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Dynamic resource allocation for high-speed railway downlink MIMO-OFDM system

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Abstract: The dynamic resource allocation problem in high-speed railway downlink orthogonal frequency-division multiplexing (OFDM) systems with multiple-input multiple-output (MIMO) antennas is investigated. Sub-carriers, antennas, time slots, and power are jointly considered. The problem of multi-dimensional resource allocation is formulated as a mixed-integer nonlinear programming problem. The effect of the moving speed on Doppler shift is analyzed to calculate the inter-carrier interference power. The optimization objective is to maximize the system throughput under the constraint of a total transmitted power that is no greater than a certain threshold. In order to reduce the computational complexity, a suboptimal solution to the optimization problem is obtained by a two-step method. First, sub-carriers, antennas, and time slots are assigned to users under the assumption of equal power allocation. Next, the power allocation problem is solved according to the result of the first-step resource allocation. Simulation results show that the proposed multi-dimensional resource allocation strategy has a significant performance improvement in terms of system throughput compared with the existing one.

Key words: dynamic resource allocation; high-speed railway; multiple-input multiple-output (MIMO); orthogonal frequency-division multiplexing (OFDM)

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The high-speed train is a kind of fast and convenient vehicle, which attracts more and more people to take it. It will cause a series of new challenges for effective wireless communication networks deployment. Conventional mobile communication networks cannot satisfy all the requirements, and the dedicated networks should be designed[1]. Orthogonal frequency-division multiplexing (OFDM) technology with multiple-input multiple-output (MIMO) antennas can improve the overall performance of the high-speed railway communication system. In particular, because hundreds of passengers are concentrated together in the carriages of the fast moving train, resource allocation for different users in high-speed railway MIMO-OFDM systems becomes very important for enhancing resource utilization efficiency and providing efficient services.

Resource allocation in MIMO-OFDM systems has aroused great research interest. Zhang et al. [2] proposed an adaptive resource allocation scheme for multi-user transmission in MIMO-OFDM systems, which optimizes sub-carrier allocation, power distribution, and bit distribution for different users according to instantaneous channel state information (CSI) and quality of service (QoS) requirements. For practical implementation, the original problem is decoupled into a simple single-user optimization problem. Margin adaptive resource allocation[3] is considered in MIMO orthogonal frequency-division multiple access (OFDMA) multi-cell networks. A distributed convergence criterion for power allocation is given. Chen et al. [4] presented a kind of resource allocation strategy for the Gaussian MIMO-OFDM multiple-access channel. The rate region is derived by solving several weighted sum-rate maximization problems. Power distribution can be obtained by a Lagrange dual-decomposition method. In Ref. [5], an efficient solution to minimize the total transmitted power for MIMO-OFDM communications under the constraint of each user's data rate requirement was given using convex optimization theory. A dynamic sub-carrier and bit allocation mechanism for MIMO-OFDMA systems was proposed in Ref. [6]. The objective is to minimize the total transmitted power subject to the QoS guarantees of different users. The sub-carrier allocation strategy is presented according to the perfect CSI, and a spatial sub-channel grouping scheme is given for bit distribution.

Most of the previous works are done for resource allocation under the condition of low moving speed in traditional cellular networks. However, for high-speed railway environments, different cells are distributed along the railway line and users move in a definite direction with more than 300 km/h[7]. These characteristics will bring about many practical problems, such as serious Doppler shift, fast and frequent handover, and changing channel conditions. Moreover, although some research works are

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done for resource allocation in MIMO-OFDM systems, most of them mainly focus on the resource allocation for one or two kinds of radio resources, without considering the joint allocation of multiple types of radio resources. The problem of joint resource allocation is meaningful and should be taken into account, which has a profound effect on the overall performance of the communication system. Therefore, there is a strong motivation to propose a kind of multi-dimensional resource allocation strategy for high-speed railway communication systems in order to realize the joint optimization of multiple kinds of radio resources and improve the efficiency of resource utilization.

In this paper, we propose a multi-dimensional resource allocation strategy for high-speed railway downlink MIMO-OFDM systems. Specifically, sub-carriers, antennas, time slots, and power are jointly taken into account, which is modeled as a mixed-integer nonlinear programming problem. The effect of the moving speed on Doppler shift is analyzed to obtain the inter-carrier interference (ICI) power. Our optimization objective is to maximize the throughput while guaranteeing the constraint on total transmitted power. In addition, a two-step method is used to derive a suboptimal solution to the optimization problem. In the first step, sub-carriers, antennas, and time slots are allocated to different users while supposing that equal power is assigned to each sub-carrier. In the second step, on the basis of the optimal resource allocation results in the first step, power allocation is done again. Simulation results are presented to compare the proposed resource allocation method with the existing one in terms of total throughput.

1 System Model

As illustrated in Fig. 1, a distributed base station is designed for the high-speed railway communication networks. It consists of the building baseband unit (BBU) and the radio remote unit (RRU). The BBU is placed in the building of the base station, and the RRU can be placed outside along the railway flexibly. Multiple RRUs are connected to a BBU by optical fiber, respectively. Therefore, the coverage area of a cell can be enlarged and the frequent handover can be reduced to some extent. The BBU and the RRU are used to process baseband signal and radio frequency signal, respectively. In this way, baseband and radio frequency signal processing are separated. The optical fiber is used to transmit baseband signals from the BBU to the RRU. Long distance transmission of radio frequency signals can be avoided, so the transmission loss can be significantly decreased.

Additionally, a vehicular station (VS) is installed on the top of the train in order to overcome the penetration loss of signals caused by the train carriage. It is used to communicate with the RRU in a wireless way. For the purpose of guaranteeing reliable communications between the RRU and the train, two VSs are installed on the top of the first and the last carriages, respectively. They can work independently or cooperatively depending on the specific situation. At the same time, there is a repeater (R) in each train carriage. Users can be accessed to the networks by repeaters.

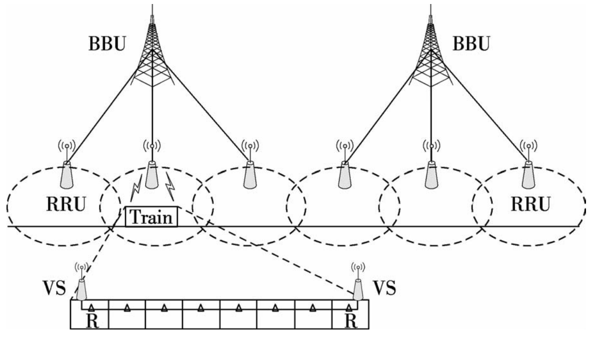

Fig. 1 Networks architecture

Furthermore, MIMO antennas are adopted in high-speed railway communication systems. The RRU and the VS are equipped with N_t transmit antennas and N_r receive antennas, respectively. The received signal can be expressed as

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n} \tag{1}$$

where $\boldsymbol{x}$ represents an N_t-dimensional transmitted signal vector; $\boldsymbol{H}$ indicates an $N_r \times N_t$ channel matrix; $\boldsymbol{n}$ denotes an N_r-dimensional noise vector; and $\boldsymbol{y}$ is an N_r-dimensional received signal vector.

It is assumed that the rank of $\boldsymbol{H}$ is described as $I = \text{rank}(\boldsymbol{H})$. According to the singular value decomposition (SVD) theorem[8], channel matrix $\boldsymbol{H}$ can be decomposed into the following form:

$$\boldsymbol{H} = \boldsymbol{U}\begin{bmatrix} \boldsymbol{D} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix}\boldsymbol{V}^{\mathrm{H}} \tag{2}$$

where $\boldsymbol{U}$ is an $N_r \times N_r$ unitary matrix; $\boldsymbol{D} = \text{diag}(\sigma_1, \sigma_2, \dots, \sigma_I)$ is an $I \times I$ diagonal matrix whose diagonal elements are the singular values of $\boldsymbol{H}$; $\boldsymbol{V}$ is an $N_t \times N_t$ unitary matrix; superscript H means conjugate transpose. As a result, the received signal can be rewritten as

$$\boldsymbol{y} = \boldsymbol{U}\begin{bmatrix} \boldsymbol{D} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix}\boldsymbol{V}^{\mathrm{H}}\boldsymbol{x} + \boldsymbol{n} \tag{3}$$

If Eq. (3) is multiplied by $\boldsymbol{U}^{\mathrm{H}}$, the following expression can be derived:

$$\boldsymbol{U}^{\mathrm{H}}\boldsymbol{y} = \boldsymbol{U}^{\mathrm{H}}\boldsymbol{U}\begin{bmatrix} \boldsymbol{D} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix}\boldsymbol{V}^{\mathrm{H}}\boldsymbol{x} + \boldsymbol{U}^{\mathrm{H}}\boldsymbol{n} = \begin{bmatrix} \boldsymbol{D} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix}\boldsymbol{V}^{\mathrm{H}}\boldsymbol{x} + \boldsymbol{U}^{\mathrm{H}}\boldsymbol{n} \tag{4}$$

At the same time, three matrix transformations are defined as

$$\left.\begin{aligned} \tilde{\boldsymbol{y}} &= \boldsymbol{U}^{\mathrm{H}}\boldsymbol{y} \\ \tilde{\boldsymbol{x}} &= \boldsymbol{V}^{\mathrm{H}}\boldsymbol{x} \\ \tilde{\boldsymbol{n}} &= \boldsymbol{U}^{\mathrm{H}}\boldsymbol{n} \end{aligned}\right\} \tag{5}$$

Then, Eq. (4) can be replaced by

$$\tilde{\boldsymbol{y}} = \begin{bmatrix} \boldsymbol{D} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix} \tilde{\boldsymbol{x}} + \tilde{\boldsymbol{n}} \tag{6}$$

which is equivalent to the following expression:

$$\left.\begin{array}{ll} \tilde{\boldsymbol{y}}_i = \sigma_i \tilde{\boldsymbol{x}}_i + \tilde{\boldsymbol{n}}_i & i = 1, 2, \ldots, I \\ \tilde{\boldsymbol{y}}_i = \tilde{\boldsymbol{n}}_i & i = I+1, I+2, \ldots, N_\mathrm{r} \end{array}\right\} \tag{7}$$

Consequently, a MIMO channel can be transformed into I parallel single-input single-output (SISO) channels that do not interfere with each other. The channel gain of each SISO channel is $\sigma_i (i = 1, 2, \ldots, I)$.

2 Problem Formulation and Suboptimal Solution

2.1 Problem formulation

The multi-dimensional resource allocation problem is taken into account in the downlink MIMO-OFDM system for high-speed railway communications. There are N sub-carriers that can be assigned to K users from I antennas during T time slots. It is assumed that perfect CSI is known at the transmitter by dedicated feedback channels. Therefore, the instantaneous channel gain can be available. In addition, a binary variable $\delta_{k,n,i,t} \in \{0, 1\}$ is used to represent the situation of resource allocation, indicating whether the n-th sub-carrier is allocated to the k-th user from the i-th antenna at the t-th time slot or not. For the high-speed railway communication scenario, users in the train move at more than 300 km/h, which will lead to serious Doppler shift. Therefore, the strict orthogonality of different sub-carriers is destroyed, which will bring about inter-carrier interference (ICI). Inspired by Refs. [9 − 10], the total ICI power on the n-th sub-carrier can be shown as

$$\mathrm{ICI}_n = \frac{(T_\mathrm{s} f_\mathrm{d})^2}{2} \sum_{j=1, j\neq n}^{N} \frac{1}{(j-n)^2} \tag{8}$$

where T_s denotes the OFDM symbol duration, and f_d indicates that the maximum Doppler shift can be obtained by

$$f_\mathrm{d} = \frac{v}{c} f_\mathrm{c} \tag{9}$$

where v represents the moving speed; c denotes the speed of electromagnetic waves; and f_c is the carrier centric frequency.

The objective of the multi-dimensional resource allocation problem is to maximize the total throughput under the total transmitted power constraint. This is an optimization problem that can be formulated as

$$\max_{\delta_{k,n,i,t}, p_{k,n,i,t}} \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{i=1}^{I} \sum_{t=1}^{T} \frac{\delta_{k,n,i,t} W}{N} \log_2 \left(1 + \frac{p_{k,n,i,t} \sigma_{k,n,i,t}^2}{\mathrm{ICI}_n + n_0 \dfrac{W}{N}} \right)$$

$$\text{s.t.} \begin{cases} \delta_{k,n,i,t} \in \{0, 1\} & \forall k, n, i, t \\ \sum_{k=1}^{K} \delta_{k,n,i,t} = 1 & \forall n, i, t \\ \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{i=1}^{I} \sum_{t=1}^{T} p_{k,n,i,t} \leqslant P_\mathrm{total} & \\ p_{k,n,i,t} \geqslant 0 & \forall k, n, i, t \end{cases} \tag{10}$$

where W is the system bandwidth; n_0 represents the noise power spectral density; $p_{k,n,i,t}$ is the transmitted power for the k-th user on the n-th sub-carrier from the i-th antenna at the t-th time slot; P_total is the maximum total transmitted power. The first constraint shows that resource allocation indicator $\delta_{k,n,i,t}$ can only be either 0 or 1. The second restriction indicates that the n-th sub-carrier can be allocated to at most one user from the the i-th antenna at the t-th time slot. The third constraint ensures that the total transmitted power in the base station is limited to P_total. The fourth restriction denotes that the transmitted power is non-negative.

2.2 Suboptimal solution

The optimization problem in (10) is a mixed-integer nonlinear programming problem, which is an NP(non-deterministic polynomial)-hard problem. It is extremely difficult to obtain a globally optimal solution with a low computational complexity. As a result, an approach that can derive a suboptimal solution at a reasonable computation cost is strongly required.

A two-step method that can significantly reduce the computational complexity is proposed. In the first step, sub-carriers, antennas, and time slots are assigned to users under the assumption of equal power allocation for each sub-carrier. Therefore, the previous mixed-integer nonlinear programming problem in (10) is converted into a binary linear programming problem which is expressed as

$$\max_{\delta_{k,n,i,t}} \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{i=1}^{I} \sum_{t=1}^{T} \frac{\delta_{k,n,i,t} W}{N} \log_2 \left(1 + \frac{\dfrac{P_\mathrm{total}}{N} \sigma_{k,n,i,t}^2}{\mathrm{ICI}_n + n_0 \dfrac{W}{N}} \right)$$

$$\text{s.t.} \begin{cases} \delta_{k,n,i,t} \in \{0, 1\} & \forall k, n, i, t \\ \sum_{k=1}^{K} \delta_{k,n,i,t} = 1 & \forall n, i, t \end{cases} \tag{11}$$

With the help of TomSym that is a modeling engine developed by the TOMLAB optimization incorporation, a branch-and-bound algorithm is applied to solve the binary linear programming problem in (11). As a consequence, an optimal resource allocation result $\delta_{k,n,i,t}^* (k \in K, n \in N, i \in I, t \in T)$ can be obtained.

In the second step, on the basis of the optimal resource allocation result in the first step, the power allocation problem is modeled as follows:

$$\max_{p_{k,n,i,t}} \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{i=1}^{I} \sum_{t=1}^{T} \frac{\delta^{*}_{k,n,i,t} W}{N} \log_2 \left(1 + \frac{p_{k,n,i,t} \sigma^2_{k,n,i,t}}{\mathrm{ICI}_n + n_0 \dfrac{W}{N}} \right)$$

$$\text{s. t.} \begin{cases} \sum_{k=1}^{K} \sum_{n=1}^{N} \sum_{i=1}^{I} \sum_{t=1}^{T} p_{k,n,i,t} \leqslant P_{\text{total}} \\ p_{k,n,i,t} \geqslant 0 \qquad \forall k, n, i, t \end{cases} \tag{12}$$

Because sub-carriers, antennas, and time slots have been allocated to different users in the first step, the specific values of $\delta^{*}_{k,n,i,t}(k \in K, n \in N, i \in I, t \in T)$ are known. We can see that the objective function is a logarithmic function. Therefore, the optimization problem in (12) is a nonlinear programming problem. In a similar way, the solution to the above optimization problem can be derived by using TomSym.

2.3 Computational complexity analysis

In this subsection, the computational complexity is analyzed. Compared with the original mixed-integer nonlinear programming problem in (10), the computational complexity of the two-step method in (11) and (12) is decreased to a great extent even if two new optimization problems are generated. On the one hand, for each objective function in (11) and (12), the number of variables is reduced from 2*KNIT* to *KNIT*. As a result, the product term about different variables is eliminated and the computational complexity can be degraded dramatically. On the other hand, the objective function in (11) is linear, which can reduce the computational complexity to a large extent.

3 Simulation Results and Discussion

In this section, we evaluate the performance of the proposed multi-dimensional resource allocation strategy. The related simulation parameters are set to be $T_s = 1.5 \times 10^{-4}$ s, $f_c = 2.6$ GHz, $c = 3 \times 10^8$ m/s, $W = 1$ MHz, $N = 10$, $I = 2$, and $n_0 = 2 \times 10^{-10}$ W/Hz. Without loss of generality, we assume that the values of channel gain $\sigma_{k,n,i,t}$ are generated by random numbers between 0 and 1. In order to show the performance of our proposed resource allocation strategy, an existing resource allocation method called OFDM-TDMA[11] is used for comparison. For the OFDM-TDMA scheme, each user is allocated a predetermined time slot and can use all the sub-carriers in the time slot.

Fig. 2 shows the relationship between the throughput and the moving speed for different numbers of users under the proposed method and the existing method. We can see that the throughput decreases gradually as the moving speed increases. That is because Doppler shift becomes more and more serious, which leads to an increase in ICI power. Thus, signal-to-interference plus noise ratio (SINR) will rise up accordingly, which results in a decline in the throughput. Additionally, the throughput of the proposed method is higher than that of the existing method. It can be explained that the existing method is a kind of fixed resource allocation strategy whose resource utilization efficiency is much lower than that of the proposed method. Moreover, for both the proposed method and the existing method, the throughput increases with the increase in the number of users. The reason is that the number of sub-carriers is enough. The larger the number of users, the higher the throughput.

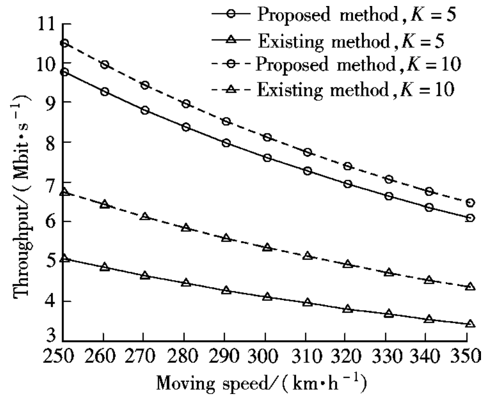

Fig. 2 Throughput vs. the moving speed with $T = 5$

Fig. 3 illustrates the relationship between the throughput and the moving speed for different numbers of time slots under the proposed method and the existing method. A similar changing trend of throughput and the moving speed can be observed. In addition, it can be seen that the throughput grows to some extent as the number of time slots increases from 5 to 10. The reason is that more bits can be transferred during a longer time as long as the numbers of sub-carriers and users are constant.

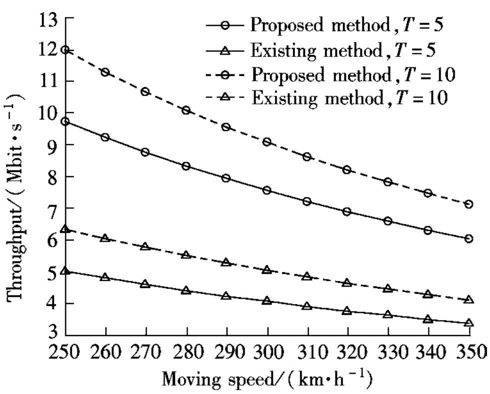

Fig. 3 Throughput vs. the moving speed with $K = 5$

Fig. 4 presents the relationship between the throughput and the total power for different numbers of users under the proposed method and the existing method. In the simulation, the moving speed is set to be 300 km/h. We can find that the throughput rises progressively as the total power increases gradually. The reason is that each user can transfer more bits under a relatively loose constraint of total power. Additionally, the throughput of the proposed method is higher than that of the existing method.

It can be explained that the proposed method is a kind of dynamic resource allocation scheme while the existing one is fixed. As a consequence, the resource utilization efficiency of the proposed method is much higher than that of the existing method. Furthermore, for both the proposed method and the existing method, the throughput increases as the number of users increases. That is because the number of sub-carriers is enough. The larger the number of users, the higher the throughput.

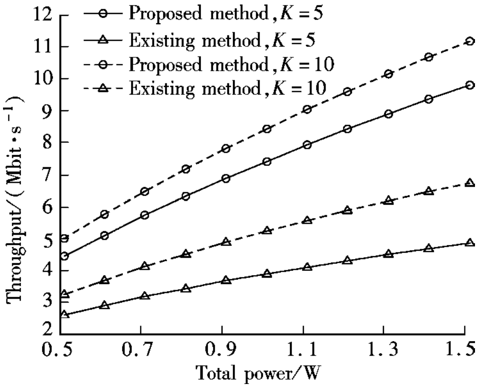

Fig. 4 Throughput vs. the total power with $T=5$ and $v=300$ km/h

Fig. 5 depicts the relationship between the throughput and the total power for different numbers of time slots under the proposed method and the existing method. In the simulation, the moving speed is set to be 300 km/h. Apart from the similar variation trend about the throughput and the total power, we can find that the throughput increases with the increase in the number of time slots from 5 to 10. The reason is that more bits will be transferred during a longer time on the condition that the numbers of sub-carriers and users are both fixed.

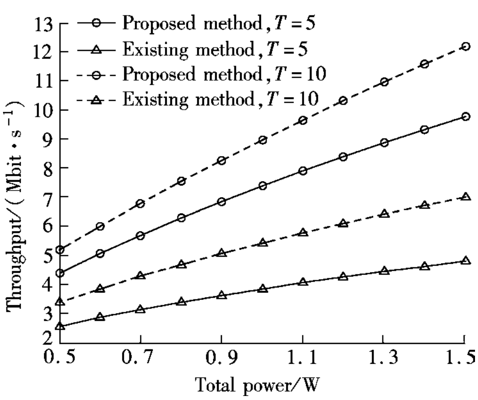

Fig. 5 Throughput vs. the total power with $K=5$ and $v=300$ km/h

4 Conclusion

This paper proposes a multi-dimensional resource allocation scheme for high-speed railway downlink OFDM systems with MIMO antennas. Sub-carriers, antennas, time slots, and power are jointly considered, which is formulated as a mixed-integer nonlinear programming problem. The effect of the moving speed on Doppler shift is analyzed to calculate the ICI power. The objective is to maximize the throughput while satisfying the restriction on total transmitted power. Furthermore, a suboptimal solution is achieved using a two-step method. Simulation results prove that the proposed resource allocation strategy has higher throughput than the existing one. Because we assume that the channel state information is known at the transmitter, future work is in progress to consider the channel estimation scheme in order to improve the flexibility.

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高速铁路下行 MIMO-OFDM 系统中的动态资源分配策略

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摘要：对高速铁路下行 MIMO-OFDM 系统中的动态资源分配问题进行研究．联合考虑子载波、天线、时隙和功率，将多维资源分配问题建模为混合整数非线性规划问题．分析移动速度对多普勒频移的影响，并计算子载波间干扰功率．在总发射功率不超过一定阈值的约束条件下，将最大化系统吞吐量作为优化目标．为了降低求解最优化问题的计算复杂度，采用两步求解法得到次优解．首先，在等功率分配的前提下，将子载波、天线和时隙分配给不同用户．然后，根据第 1 步资源分配的结果，进行功率分配．仿真结果显示，提出的多维资源分配策略与已有策略相比在系统吞吐量方面具有较大的性能提高．

关键词：动态资源分配；高速铁路；多输入多输出；正交频分复用

中图分类号：TN91