

Adaptive Radio Resource Management Based on Soft Frequency Reuse (SFR) in Urban Rail Transit Systems



Ye Zhu and Hailin Jiang

Abstract Due to limited spectrum resources and intercell interference (ICI), the increasingly high throughput requirements cannot be satisfied in urban rail transit system in future. Soft frequency reuse (SFR), as a technology of ICI coordination (ICIC), has been proposed to reduce ICI. A static SFR scheme, whose resource management is fixed prior to system deployment, limits the potential performance of users. Especially in urban rail transit system, trains are in moving states. An adaptive intercell resource-allocation algorithm is proposed in this paper, focusing on the performance from the perspective of individual directly. The algorithm dynamically optimizes resource allocation and transmission power in multi-cell wireless communication network to improve the throughput of every Train Access Unit (TAU). For the given locations of trains, we adopt exhaustive search and greedy descend methods to calculate resource allocation and transmission power and then repeat that in all cells until the pre-defined convergence criterion is satisfied. The simulation shows that the algorithm can effectively improve the performance for individuals in the general scenarios compared to where no joint optimization methods of resource allocation and transmission power are performed.

Keywords Long-term evolution for metro (LTE-M) · Soft frequency reuse (SFR) · Power optimization · Resource allocation · Transit system · Interference coordination (ICIC)

1 Introduction

Communication-Based Train Control (CBTC) systems achieve continuous bi-directional and large-capacity train-wayside wireless information exchange to ensure

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safety control and effective operation of trains in urban rail transit systems [1]. In recent years, 3GPP long-term evolution (LTE) has been employed in train-wayside wireless communication system of the CBTC systems, which is called as 3GPP long-term evolution for metro (LTE-M) [2]. Unfortunately, spectrum resources distributed in urban rail transit systems are very limited [3]. Besides, both image monitoring system (IMS) service and passenger information system (PIS) service put forward high requirements of individual's throughput. Thus, it is necessary to reuse the resource in each cell. However, intra-frequency networking inevitably causes intercell interference (ICI). Then, ICI coordination (ICIC) techniques have been proposed [4].

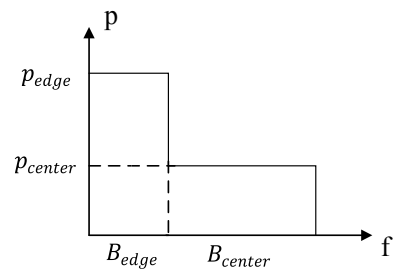
And there are two major methods about ICIC, i.e., soft frequency reuse (SFR) [5] and fractional frequency reuse (FFR) [6]. In both FFR and SFR, the spectrum is divided into several segments and respective groups of subcarriers are allocated to users. Besides, the transmission power should be improved in the cell center while the transmission power should be reduced in the cell edge. It has been proved that SFR achieves higher spectrum efficiency than the FFR [7].

Giambene et al. [8] proposed SFR-3 schemes and presented the iterative methods to solve the problem related to power control parameters and cell association, which is non-convex. Nevertheless, in urban transit systems, the number of trains in a cell is quite small, so there is no need to apply a multi-level method. In static SFR schemes, the resource allocation and transmission power in different regions of cells are fixed beforehand. However, the throughput in each cell significantly fluctuates with time and space domains due to user mobility. Thus, the static resource allocation is not suitable in the urban rail transit systems. Qian et al. [4] determined the number of subcarriers and transmission power for different regions of cells and did not consider the performance from the perspective of the individual.

In our paper, we consider a distributed adaptive-SFR scheme related to power control and resource allocation. As shown in Fig. 1, to consider safe distance between high-speed trains and simplify the resource scheduling method, we only consider the SFR in which the subcarriers are divided into two parts, center and edge, respectively.

The adaptive SFR determines the major and minor subcarriers and ensures that the frequencies used in adjacent cell edge areas must be orthogonal to each other to minimize the ICI among the cells. Besides, the SFR operates by decomposing the multi-cell problems into a sequence of subproblems in the single cell [9]. The

Fig. 1 Frequency segments and power control in soft frequency reuse



decomposition results in a dramatically lower computation than centralized resource allocation schemes.

2 System Model

In this section, we consider the scenario about downlink communication transmission in LTE-M network with a group of C cells. We assume the cells are in liner and zonal distribution, as shown in Fig. 2. Each cell can calculate its resource allocation and transmission power locally based on resource occupation in its adjacent cells. Then, SFR-2 scheme is designed for LTE-M.

Then, we assume that there are K_i trains in cell i in bandwidth B . And $\{k\}_t$ mean that locations of trains in the cells at the time t . The total system spectrum of LTE-M is divided into a set of N physical resource blocks (PRBs). We select one PRB as a unit of resource allocation, because the subcarriers are grouped into PRBs. For each cell $i \in C$ we chooses N_i^{major} and N_i^{minor} PRBs as its major and minor resource groups, and transmission power along with the major and minor PRBs is denoted by P_i^{major} and P_i^{minor} , respectively. Each cell is divided into center and edge. The boundary between the two parts in each cell is defined based on the distance to the serving BS in this paper.

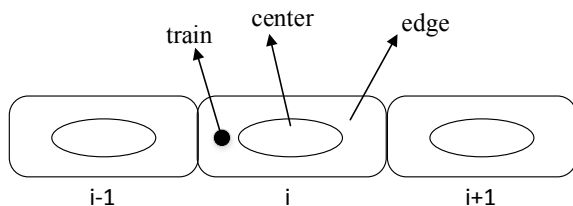
In wireless systems, the throughput of trains in a cell is determined by large-scale fading and the related message received from its adjacent cells. And the channel gain on all the PRBs $j \in N$ between a train and the serving BS are statistically identically independent because the path losses are only determined by the locations of the trains. We define the channel gain for train k operated in cell i (served by BS i) on the PRBs $j \in N$ transmitted by BS m as $g_{i,m,k}$, where $k \in K_i, m \in C$.

Assuming that for train k , the interference only comes from adjacent cells. Thus, the SINR on PRB $j \in N$ is calculated as

$$\text{SINR}_k^j = \frac{P_i^j g_{i,i,k}}{\sum_{m \in B_{\text{adj}}^i} p_m^j g_{i,m,k} + N_0 B_{\text{sub}}} \tag{1}$$

where p_i^j is transmission power on PRB j in cell i . Besides, p_i^{major} and p_i^{minor} denote PRB j deployed as a major PRB and a minor PRB in cell i , respectively; B_{adj}^i represents

Fig. 2 Cells distribution in urban transit rail system



the cells adjacent to the cell i . N_0 is thermal noise power density. B_{sub} is bandwidth of one PRB.

In the system used SFR-2 scheme, the throughput of trains in edge and in center of cell i using (1) and Shannon capacity formula can be written as

$$R_i^E = N_i^{\text{major}} B_{\text{sub}} \log_2 \left(1 + \frac{P_i^{\text{major}} g_{i,i,k_i,E}}{\sum_{m \in B_{\text{adj}}^i} p_m^{\text{minor}} g_{i,m,k_i,E} + N_0 B_{\text{sub}}} \right) \quad (2)$$

Similarly,

$$R_i^C = N_i^{\text{minor}} B_{\text{sub}} \log_2 \left(1 + \frac{P_i^{\text{minor}} g_{i,i,k_i,E}}{\sum_{m \in B_{\text{adj}}^i} p_m^{\text{major}} g_{i,m,k_i,E} + N_0 B_{\text{sub}}} \right) \quad (3)$$

3 Problem Formulation

We adopt the maximization of the minimum throughput among the trains to achieve the objective function. The method is to determine the number of PRBs in different regions and their corresponding transmission power in each cell. The mathematical formulations about the resource allocation problem are written as

$$\max_{q_{i,j}, p_i^{\text{major}}, p_i^{\text{minor}}} \min_{i \in C} R_i^k \quad (4)$$

$$\text{s.t. } R_i^E \geq r_{\text{min}} \quad (5)$$

$$R_i^C \geq r_{\text{min}} \quad (6)$$

$$p_i^{\text{total}} \leq P_{\text{max}} \quad (7)$$

$$N_i^{\text{major}} + N_i^{\text{minor}} = N \quad (8)$$

$$N_i^{\text{major}}, N_i^{\text{minor}} \in \{1, 2, \dots, N-1\} \quad (9)$$

$$N_i^{\text{major}} = \sum_{j \in N} q_{i,j} \quad (10)$$

$$q_{i,j} \in \{0, 1\} \quad \forall j \in N, \quad m \in B_{\text{adj}}^i \quad (11)$$

$$\sum_{m \in B_{\text{adj}}^i} q_{k,j} \leq 1 \quad (12)$$

where r_{\min} is the minimum data rate requirement for trains. Constraints (5) and (6) represent that all trains should satisfy r_{\min} ; Constraint (7) limits the transmission power in cells, denoted by p_i^{total} . And Constraints (8) and (9) indicate that the number of PRBs should be integers and within total number N . Constraints (10) and (11) ensure that the optimal reuse factor could be achieved when the major PRBs allocated in cell i are orthogonal to adjacent cells, where $q_{i,j}$ is the PRB allocation variable indicating the PRB j is deployed in edge or in center of a cell.

4 Adaptive Soft Frequency Reuse Resource Allocation Algorithm

The algorithm decomposes the total optimization in (5) into C single-cell SFR optimization stages. The variables N_i^{major} , N_i^{minor} , P_i^{major} , P_i^{minor} should be found in each cell. We propose the solving algorithm in a single cell, then it can be applied in the multi-cell scenarios sequentially.

We assume that the information about resource occupation in adjacent cells is known. Based on the locations of trains, we first calculate the minimum transmission power that satisfies minimum rate requirement r_{\min} for each train. Then, we reallocate the remaining power to improve the throughput. And the new throughput of trains will be denoted as r_{\min} in the next iteration. We repeat the process until the single cell throughput does not change anymore.

We determine the optimal number of PRBs allocated in different regions and their corresponding transmission power based on the locations of the trains. The formulations are written as

$$\min N_1^{\text{major}} \times P_1^{\text{major}} + P_1^{\text{minor}} \times N_1^{\text{minor}} \quad (13)$$

$$\text{s.t. } N_1^{\text{major}} \leq N_1^{\text{max}} \quad (14)$$

Constraint (14) indicates that the major PRBs in a given cell are non-overlapping with adjacent cells. And N_1^{max} denote that the maximum PRBs can be used as major PRBs for the single cell, which can be formulated as

$$N_1^{\text{max}} = N - \max \left\{ \sum_{B_{\text{adj}}^i} N_i^{\text{major}}, \quad i = 2 \right\} \quad (15)$$

The formula (15) indicates that the maximum PRBs used as major PRBs in cell i are related to the major PRBs allocation in the adjacent cells. And the minimum transmission power could be achieved when the Constraints (5) and (6) become equality constraints. And P_i^{major} , P_i^{minor} can be formulated as follows:

$$P_1^{\text{major}} = \left(2^{\frac{R_1^E}{N_1^{\text{major}} \times B_{\text{sub}}}} - 1\right) \cdot \frac{P_2^{\text{minor}} g_{1,2,k_1,E} + N_0 B_{\text{sub}}}{g_{1,1,k_1,E}} \quad (16)$$

$$P_1^{\text{minor}} = \left(2^{\frac{R_1^C}{N_1^{\text{minor}} \times B_{\text{sub}}}} - 1\right) \cdot \frac{P_2^{\text{major}} g_{1,2,k_1,C} + N_0 B_{\text{sub}}}{g_{1,1,k_1,C}} \quad (17)$$

By using (16), (17), and (8), we can calculate transmission power P_1 with N_i^{major} , N_i^{minor} , P_i^{major} , P_i^{minor} . First, we propose an exhaustive search among all possible $(N_i^{\text{major}}, N_i^{\text{minor}})$ that yields the lowest transmission power, denoted P_{\min} .

If P_{\min} is less than the maximum available power, we reallocate the remaining power to the cell edge by major PRBs. Thus, they can be transmitted with higher power. Therefore, a smaller number of major PRBs are required to be employed for the trains in the cell edge. This modification can bring more considerable PRBs used in the adjacent cells.

To allocate the remaining power, we gradually decrease major PRBs and increase their transmission power using the descent method. And the iterative algorithm stops when the maximum power is achieved. Besides, the optimization objective is nondecreasing as the number of iterations increases.

Single-cell algorithm is illustrated as follows:

1. Input the locations of trains.
2. For each $(N_1^{\text{major}}, N_1^{\text{minor}})$ that satisfies (8) and (9), find the corresponding $(P_1^{\text{major}}, P_1^{\text{minor}})$ according to (16) and (17).
3. Calculate the minimum transmission power
 - (3.1) If $P_{\min}(k) \leq P_{\max}$, go to step 4;
 - (3.2) If $P_{\min}(k) > P_{\max}$, terminate the algorithm.
4. If $P_{\min}(k) \leq P_{\max}$, repeat:
 - (4.1) Fixed $P_1^{\text{minor}}, N_1^{\text{minor}} \leftarrow N_1^{\text{minor}} + 1$. $R_1^C(k+1) > R_1^C(k)$.
 - (4.2) Update the number of major PRBs $N_1^{\text{major}} \leftarrow N - N_1^{\text{minor}}$; Calculate the major transmission power P_1^{major} . $R_1^E(k+1) > R_1^E(k)$.
 - (4.3) Calculate p_1^{total} ; If $p_1^{\text{total}} < p_1^{\text{max}}$, use the newly obtained throughput as the target value for the next iteration.
5. Set $k = k + 1$ and repeat steps 2–4 until the objective does not change any more.

5 Simulation

We consider that the system bandwidth is 10 MHz (50 PRBs). Besides, the simulation is built on the scenario that there exist two trains in the edge and the region of a cell.

We record the results on how resource allocation and transmission power to each train change during the iterative process when the trains' locations are given. From Fig. 3, we can see that the resource allocation satisfying the minimum requirement for each train keeps monotony and remains stable after 25 iterations. Note that after the power is reduced, more resources are needed to ensure the minimum rate requirement.

And the power distributed to the train in the central area is gradually increasing because more resources could be allocated to the user with better conditions of the communication channel.

As the number of iterations increases, the throughput difference gradually decreases, as Fig. 4 shows. The simulation validates the expectation that the resource should not be allocated to the users with good conditions as much as possible.

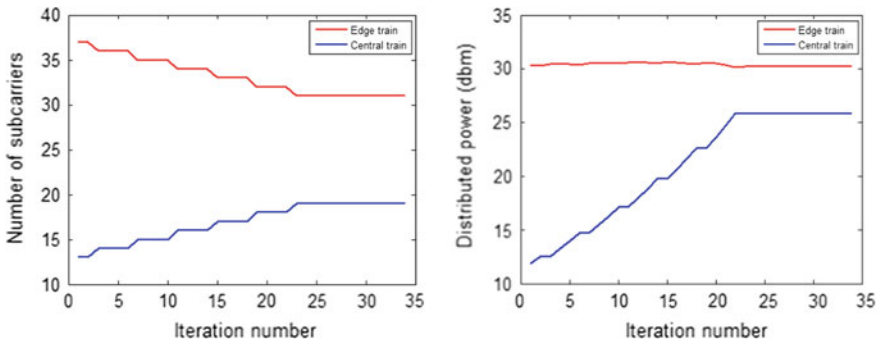


Fig. 3 Number of PRBs and transmission power versus iterations

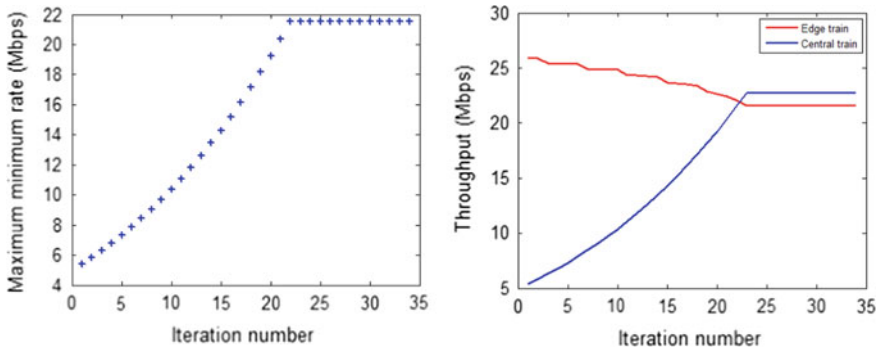
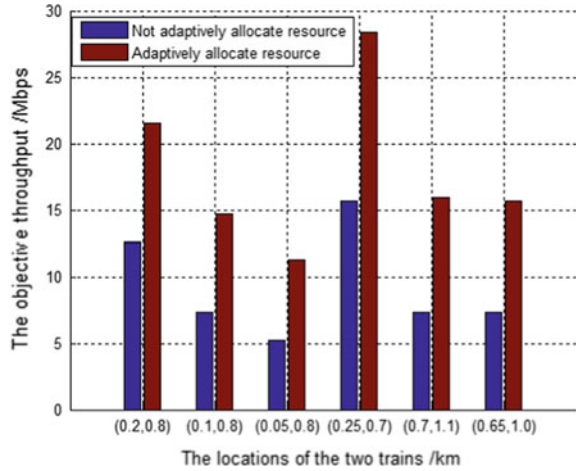


Fig. 4 Maximum minimum rate and individual throughput versus iterations

Fig. 5 Maximum minimum throughput of two trains under different scenarios



Then, we compare the maximum value of the minimum throughput of two trains according to the different locations. Note that the adaptive resource allocation algorithm can dramatically improve the throughput of the train with the smallest throughput in the cell, as Fig. 5 shows.

6 Conclusion

In this paper, we have studied a joint optimization of transmission power and resource allocation based on SFR that aims to maximize the minimum value among the train’s throughput, provided the locations of trains. We have presented an algorithm jointly optimizing resource allocation and transmission power. The proposed algorithm effectively improves the performance for individuals in the general compared with no joint optimization case and exhibits a low computation complexity with reliable convergent property.

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