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Resource Management Techniques for OFDM Systems with the Presence of Inter-Carrier Interference

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Abstract The aim of the paper is to study the problems of resource management in the presence of inter-carrier interference (ICI) and multipath fading channel for orthogonal frequency division multiplexing (OFDM) systems. OFDM is a promising technique for the broadband wireless communication systems. However, the OFDM communication system is sensitive to ICI which arises because of Doppler spread and carrier frequency offset (CFO). To solve these problems, an optimization method has been exploited, and a computationally efficient method using numerical optimization techniques is proposed. The simulation results show that these derived optimal solutions and proposed suboptimal algorithms as compared with the uniform power allocation algorithm or conventional water-filling algorithm can significantly improve the performance of the OFDM systems.

Keywords Orthogonal frequency division multiplexing · Inter-carrier interference · Doppler spread · Carrier frequency offset · Water-filling

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1 Introduction

Orthogonal frequency division multiplexing (OFDM) systems is an attractive transmission technique for high-bit-rate communication system [1,2]. OFDM has been recognized as a promising technology for wireless metropolitan area networks (WMANs), discrete multi-tone systems (DMT) for x digital subscriber line (xDSL)/asymmetric digital subscriber line (ADSL) applications, IEEE 802.11a/g wireless local area network (WLAN), digital audio broadcasting (DAB) system, digital video broadcasting terrestrial TV (DVB-T) system and recent IEEE 802.16 worldwide interoperability for microwave access (WiMax) systems [1–4].

The advantage of OFDM technique is that it can support high transmission data rate, high spectral efficiency and it has a strong capability to combat multipath fading [5–7]. In a classical OFDM system, the entire bandwidth is divided into many orthogonal subcarriers and information symbols are transmitted in parallel over these subcarriers by using computationally efficient fast Fourier transform, then a cycle prefix is inserted to combat inter-symbol interference (ISI). Hence the OFDM technology has a strong ability to cope with frequency selective channels. Unfortunately, one of the main drawbacks of OFDM is its sensitivity to the frequency offset, which comes from local oscillators between the transmitter and the receiver, and the Doppler frequency shifts in wireless channels. A key issue for OFDM systems is the resource management. The frequency offset induces a loss of the orthogonality among subcarriers so that inter-carrier interference (ICI) is caused, which would significantly degrade the system performance [8,9]. Sever approaches to reducing ICI have been developed, such as time domain windowing [10], frequency-domain equalization [11,12] and the ICI self-cancellation scheme [13]. Among these approaches, the ICI self-cancellation scheme can achieve outstanding performance with an easy implementation. The resource allocation schemes can exploit frequency diversity to improve system performance. There are various resource allocation issues subject to different objective in OFDM systems, such as power allocation, bit loading and adaptive coding, etc. Resource allocation schemes can be classified into two categories: fixed resource allocation [14] and dynamic resource allocation [15–18]. A fixed resource allocation scheme is not optimal since the scheme is fixed regardless of the current channel state information (CSI). On the other hand, dynamic resource allocation allocates a dimension adaptively to the users based on their CSI. Several dynamic resource allocation schemes subject to different optimization criteria for single-user OFDM systems can be classified as follows: Rate adaptive (RA): Maximize sum capacity while maintaining total transmission power constraint [16,17,19]. In [17], the optimization problem of the RA in OFDM systems is formulated to balance the tradeoff between sum capacity and fairness. The algorithm proposed in this paper can achieve almost the maximum sum capacity while keeping the proportional fairness. Minimum average bit-error-rate (BER): Minimize average BER of all subcarriers under total transmission power constraint [20,21]. Margin adaptive (MA): Achieve minimum overall transmission power with constraint on the user's required data rate [22]. In [22], the total transmit power is minimized by assigning each user a set of subcarriers and by determining the number of bits and the transmit power level for each subcarrier based on the instantaneous channel gain.

For maximization optimization problem, it is well known that water-filling is the optimal power distribution algorithm for the single-user communication and provides the basis for the power and bit allocation schemes in the OFDM system. Assuming that the CSI is perfectly known at transmitter, the optimal power allocation maximizing the sum capacity is obtained by allocating more power to subcarriers with higher channel gain. The single user of water-filling procedure is given in [23]. The optimization criteria of this paper focuses on RA and minimum average BER to adaptive allocate resource for signal-user OFDM Systems.

As mentioned above, resource allocation schemes can efficiently improve the system performance in terms of throughput or BER, respectively, while the CSI is perfectly known both at the transmitter and the receiver. However, the performance of OFDM system not only depends on the effect of fading channel, but also on ICI, which arises because of Doppler frequency spread and carrier frequency offset (CFO) [24]. Involving the Doppler frequency spread and CFO, the orthogonality among subcarriers may be destroyed and then degrades the system performance. Therefore, the resource allocation schemes need to take the ICI effect into account to improve the system performance; even most methods to combat ICI tend to use frequency synchronization or interference cancelation [25,26]. These methods have a complex receiver structure and sometimes cause a loss in bandwidth efficiency. In all existing OFDM communication systems, the subcarrier bandwidth is kept constant. The bandwidth is chosen large enough to tolerate a certain amount of Doppler spread or CFO. By considering both multipath fading channel and ICI situations, if complete CSI which includes both the Doppler frequency spread and channel response is perfectly known at transmitter, resource allocation scheme can effectively exploit it to reduce the ICI effect and the implementation complexity at the receiver. Some researches have focused on dealing with this resource allocation issue [27,28]. One novel idea, named adaptive subcarrier bandwidth scheme [27], uses variable subcarrier bandwidth for OFDM systems to overcome the impact of ICI since ICI is inversely proportional to the subcarrier bandwidth [29]. An adaptive bit loading algorithm in conjunction with adaptive subcarrier bandwidth scheme is proposed in [27], nevertheless, the adaptive power distribution among subcarriers is not considered.

Observations above motivate us to design an optimal joint bit loading and power allocation scheme that attempts to maximize the system throughput while each subcarrier maintaining equal target BER while maintaining total power constraint in both multipath fading channel and ICI situations. As the optimal solution for OFDM systems in the presence ICI is prohibitively complex to obtain, we propose suboptimal joint bit loading and power allocation schemes for above optimization criterion, respectively.

The remaining sections of this article are organized as follows. In Sect. 2, we present the uplink OFDM system model. Section 3, we derive optimal initial power allocation in the average sense and develop a suboptimal subcarrier assignment algorithm. Some simulation results and discussions are given in Sect. 4. Comparisons with other algorithms are also given in this Section. Finally, the conclusions are drawing in Sect. 5.

2 System Model

Considering an OFDM system with N subcarriers, the baseband time domain transmitted signal of sth OFDM symbol can be expressed as

$$x_s(t) = \frac{1}{\sqrt{T_{\Delta f_{sc}}}} \sum_{n=1}^{N_{\Delta f_{sc}}} X_{s,n} \exp\left(j2\pi \frac{n}{T_{\Delta f_{sc}}}(t - sT_s - T_{gi})\right) u(t - sT_s), \tag{1}$$

where n is the subcarrier index, and $X_{s,n}$ denotes the frequency domain modulated data symbol on the nth subcarrier. From the available options of subcarrier frequency spacing Δf_{sc}, $N_{\Delta f_{sc}}$ and $T_{\Delta f_{sc}}$ represent the total number of subcarriers and the OFDM symbol duration respectively, T_s is the symbol duration which includes $T_{\Delta f_{sc}}$ and the GI duration T_{gi}. Each data symbol is shaped by

$$u(t) = \begin{cases} 1, & 0 \le t < T_s \\ 0, & \text{O.W}. \end{cases} \tag{2}$$

We consider a multipath Rayleigh fading channel which is assumed to be slowly fading, so the channel coefficients are considered as constant during one OFDM symbol. After passing through the channel, the transmitted signal can be represented as

$$y(t) = \int_0^{\tau_{\max}} h(\tau) \exp\left(j2\pi f_{d_\tau}(t-\tau)\right) x_s(t-\tau)\, d\tau + n(t), \tag{3}$$

where $\tau_{\max}$ is the maximum delay spread, $h(\tau)$ is the channel impulse response, $n(t)$ is the additive white Gaussian noise (AWGN) with zero mean and variance σ_n^2, and f_{d_τ} is the Doppler shift frequency for delay τ. Assuming perfect timing synchronization between transmitter and receiver but CFO δf_c occurs, the sth received OFDM symbol can be represented as [27]

$$\begin{aligned} y_s(t) &= y(t)\, e^{j2\pi\delta f_c t} \\ &= \int_0^{\tau_{\max}} x_s(t-\tau)\, h(\tau) \exp\left(j2\pi f_{d_\tau}(t-\tau)\right) \exp\left(j2\pi\delta f_c t\right) d\tau + n(t) \end{aligned} \tag{4}$$

Since $h(\tau)\exp\left(-j2\pi f_{d_\tau}\tau\right)$ can't be distinguished from $h(\tau)$, we can represent $h(\tau)\exp(j2\pi f_{d_\tau}\tau)$ as $h(\tau)$. Therefore,

$$y_s(t) = \int_0^{\tau_{\max}} x_s(t-\tau)\, h(\tau) \exp\left(j2\pi f_{d_\tau}\tau\right) \exp\left(j2\pi t\left(\delta f_c + f_{d_\tau}\right)\right) d\tau + n(t) \tag{5}$$

Further, there exists a Doppler frequency offset ε between transmitter and receiver. The Doppler frequency offset $\varepsilon = \frac{\delta f}{\Delta f_{sc}}$ is normalized to the subcarrier frequency spacing $\Delta f_{sc} = \frac{1}{T_{\Delta f_{sc}}}$, where $\delta f = \delta f_c + f_{d_\tau}$.

After demodulating by FFT, the sth received OFDM symbol at the nth subcarrier can be represented as

$$Y_{s,n} = \underbrace{X_{s,n} H_{s,n} S_{n,n}(\varepsilon)}_{\text{desired signal term}} + \underbrace{\sum_{m=1,\, m\neq n}^{N_{\Delta f_{sc}}} X_{s,m} H_{s,m} S_{n,m}(\varepsilon)}_{\text{ICI term}} + W_n, \tag{6}$$

where $H_{s,n}$ is the channel gain for the nth subcarrier of the sth OFDM symbol, W_n is the frequency domain noise component for the nth subcarrier, and $S_{n,m}$ is the ICI effect of subcarrier n from the subcarrier m in the same OFDM symbol which is given by

$$S_{n,m}(\varepsilon) = \left(\frac{\sin\left(\pi\,(m-n+\varepsilon)\right)}{N_{\Delta f_{sc}} \sin\left(\frac{\pi}{N_{\Delta f_{sc}}}(m-n+\varepsilon)\right)} \exp\left(j\pi\left(1-\frac{1}{N_{\Delta f_{sc}}}\right)(m-n+\varepsilon)\right)\right). \tag{7}$$

Assuming that $X_{s,n}$ is zero mean, which implies that the interference term is also zero mean, the power of the ICI term is the same as its variance, which can be expressed as follows

$$\sigma^2_{\mathrm{ICI}_{X_n}} = \sum_{m=1, m\neq n}^{N_{\Delta f_{sc}}} \mathrm{E}\left(|X_m|^2\right) |H_m|^2 \left|S_{n,m}(\varepsilon)\right|^2, \tag{8}$$

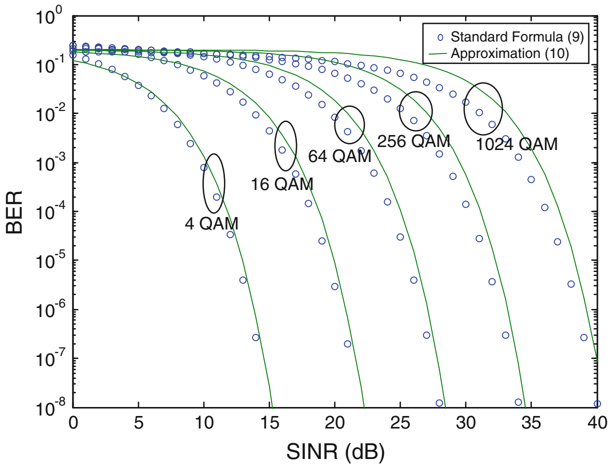

Fig. 1 BER approximations for M-QAM

where E $(\cdot)$ is the expectation operator. Denoting E $\left(|X_m|^2\right)$ by P_m which is the transmitted power assigned to subcarrier m. Hence, the average signal-to-interference plus noise ratio (SINR) in the presence of ICI on the subcarrier n can be expressed as follows

$$SINR_n\left(\Delta f_{sc}\right) = \frac{P_n\left|H_n\right|^2\left|S_{n,n}\left(\varepsilon\right)\right|^2}{\sum_{m=1,m\neq n}^{N_{\Delta f_{sc}}} P_m\left|H_m\right|^2\left|S_{n,m}\left(\varepsilon\right)\right|^2+\sigma_n^2},\ \text{for}\ \forall n. \tag{9}$$

The expression for the BER of square M-QAM with Gray bit mapping as a function of received SINR and bits load on the nth subcarrier b_n is approximately [30],

$$BER_n\left(SINR_n\left(\Delta f_{sc}\right),b_n\right)\approx\frac{2}{b_n}\left(1-\frac{1}{\sqrt{2^{b_n}}}\right)\times erfc\left(\sqrt{1.5\frac{SINR_n\left(\Delta f_{sc}\right)}{2^{b_n}-1}}\right). \tag{10}$$

Above expression is not easily differentiable or invertible in its SINR or bits. Another approximation for BER on the nth subcarrier tight to within 1 dB for $BER \leq 10^{-3}$ and $b \geq 2$is expressed as [31]

$$BER_n\left(SINR_n\left(\Delta f_{sc}\right),\ b_n\right)\approx 0.2\times\exp\left(\frac{-1.6SINR_n\left(\Delta f_{sc}\right)}{2^{b_n}-1}\right). \tag{11}$$

The tightness of this BER approximation from Eq. (11) to the standard formula from Eq. (10) is shown in Fig. 1.

Rearranging the Eq. (11), a maximum number of bits on the nth subcarrier in a symbol is a function of BER and the transmitted power distribution vector $\mathbf{P}=\left[P_1\ P_2\ \ldots\ P_{N_{\Delta f_{sc}}}\right]^T$, and can be expressed as

$$b_n\left(P_1,\ldots P_{N_{\Delta f_{sc}}},\Delta f_{sc}\right) = \log_2\left(1+\frac{SINR_n\left(P_1,\ldots P_{N_{\Delta f_{sc}}},\Delta f_{sc}\right)}{\Gamma}\right) \tag{12}$$

where $\Gamma = -\ln\left(5BER_n\right)/1.6$, which is a function of the required BER on the nth subcarrier.

2.1 Optimization Criteria and Applications

Adaptive resource allocation schemes for signal-user OFDM systems have in common that they always follow an optimization criterion that can be any of the following three:

1. Rate adaptive (RA):

$$\begin{aligned} &\underset{P_1, P_2, \ldots, P_N}{\text{Max}} \quad \sum_{n=1}^{N} b_n \left(P_1, \ \ldots, \ P_N\right) \\ &\text{subject to:} \\ &\qquad \sum_{n=1}^{N} P_n \le P_{total} \\ &\qquad P_n \ge 0, \qquad \text{for } \forall n \end{aligned} \tag{13}$$

2. Minimize average BER:

$$\begin{aligned} &\underset{P_1, P_2, \ldots, P_N}{\text{Min}} \quad \frac{\sum_{n=1}^{N} BER_n(P_1, \ldots, P_N)}{N} \\ &\text{subject to:} \\ &\qquad \sum_{n=1}^{N} P_n \le P_{total} \\ &\qquad \sum_{n=1}^{N} b_n = R_{total} \\ &\qquad P_n \ge 0 \qquad \text{for } \ \forall n, \\ &\qquad b_n \ge 0 \qquad \text{for } \ \forall n \end{aligned} \tag{14}$$

3. Margin adaptive (MA):

$$\begin{aligned} &\underset{b_1, b_2, \ldots, b_N}{\text{Min}} \quad \sum_{n=1}^{N} P_n \\ &\text{subject to:} \\ &\qquad \sum_{n=1}^{N} b_n \ge R_{total} \\ &\qquad P_n \ge 0, \qquad \text{for } \ \forall n \\ &\qquad b_n \ge 0 \qquad \text{for } \ \forall n \end{aligned} \tag{15}$$

where P_n is the transmitted power assigned to the nth subcarrier, P_{total} is the total transmission power constraint, R_{total} is the required data rate-sum. The optimization criteria of this paper focus on RA and minimum average BER to adaptive allocate bit and power for signal-user OFDM Systems.

2.2 Adaptive Resource Allocation for the ICI Scenario: Maximize Overall Throughput: Under Equal Target Bit-Error-Rate Constraint Among All Subcarriers

Resource allocation schemes can exploit frequency diversity to improve system performance. There are various resource allocation schemes subject to different objective in OFDM systems. Some of these schemes focus on maximizing the system overall throughput among all subcarriers [10,11,13]. These resource allocation schemes can efficiently provide throughput improvement, while the channel response is perfectly known both at the transmitter and the receiver. However, these schemes are not take the effect of ICI into account. The above observation motivates us to design an optimal joint bit loading and power allocation scheme that attempts to maximize the system throughput while each subcarrier maintaining required equal *tBER* in both multipath fading channel and ICI situations.

In this section, we derive the above optimization problem by using the Lagrangian method to obtain an optimal solution. However, the optimal solution is extremely computationally complex to obtain. Therefore, a low-complexity and simple suboptimal algorithm is proposed.

Mathematically, the optimization problem considered in this section is formulated as following criterion A: Maximize the overall throughput under constant total power and each subcarrier satisfying equal *tBER* constraints. The optimization problem is formulated as

$$\begin{aligned} &\max_{P_1, P_2, \ldots, P_N} \sum_{n=1}^{N} b_n\left(P_1, \ldots, P_N\right) \\ &\text{subject to:} \\ &\qquad \sum_{n=1}^{N} P_n \le P_{total} \\ &\qquad P_n \ge 0, \qquad \text{for } \forall n \\ &\qquad BER_n \le tBER, \qquad \text{for } \forall n \\ &\qquad b_n \in \{0, 2, 4, 6.., b_{\max}\}, \qquad \text{for } \forall n. \end{aligned} \tag{16}$$

where P_{total} is the total transmission power constraint, and $b_{\max}$ is the highest number of modulation bits for each subcarrier.

3 Lagrangian Method

The optimization problem (16) is a nonconvex mixed integer programming (IP) problem and can be solved by IP method. However, the IP method is not practical, since the complexity of nonconvex mixed IP problem increases exponentially with the number of constraints and integer variables. Therefore, we relax the requirement $b_n \in \{0, 2, 4, 6.., b_{\max}\}$ to be a real number within the interval $[0, b_{\max}]$ and reformulate the above optimization problem as follows

$$\begin{aligned} &\max_{P_1, P_2, \ldots, P_N} \sum_{n=1}^{N} b_n\left(P_1, \ldots, P_N\right) \\ &\text{subject to:} \\ &\qquad \sum_{n=1}^{N} P_n \le P_{total} \\ &\qquad P_n \ge 0, \qquad \text{for } \forall n \\ &\qquad BER_n \le tBER, \qquad \text{for } \forall n. \end{aligned} \tag{17}$$

By using the KKT conditions to determine the optimal solution of the above throughput maximization problem in (17) with the Lagrangian function $L(P_1, \ldots P_N, \lambda)$ as:

$$L(P_1, \ldots P_N, \lambda, \beta_1, \ldots \beta_N) = \sum_{n=1}^{N} \log_2 \left(1 + \frac{1}{\Gamma} \frac{P_n \left|H_n\right|^2 \left|S_{n,n}(\varepsilon)\right|^2}{\sum\limits_{m=1, m \ne n}^{N} P_m \left|H_m\right|^2 \left|S_{n,m}(\varepsilon)\right|^2 + \sigma_n^2} \right) + \lambda \left(\sum_{n=1}^{N} P_n - P_{total} \right) + \sum_{n=1}^{N} \beta_n P_n \tag{18}$$

where $\Gamma = -\ln(5tBER)/1.6$, λ and β in Eq. (18) are called the Lagrangian multiplier and KKT multiplier respectively. Using the KKT condition, the optimal solution $\mathbf{P} = [P_1\ P_2\ \ldots\ P_N]^T$ satisfies the following conditions:

$$\begin{aligned} \nabla_{\mathbf{P}} L(\mathbf{P}, \lambda,\ \beta_1, \ldots \beta_N) &= 0 \\ \textstyle\sum_{n=1}^{N} P_n - P_{total} &\le 0 \\ P_n &\ge 0 \qquad \text{for } \forall n \\ \beta_n &\ge 0 \qquad \text{for } \forall n \\ \beta_n P_n &= 0 \qquad \text{for } \forall n \end{aligned} \tag{19}$$

We differentiate the Lagrangian function $L(\mathbf{P}, \lambda,\ \beta_1, \ldots \beta_N)$ with respect to P_n and set each derivative to 0. $\frac{\partial L}{\partial P_n} = 0$

$$\begin{aligned} &\Rightarrow \frac{1}{\ln 2} \cdot \frac{1}{P_n + \Gamma\left(\sum_{m \ne n} P_m \frac{|H_m|^2 |S_{n,m}(\varepsilon)|^2}{|H_n|^2 |S_{n,n}(\varepsilon)|^2} + \frac{\sigma_n^2}{|H_n|^2 |S_{n,n}(\varepsilon)|^2}\right)} = -\lambda - \beta + t_n \\ &\Rightarrow \frac{1}{\ln 2} \cdot \frac{1}{P_n + \Gamma\left(\sum_{m \ne n} P_m \frac{|H_m|^2 |S_{n,m}(\varepsilon)|^2}{|H_n|^2 |S_{n,n}(\varepsilon)|^2} + \frac{\sigma_n^2}{|H_n|^2 |S_{n,n}(\varepsilon)|^2}\right)} = \lambda_0 + \beta_0 + t_n \end{aligned} \tag{20}$$

where $\lambda_0 = -\lambda,\ \beta_0 = -\beta$.

where

$$\begin{aligned} t_n &= \frac{1}{\ln 2} \cdot \sum_{m \ne n} \\ &\times \left(\frac{P_m |H_m|^2 \left|S_{m,m}(\varepsilon)\right|^2}{\Gamma \cdot \left(P_n |H_n|^2 \left|S_{n,m}(\varepsilon)\right|^2 + \sum_{r \ne m \ne n} P_r |H_r|^2 \left|S_{m,r}(\varepsilon)\right|^2 + \sigma_n^2 \right) + P_m |H_m|^2 \left|S_{m,m}(\varepsilon)\right|^2} \right) \\ &\times \left(\frac{|H_n|^2 \left|S_{m,n}(\varepsilon)\right|^2}{P_n |H_n|^2 \left|S_{m,n}(\varepsilon)\right|^2 + \sum_{r \ne m \ne n} P_r |H_r|^2 \left|S_{m,r}(\varepsilon)\right|^2 + \sigma_n^2} \right) \\ &= \frac{1}{\ln 2} \cdot \sum_{m \ne n} \frac{(SINR_m)^2}{\Gamma^2 (1 + SINR_m)} \cdot \frac{|H_n|^2 \left|S_{m,n}(\varepsilon)\right|^2}{P_m |H_m|^2 \left|S_{m,m}(\varepsilon)\right|^2}, \end{aligned} \tag{21}$$

where

$$SINR_m = \frac{P_m |H_m|^2 \left|S_{m,m}(\varepsilon)\right|^2}{P_n |H_n|^2 \left|S_{m,n}(\varepsilon)\right|^2 + \sum_{r \ne m \ne n} P_r |H_r|^2 \left|S_{m,r}(\varepsilon)\right|^2 + \sigma_n^2} \tag{22}$$

To solve this optimization problem in (17), we fix both the t_n and the interference term from other subcarriers, denoted by I_n, where

$$I_n = \sum_{m=1,\, m \ne n}^{N} P_m |H_m|^2 \left|S_{n,m}(\varepsilon)\right|^2 \tag{23}$$

Using Eq. (19), if $P_n > 0$, then $\beta_n = 0$. Solving Eq. (20), if $P_n > 0$ then Eq. (20) satisfies the following condition:

$$\ln 2 \cdot \left(P_n + \Gamma \left(\frac{I_n + \sigma_n^2}{|H_n|^2 \left|S_{n,n}(\varepsilon)\right|^2} \right) \right) = \frac{1}{\lambda_0 + t_n} \tag{24}$$

Solve above equation to get the optimal power distribution across subcarrier which can be obtained as follows:

$$P_n = \left(\frac{1}{\ln 2} \cdot \frac{1}{\lambda_0 + t_n} - \Gamma \left(\frac{I_n + \sigma_n^2}{|H_n|^2 \left|S_{n,n}(\varepsilon)\right|^2} \right) \right)^+ \tag{25}$$

where $(\cdot)^+ = \max(0, \cdot)$ and λ_0 is essentially the inverse of water-level but modified by t_n. Equation (25) has the form of "water-filling" solution with the water-level as $\left(\frac{1}{\ln 2} \cdot \frac{1}{\lambda_0 + t_n} \right)$, and the terrain that holds the poured power as $\Gamma \left(\frac{I_n + \sigma_n^2}{|H_n|^2 |S_{n,n}(\varepsilon)|^2} \right)$. The λ_0 can be solved from the total power constraint that sum above equation over n and get

$$P_{total} = \sum_{n=1}^{N} \left(\frac{1}{\ln 2} \cdot \frac{1}{\lambda_0 + t_n} - \Gamma \left(\frac{I_n + \sigma_n^2}{|H_n|^2 \left|S_{n,n}(\varepsilon)\right|^2} \right) \right)^+ \tag{26}$$

With t_n and I_n fixed, this is now an equation of a single variable λ_0. Thus, Eq. (26) can be solved efficiently via a one dimensional search (e.g. using bisection). After λ_0 is found, P_n can then be obtained from Eq. (25). The complete operation of proposed optimal algorithm is given below:

(1) Let $\mathbf{N} = \{1, 2, \ldots, N\}$
(2) Initialize P_n for $\forall n \in \mathbf{N}$
(3) Loop

- (a) Calculate t_n from (21) and I_n from (23).
- (b) Obtain λ_0 from the total power constraint (26).
- (c) Substitute λ_0 and t_n into (25) to obtain P_n.
- (d) If P_n converges, terminate algorithm. Otherwise, go to step a).

3.1 Bit Adding Iteration Method

Even though the above optimization problem is released as a nonconvex nonlinear programming problem, the optimal solution is still difficult to obtain. To further reduce the computation complexity, we present a low-complexity suboptimal joint bit and power loading algorithm that based on the iterative mechanism. We propose an approximation algorithm by applying the Perron-Frobenius theorem. For a given *tBER*and bits b_n on the nth subcarrier, the necessary minimum SINR threshold can be calculated by

$$mSINR(b_n, tBER) = \frac{-\ln(5 \cdot tBER) \cdot \left(2^{b_n} - 1\right)}{1.6}, \text{ for } \forall n. \tag{27}$$

For reliable transmission, the received SINR should satisfy the following constraint:

$$SINR_n \geq mSINR(b_n, tBER), \text{ for } \forall n. \tag{28}$$

Substituting (9) into (28), we can obtain

$$\frac{mSINR\left(b_n, tBER\right)\sigma_n^2}{\left|H_n\right|^2} \le P_n \left|S_{n,n}\left(\varepsilon\right)\right|^2 - \frac{mSINR\left(b_n, tBER\right)}{\left|H_n\right|^2} \times \sum_{m=1,m\neq n}^{N_{\Delta fsc}} P_m \left|H_m\right|^2 \left|S_{n,m}\left(\varepsilon\right)\right|^2 \tag{29}$$

The above equation can be rearranged in a matrix form as

$$\underbrace{\begin{bmatrix} \frac{mSINR(b_1,tBER)\sigma_1^2}{|H_1|^2|S_{1,1}(\varepsilon)|^2} \\ \frac{mSINR(b_2,tBER)\sigma_2^2}{|H_2|^2|S_{2,2}(\varepsilon)|^2} \\ \vdots \\ \frac{mSINR(b_N,tBER)\sigma_N^2}{|H_N|^2|S_{N,N}(\varepsilon)|^2} \end{bmatrix}}_{\mathbf{y}} \le \mathbf{I} \underbrace{\begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_N \end{bmatrix}}_{\mathbf{P}} \text{-}\mathbf{A} \underbrace{\begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_N \end{bmatrix}}_{\mathbf{P}}, \tag{30}$$

where $\mathbf{I}$ is an $N \times N$ identity matrix and matrix $\mathbf{A}$ is defined as

$$\{\mathbf{A}\}_{i,j} = \begin{cases} \frac{mSINR(b_i,tBER)}{|H_i|^2} \frac{|S_{i,j}(\varepsilon)|^2|H_j|^2}{|S_{i,i}(\varepsilon)|^2}, & \text{for } i \neq j \\ 0, & \text{for } i = j. \end{cases} \tag{31}$$

From the above equation, we can observe that $\mathbf{A}$ is a nonnegative matrix, which means that the element of matrix is nonnegative. By applying Perron–Frobenius theorem, the power distribution $\mathbf{P}^* = \left[P_1^*\ P_2^*\ \ldots\ P_N^*\right]^T$ for a given bit loading vector $\mathbf{b} = [b_1\, b_2\, \ldots\, b_N]^T$ and *tBER* can be represented as

$$\mathbf{P}^* = (\mathbf{I} - \mathbf{A})^{-1}\,\mathbf{y}. \tag{32}$$

where $\mathbf{P}^*$ is the Pareto optimal solution. Thus, the minimum transmission power $P\left(\mathbf{b}\right)$ corresponding to bit loading vector $\mathbf{b}$ among all subcarriers is obtained as

$$P\left(\mathbf{b}\right) = [1\ 1\ \ldots 1]\,\mathbf{P}^*. \tag{33}$$

The cost function J_n of adding two additional bits on nth subcarrier is defined as

$$J_n = P\left(\mathbf{b} + 2\mathbf{e}_n\right) - P\left(\mathbf{b}\right), \tag{34}$$

where $\mathbf{e}_n$ is an unit vector whose n^{th} component is 1, and the others are 0. This calculation needs to be done on all subcarriers. For each bit allocation iteration, the subcarrier that needs the minimum cost is allocated additional bit while the total transmission power constraint is satisfied, and the total transmission power among all subcarriers is updated. The complete operation of proposed algorithm is given below:

(1) Initialization:

  (a) $\mathbf{N} = \{1,\ 2,\ \ldots,\ N\}$, $\mathbf{b} = [0\,0\ \ldots\ 0]^T$ and $\mathbf{P} = [0\,0\ \ldots\ 0]^T$
  (b) $\mathbf{P}_n = [0\,0\ \ldots\ 0]^T$ for all n

(2) Bit adding iteration:

  (c) Calculate the cost to transmit two additional bit:
  For all $n \in \mathbf{N}$:

Calculate and store the power distribution vector $\mathbf{P}_n$ corresponding to $\mathbf{b} + 2\mathbf{e}_n$ vector.

Use $\mathbf{P}_n$ and $\mathbf{P}$ to Calculate the $P\left(\mathbf{b} + 2\mathbf{e}_n\right)$ and $P\left(\mathbf{b}\right)$ by using (33).

Calculate and store the J_n by (34).

End for

(d) Select the subcarrier n^* that has the minimum cost to transmit two additional bits:

$$n^* = \arg\min_{n \in \mathbf{N}} \; J_n$$

(e) Check the total transmission power constraint:

If the resulting $P\left(\mathbf{b} + 2\mathbf{e}_{n^*}\right)$ is above P_{total}, set the final allocation to the $\mathbf{b}$ and $\mathbf{P}$, and terminate the algorithm.

(f) Update the bit loading vector$\mathbf{b}$ and power distribution vector $\mathbf{P}$:

$$\mathbf{b} = \mathbf{b} + 2\mathbf{e}_{n^*}$$
$$\mathbf{P} = \mathbf{P}_{n^*}$$

(g) If $b_{n^*}$is equal to $b_{\max}$ then $\mathbf{N} = \mathbf{N} - \{n^*\}$.

(h) Go to step 2).

3.2 Adaptive Resource Allocation for the ICI Scenario: Maximize Overall Throughput: Under Average Target Bit-Error-Rate Constraint Among All Subcarriers

The resource allocation scheme is usually formulated as a constrained optimization problem [32–34], to maximize the throughput with total power and equal *tBER* constraints. At the alternative constrained optimization problem, we discuss a throughput maximization problem under average *tBER* among all subcarriers and total power constraints. However, the optimization problem is generally very hard to solve.

The above observation motivates us to design a two-step suboptimal algorithm that attempts to maximize the system throughput while all subcarrier maintaining average *tBER* constraint in both multipath fading channel and ICI situations.

We consider a different but similar optimization problem as mentioned in above section. We relax the equal *tBER* on each subcarrier constraint to allow different *tBER* among subcarriers but under an average *tBER* constraint. The optimization problem considered in this section can be formulated as criterion B:

$$\begin{aligned}
&\underset{\substack{P_1, P_2, \ldots, P_N \\ BER_1, BER_2, \ldots, BER_N}}{\text{Max}} \quad \sum_{n=1}^{N} b_n\left(P_1, \ldots, P_N\right) \\
&\text{subject to:} \\
&\qquad \sum_{n=1}^{N} P_n \le P_{total} \\
&\qquad P_n \ge 0, \qquad \text{for } \forall n \\
&\qquad \overline{BER} = \frac{\sum_{n=1}^{N} b_n BER_n}{\sum_{n=1}^{N} b_n} \le tBER \\
&\qquad b_n \in \{0, 2, 4, 6.., b_{\max}\}, \qquad \text{for } \forall n.
\end{aligned} \tag{35}$$

P_{total} is the total transmission power constraint, $\overline{BER}$ is the average BER, and $b_{\max}$ is the highest number of modulation bits for each subcarrier.

4 Numerical Results and Performance Analysis

An OFDM system employing a relatively high carrier frequency of 3.6 GHz with bandwidth 5 MHz over the multipath Rayleigh fading channels is considered. Exponential power delay profile with maximum excess delay of 2 μs is used. The numbers of bits that can be allocated to the subcarrier are 0, 2, 4, 6and 8. The predefined *tBER* is 10^{-3} at SNR = 15 dB. The simulations are conducted on the systems with different numbers of subcarriers: 64, 128, 256, 512, and 1024 corresponding to 78.512 KHz, 39.062 KHz, 19.531 KHz 9.765 KHz, and 4.882 KHz of subcarrier bandwidth, respectively. Several Doppler velocities, 10, 80, 160, and 240 Kmph corresponding to various Doppler shift frequency f_d are considered. And the normalized frequency offset are presented in Table 1. In the paper simulations, the Doppler shift frequency f_d are considered simply so the normalized frequency offset $\varepsilon = \frac{\delta f}{\Delta f_{sc}} = \frac{f_d}{\Delta f_{sc}}$, which are presented in Table 1 .

This scheme also has the problem that the bit loading for subcarriers should be discrete numbers instead of arbitrary real numbers. Therefore, the discrete bit load on the nth subcarrier, for a given BER requirement can be expressed as Eq. (12). The following Fig. 2 and 3 show the throughput performance of proposed optimal scheme by Lagrangian method with real number of bit loading and discrete number of bit loading respectively, as a function of Doppler velocities for different number of subcarriers. In Fig. 2, in low mobility region (about

Table 1 Several Doppler velocities v corresponding to different normalized frequency offset ε

	$N_{\Delta f_{sc}} = 1024$	$N_{\Delta f_{sc}} = 512$	$N_{\Delta f_{sc}} = 256$	$N_{\Delta f_{sc}} = 128$	$N_{\Delta f_{sc}} = 64$
$v = 10$ Kmph	$\varepsilon = 6.85e-3$	$\varepsilon = 3.42e-3$	$\varepsilon = 1.71e-3$	$\varepsilon = 8.56e-4$	$\varepsilon = 4.25e-4$
$v = 80$ Kmph	$\varepsilon = 5.46e-2$	$\varepsilon = 2.73e-2$	$\varepsilon = 1.36e-2$	$\varepsilon = 6.83e-3$	$\varepsilon = 3.39e-3$
$v = 160$ Kmph	$\varepsilon = 1.09e-1$	$\varepsilon = 5.46e-2$	$\varepsilon = 2.73e-2$	$\varepsilon = 1.36e-2$	$\varepsilon = 6.79e-3$
$v = 240$ Kmph	$\varepsilon = 1.64e-1$	$\varepsilon = 8.19e-2$	$\varepsilon = 4.09e-2$	$\varepsilon = 2.04e-2$	$\varepsilon = 1.01e-2$

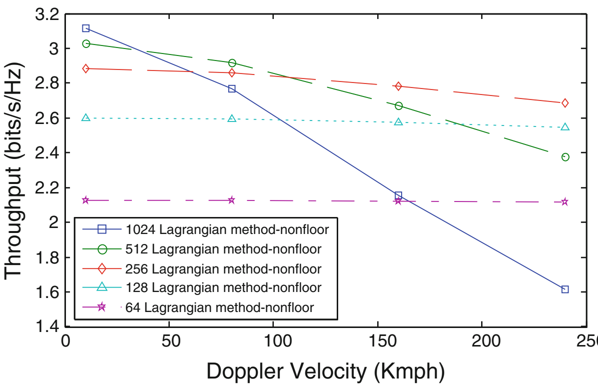

Fig. 2 Throughput performance with optimal power allocation by Lagrangian method-nonfloor for different number of subcarriers

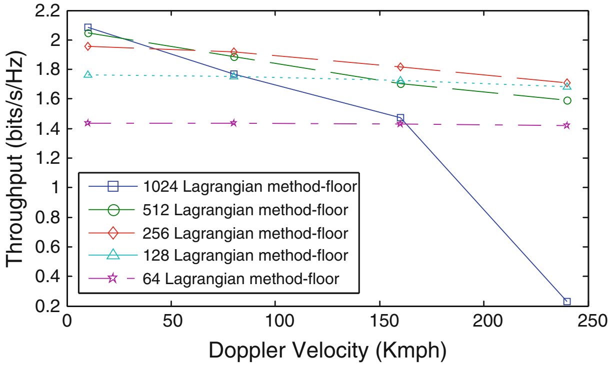

Fig. 3 Throughput performance with optimal power allocation by Lagrangian method-floor for different number of subcarriers

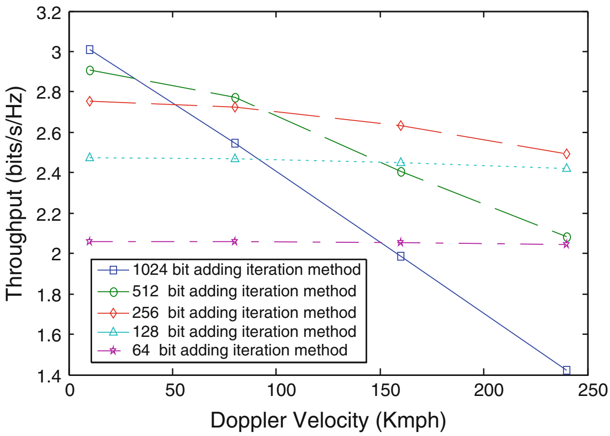

Fig. 4 Throughput of proposed suboptimal algorithm by bit adding iteration method for different number of subcarriers

10 Kmph to 25 Kmph), the performance of adaptive subcarrier bandwidth system with 1024 subcarriers is better than the system with 512 subcarriers; in high mobility region (about 100 Kmph to 240 Kmph), the performance of adaptive subcarrier bandwidth system with 256 subcarriers is better than the system with 1024, 512, 128, and 64 subcarriers. From both following two figures, the performance of adaptive subcarrier bandwidth scheme is compared with fixed subcarrier bandwidth systems. They are clearly observed that a given subcarrier bandwidth has the highest throughput over a range of Doppler velocity, while adaptive subcarrier bandwidth has the highest throughput over the entire range.

Figure 4 shows the overall throughput of proposed suboptimal joint bit loading and power allocation scheme by bit adding iteration method as a function of Doppler velocities for different numbers of subcarriers. Compared with fixed subcarrier bandwidth systems, it is clearly observed that a given subcarrier bandwidth has the highest throughput over a range of Doppler velocity, while adaptive subcarrier bandwidth has the highest throughput over the entire range. In low mobility region (about 10 Kmph to 25 Kmph), the performance of adaptive subcarrier bandwidth system with 1024 subcarriers is better than the system with 512 subcarriers; and in high mobility region (about 100 Kmph to 240 Kmph), the performance

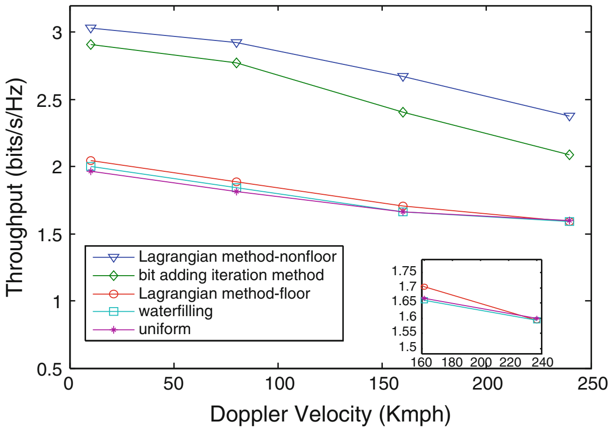

Fig. 5 Throughput comparisons of variety power allocation schemes under equal *tBER* constraint for 512 subcarriers

of adaptive subcarrier bandwidth system with 256 subcarriers is better than the system with 1024, 512, 128, and 64 subcarriers.

The two proposed schemes are compared with uniform power allocation and power allocation method with conventional water-filling algorithm for 512 and 256 subcarriers in Fig. 5 and Fig. 6 respectively. As shown in Fig. 7, we can observe that with decreasing numbers of subcarriers, i.e. increasing subcarrier bandwidth, resilience to ICI is increased. We can observe that the system with the smallest number of subcarriers always has better SINR. It can be seen that the performance of optimal joint bit loading and power allocation scheme by Lagrangian method is better than suboptimal joint bit loading and power allocation scheme by bit adding iteration method. However, the bit loading for subcarriers should be discrete numbers instead of arbitrary real numbers.

While the performance of proposed optimal joint bit loading and power allocation scheme by Lagrangian method with discrete number of bit loading constraint is lower than suboptimal joint bit loading and power allocation scheme by bit adding iteration method. In these figures, it also can be seen that the proposed optimal and suboptimal algorithm outperforms the uniform and conventional water-filling algorithm. Therefore, the two proposed algorithms are more suitable to reduce the ICI effects. The simulation results show that the proposed algorithm provides a better performance than other algorithms within any Doppler velocity.

As shown in Fig. 8, we can observe that the SINR improves with increasing subcarrier bandwidth for a given Doppler spread. But this does not ensure a monotonically increasing throughput with increasing subcarrier bandwidth. According to the plot of throughput vs. subcarrier bandwidth for different velocity conditions in Fig. 9 and Fig. 10, we can observe that the throughput, for a given Doppler velocity, is maximum for a certain subcarrier bandwidth only. It is obviously to seen that by choosing the appropriate subcarrier bandwidth there is potential for significant improvement in throughput. The optimal options of subcarrier bandwidth for different mobility conditions suffer from different amount of ICI are clearly presented in Table 2.

Figure 11 shows the overall throughput of proposed two-step suboptimal joint bit loading and power allocation algorithm initialized power by Lagrangian method of criterion A. Comparing against fixed subcarrier bandwidth systems, it is clearly seen that a given subcarrier bandwidth has the highest throughput over a range of Doppler velocity, while adaptive

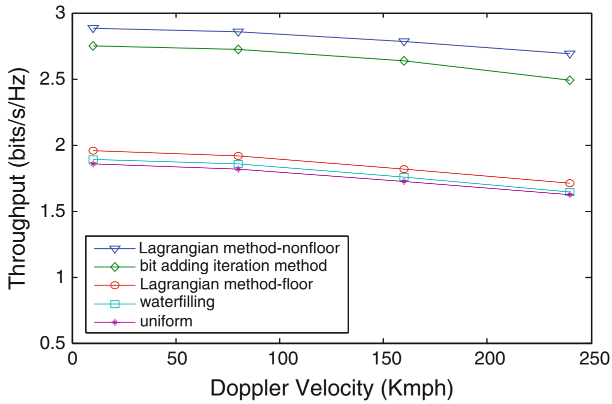

Fig. 6 Throughput comparisons of variety power allocation schemes under equal *tBER* constraint for 256 subcarriers

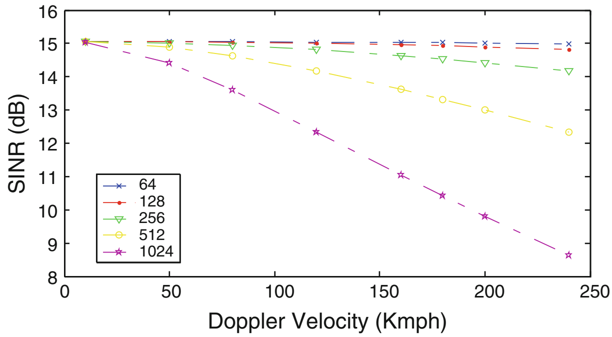

Fig. 7 SINR of a standard OFDM system with uniform power allocation

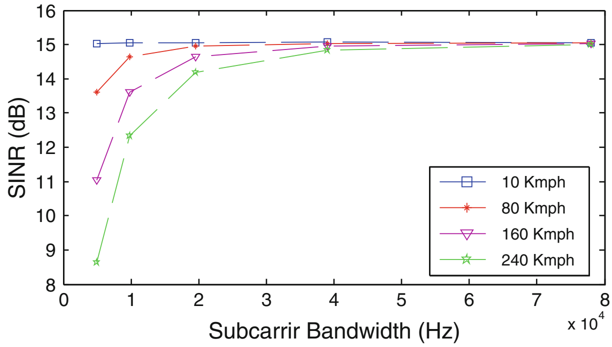

Fig. 8 SINR of a standard OFDM system with uniform power allocation versus subcarrier bandwidth

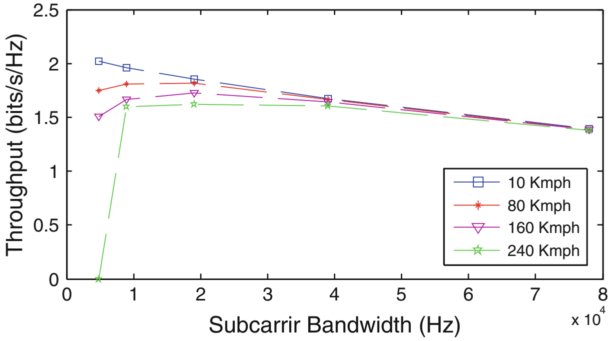

Fig. 9 Throughput performance with uniform power allocation versus subcarrier bandwidth

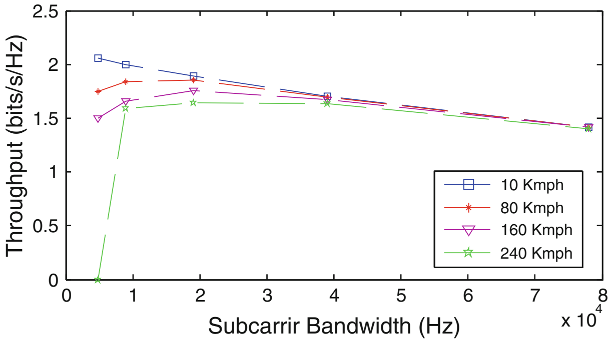

Fig. 10 Throughput performance with conventional water-filling algorithm versus subcarrier bandwidth

subcarrier bandwidth has the highest throughput over the entire range. In the low mobility region (about 10 Kmph to 20 Kmph), the performance of adaptive subcarrier bandwidth system with 1024 subcarriers is better than the system with 512 subcarriers; in the high mobility region (about 90 Kmph to 230 Kmph), the performance of adaptive subcarrier bandwidth system with 256 subcarriers is better than the system with 1024 subcarriers. Even the performance of adaptive subcarrier bandwidth system with 128 subcarriers at 240 Kmph is better than the system with the other number of subcarriers.

Considering the BER subtracting iteration method with different initialized power allocation algorithm as mentioned from section 3, the throughput for 512 subcarriers are analyzed in Fig. 12. The bit loading for subcarriers should be discrete numbers instead of arbitrary real numbers, the performance of this section proposed two-step suboptimal algorithm initialized power by Lagrangian method of criterion A while all subcarriers satisfying average *tBER* constraint outperforms above section proposed optimal power allocation algorithm with discrete number of bit loading, uniform and conventional water-filling algorithm while each subcarrier satisfying equal *tBER* constraint. The simulation results show that the proposed algorithm with average *tBER* constraint provides a better throughput improvement than other algorithms satisfying equal *tBER* constraint with any Doppler velocity.

Table 2 Throughput performance of various power allocation schemes vs. subcarrier bandwidth for different Doppler velocity conditions

Doppler velocity	Algorithm	Subcarrier bandwidth				
		4.882K (N = 1024)	9.765K (N = 512)	19.531K (N = 256)	39.063K (N = 128)	78.512K (N = 64)
10 Kmph	Lagrangian method (non-floor)	**3.1147**	3.0283	2.8844	2.6015	2.1283
	Bit adding iteration method	**3.010**	2.909	2.753	2.475	2.058
	Lagrangian method (floor)	**2.0833**	2.0464	1.9569	1.7617	1.4381
	Waterfilling	**2.059**	2.003	1.891	1.703	1.419
	Uniform	**2.019**	1.963	1.854	1.670	1.391
80 Kmph	Lagrangian method (non-floor)	2.7672	**2.9193**	2.8576	2.5945	2.1269
	Bit adding iteration method	2.545	**2.773**	2.724	2.469	2.056
	Lagrangian method (floor)	1.767	1.8866	**1.9162**	1.7515	1.4362
	Waterfilling	1.749	1.842	**1.856**	1.696	1.417
	Uniform	1.752	1.811	**1.818**	1.663	1.389
160 Kmph	Lagrangian method (non-floor)	2.1576	2.6727	**2.7842**	2.576	2.1226
	Bit adding iteration method	1.988	2.406	**2.635**	2.450	2.052
	Lagrangian method (floor)	1.4743	1.7037	**1.819**	1.7239	1.4293
	Waterfilling	1.501	1.659	**1.755**	1.673	1.413
	Uniform	1.504	1.664	**1.723**	1.639	1.385
240 Kmph	Lagrangian method (non-floor)	1.6139	2.3769	**2.6874**	2.5471	2.1165
	Bit adding iteration method	1.419	2.085	**2.492**	2.419	2.046
	Lagrangian method (floor)	0.2296	1.5938	**1.7081**	1.6831	1.4209
	Waterfilling	0	1.594	**1.642**	1.636	1.405
	Uniform	0	1.598	**1.622**	1.603	1.377

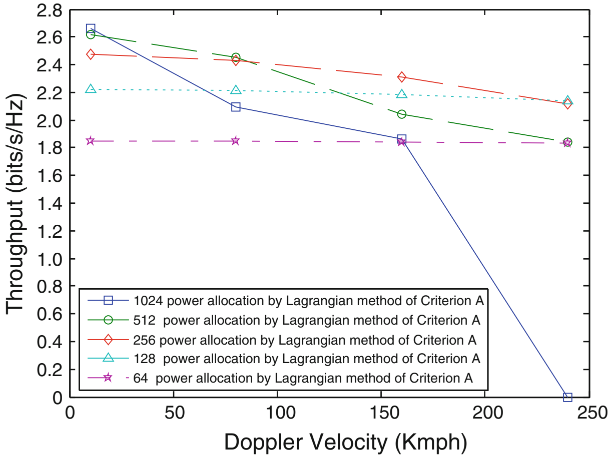

Fig. 11 Throughput of proposed algorithm initialized power by Lagrangian method of criterion A under average *tBER* constrain for different number of subcarriers

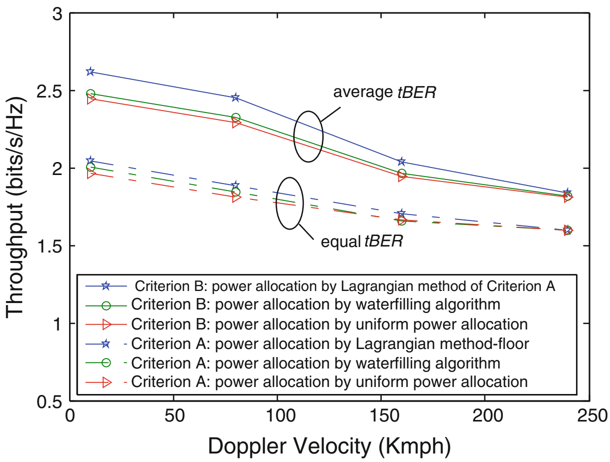

Fig. 12 Throughput comparisons of criterion B under average *tBER* constraint and criterion A under equal*tBER* constraint for 512 subcarriers

5 Conclusion

In this paper, we have devised a new robust algorithm for the problem of resource management and ICI suppression to achieve desired performance in OFDM system. For the different optimization problems, we derive the optimal solutions and proposed suboptimal algorithm, respectively. For the first optimization problem, it has been shown that the performance of the Lagrangian method with continues bit loading is better than suboptimal algorithm by bit adding iteration method. However, in practical transmission, the bit loading for subcarriers should be discrete numbers instead of arbitrary real numbers. While the performance of proposed optimal solution with discrete number of bit loading is lower than suboptimal algorithm. As the optimal solution with discrete number of bit loading under equal *tBER* constraint compared with the two-step suboptimal algorithms with different power allocation schemes under average *tBER* constraint, it has been shown that the latter outperform the former within any Doppler velocities. For the last optimization problem, the optimal solution of the joint bit and power allocation algorithm compared with uniform power allocation algorithm can significantly improve the BER performance. Simulation results have clearly verified that the proposed scheme is efficient and outperforms other compared algorithms. Therefore, the proposed algorithm is a good candidate for application to wideband wireless networks in future.

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References

1. Prasad, R. (2004). *OFDM for wireless communications*. Norwood, MA: Artech House Publishers.
2. Hanzo, L., Webb, W., & Keller, T. (2000). *Single- and multi-carrier quadrature amplitude modulation—principles and applications for personal communications, WLANs and broadcasting*. New York: Wiley.
3. Rohling, H., May, T., Bruninghaus, K., & Grunheid, R. (1999). Broad-band OFDM radio transmission for multimedia applications. *Proceedings of the IEEE, 87*(10), 1778–1789.
4. Ma, L., & Jia, D. (2005). The competition and cooperation of WiMAX, WLAN and 3G. In *Proceedings of international conference on mobile technology*, *applications and systems*, Munich, Germany, pp. 1–5.
5. IEEE Std 802.11a-1999, Part 11, *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications; high-speed physical layer in the 5 GHz band*.
6. ETS 300 744 rev 1.2.1, (1999-01) *Digital broadcasting systems for television, sound and data services (DVB-T); framing structure, channel coding and modulation for digital terrestrial*.
7. IEEE Std. 802.16-2004 (Revision of IEEE Std. 802.16-2001), *IEEE Standard for Local and metropolitan area networks, Part 16: Air interface for fixed broadband wireless access systems*.
8. Russell, M., & Stuber, G. L. (1995). Interchannel interference analysis of OFDM in a mobile environment. *Proceedings of VTC, 2*, 820–824.
9. Li, Y., & Cimini, L. J., Jr. (2001). Bounds on the interchannel interference of OFDM in time-varying impairments. *IEEE Transactions on Communications, 49*, 401–404.
10. Li, R., & Stette, G. (1995). Time-limited orthogonal multicarrier modulation schemes. *IEEE Transactions on Communications, 43*, 1269–1272.
11. Ahn, J., & Lee, H. S. (1993). Frequency domain equalization of OFDM signal over frequency nonselective Rayleigh fading channel. *Electronics Letters, 29*, 1476–1477.
12. Al-Dhahir, N. (1996). Optimum finite-length equalization for multicarrier transceivers. *IEEE Transactions on Communications, 44*, 56–64.
13. Zhao, Y. P., & Haggman, S. G. (2001). Intercarrier interference self-cancellation scheme for OFDM mobile communication system. *IEEE Transactions on Communications, 49*, 1185–1191.
14. Lawrey, E. (1999). Multiuser OFDM, ISSPA '99. In *Proceedings of the fifth international symposium on signal proceeding and its applications* (Vol. 2, pp. 761–764).
15. Wong, C. Y., Cheng, R. S., Lataief, K. B., & Murch, R. D. (1999). Multicarrier OFDM with adaptive subcarrier, bit and power allocation. *IEEE Journal on Selected Areas in Communications, 17*(10), 1747–1758.
16. Jang, J., & Lee, K. B. (2003). Transmit power adaptation for multiuser OFDM systems. *IEEE Journal on Selected Areas in Communications, 21*(2), 171–178.
17. Shen, Z., Andrews, J. G., & Evans, B. L. (2005). Adaptive resource allocation in multiuser OFDM systems with proportional rate constraints. *IEEE Transactions on Wireless Communications, 4*(6), 2726–2737.
18. Kim, I., Lee, H. L., Kim, B., & Lee, Y. H. (2001). On the use of linear programming for dynamic subchannel and bit allocation in multiuser OFDM. In *Proceeding IEEE global telecommunications conference, San Antonio, Texas, USA* (Vol. 6, pp. 3648–3652).
19. Ho, W. L., & Liang, Y.-C. (2009). Optimal resource allocation for multiuser MIMO-OFDM systems with user rate constraints. *IEEE Transactions on Vehicular Technology, 58*(3), 1190–1203.

20. Park, C. S., & Lee, K. B. (2004). Transmit power allocation for BER performance improvement in multicarrier systems. *IEEE Transactions on Communications, 52*(10).
21. Goldfeld, L., Lyandres, V., & Wulich, D. (2002). Minimum BER power loading for OFDM in fading channel. *IEEE Transactions on Communications, 50*(11).
22. Wong, C. Y., Cheng, R. S., Letaief, K. B., & Murch, R. D. (1999). Multicarrier OFDM with adaptive subcarrier, bit, and power allocation. *IEEE Journal on Selected Areas in Communications, 17*(10), 1747–1758.
23. Jang, J., Lee, K. B., & Lee, Y.-H. (2002). Frequency-time domain transmit power adaptation for a multicarrier system in fading channels. *IEE Electronics Letters, 38*(5), 218–220.
24. Robertson, P., & Kaiser, S. (1999). The effects of Doppler spreads in OFDM(A) mobile radio systems. *Proceedings of the IEEE Vehicular Technology Conference, 1*, 19–22.
25. Zhao, Y., & Haggman, S. G. (2001). Intercarrier interference self-cancellation scheme for OFDM mobile communication systems. *IEEE Transactions on Communications, 49*(7), 1185–1191.
26. Hou, W., & Chen, B. (2005). ICI cancellation for OFDM communication systems in time-varying multipath fading channels. *IEEE Transactions on Wireless Communications, 4*(5), 2100–2110.
27. Das, S. S., Carvalho, E. D., & Prasad, R. (2008). Performance analysis of OFDM systems with adaptive sub-carrier bandwidth. *IEEE Transactions on Communications, 7*(4), 1117–1122.
28. Fu, Y., Tellambura, C., & Krzymien, W. A. (2007). Transmitter precoding for ICI reduction in closed-loop MIMO OFDM systems. *IEEE Transactions on Vehicular Technology, 56*, 115–125.
29. Speth, M., Fechtel, S. A., Fock, G., & Meyr, H. (1999). Optimum receiver design for wireless broad-band systems using OFDM, Part I. *IEEE Transactions on Communications, 47*(11), 1668–1677.
30. Goldsmith, A. J., & Chua, S.-G. (1997). Variable-rate variable-power MQAM for fading channels. *IEEE Transactions on Communications, 45*, 1218–1230.
31. Cover, T. M., & Thomas, J. A. (1991). *Elements of information theory*. New York: Wiley.
32. Chung, S. T., & Goldsmith, A. J. (2001). Degrees of freedom in adaptive modulation: A unified view. *IEEE Transactions on Communications, 49*(1), 1561–1571.
33. Ho, W. W. L., & Liang, Y.-C. (2009). Optimal resource allocation for multiuser MIMO-OFDM systems with user rate constraints. *IEEE Transactions on Vehicular Technology, 58*, 1190–1203.
34. Cheng, P., Zhang, Z., Chen, H.-H., & Qiu, P. (2008). Optimal distributed joint frequency, rate and power allocation in cognitive OFDMA systems. *IEEE Transactions on Communications, 2*, 815–826.

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