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ADAPTIVE RESOURCE ALLOCATION AND CAPACITY COMPARISON OF OFDMA AND MC-CDMA SCHEMES BASED ON IMPERFECT POWER-LINE CSI

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Abstract. *The challenge of imperfect channel state information (CSI) has been generally ignored in the literature for resource allocation in power-line communication (PLC) systems. However, power-line channels have a time varying nature, frequency selective attenuation, and inevitable impulsive noise due to the random switching of power appliances. Thus, it is unrealistic to expect to have perfect CSI. In this paper, the potential maximum ergodic capacity of the orthogonal frequency division multiple access (OFDMA) scheme and that of a proposed improved multicarrier code division multiple access (MC-CDMA) scheme are investigated and compared for imperfect power-line CSI. The resource allocation with fairness constraint is formulated as a convex optimization framework, and optimal user selection and power allocation algorithms are proposed for both schemes. The simulation results and analyses show that higher capacity gain can be achieved by modelling the statistical characteristics of the imperfect CSI and solving the expectation of CSI correlation function. Furthermore, the capacity loss of the proposed improved MC-CDMA scheme when compared with that of OFDMA is significantly reduced by the relaxation of fairness constraint, and the loss can be ignored in some cases.*
Keywords: Power-line communication, Resource allocation, OFDMA, MC-CDMA, Imperfect channel state information

1. **Introduction.** In recent years, power-line communication (PLC) technologies have become widely accepted due to the ubiquitous nature and ready availability of power-lines [1]. However, the PLC environment presents several challenges for information delivery, including high levels of frequency dependent attenuation, fluctuating impedances, and impulsive noise (IN) interference [2]. In such environments, orthogonal frequency division multiplexing (OFDM) is robust against frequency selectivity and interference, and has therefore been adopted in many existing PLC standards [3]. At present, there are two common types of OFDM-based multiple access technology. One is orthogonal frequency division multiple access (OFDMA) in which users utilize different subsets of subcarriers to communicate [4]. Another is multicarrier code division multiple access (MC-CDMA) in which users communicate using the same set of subcarriers but different spreading codes [5].

Adaptive resource allocation is a type of technique that adaptively allocates subcarriers/codes, rates, and power to the users based on the channel state information (CSI), which can maximize the system utility. Over the past few years, the resource allocation capability of OFDMA has been applied in PLC systems. The problem of resource allocation for mixed traffic has been discussed in [6], and the proposed algorithm can effectively balance the capacity among all types of traffics. In [7], improvements in the probability of outage have been investigated, and the proposed algorithms select an optimal set of subcarriers for each user based on the average power distribution. A spectrally compressive resource allocation technique has been proposed in [8], in which the computational complexity and signalling overhead have been reduced by grouping subcarriers into chunks. Nevertheless, these algorithms assume that perfect CSI is available, which is an unrealistic expectation primarily due to the presence of IN and channel estimation errors (CEE) in actual PLC scenarios [9]. The IN generated from electrical/electromagnetic (EM) appliances is short in duration and much larger in power than the background noise, and cannot be completely suppressed [10, 11]. Although methods for efficient resource allocations have been introduced to maximize the throughput while considering the IN, they only involve one special type of IN and do not consider CEE at all [12, 13]. The resource allocation of OFDMA based on imperfect CSI has been widely studied in wireless networks, where the noise is Gaussian white, and there is no electromagnetic interference (EMI) limitation [14, 15]. However, PLC systems suffer from serious non-Gaussian IN and power spectral density (PSD) constraints due to the EMI, the resource allocation is more complex.

In addition to OFDMA technology, MC-CDMA has also been widely adopted in PLC systems. The motivation for using MC-CDMA in PLC systems resides in its flexibility as a multiple access method, its resilience to IN, as well as its lower peak-to-average power ratio (PAPR) features compared with that of OFDMA. In [16], the performance of an MC-CDMA system over a power-line channel has been examined based on a statistical description of the channel impairments. A system model for high speed data communication through a power-line channel has been proposed in [17], in which an analytical approach has been developed to combine MC-CDMA technique with the features and characteristics of PLC systems. To overcome the effects of IN and multipath fading, the application of orthogonal poly-phase based MC-CDMA with the addition of a minimum-mean square error equalizer combined with nonlinear pre-processing has been proposed in [18]. Nevertheless, these algorithms only address the IN by using a binary phase shift keying (BPSK) mode, and do not involve adaptive resource allocation. In [19], an adaptive allocation algorithm for a projection matrix receiver has been proposed, where the receiver has an extra unit to adaptively optimize the threshold level, but neither IN nor CEE is considered. Furthermore, compared with OFDMA, the MC-CDMA algorithms have gain much lower capacity, because multiuser diversity can be exploited only by means of power allocation.

In this paper, an improved MC-CDMA scheme is proposed in which each user can be allocated any spreading codes in any subcarrier, thereby improving the available multiuser diversity by means of both subcarrier selection and power allocation. The adaptive resource allocation schemes for OFDMA and improved MC-CDMA are investigated based on imperfect power-line CSI from the PLC perspective, and the maximum ergodic capacities of both schemes are compared. The contributions are as follows. Firstly, the universal resource allocation problems in both schemes are modelled for overall imperfect CSI cases that include IN and CEE. Secondly, the problems are subjected to a series of equivalent transformations and resolved by dual optimization. As a result, higher capacity gain has been achieved by solving the expectation of the CSI correlation function. Finally, the proposed improved MC-CDMA scheme is shown to support a capacity similar to that of OFDMA in certain cases. By using the proposed schemes, the PLC system can provide high speed and high reliability communication under the IN interference environment, and that will lay the foundation for its wide application.

The remainder of this paper is structured as follows. Section 2 discusses the system models for the respective OFDMA and improved MC-CDMA schemes. Section 3 provides formulations of the optimization problems. Section 4 describes a method for optimal user selection and power assignment for both schemes, and is followed by a description of the proposed algorithms in Section 5. The numerical results and analysis are presented in Section 6. Finally, Section 7 concludes the paper.

2. **System Models.** In this paper, a downlink PLC system is considered which consists of N subcarriers and K users. As shown in Figure 1, for both the OFDMA and improved MC-CDMA schemes, the subcarriers are grouped into N_B subbands and each subband is subdivided into N_S subcarriers. Although the smallest resource unit in the OFDMA scheme is one subcarrier, that of the MC-CDMA scheme is one subband. The unit power signal-to-noise ratio (SNR) in one subband is the mean value of that of the subcarriers within this subband. To simplify the problem, the subband size is selected such that it is within the coherence bandwidth. Then each subband will experience flat fading, and each subcarrier within one subband has the same channel gain.

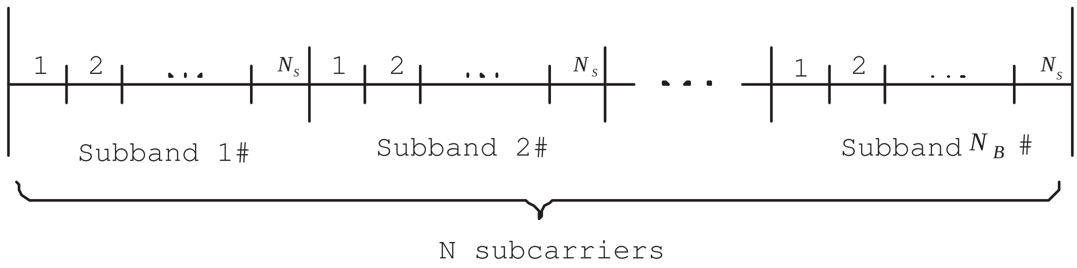

FIGURE 1. The model of power-line subcarriers partition

In contrast to the assumption in the traditional algorithm that the CSI is perfectly known, the proposed algorithm considers the IN and CEE over the power-line channel. PLC systems are subject to a mixture of background noise and IN. According to the noise model in [1], the IN, which is introduced by the random transients of appliance electrical switching, fluctuates more rapidly than the background noise and the two are independent. The total noise can be written as $\sigma^2[b] = \sigma_B^2[b] + \sigma_I^2[b]$, where $\sigma^2[b]$, $\sigma_B^2[b]$ and $\sigma_I^2[b]$ are the total noise, background noise, and IN in subband b, respectively. Thus, the corresponding SNR in subband b for user k can be expressed as:

$$\gamma_{k,b} = \frac{|h_{k,b}|^2}{\Gamma\sigma^2[b]} = \frac{|h_{k,b}|^2}{\Gamma\left(\sigma_B^2[b] + \sigma_I^2[b]\right)} \tag{1}$$

where $h_{k,b}$ is the channel gain in subband b for user k, and $\Gamma = -\ln(5BER)/1.5$ is the SNR gap, which depends on the target bit error rate (BER).

Assuming the minimum mean square error (MMSE) estimation over the power-line, the channel gain can be written as:

$$h_{k,b} = \hat{h}_{k,b} + e_{k,b} \tag{2}$$

where $\hat{h}_{k,b}$ and $e_{k,b}$ are the estimated channel gain and estimation error in subband b for user k, respectively.

In summary, the actual PLC system model based on imperfect CSI is shown in Figure 2. The background noise is assumed to be known as additive white Gaussian noise, because

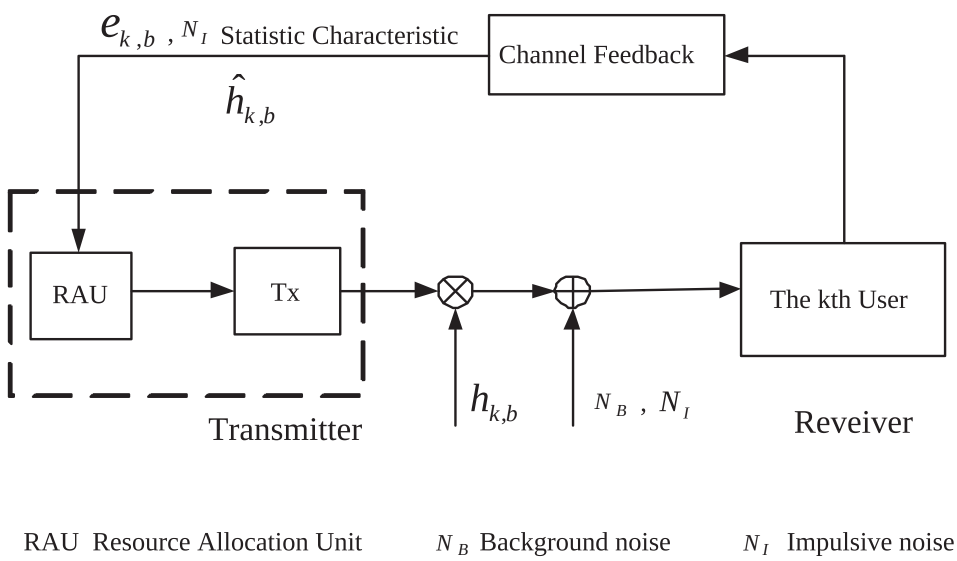

Figure 2. Power-line communication system model based on imperfect CSI

the long term real-time experiments suggest that the root meam square (RMS) amplitude of the background noise changes very slowly (see, e.g., [11]).

Among the different statistical IN models, the Bernoulli-Gaussian (BG) model has been widely used due to its suitability for theoretical analysis and relatively simple mathematical form [20]. It is selected here because it is able to accurately represent the IN characteristics, i.e., the random occurrences and high power impulses. Let λ denote the Bernoulli random variable, which is the IN occurrence probability (INOP) within each OFDM symbol, and let η denote the impulse-to-background noise power ratio, and then the IN can be expressed as:

$$\sigma_I^2[b] = \eta\sigma_B^2[b]\Phi \tag{3}$$

where Φ is the BG distribution with probability λ.

Though altering the gain of the power-line channel can be very serious due to its frequency-selective fading characteristics, we adopted a type of top-down modelling approach based on the multipath technique. In the proposed method, the estimated channel gain has its frequency response as [6]:

$$\hat{h}_{k,b} = \sum_{i=1}^{M} |g_{k,i}| \cdot \exp\left\{-\left(a_0 + a_1 f_b^l\right)\right\} \exp\left\{-j2\pi f_b d_{k,i}/v_p\right\} \tag{4}$$

where f_b is the frequency corresponding to subband b; M is the number of paths; a_0, a_1 and l are the attenuation parameters of the power-line; v_p is the signal transmission speed on the power-line; $g_{k,i}$ and $d_{k,i}$ are the complex gain and distance of the ith path for user k, respectively.

Assuming the distribution of $h_{k,b}$ conditioned on $\hat{h}_{k,b}$ is a non-zero mean complex Gaussian random variable, it can be written as $h_{k,b}|\hat{h}_{k,b} \sim CN\left(\hat{h}_{k,b}, \hat{\sigma}_{k,b}^2\right)$, where $\hat{\sigma}_{k,b}^2$ is the estimation error variance in subband b for user k. Assuming the distribution is independent of $\sigma^2[b]$, $\gamma_{k,b} = |h_{k,b}|^2/\Gamma\sigma^2[b]$ conditioned on $\hat{\gamma}_{k,b} = \left|\hat{h}_{k,b}\right|^2/\Gamma\sigma^2[b]$ is a non-central Chi-squared distributed random variable with two degrees of freedom for a given $\sigma^2[b]$, and the probability density function (PDF) can be approximated by a Gamma distribution as [21]:

$$f\left(\gamma_{k,b}|\hat{\gamma}_{k,b}\right) \approx \frac{\beta^{\alpha}}{\Gamma(\alpha)}\gamma_{k,b}^{\alpha-1}e^{-\beta\gamma_{k,b}} \tag{5}$$

where $\alpha = \left(\hat{\gamma}_{k,b}\rho_{k,b}^{-1}+1\right)^2 / \left(2\hat{\gamma}_{k,b}\rho_{k,b}^{-1}+1\right)$, $\beta = \alpha / \left(\hat{\gamma}_{k,b}+\rho_{k,b}\right)$, and $\rho_{k,b} = \hat{\sigma}_{k,b}^2/\sigma^2[b]$ is the estimation error-to-noise variance ratio (ENVR) in subband b for user k.

As a consequence of the IN and CEE, the instantaneous rate transmitted by the subcarriers is uncertain. This is termed the ergodic rate in this paper. Hence, the ergodic rate of user k in subband b can be expressed as:

$$\begin{aligned} R_{k,b} &= E\left\{\log_2\left(1+p_{k,b}\gamma_{k,b}\right)\right\} \\ &= (1-\lambda)E\left\{\log_2\left(1+p_{k,b}\gamma_{k,b}^{B}\right)\right\} + \lambda E\left\{\log_2\left(1+p_{k,b}\gamma_{k,b}^{I}\right)\right\} \end{aligned} \tag{6}$$

where $\gamma_{k,b}^{I} = |h_{k,b}|^2/\Gamma(1+\eta)\sigma_B^2[b]$ and $\gamma_{k,b}^{B} = |h_{k,b}|^2/\Gamma\sigma_B^2[b]$ are the SNRs of user k in subband b with and without the IN, respectively; $p_{k,b}$ is the allocated power in subband b for user k; $E\{\cdot\}$ is the expectation operator.

Because the instantaneous rate transmitted by subcarriers is replaced by the ergodic rate, the capacity of the system is termed the ergodic capacity. In this paper, the ergodic capacities of OFDMA and improved MC-CDMA schemes are investigated and compared. For the OFDMA scheme, users are separated by different subbands, each subcarrier in a subband is assumed to be allocated to only one user, and the subcarrier allocation information is transmitted to the receiver via a signalling channel. In traditional MC-CDMA, each user can be allocated a set of spreading codes that occupy the entire spectrum. It is relatively simple, and only the spreading code allocation information needs to be transmitted to the receiver. However, multiuser diversity can only be provided by means of the power allocation. To address this limitation, an improved MC-CDMA scheme is proposed here in which each user can be allocated any spreading code in any subband. The improved scheme is relatively complex in that the receiver needs both the spreading code and subband allocation information; however, multiuser diversity can be exploited by means of both the subband selection and power allocation. Hence, a higher capacity gain can be achieved. It is assumed that the number of codes is equal to the number of subcarriers in one subband, then there are a total of N_S codes and each code includes N_S chips. Although a multiuser detection (MUD) technique is not available in a downlink system, the multiuser interference (MUI) of the MC-CDMA system can be suppressed by using zero-forcing filtering [22]. It is therefore ignored in this paper.

3. **Problem Formulation.**

In this section, the ergodic capacities of the OFDMA and improved MC-CDMA schemes are investigated and compared based on imperfect power-line CSI. The investigations include considering the fairness among users, where fairness is based on the maximum number of subcarriers/codes allocated to each user.

3.1. **Problem formulation for OFDMA scheme.**

In this scheme, each subcarrier within a subband is assumed to be allocated to only one user. As stated previously, each subcarrier within one subband experiences flat fading and has the same channel properties. Thus, the allocated rate within subband b for user k is $N_S R_{k,b}$, where $R_{k,b}$ is the ergodic rate allocated in each subcarrier of subband b according to Equation (6). Consequently, the ergodic capacity is $\sum_{k,b} a_{k,b} N_S R_{k,b}$, where $a_{k,b}$ is the subband allocation index in subband b for user k. The resource allocation problem is to maximize the ergodic capacity under certain constraints, which can be formulated as follows:

$$C^{OFDMA} = \max_{p_{k,b},\, a_{k,b}} \sum_{k=1}^{K}\sum_{b=1}^{N_B} a_{k,b} N_S R_{k,b} \tag{7a}$$

$$\text{s.t.} \quad \sum_{k=1}^{K}\sum_{b=1}^{N_B} a_{k,b} p_{k,b} N_S \le P_t \tag{7b}$$

$$\sum_{k=1}^{K} a_{k,b} = 1, \quad a_{k,b} \in \{0,1\}, \quad \forall b \in \{1,\dots,N_B\} \tag{7c}$$

$$\sum_{k=1}^{K} a_{k,b} p_{k,b} \le \bar{p}_b, \quad \forall b \in \{1,\dots,N_B\} \tag{7d}$$

$$\sum_{b=1}^{N_B} a_{k,b} \le \theta_k N_B, \quad \forall k \tag{7e}$$

where P_t is the system total power; $\bar{p}_b$ is PSD mask of each subcarrier within subband b; θ_k is the fairness guarantee factor (FGF) for user k, which is a predefined non-negative real number and satisfies $\sum_{k=1}^{K} \theta_k \ge 1$.

The first constraint limits the total power allocated to P_t, where $p_{k,b}N_S$ is the allocated power in subband b for user k. The second constraint imposes the exclusive subcarrier allocation, while the third constraint satisfies the PSD mask $\bar{p}_b$ corresponding to the EMC of the PLC system. The last constraint indicates the maximum number of subbands that each user can occupy, where $\theta_k N_B$ is the maximum value. Thus, the allocated rate R_k for user k can be adjusted by θ_k to ensure fairness for all users.

Note that the above model is similar to that used in wireless networks. However, the expression of the ergodic rate $R_{k,b}$ in the objective function is more complex because it involves both IN and CEE. Furthermore, the third constraint is a particular problem associated with PLC systems.

3.2. **Problem formulation for improved MC-CDMA scheme.** In this scheme, each user can be allocated any spreading codes of any subband. Let the ergodic rate in code channel c of subband b for user k be $R_{k,b,c}$. By substituting $p_{k,b}$ with $p_{k,b,c}$ in Equation (6), the expression $R_{k,b,c} = E\{\log_2(1 + p_{k,b,c}\gamma_{k,b})\}$ can be derived, where $p_{k,b,c}$ is the allocated power in code channel c of subband b for user k. Thus, the ergodic capacity is $\sum_{k,b,c} a_{k,b,c}R_{k,b,c}$, where $a_{k,b,c}$ is the allocation index. The optimization problem can be written as:

$$C^{MC\text{-}CDMA} = \max_{p_{k,b,c},\, a_{k,b,c}} \sum_{k=1}^{K}\sum_{b=1}^{N_B}\sum_{c=1}^{N_S} a_{k,b,c} R_{k,b,c} \tag{8a}$$

$$\text{s.t.} \quad \sum_{k=1}^{K}\sum_{b=1}^{N_B}\sum_{c=1}^{N_S} a_{k,b,c} p_{k,b,c} \le P_t \tag{8b}$$

$$\sum_{k=1}^{K} a_{k,b,c} = 1, \quad a_{k,b,c} \in \{0,1\}, \quad \forall b \in \{1,\dots,N_B\}, \quad \forall c \tag{8c}$$

$$\sum_{k=1}^{K}\sum_{c=1}^{N_S} a_{k,b,c} p_{k,b,c} \le \bar{p}_b, \quad \forall b \in \{1,\dots,N_B\} \tag{8d}$$

$$\sum_{c=1}^{N_S} a_{k,b,c} \le \theta_k N_S, \quad \forall b \in \{1,\dots,N_B\}, \quad \forall k \tag{8e}$$

The objective function is different from that of traditional MC-CDMA. The latter can be expressed as $\sum_{k,c} a_{k,c} \sum_b R_{k,b,c}$, where $a_{k,c}$ is the code allocation index, i.e., each user is allocated a set of spreading codes that occupy the entire spectrum, and then multiuser diversity can only be provided by means of the power allocation. The former means that each user can be allocated any spreading codes in any subband, so it is more flexible, and multiuser diversity can be exploited by means of both subband selection and power allocation.

Similar to the OFDMA scheme, the constraints in this scheme are the total power allocation, the exclusive subcarrier and code allocation, the PSD mask, and fairness guarantee. The maximum number of codes for each user in each subband is denoted $\theta_k N_S$, which ensures fairness for the users. Note that $\bar{p}_b$ here is the sum of the PSD mask of each subcarrier within subband b.

As can be seen, the objectives of the two models have shown the potential maximum ergodic capacity of the OFDMA and improved MC-CDMA schemes, respectively, and the imperfect CSI is implied in the expression of the ergodic rate. At the same time, the constraints reflect the actual PLC environment and fairness for the users. Hence, by comparing the two models, the performance of the two schemes can be investigated and compared.

4. **Optimal Resource Allocation.**

4.1. **Resource allocation for OFDMA scheme.**

The original resource allocation model for the OFDMA scheme described in (7) is a mixed-integer nonlinear optimization problem. Consequently, it is impractical to use an exhaustive search to determine the optimal solution. Instead, to solve the optimization problem, we adopted an approach similar to the time-sharing technique (see, e.g., [23]). The range of the indicator function $a_{k,b} \in \{0, 1\}$ is relaxed to include the real numbers within the interval $[0, 1]$, and can be interpreted as a time-sharing factor that indicates the portion of time during which subband b is assigned to user k. However, because the problem still has nonconvex constraints, we set the "actual" power allocated to each subcarrier within subband b for user k as $x_{k,b} = a_{k,b} p_{k,b}$. Then, the problem (7) can be relaxed as follows:

$$C_{relaxation}^{OFDMA} = \max_{x_{k,b},\, a_{k,b}} \quad \sum_{k=1}^{K} \sum_{b=1}^{N_B} a_{k,b} N_S R_{k,b} \tag{9a}$$

$$\text{s.t.} \quad \sum_{k=1}^{K} \sum_{b=1}^{N_B} x_{k,b} N_S \leq P_t \tag{9b}$$

$$\sum_{k=1}^{K} a_{k,b} = 1, \quad a_{k,b} \in [0, 1], \quad \forall b \in \{1, \ldots, N_B\} \tag{9c}$$

$$\sum_{k=1}^{K} x_{k,b} \leq \bar{p}_b, \quad \forall b \in \{1, \ldots, N_B\} \tag{9d}$$

$$\sum_{b=1}^{N_B} a_{k,b} \leq \theta_k N_B, \quad \forall k \tag{9e}$$

According to (6), $\partial(a_{k,b} N_S R_{k,b})/\partial x_{k,b}$ is a decreasing function of $x_{k,b}$, which means that the objective function in (9) is convex. Furthermore, the constraints are all linear. So the relaxed problem (9) is a convex optimization problem. In writing the dual formulation, the Lagrangian is:

$$
\begin{aligned}
L = {} & \sum_{k,b} a_{k,b} N_S R_{k,b} + \mu \left(P_t - \sum_{k,b} x_{k,b} N_S \right) + \sum_b \nu_b \left(1 - \sum_k a_{k,b} \right) \\
& + \sum_b \beta_b \left(\bar{p}_b - \sum_k x_{k,b} \right) + \sum_k \delta_k \left(\theta_k N_B - \sum_b a_{k,b} \right)
\end{aligned}
\tag{10}
$$

where μ, ν_b, β_b and δ_k are Lagrange multipliers.

Since the problem (9) is convex, the optimal $a_{k,b}$ and $x_{k,b}$ required to maximize L are the solution to (9) based on dual optimization theory [24]. The Lagrangian in (10) is a convex function of $x_{k,b}(\forall k, b)$. Therefore, any local maximum of the function is a global maximum. Calculating the derivative of L w.r.t. $x_{k,b}$, the expression becomes:

$$
\frac{\partial L}{\partial x_{k,b}} = \begin{cases} N_S E \left\{ \dfrac{\gamma_{k,b}}{(1 + \gamma_{k,b} x_{k,b}/a_{k,b}) \ln 2} \right\} - \mu N_S - \beta_b, & a_{k,b} \neq 0 \\ -\mu N_S - \beta_b, & \text{else} \end{cases}
\tag{11}
$$

If $a_{k,b} = 0$, then L is a decreasing function of $x_{k,b}$ since μ and β_b are greater than zero. Therefore, the optimal value of $x_{k,b}$ is zero. If $a_{k,b} \neq 0$, then $\partial L / \partial x_{k,b}$ is a decreasing function of $x_{k,b}$, and L will achieve the maximum value when the derivative value is zero. Thus, the following equation is satisfied:

$$
E \left\{ \frac{\gamma_{k,b}}{1 + \gamma_{k,b} p^*_{k,b}} \right\} = (\mu + \beta_b / N_S) \ln 2
\tag{12}
$$

where $p^*_{k,b} = x^*_{k,b}/a_{k,b}$ and $x^*_{k,b}$ are the optimal values of $p_{k,b}$ and $x_{k,b}$, respectively.

Since the power value cannot be negative, (12) can be modified as:

$$
p^*_{k,b} = \begin{cases} 0, & E\{\gamma_{k,b}\} < (\mu + \beta_b/N_S) \ln 2 \\ p^*_{k,b} : E \left\{ \dfrac{\gamma_{k,b}}{1 + \gamma_{k,b} p^*_{k,b}} \right\} = (\mu + \beta_b/N_S) \ln 2, & \text{else} \end{cases}
\tag{13}
$$

According to the BG distribution of IN in (2), the equation can be expressed as:

$$
E \left\{ \frac{\gamma_{k,b}}{1 + \gamma_{k,b} p^*_{k,b}} \right\} = (1 + \lambda) E \left\{ \frac{\gamma^B_{k,b}}{1 + p^*_{k,b} \gamma^B_{k,b}} \right\} + \lambda E \left\{ \frac{\gamma^I_{k,b}}{1 + p^*_{k,b} \gamma^I_{k,b}} \right\}
\tag{14}
$$

Using the PDF as (5), the closed form approximation can be derived as [21]:

$$
\begin{aligned}
E \left\{ \frac{\gamma^B_{k,b}}{1 + p^*_{k,b} \gamma^B_{k,b}} \right\} & \approx \frac{\beta^\alpha}{\Gamma(\alpha)} \int_0^\infty \frac{\left(\gamma^B_{k,b}\right)^\alpha}{1 + p^*_{k,b} \gamma^B_{k,b}} e^{-\beta \gamma_{k,b}} d\gamma_{k,b} \\
& = \frac{\alpha}{p^*_{k,b}} \left(\frac{\beta}{p^*_{k,b}} \right)^\alpha e^{\frac{\beta}{p^*_{k,b}}} \Gamma \left(-\alpha, \frac{\beta}{p^*_{k,b}} \right)
\end{aligned}
\tag{15}
$$

where $\Gamma(\alpha, x)$ is the incomplete Gamma function.

Substituting $\gamma^B_{k,b}$ with $\gamma^I_{k,b}$ into (15), the second part of the right-hand side of (14) can be calculated. Thus, (13) can be resolved to a closed form expression.

Then, the Lagrangian in (10) can be expressed as:

$$
L = \mu P_t + \sum_k \delta_k \theta_k N_B + \sum_b \beta_b \bar{p}_b + \sum_b \nu_b \left(1 - \sum_k a_{k,b} \right) + \sum_{k,b} a_{k,b} Y_{k,b}
\tag{16}
$$

where

$$Y_{k,b} = N_S E\left\{\log_2\left(1 + p^*_{k,b}\gamma_{k,b}\right)\right\} - \left(\mu N_S + \beta_b\right) p^*_{k,b} - \delta_k \tag{17}$$

where the expectation expression is shown in (6).

The Lagrange multiplier ν_b in (16) must be chosen such that $\sum_k a_{k,b} = 1$, then $\sum_b \nu_b \left(1 - \sum_k a_{k,b}\right)$ is zero. To maximize L, $\sum_{k,b} a_{k,b} Y_{k,b}$ in (16) must be maximized. So, for each b, let $a_{k,b} = 1$ if the value of the corresponding $Y_{k,b}$ is the maximum; otherwise, $a_{k,b} = 0$. This means that subband b is completely allocated to the best user k. In other words,

$$k^*_b = \arg\max_k (Y_{k,b}) \tag{18}$$

As a result, the optimal user selection and power assignment for the relaxed problem in (9) can be formulated, respectively, by

$$a^*_{k,b} = \begin{cases} 1 & k = k^*_b \\ 0 & \text{else} \end{cases} \tag{19}$$

$$p^*_{k,b} = \begin{cases} p^*_{k,b} & a^*_{k,b} = 1 \\ 0 & \text{else} \end{cases} \tag{20}$$

Proposition 4.1. *Equations (19) and (20) provide the optimal solution to the original problem (7).*

Proof: Since the relaxed problem in (9) is a convex problem, the duality gap between the problem in (9) and the Lagrangian in (10) is zero, which means that (19) and (20) represent the optimal solution to (9). Furthermore, the problem in (9) is a relaxation of the original problem in (7), which indicates that the optimal solution to (9) is the upper bound on the solution to (7). Meanwhile, (19) and (20) satisfy all the constraints in (7). Therefore, they are also the optimal solution to the original problem (7).

4.2. **Resource allocation for improved MC-CDMA scheme.** Similar to the above convex optimization process, $a_{k,b,c} \in \{0, 1\}$ is relaxed to include the real numbers within the interval $[0, 1]$, and the "actual" power in code channel c of subband b for user k is set to $x_{k,b,c} = a_{k,b,c} p_{k,b,c}$. Then, the original problem (8) is relaxed to be a convex problem, and the corresponding Lagrangian is

$$\begin{aligned} L = &\sum_{k,b,c} a_{k,b,c} R_{k,b,c} + \mu\left(P_t - \sum_{k,b,c} x_{k,b,c}\right) + \sum_{b,c} \nu_{b,c}\left(1 - \sum_k a_{k,b,c}\right) \\ &+ \sum_b \beta_b\left(\bar{p}_b - \sum_{k,c} x_{k,b,c}\right) + \sum_{k,b} \delta_{k,b}\left(\theta_k N_S - \sum_c a_{k,b,c}\right) \end{aligned} \tag{21}$$

where μ, $\nu_{b,c}$, β_b and $\delta_{k,b}$ are Lagrange multipliers.

The optimal power value can be written as:

$$p^*_{k,b,c} = \begin{cases} 0, & E\{\gamma_{k,b}\} < (\mu + \beta_b)\ln 2 \\ p^*_{k,b,c} : E\left\{\dfrac{\gamma_{k,b}}{1 + \gamma_{k,b} p^*_{k,b,c}}\right\} = (\mu + \beta_b)\ln 2, & \text{else} \end{cases} \tag{22}$$

Similarly, (22) can be resolved to a closed form expression using (14) and (15).

Then the best user k for code c in subband b can be selected to maximize L, that is:

$$k^*_{b,c} = \arg\max_k \left(F_{k,b,c} - \delta_{k,b}\right) \tag{23}$$

where

$$F_{k,b,c} = E\left\{\log_2\left(1 + p^*_{k,b,c}\gamma_{k,b}\right)\right\} - (\mu + \beta_b) p^*_{k,b,c} \tag{24}$$

Therefore, the optimal user selection and power assignment for the relaxed problem can be written as:

$$a^*_{k,b,c} = \begin{cases} 1 & k = k^*_{b,c} \\ 0 & \text{else} \end{cases} \tag{25}$$

$$p^*_{k,b,c} = \begin{cases} p^*_{k,b,c} & a^*_{k,b,c} = 1 \\ 0 & \text{else} \end{cases} \tag{26}$$

Proposition 4.2. *Equations (25) and (26) represent the optimal solution to the original problem in (8).*

Proof: The proof is similar to that for Proposition 4.1 above.

5. **Algorithm Implementation.** To obtain the optimal resource allocation, the key is to find the optimal Lagrange multipliers. For the OFDMA scheme, the multipliers are updated by the following subgradient methods:

$$\mu^{t+1} = \left[\mu^t - \kappa_1 \left(P_t - \sum_{k,b} p^*_{k,b} N_S\right)\right]^+ \tag{27}$$

$$\beta_b^{t+1} = \left[\beta_b^t - \kappa_2 \left(\bar{P}_b - \sum_{k} p^*_{k,b}\right)\right]^+ \tag{28}$$

$$\delta_k^{t+1} = \left[\delta_k^t - \kappa_3 \left(\theta_k N_B - \sum_{b} a^*_{k,b}\right)\right]^+ \tag{29}$$

where $\kappa_1 = d_1/\sqrt{t}$, $\kappa_2 = d_2/\sqrt{t}$, and $\kappa_3 = d_3/\sqrt{t}$ are a diminishing step size; d_1, d_2, and d_3 are the step size control coefficients; t is the iteration index; $[\cdot]^+$ denotes $\mathbf{max}(\cdot, 0)$.

For the improved MC-CDMA system, all code channels for a particular user are identical only in each subband. The codes can be allocated to users in a descending order of $F_{k,b,1}$ in (24) for each subband. Only when the current user has been allocated the maximum number of codes, the allocation process will move to the next user. This process will be repeated until all the codes are allocated. This ensures that the fairness constraint is satisfied and the multiplier $\delta_{k,b}$ can be ignored. The other multipliers are updated by the following subgradient methods:

$$\mu^{t+1} = \left[\mu^t - \bar{\kappa}_1 \left(P_t - \sum_{k,b,c} p^*_{k,b,c}\right)\right]^+ \tag{30}$$

$$\beta_b^{t+1} = \left[\beta_b^t - \bar{\kappa}_2 \left(\bar{P}_b - \sum_{k,c} p^*_{k,b,c}\right)\right]^+ \tag{31}$$

where $\bar{\kappa}_1 = \bar{d}_1/\sqrt{t}$ and $\bar{\kappa}_2 = \bar{d}_2/\sqrt{t}$ are a diminishing step size; $\bar{d}_1$ and $\bar{d}_2$ are the step size control coefficients.

The specific steps of the proposed algorithms for both schemes are shown in Table 1.

The complexity of both algorithms can be compared as follows. For Algorithm 1, let I_p denote the number of zero-finding iterations in line 4, and I_c denote the number of evaluations in line 5. The number of operations in lines 7 and 8 can be neglected relative to the numbers of operations in the previous lines. Then, the loop in lines 2 to 9 requires $o\left(KN_B(I_p + I_c)\right)$ operations. Let I_μ, I_δ, and I_β respectively denote the number of iterations required for lines 10, 12 and 14 to converge. Then, the overall complexity is $o\left(I_\beta I_\delta I_\mu KN_B(I_p + I_c)\right)$. The proposed algorithm is linear in terms of the number of subbands, while the traditional exhaustive search is exponential. This implies a significant

TABLE 1. Proposed algorithms for both schemes

Algorithm 1 : OFDMA scheme	**Algorithm 2 : MC-CDMA scheme**
1 Initialize μ, $\beta_b(\forall b)$ and $\delta_k(\forall k)$ 2 For $b = 1$ to N_b 3 For $k = 1$ to K 4 Use (13) to calculate $p^*_{k,b}$ 5 Use (17) to calculate $Y_{k,b}$ 6 end for 7 Use (18) to calculate k^*_b 8 Use (19), (20) to modify $p^*_{k,b}$ 9 end for 10 Use (27) to update μ 11 Repeat lines 2 to 10 until convergence 12 Use (29) to update $\delta_k(\forall k)$ 13 Repeat lines 2 to 12 until convergence 14 Use (28) to update $\beta_b(\forall b)$ 15 Repeat lines 2 to 14 until convergence	1 Initialize μ, $\beta_b(\forall b)$ 2 For $b = 1$ to N_b 3 For $k = 1$ to K 4 If $c = 1$, use (22) to calculate $p^*_{k,b,1}$; otherwise, let $p^*_{k,b,c} = p^*_{k,b,1}$ 5 Use (24) to calculate $F^*_{k,b,1}$ 6 end for 7 For each k, sort $p^*_{k,b,1}$ in a descending order 8 Allocate $\theta_k N_S$ codes to each front user (i.e., let $k^*_{b,c} = 1$) by turn until all codes allocated 9 For each k, use (25), (26) to modify $p^*_{k,b,c}$ 10 end for 11 Use (30) to update μ 12 Repeat lines 2 to 11 until convergence 13 Use (31) to update $\beta_b(\forall b)$ 14 Repeat lines 2 to 13 until convergence

reduction in the computational complexity. For Algorithm 2, the numbers of operations in lines 4 and 5 are the same as those in lines 4 and 5 of Algorithm 1, respectively, while the number of operations in lines 8 to 10 can be neglected in comparison to the numbers in the previous lines. Thus, the loop in lines 2 to 10 also requires $o(KN_B(I_p+I_c))$ operations. Let $\bar{I}_\mu$ and $\bar{I}_\beta$ respectively denote the number of iterations required for lines 11 and 13 to converge, and then the overall complexity is $o\left(\bar{I}_\beta \bar{I}_\mu K N_B(I_p + I_c)\right)$. In summary, the complexity of Algorithm 1 is higher than that of Algorithm 2. The algorithm is easier for MC-CDMA because only two multipliers are involved.

6. **Simulation and Analysis.** In this section, we present and compare the performance of the proposed algorithms in the power-line channel environment. In the simulation, the following parameters are consistent with [6]. The spectrum band is 0-20 MHz with 256 subcarriers, and the number of users is 4. The total system total power is 4-20 mW. The parameters of the estimated channel gain in (4) are $a_0 = 0$, $a = 7.8e^{-10}$, $l = 1$, $M = 5$, and $v_p = 3 \times 10^8$; the matrices composed of $g_{k,i}$ and $d_{k,i}$ of each multipath for each user are [0.48, 0.44, −0.37, 0.29, −0.25; 0.44, −0.37, 0.29, −0.25, 0.21; −0.37, 0.29, −0.25, 0.21, −0.17; 0.29, −0.25, 0.21, −0.17, 0.12] and [132.5, 143, 152, 161, 172.4; 143, 152, 161, 172.4, 194.8; 152, 161, 172.4, 194.8, 217.5; 161, 172.4, 194.8, 217.5, 229], respectively. The signal PSD mask is $-50 - 0.8f$ (dBm/Hz) and the background noise PSD is $-116 + 46.7e^{-1.6f}$ (dBm/Hz), where the unit for f is MHz.

The other simulation parameters that are relevant to this investigation are listed in Table 2. The target BER in (1) is set to 1×10^{-6}, which satisfies data transmission requirement, and N_S is set equal to eight, which causes the subband bandwidth to be small enough. Correspondingly, N_B is set to 32. The values of INOP and η refer to the IN environment in [10, 11]. Three typical values have been chosen for ENVR, namely, − infinity dB, 0 dB, or 5 dB, which mean that the CEE is nonexistent, slight, or severe,

TABLE 2. System simulation parameters

Parameter	**Value**
Target BER	1×10^{-6}
No. of spreading codes N_S	8
No. of subbands N_B	32
INOP	$0 \sim 0.2$
Impulsive-to-background noise power ratio η	10
ENVR (dB)	$-$ infinity, 0 or 5
FGF (per user)	1, 0.5 or 0.25

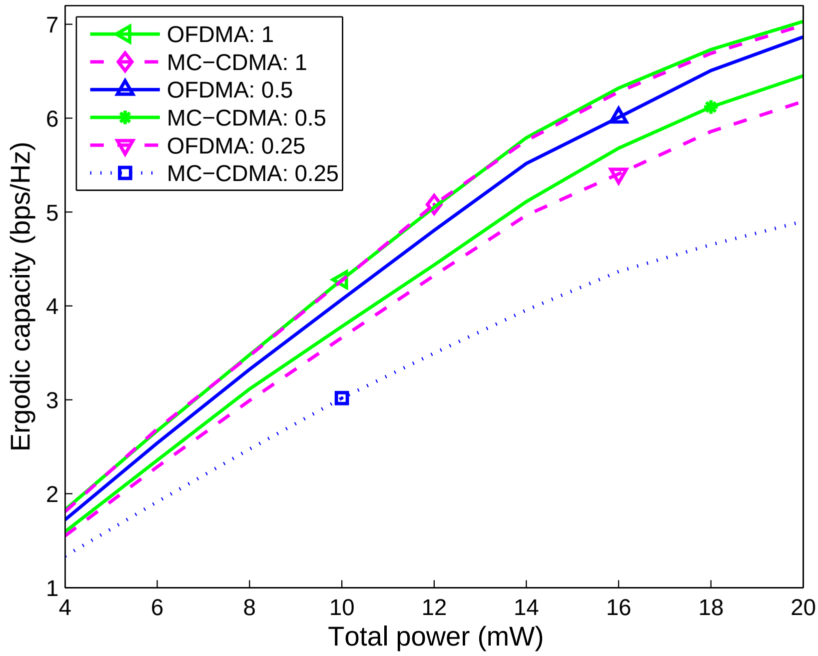

FIGURE 3. Relationship between the system total power and ergodic capacity under different FGFs

respectively. The FGF is set to 1, 0.5, or 0.25 to denote that the maximum number of subbands or codes is allocated without restriction, partially restricted, or equally restricted, respectively.

Figure 3 illustrates the relationship between the system total power and the ergodic capacity under different FGFs for both schemes with INOP 0.1 and ENVR 0 dB. As can be seen, the capacity increases with the total power, while the increase is relatively slow when the total power is large because the power assignment for some subcarriers reaches the PSD constraint. When the FGF is 1, the improved MC-CDMA scheme can reach a capacity similar to that of OFDMA, because it can leverage multiuser diversity by means of both the subband selection and power allocation. With the decrease of the FGF, the capacity of OFDMA decreases slowly because users that reach the maximum number of allocated subbands have to first release some subbands, while that of the improved MC-CDMA scheme decreases relatively quickly because high SNR subbands have been shared among more users. When the FGF is 0.25, the capacity of the improved MC-CDMA scheme is much lower than that of the OFDMA scheme because each subband has been shared among all users. In this case, multiuser diversity can only be leveraged by means of the power allocation, as is the case for traditional MC-CDMA. This also implies the actual capacity difference between the OFDMA and traditional MC-CDMA schemes based on imperfect CSI. The aforementioned cases illuminate that OFDMA can exploit multiuser diversity better in the frequency domain and achieve a higher capacity than traditional MC-CDMA, while the improved MC-CDMA scheme can take advantage of the available multiuser diversity when the fairness constraint is not strict.

Figure 4 compares the fairness performance under the same conditions as Figure 3. By using Jain's fairness index, the fairness is defined as $\left(\sum_{k=1}^{K} R_k\right)^2 \Big/ \left(K \sum_{k=1}^{K} R_k^2\right)$ [4]. As can be seen, the fairness increases with the total power because the redundant power has been allocated to weak users. When the FGF is 1, the fairness of MC-CDMA is similar to that of OFDMA, which is relative minimum because the fairness is not guaranteed. With the decrease of the FGF, the fairness of both schemes increases, and that of MC-CDMA is higher than OFDMA, because the high SNR subbands have been shared among more users. As can be seen from Figure 3 and Figure 4, both schemes can balance the capacity and fairness well when FGF is 0.5.

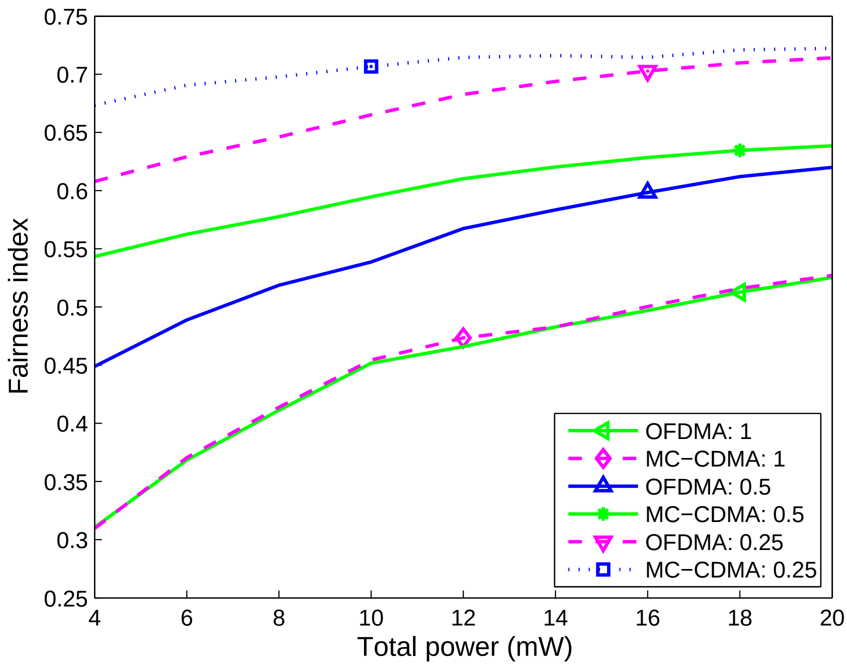

FIGURE 4. Relationship between the system total power and fairness under different FGFs

Figure 5 shows the computation complexity of the proposed algorithms with INOP 0.1, the ENVR is 0 dB, the total system power is 10 mW, and the FGF is 0.5. As can be seen, the fairness of MC-CDMA is also converged when the power is converged, because the fairness constraint is satisfied by allocating the maximum number of codes in the allocation process. However, the fairness of OFDMA needs to be converged when the power is firstly converged, and then the latter needs to be converged again. The iteration number of OFDMA is about 120, while that of MC-CDMA is about 40, and the computation complexity of MC-CDMA is much lower.

Figure 6 shows the relationship between the system total power and ergodic capacity under different ENVRs with INOP 0.1 and FGF 0.5. It can be observed that the capacity of both schemes, respectively, decreases as ENVR increases, which causes the estimation

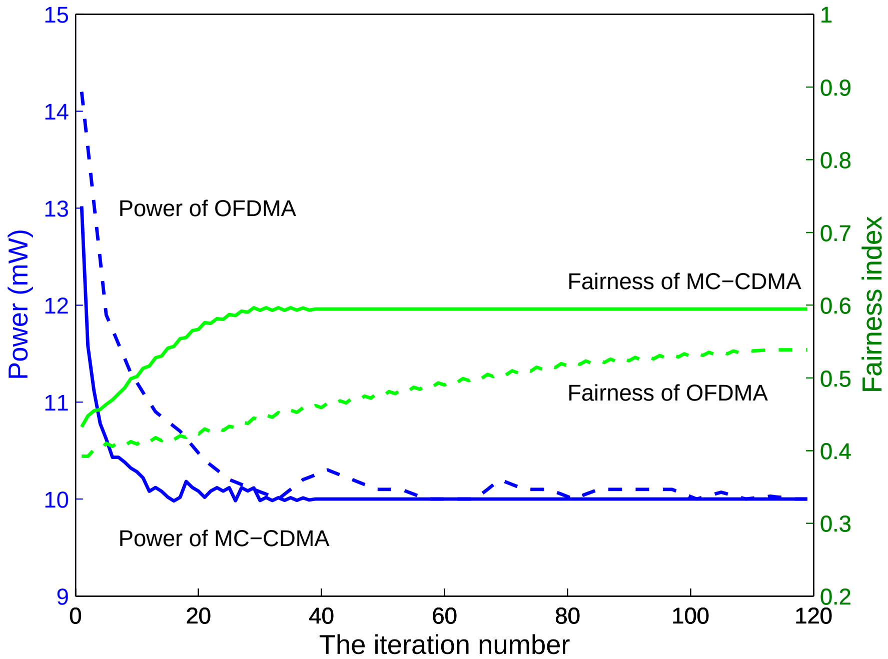

FIGURE 5. Computation complexity of the proposed algorithms

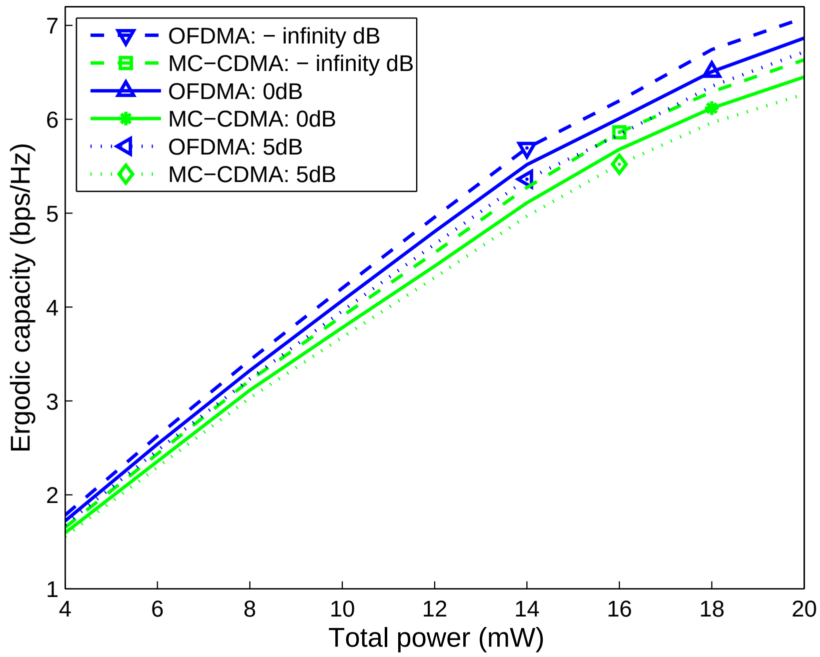

FIGURE 6. Relationship between the system total power and ergodic capacity under different ENVRs

errors to become more severe. This is expected, since the capacity depends on the PDF of the channel distribution, which is sensitive to the CEE.

Figure 7 compares the ergodic capacity of the four algorithms under different INOPs with ENVR −infinity dB, the total system power is 10 mW, and the FGF is 0.5. The notation "*OFDMA in [12]*" in the figure means the algorithm refers to the OFDMA scheme proposed in [12], which deals with IN but does not consider the CEE. Similarly,

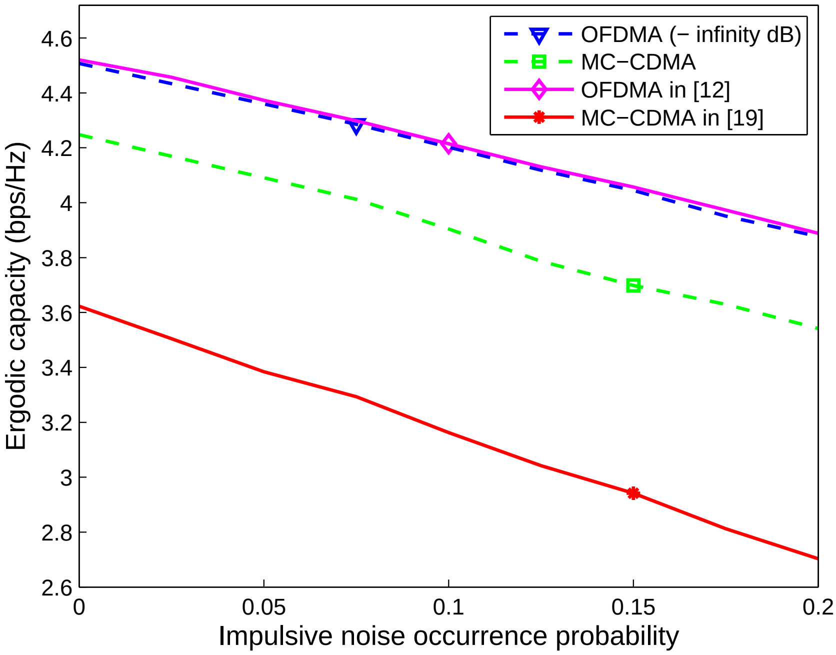

FIGURE 7. Ergodic capacity comparison of the four algorithms under different INOPs with ENVR − infinity dB

the notation "*MC-CDMA in [19]*" refers to the algorithm for traditional MC-CDMA introduced in [19], in which both IN and CEE were not considered. As can be seen, the two OFDMA algorithms have a similar highest capacity, while the capacity of the *MC-CDMA in [19]* is always on the lowest side. With the increase of INOP, the SNR becomes worse, and the capacity of the *MC-CDMA in [19]* decreases rapidly, while that of the others decreases relatively slowly. Consistent with Figure 3, there is a gap between *OFDMA* and *MC-CDMA* because the multiuser diversity by means of subband selection is worsened for the latter when the FGF is 0.5. When the INOP is zero, there is a gap between *MC-CDMA* and *MC-CDMA in [19]* because the latter exploits multiuser diversity only by means of power allocation; the gap becomes large with the increase of INOP because the latter does not consider IN.

Figure 8 is similar to Figure 7, except that the ENVR is 0 dB and the comment about *OFDMA in [14]* proposed in [14] is added. Compared with Figure 7, the capacity of the five algorithms decreases slightly because of the CEE; there is a gap between *OFDMA* and *OFDMA in [12]* because the latter does not consider CEE; the gap between *MC-CDMA* and *MC-CDMA in [19]* is partly because the latter does not consider the CEE. In addition, the capacity of *OFDMA in [14]* is slightly larger than *OFDMA* when the INOP is small, but the capacity decreases rapidly as the INOP increases. This is because the algorithm in [14] considers the imperfect CSI to include CEE, but not INOP. The results in these cases indicate that the proposed two algorithms can achieve higher capacity gain by modelling the overall imperfect CSI cases and solving the expectation of CSI correlation function. Furthermore, improved MC-CDMA scheme can better exploit multiuser diversity than in the traditional MC-CDMA, and can thereby reduce the capacity gap with OFDMA. In essence, the improved scheme integrates the benefits of traditional MC-CDMA with those of OFDMA.

Figure 9 compares the fairness performance under the same conditions as those in Figure 8. The fairness of *MC-CDMA in [19]* is relatively high because the number of

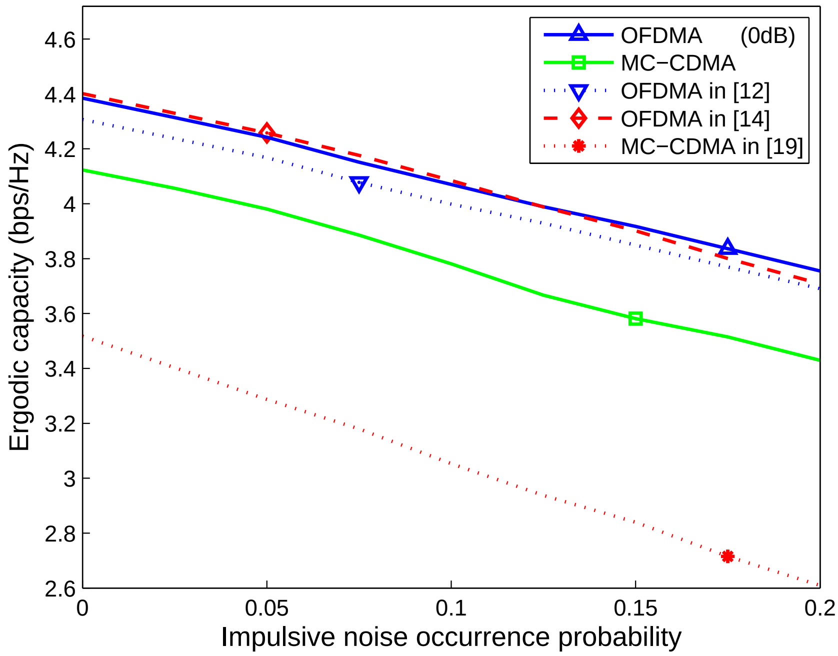

FIGURE 8. Ergodic capacity comparison of the five algorithms under different INOPs with ENVR 0 dB

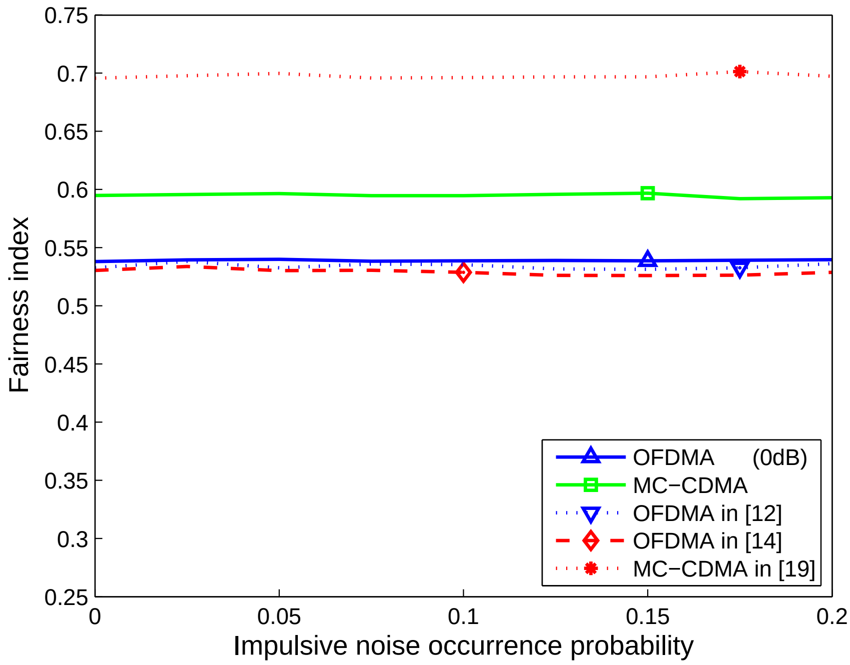

FIGURE 9. Fairness comparison of five algorithms under different INOPs with ENVR 0 dB

codes is allocated equally, which is at the expense of capacity loss. As can be seen, the proposed two algorithms can achieve higher fairness than the other two algorithms.

7. **Conclusions.** Considering that perfect power-line CSI is not available, the ergodic capacities of the OFDMA and improved MC-CDMA schemes are investigated based on imperfect CSI. The schemes are evaluated with a fairness constraint, which is modelled

by constraining the maximum number of subbands or codes occupied per user. The resource allocation problems are modelled for the overall imperfect CSI cases, which include IN and CEE. The optimal user selection and power allocation are resolved by dual optimization. It is demonstrated that higher capacity gain has been achieved compared with existing algorithms by solving the closed form expression of the imperfect CSI correlation function and by implementing a more reasonable resource allocation technique. The proposed improved MC-CDMA scheme can achieve higher capacity and reduce the capacity gap with OFDMA because the former can also exploit multiuser diversity by means of subband selection. Furthermore, the two proposed schemes can balance capacity and fairness well. Our future research work will focus on cross-layer resource allocation techniques for OFDMA and MC-CDMA schemes over imperfect power-line channels via acknowledge/not-acknowledge (ACK/NAK) feedback.

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