performance requirements. Initially, the allocation process allocates the set of minimum user rates, while at the next step, the remaining resources are allocated so that proportional rate fairness is achieved. Based on the above two requirements, the new resource allocation algorithm consists of two discrete phases. Fig. 4 shows the general network resource management plan based on the proposed resource allocation strategy including the two different options discussed previously regarding the minimum user rates. This figure also includes an alternative allocation option, which can be followed according to the preferred strategy (e.g., after the minimum data rates are met, the remaining resources are allocated so that the total network rate is maximized); however, in this case, fairness is not guaranteed.

IV. Multiuser Loading Algorithm

Based on the resource management strategy in Fig. 4, the proposed algorithm consists of two phases: in the first phase (Phase A), the algorithm allocates the available resources so that the minimum rate requirements are met for all users, while in the second phase (Phase B), the remaining resources are allocated to the users so that proportional rate fairness is satisfied. The new algorithm is based on an iterative process of allocation rounds. In each round, the algorithm jointly assigns subchannels and power to all users according to a user-priority scheme. In general, the least satisfied user is the first to select resources in each allocation round, while the user-satisfaction metric depends on the allocation objective that has to be achieved in each phase of the algorithm (e.g., the allocation objective in Phase A is the minimum user rates, while in Phase B, it is the proportional rate fairness).

More specifically, we define the vector $\mathbf{C} = [C_k]_{K \times 1}$, where the quantities C_k represent the user-satisfaction metric (i.e., C_k are the objectives on which the priority criterion is applied). At the beginning of each allocation round, vector $\mathbf{C}$ is calculated and all active users are ordered according to their C_k values. The values in vector $\mathbf{C}$, as well as the priority criterion, depend on the allocation phase and details are provided below. We define the user priority array $\mathbf{U} = [U_{i,j}]_{K \times K}$ that indicates the priority of the users. The row index i indicates the user priority, with $i = 1$ having the highest priority; however, there is no priority between the users in the same row (i.e., when several users have the same C_k, they belong to a group of users with the same priority). The dimensions of $\mathbf{U}$ ensure that the array can describe all possible arrangements that can be formed by ordering the K users. The elements of $\mathbf{U}$ are equal to the corresponding user identifier or equal to zero.

For example, let $K = 4$ and $\mathbf{C} = [180, 193, 180, 165]^T$, where $[\cdot]^T$ means transpose, and assume that the priority criterion implies that the users are ordered in ascending order according to their C_k values. Then, the user-priority array is

$$\mathbf{U} = \begin{bmatrix} 4 & 0 & 0 & 0 \\ 1 & 3 & 0 & 0 \\ 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{2}$$

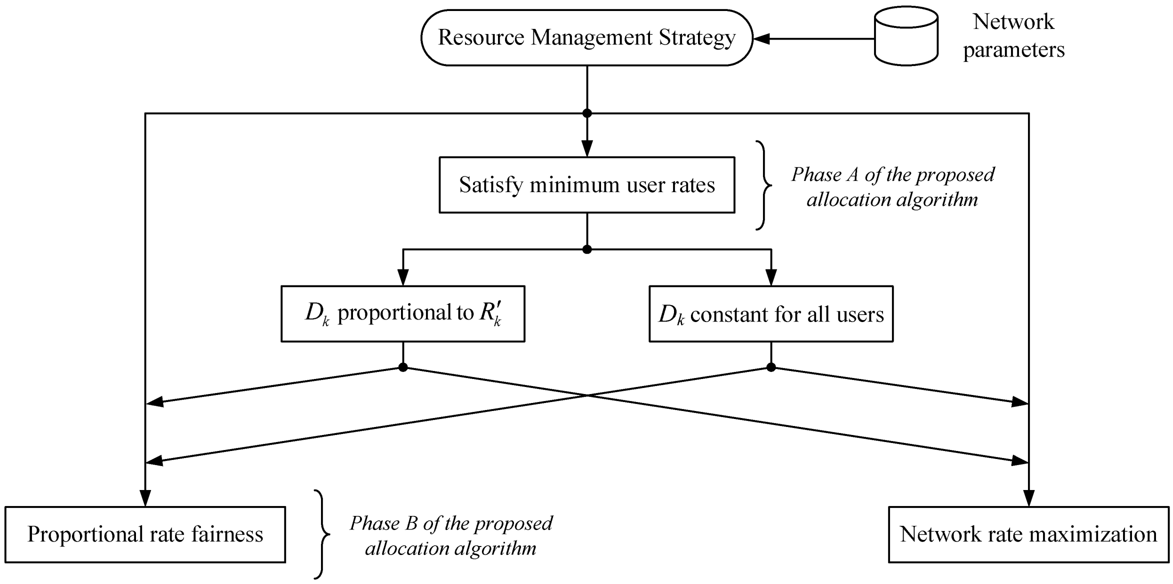

Fig. 4. Network resource-management strategies.

where three groups of users (two groups with a single user and one group with two users) with different priorities are formed: user 4 has the highest priority, user 2 has the lowest priority, while there is no priority between users 1 and 3.

In each allocation round, the new algorithm performs resource allocation to all users based on a round-robin allocation scheme starting from the highest to the lowest priority user group. Given $\mathbf{U}$, the algorithm provides joint subchannel and power allocation according to the following rule:

- for a single-user group: from the available subchannels allocate the subchannel with the maximum supported rate to that particular user;
- for a multiuser group: from the available subchannels allocate the best subchannels, one for each user, that support the maximum rates.

The allocation steps in each allocation round are described by the following "best effort and fairness" (BEAF) scheme, where $S_i := \{U_{i,1}, \ldots, U_{i,K}\}$ denotes the group of users, $U_{i,j} \neq 0$, in the ith row of $\mathbf{U}$. We also introduce the following arrays: $\mathbf{G} = [g_{k,n}]_{K\times N}$, $\mathbf{D} = [D_k]_{K\times 1}$, $\mathbf{P_{max}} = [\bar{p}_{k,n}]_{K\times N}$, $\mathbf{R_{max}} = [\bar{r}_{k,n}]_{K\times N}$, $\mathbf{R} = [r_{k,n}]_{K\times N}$, $\mathbf{P} = [p_{k,n}]_{K\times N}$.

BEAF Allocation Round:

R1. Start with the group of users having the highest priority, $i = 1$.

R2. For the users $\{k_1^*, \ldots, k_K^*\} \in S_i$, find subchannel $n^* \in \Omega$ with the maximum $g_{k,n}$ within the rows $k_1^*, \ldots, k_K^*$ of $\mathbf{G}$. Let n^* belong to row k^*.

R3. Assign subchannel n^* to user $k^* : a_{k^*,n^*} = 1$, $S_i = S_i - \{k^*\}$, and $\Omega = \Omega - \{n^*\}$.

R4. Update $\mathbf{R}$ and $\mathbf{P}$: $r_{k^*,n^*} = \bar{r}_{k^*,n^*}$ and $p_{k^*,n^*} = (2^{\bar{r}_{k^*,n^*}} - 1) \cdot \Gamma / g_{k^*,n^*}$.

R5. Update user rate $R_{k^*} = R_{k^*} + r_{k^*,n^*}$.

R6. Repeat steps R2–R5 with the remaining users in S_i.

R7. Repeat steps R2–R6 with the remaining groups in $\mathbf{U}$, $i = 2, \ldots, K$.

We call the above allocation process BEAF (best effort and fairness), since in every allocation step the algorithm assigns the best subchannel to the selected user by applying a fair allocation rule: all users participate once in the allocation round according to their priorities. As will be evident in the numerical results section, this priority-based round-robin allocation rule provides proportional rate fairness. Using the BEAF allocation round, we can describe the two phases of the new algorithm.

A. Minimum User Rate Allocation (Phase A)

In Phase A, the algorithm guarantees a minimum data rate; a set of target-rates, D_k, is allocated to all downstream and upstream users. During Phase A, the $\mathbf{C}$ array equals to the total rate that remains to be allocated to each user after every allocation round and the users are ordered in descending order (i.e., we assign higher priority to the users with the less satisfied minimum rate requirements). However, due to the fact that the minimum data rates for downlink and uplink are defined based on the downstream-to-upstream rate ratio requirement, β, proper rate scaling is necessary, otherwise downlink users will always be the first to select resources. Thus, the $\mathbf{C}$ vector is calculated by $C_k = \omega_k \cdot (D_k - R_k)$, where $\omega_k = 1$ for the downlink $(k = 1, \ldots, L)$ and $\omega_k = \beta$ for the uplink $(k = L+1, \ldots, K)$.

Moreover, since the BEAF algorithm is used to allocate resources to all users, it is necessary to introduce a downstream-to-upstream rate ratio control; otherwise, the latter may not converge to the desired value. Thus, we define a flag vector $\mathbf{F} = [f_k]_{K\times 1}$ that determines whether user k should participate in the next allocation round $(f_k = 1)$ or not $(f_k = 0)$. If $f_k = 0$, user k is excluded from the priority array $\mathbf{U}$. Vector $\mathbf{F}$ is used only for asymmetric traffic (i.e., $\beta > 1$), and is calculated according to the following rule: At the beginning of each allocation round,

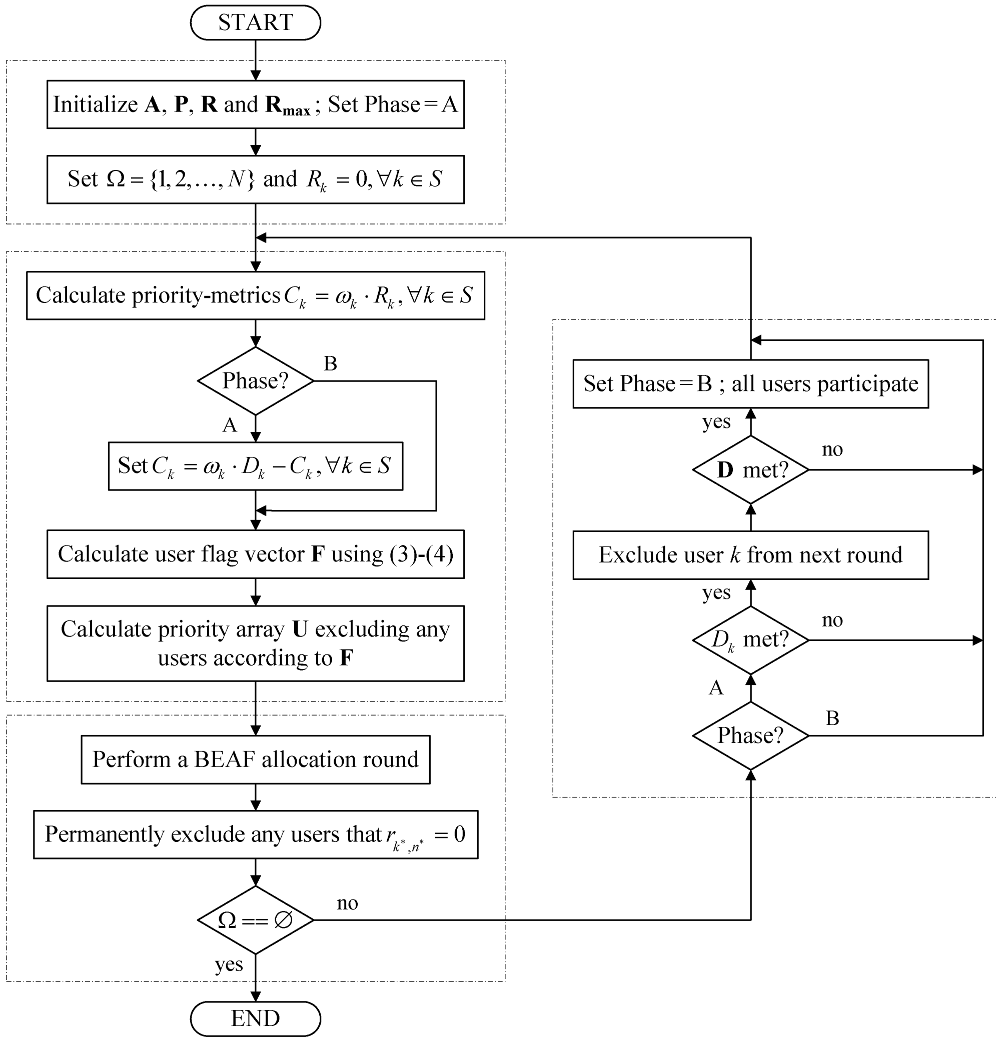

Fig. 5. Multiuser loading algorithm flowchart for asymmetric traffic.

we calculate the downstream-to-upstream rate ratio for all bidirectional links $\zeta_k = R_k/R_{k+L}$ for $k = 1, \dots, L$. The flag of each downlink user is given by

$$f_k = \begin{cases} 0, & \text{if } \zeta_k^- \geq \beta \text{ AND } \zeta_k \geq \zeta_k^- \\ 1, & \text{otherwise} \end{cases}, \quad \forall k = 1, \dots, L \tag{3}$$

where ζ_k^- denotes the downstream-to-upstream rate ratio of the previous allocation round, while the flag of each uplink user is given by

$$f_{k+L} = \begin{cases} 0, & \text{if } \zeta_k < \beta \\ 1, & \text{otherwise} \end{cases}, \quad \forall k = 1, \dots, L. \tag{4}$$

The condition in (4) implies that, if the current downstream-to-upstream rate ratio of a link is less than the desired value, the corresponding uplink user is excluded from the next allocation round. On the other hand, the condition in (3) implies that a downlink user is excluded from an allocation round only when the corresponding uplink user participated in the previous round ($\zeta_k^- \geq \beta$), however the resulting downstream-to-upstream rate ratio became higher ($\zeta_k \geq \zeta_k^-$). The latter means that the downlink user was allocated more rate than the uplink user, although the uplink user had higher priority since $\zeta_k^- \geq \beta$. Such a situation may result in ζ_k increasing after every allocation round, thus it should be avoided.

The following steps describe the first allocation phase of the proposed algorithm.

Initialization.

I1. Initialize $\mathbf{A}$, $\mathbf{P}$ and $\mathbf{R}$ with zeros.

I2. Calculate $\mathbf{R_{max}}$ based on $\mathbf{G}$ and $\mathbf{P_{max}}$.

I3. Set $\Omega = \{1, 2, \dots, N\}$ and $R_k = 0, \forall k \in S$.

Phase A: Minimum Rate Allocation.

A1. Calculate $\mathbf{C}$ by $C_k = \omega_k \cdot (D_k - R_k), \forall k \in S$.

A2. Calculate flag vector $\mathbf{F}$ using (3) and (4).

A3. Calculate array $\mathbf{U}$ excluding any users according to $\mathbf{F}$.

A4. Perform a BEAF allocation round.

A5. If minimum rate D_k is met (i.e., $R_k \geq D_k$), exclude user k from the next round.

A6. Repeat steps A1–A5 until all minimum rates are met or $\Omega = \emptyset$.

The algorithm performs resources allocation using BEAF rounds. Since the algorithm aims to satisfy D_k for each user, once a minimum target-rate is met, the corresponding user is removed from the allocation process. When all minimum user rates are met, the algorithm proceeds to the second phase.

TABLE II
DOWNLINK (D)-UPLINK (U) USER IDENTIFIERS AND SINGLE-USER RATES (SUR)

Link	T_1-T_2		T_1-T_7		T_1-T_8		T_1-T_{10}		T_1-T_{13}	
Down/Uplink	D	U	D	U	D	U	D	U	D	U
User ID	1	6	2	7	3	8	4	9	5	10
SUR	3706		3003		2267		2143		4298	

B. Proportional User Rate Allocation (Phase B)

In Phase B, the algorithm provides allocation of the remaining resources with fairness according to the quality of each link. During Phase B, the $\mathbf{C}$ array equals to the total rate of each user, i.e., $C_k = \omega_k \cdot R_k$, where $\omega_k = 1$ for $k = 1, \ldots, L$ and $\omega_k = \beta$ for $k = L+1, \ldots, K$, and the users are ordered in ascending order (i.e., in every allocation round, we assign higher priority to the users with the less allocated rate).

The following steps describe the second allocation phase of the proposed algorithm.

Phase B: Proportional Rate Allocation.

B1. Calculate $\mathbf{C}$ by $C_k = \omega_k \cdot R_k, \forall k \in S$.

B2. Calculate flag vector $\mathbf{F}$ using (3) and (4).

B3. Calculate array $\mathbf{U}$ excluding any users according to $\mathbf{F}$.

B4. Perform a BEAF allocation round.

B5. Repeat steps B1–B4 until $\Omega = \emptyset$.

Fig. 5 presents the network resource allocation algorithm for asymmetric traffic $(\beta > 1)$ using an illustrative flowchart. With reference to the above algorithm, we provide the following remark. In step R.4 of the BEAF algorithm, user k^* is allocated the maximum achievable rate, $\bar{r}_{k^*,n^*}$, in the selected subchannel, n^*. If $\bar{r}_{k^*,n^*} = 0$ due to very low subchannel gain-to-noise ratio, then user k^* is removed from the allocation process. Indeed, due to the maximum subchannel gain-to-noise ratio selection rule in R.2, the remaining subchannels of user k^* cannot support any data rate, thus the available resources should be allocated to the rest of the users.

V. NUMERICAL RESULTS

This section presents numerical results that demonstrate the performance of the new multiuser loading algorithm. We examine the indoor network topology presented in Fig. 2. There are $L = 5$ bidirectional links that correspond to $K = 10$ network users, 5 downlink and 5 uplink, while Table II shows the user identifiers as they appear in the simulation results. We have used the following parameters: fast Fourier transform (FFT) size 1024, sampling frequency 20.48 MHz, subchannel spacing 20 kHz, frequency band of interest 1–10 MHz with $N = 450$ total available subchannels, transmit PSD mask -60 dBm/Hz. We also considered 10^{-7} bit-error rate (BER), $r_{\max} = 15$, no coding, and 6-dB margin for all users.

For performance analysis, we use the loading scenarios in Table I. The subchannel gains between uplink and downlink are symmetric, since they exhibit identical behavior on both directions of transmission [25]. We also consider additive white Gaussian noise (AWGN) -120 dBm/Hz in all network links. The different scenarios of Table I correspond to a variety of channel characteristics for the various links, thus we can evaluate the effectiveness of the proposed algorithm using a channel environment that displays strong frequency selectivity. Table II also shows the average single-user rate (in bits per OFDM symbol) of each bidirectional link for all scenarios of Table I. It is clear, that the single-user rates depend on the channel conditions and represent a figure of merit of the quality of each link (e.g., link T_1-T_{13} displays almost twice the average single-user rate than link T_1-T_8 due to higher subchannel gains).

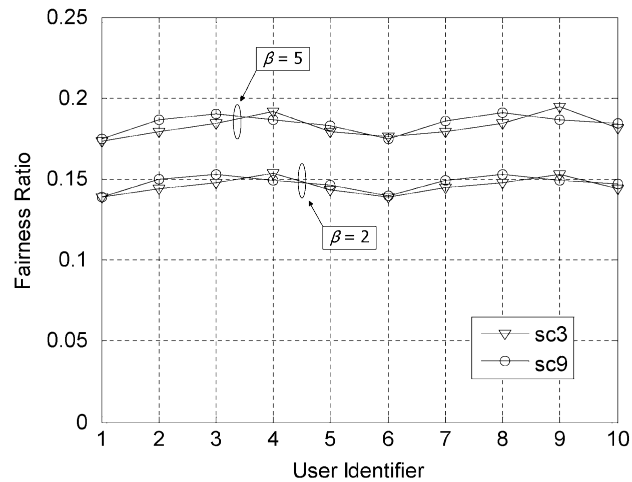

Fig. 6. Proportional rate fairness for different downstream-to-upstream rate ratio.

TABLE III
AVERAGE TOTAL RATE OF EACH BIDIRECTIONAL LINK FOR DIFFERENT DOWNSTREAM-TO-UPSTREAM RATE RATIO

β	T_1-T_2	T_1-T_7	T_1-T_8	T_1-T_{10}	T_1-T_{13}
1	799	664	528	507	945
2	800	666	528	506	947
3	801	665	526	506	947
4	802	665	526	506	949
5	803	664	525	506	948
6	802	665	525	505	950

A. Performance Results on Fairness

Fig. 6 presents the fairness ratio, ρ_k, of each user for the loading scenarios 3 and 9, when $\beta = 2$ and $\beta = 5$. The results correspond to $D_k = 0$ for all users in Phase A (i.e., only Phase B of the algorithm is executed). We observe that for both values of β, the proposed BEAF algorithm provides proportional user rate allocation. Although the new algorithm does not explicitly encounter the values R_k/γ_k in a subchannel-by-subchannel allocation basis as in [21] and [22], the proposed round-robin allocation process with user priorities according to the user data rates, provides fair user rate allocation that is proportional to the single-user rates. As mentioned in Section III-A, we expect that the achieved fairness ratios will be slightly different due to the integer bit restriction. It is interesting to note that the achieved fairness ratios depend on β; for higher β, the ratios are higher, as it is explained below.

Table III shows the average total rate (in bits per OFDM symbol) of each link for all scenarios of Table I using the

TABLE IV
PERFORMANCE STATISTICS OF THE NEW ALGORITHM

	T_1-T_2			T_1-T_7			T_1-T_8			T_1-T_{10}			T_1-T_{13}		
β	x	ρ	β'	x	ρ	β'	x	ρ	β'	x	ρ	β'	x	ρ	β'
1	0.216	0.108	1.002	0.221	0.111	1.001	0.233	0.117	1.003	0.237	0.118	1.001	0.220	0.110	1.001
2	0.216	0.144	1.991	0.222	0.148	1.996	0.233	0.155	1.997	0.236	0.157	1.997	0.220	0.147	1.996
3	0.216	0.162	2.975	0.221	0.166	2.987	0.233	0.174	2.994	0.236	0.177	2.987	0.220	0.165	2.981
4	0.217	0.173	3.980	0.221	0.177	3.989	0.232	0.186	3.981	0.236	0.189	3.976	0.221	0.176	3.976
5	0.217	0.180	4.942	0.221	0.184	4.970	0.232	0.193	4.961	0.236	0.196	4.965	0.221	0.183	4.947
6	0.217	0.185	5.903	0.222	0.190	5.912	0.232	0.198	5.935	0.236	0.202	5.949	0.221	0.189	5.895

TABLE V
USER FAIRNESS RATIO FOR PROPORTIONAL MINIMUM DATA RATES (α IN %)

$(\beta = 3)$	1	2	3	4	5	6	7	8	9	10
$\alpha = 0$	0.162	0.166	0.174	0.177	0.165	0.163	0.167	0.175	0.178	0.166
$\alpha = 5$	0.168	0.165	0.168	0.172	0.170	0.168	0.166	0.169	0.172	0.170
$\alpha = 10$	0.171	0.166	0.164	0.168	0.173	0.172	0.167	0.164	0.168	0.174
$\alpha = 15$	0.171	0.169	0.165	0.168	0.173	0.172	0.169	0.165	0.168	0.173
$\alpha = 20$	0.163	0.166	0.172	0.175	0.167	0.165	0.167	0.173	0.175	0.169
$(\beta = 5)$	1	2	3	4	5	6	7	8	9	10
$\alpha = 0$	0.180	0.184	0.193	0.196	0.183	0.182	0.185	0.195	0.198	0.185
$\alpha = 5$	0.186	0.183	0.187	0.191	0.189	0.189	0.185	0.189	0.193	0.190
$\alpha = 10$	0.190	0.184	0.182	0.187	0.192	0.191	0.186	0.184	0.189	0.194
$\alpha = 15$	0.191	0.185	0.183	0.186	0.193	0.192	0.186	0.183	0.187	0.195
$\alpha = 20$	0.183	0.185	0.191	0.192	0.187	0.183	0.187	0.192	0.193	0.189

proposed algorithm for different requested downstream-to-upstream rate ratios, β. The results are obtained for $D_k = 0$ for all users. We observe that the average total rates of all links are practically the same for all values of β. If ρ denotes the optimum user fairness ratio in (1) (i.e., $\rho_k = \rho$ for all users), then the total rate in the downstream and upstream of each link is $R_k + R_{k+L} = x \cdot R'_k$ for $k = 1, \ldots, L$, where $x = \rho \cdot (1 + \beta^{-1})$, i.e., the total rate of each bidirectional link is proportional to the single-user rate of the corresponding downlink and x is the fairness ratio of the bidirectional links. In Table IV, we show the average values of the achieved user fairness ratio and downstream-to-upstream rate ratio, denoted as ρ' and β', respectively, as well as the resulting x calculated by $\rho' \cdot (1 + \beta'^{-1})$. We observe that ρ' changes with β' and that results to almost constant x value.

The results in Tables III and IV provide an insight of the proposed resource management performance characteristics. The BEAF algorithm provides proportional rate allocation, while the conditions in (3) and (4) control the convergence of the downstream-to-upstream rate ratio to the desired value. The downstream users participate in almost all allocation rounds, while the upstream users participate roughly in one out of $\lfloor \beta \rfloor$ rounds. As a result, the total rate of each bidirectional link is proportional to the single-user rate in the downstream and practically constant for all values of β.

B. Minimum Rate Strategy Performance

In this section, we investigate the performance of the algorithm with respect to the minimum rate strategies presented in Section III-B for Phase A. Note, that the definition of the minimum rates should follow the downstream-to-upstream rate ratio requirement.

Tables V and VI show the average fairness ratio of each user for different minimum rates when $\beta = 3$ and $\beta = 5$. The results in Table V correspond to the case of minimum rates which are proportional to the single-user rates, that is, $D_k = \alpha \cdot R'_k$ and $D_{k+L} = D_k/\beta$ for $k = 1, \ldots, L$, while the results in Table VI correspond to minimum rates which are the same for all users: we have used $D_k = \min(\alpha \cdot R'_k)$ and $D_{k+L} = D_k/\beta$ for $k = 1, \ldots, L$, so that the requested rates can be supported for all downstream and upstream users. The results in both tables are obtained for different values of the parameter α.

We observe that the fairness ratios in Table V are quite similar for all users and for all values of α. The latter stems from the fact that the definition of proportional minimum rates results in proportional rate allocation in both phases of the algorithm. However, when equal minimum rates are requested, we observe in Table VI that the fairness ratios decrease for some users with respect to α and increase for others. The constant minimum rate strategy in Phase A is in contradiction to the proportional rate fairness, since more subchannels are allocated to the users with poor channel quality in order to meet the target-rate constraint. For higher values of α (i.e., for higher minimum target rates), the users with poor channel quality achieve higher rates compared with the proportional minimum rate strategy, and as a result, the values in Table VI increase for the links with poor channel quality and decrease for the links with high channel quality. Thus, in the constant minimum rate strategy, the higher the minimum target-rates, the more 'unfair' is the allocation of the system resources with respect to the channel quality of each user.

TABLE VI
USER FAIRNESS RATIO FOR CONSTANT MINIMUM DATA RATES (α IN %)

$(\beta = 3)$	1	2	3	4	5	6	7	8	9	10
$\alpha = 0$	0.162	0.166	0.174	0.177	0.165	0.163	0.167	0.175	0.178	0.166
$\alpha = 5$	0.160	0.164	0.179	0.186	0.157	0.160	0.164	0.180	0.187	0.158
$\alpha = 10$	0.154	0.162	0.186	0.195	0.149	0.154	0.163	0.187	0.195	0.149
$\alpha = 15$	0.148	0.162	0.193	0.204	0.137	0.149	0.163	0.194	0.205	0.138
$\alpha = 20$	0.136	0.160	0.204	0.216	0.122	0.137	0.161	0.204	0.217	0.122
$(\beta = 5)$	1	2	3	4	5	6	7	8	9	10
$\alpha = 0$	0.180	0.184	0.193	0.196	0.183	0.182	0.185	0.195	0.198	0.185
$\alpha = 5$	0.176	0.183	0.199	0.206	0.176	0.177	0.184	0.200	0.207	0.180
$\alpha = 10$	0.172	0.181	0.205	0.214	0.168	0.175	0.184	0.206	0.217	0.171
$\alpha = 15$	0.166	0.180	0.211	0.224	0.158	0.167	0.182	0.213	0.225	0.159
$\alpha = 20$	0.158	0.179	0.221	0.235	0.143	0.160	0.181	0.223	0.236	0.146

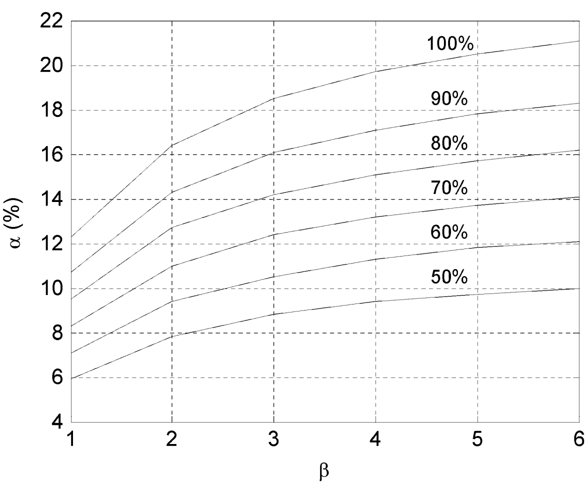

Fig. 7. Parameter α versus β for various ratios of minimum to total allocated rates.

Fig. 7 shows the different combinations between α and β with respect to the average ratio (in %) between the rate that is allocated in Phase A and the total user rate. The results correspond to proportional minimum rate strategy and show the percentage of the total user rate, which can be requested in Phase A for given β and α.

VI. CONCLUSION

In this paper, we addressed the problem of resource allocation management in the indoor PLC network with multiple OFDM links and we presented a multiuser loading algorithm. The proposed algorithm is based on a round-robin priority-based resource allocation process that provides rate allocation with proportional rate fairness according to the channel quality of each user. The proposed resource allocation management encounters both downstream and upstream and satisfies the following requirements. First, a set of minimum rates are provided to all users, and then, the remaining resources are allocated with fairness according to channel quality of each user. Numerical results using different network channel conditions, as well as downstream-to-upstream traffic configurations, demonstrated the performance of the proposed algorithm.

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