Research on Minimizing PCI Interference Based on Intelligent Optimization Algorithms

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Abstract. This study focuses on optimizing the allocation of Physical Cell Identities (PCIs) in wireless communication networks to minimize Measurement Report (MR) conflicts, confusion, and mod-3 interference. Starting with a raw dataset containing conflicting and confusing MR data, as well as mod-3 interference, the dataset is cleaned and refined to retain 2,890 communities with MR-related data. A model is then developed to allocate PCIs to 2,067 core communities, aiming to minimize the total MR conflicts, confusion, and mod-3 interference. The problem is formulated as an integer linear programming (ILP) model, where the decision variable indicates whether a specific PCI is assigned to a community. The objective function minimizes the sum of MR conflicts, confusion, and mod-3 interference, subject to constraints such as unique PCI allocation and mod-3 interference conditions. To solve the problem, two optimization techniques are explored: the Monte Carlo method and simulated annealing. While the Monte Carlo method was less effective due to the complexity of the relationships between variables, the simulated annealing algorithm provided better results for PCI reallocation. This study demonstrates an effective approach for PCI allocation and highlights the benefits of using simulated annealing for complex network optimization.

Keywords: Pci Allocation, Integer Programming, Simulated Annealing, Monte Carlo.

1. Introduction

With the rapid development of wireless communication technologies, the complexity and coverage of networks have increased significantly[1,2]. As networks continue to expand, managing their performance and ensuring seamless connectivity becomes increasingly challenging. Physical Cell Identifier (PCI), as a crucial parameter in wireless network planning and optimization, plays a vital role in the performance of communication systems[3,4]. The PCI assignment process is essential for minimizing interference and ensuring stable connections between base stations and mobile devices. However, due to physical overlap and signal interference between cells, PCI allocation often faces challenges such as conflicts, confusion, and mod-3 interference[3,5]. These issues not only degrade network performance but also significantly impact user experience. Given the rising demand for high-quality wireless services, addressing these issues has become a key concern in the design and operation of modern communication networks.

Traditional PCI allocation methods often rely on heuristics or experience-based approaches, which may work for small-scale networks but are inadequate for addressing the complex interference relationships and resource optimization challenges in large-scale networks[6]. While heuristic methods can provide quick solutions, they often lack the precision required to handle the intricate interference patterns that arise in more densely populated or expansive networks. These methods are also typically not scalable and may not provide optimal solutions as network sizes grow. Therefore, developing an efficient and intelligent optimization algorithm to tackle PCI conflicts, confusion, and mod-3 interference has become a critical focus in the field of wireless network planning.

This study leverages intelligent optimization algorithms, integrating integer linear programming, the Monte Carlo method, and the simulated annealing algorithm to systematically analyze and optimize PCI allocation. By constructing a mathematical model, the research aims to minimize the impact of PCI conflicts, confusion, and mod-3 interference on network performance, providing a novel solution for efficient wireless network planning.

2. PCI Assignment Optimization via Integer Programming

The data used in this paper originates from http://mathorcup.org/. Given that the original data includes conflicting MR data, confusing MR data, and mod-3 interference MR data, which can be regarded as comparison values for PCI data, and considering the redundancy in community information, which consumes memory resources during subsequent calculations, the data is first cleaned. This process results in 2,890 communities with MR-related data, significantly improving the efficiency of the model solution.

After obtaining the raw data, this study simplifies the model by focusing on 2,067 communities and disregarding peripheral communities. The objective is to reasonably assign PCIs to these 2,067 communities and establish an effective mathematical model. The goal is to minimize the sum of MR values for PCI conflicts, PCI confusion, and PCI mod-3 interference. For the conflicting MR count and confusing MR count, if community i and community j share the same PCI, their algorithms are the same and they are grouped into one category. For mod-3 interference, the mod-3 operation on the PCI must be performed to determine the interference, and it is categorized separately. Therefore, the objective function should be the sum of the effective values of conflicting, confusing, and mod-3 interference MR counts. Since the PCI values, community MR counts, and the virtual variable indicating whether a community is optimized are all integers, an integer programming model is adopted.

In summary, this study aims to utilize an integer programming model within Integer Linear Programming (ILP), with the possibility of further modifications and adjustments to the model as needed in the future. Let x_{kj} represent whether the k-th PCI value is assigned to the j-th community; if it is, x_{kj}=1, otherwise x_{kj}=0. Thus, the matrix X[x_{kj}], with dimensions 1008×2067, represents the assignment of PCI values PCI_k to different communities j, as shown in Table 1.

Table 1. Schematic diagram of matrix X[xkj] (portion)

PCI_k \ Community j	$\boldsymbol{j}$ = 1	$\boldsymbol{j}$ = 2	……..	$\boldsymbol{j}$ = 2066	$\boldsymbol{j}$ = 2067
$\boldsymbol{k}$ = 0	0	0	……..	0	1
$\boldsymbol{k}$ = 1	0	1	……..	0	0
……..	……..	……..	……..	……..	……..
$\boldsymbol{k}$ = 1007	1	0	……..	1	0

Let x_{kj} be the decision variable in the integer programming model. For the constraints, this study stipulates that each cell must be allocated and can only be allocated once, which is expressed by the formula $\sum_{k=0}^{1007} x_{kj} = 1$ (j=1,2,…,2067). Now that the decision variables and constraints have been specified, this study only need to use the integer programming model to establish the objective function to solve it. Before solving the problem, it is necessary to clean the files in the data set, filter out the targets to be optimized, find the initial data, and solve it. Of course, in actual problems, it is necessary to consider the priority of MR data for PCI conflicts, PCI confusion, and PCI mode 3 interference. Therefore, the permissions for different MR data can be added in the objective function, which is more comprehensive.

The decision variable is x_{kj}, which indicates whether the k-th PCI value is assigned to the j-th cell. If yes, it is 1, otherwise it is 0.

According to the previous analysis, the sum of the effective values of the conflict MR number, the confusion MR number, and the modulo 3 interference MR number must be minimized. The conflict MR number and the confusion MR number can be expressed as:

$$\mu(x_i, x_j) = \begin{cases} 1, PCI_i = PCI_j \\ 0, otherwise \end{cases} \tag{1}$$

Where $\mu(x_{ki}, x_{kj})$ indicates that the PCI values of community i and community j are equal; PCI_i indicates the PCI value corresponding to community i.

The modulo 3 interference MR number can be expressed as:

$$\varepsilon(y_{i(k\%3)}, y_{j(k\%3)}) = \begin{cases} 1, Pmod3_i = Pmod3_j \\ 0, otherwise \end{cases} \tag{2}$$

Where $\varepsilon(y_{i(k\%3)}, y_{j(k\%3)})$ indicates whether the PCI mod 3 of community i and community j are equal; $Pmod3_i$ represents the PCI mod 3 value corresponding to community i. So the objective function is:

$$\min \sum_{i=1}^{N} \sum_{j=1}^{N} \mu(x_i, x_j) \cdot [(a_{ij} + a'_{ij}) + (b_{ij} + b'_{ij})] + \varepsilon(y_{i(k\%3)}, y_{j(k\%3)}) \cdot (c_{ij} + c'_{ij}) \tag{3}$$

Where the calculation formula of a'_{ij}, b'_{ij}, c'_{ij} are as follows:

$$a'_{ij} = a_{ij} + a_{ji} \tag{4}$$

$$b'_{ij} = b_{ij} + b_{ji} \tag{5}$$

$$c'_{ij} = c_{ij} + c_{ji} \tag{6}$$

Among them, a'_{ij} represents the value of $a_{ij} + a_{ji}$ when the PCI values of cell i and cell j are the same; b'_{ij}represents the value of $b_{ij} + b_{ji}$ when the PCI values of cell i and cell j are the same; c'_{ij} represents the value of $c_{ij} + c_{ji}$ when the modulo 3 values of the PCI of cell i and cell j are the same.

There are three constraints in total, which will be described below one by one. Firstly, Each cell must and can only be allocated once, then:

$$\sum_{i=1}^{N} x_{ij} = 1(j = 0, 1 ..., 1007) \tag{7}$$

In order to better establish the direct connection between the matrix $X[x_{kj}]$ and $\mu(x_{ki}, x_{kj})$ and $\varepsilon(y_{i(k\%3)}, y_{j(k\%3)})$, this paper adjust the constraints and redefine and to obtain better results.

Secondly, $\mu(x_{ki}, x_{kj})$ indicates whether the PCIs allocated to cell i and cell j are the same:

$$\begin{cases} \mu(x_{ki}, x_{kj}) \geq \dfrac{x_{ki} + x_{kj}}{2} - \dfrac{1}{2} \\ \mu(x_{ki}, x_{kj}) < \dfrac{x_{ki} + x_{kj}}{2} \\ \mu \in \{0, 1\} \end{cases} \tag{8}$$

Eq 8 represents that only when x_{ki} and x_{kj} are 1, then $\mu(x_{ki}, x_{kj})$ is 1, otherwise is 0.

Thirdly, $y_{i(k\%3)}$ is expressed as a 3×2067 matrix of PCI modulo 3 values of cell i. The relationships with matrix X[x_{kj}] can be express as $y_{i(k\%3)} = O_{3\times1008} \cdot X[x_{ki}]_{1008\times2067}$.

The specific expression of $O_{3\times1008}$ is:

$$\begin{pmatrix} 1 & 0 & 0 & 1 & 0 & 0 & \cdots & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & \cdots & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & \cdots & 0 & 0 & 1 \end{pmatrix}_{3\times1008} \tag{9}$$

Fourth, $\varepsilon(y_{i(k\%3)}, y_{j(k\%3)})$ indicates whether the PCI mode 3 allocated to cell i and cell j is the same:

$$\begin{cases} \varepsilon(y_{i(k\%3)}, y_{j(k\%3)}) \geqslant \dfrac{y_{i(k\%3)} + y_{j(k\%3)}}{2} - \dfrac{1}{2} \\ \varepsilon(y_{i(k\%3)}, y_{j(k\%3)}) < \dfrac{y_{i(k\%3)} + y_{j(k\%3)}}{2} \\ \varepsilon \in \{0, 1\} \end{cases} \tag{10}$$

Equation (10) means that $\varepsilon(y_{i(k\%3)}, y_{j(k\%3)})$ takes the value 1 when both $y_{i(k\%3)}$ and $y_{j(k\%3)}$ are 1, and 0 otherwise.

Based on this, the final model for solving the three MR counts can be derived as:

$$\min \sum_{i=1}^{N} \sum_{j=1}^{N} \mu(x_i, x_j) \cdot [(a_{ij} + a'_{ij}) + (b_{ij} + b'_{ij})] + \varepsilon(y_{i(k\%3)}, y_{j(k\%3)}) \cdot (c_{ij} + c'_{ij}) \tag{11}$$

The constraints are:

$$\sum_{i=1}^{N} x_{ij} = 1 (j = 0, 1 \ldots, 1007) \tag{12}$$

$$y_{i(k\%3)} = O_{3\times1008} \cdot X[x_{ki}]_{1008\times2067} \tag{13}$$

$$\begin{cases} \varepsilon(y_{i(k\%3)}, y_{j(k\%3)}) \geqslant \dfrac{y_{i(k\%3)} + y_{j(k\%3)}}{2} - \dfrac{1}{2} \\ \varepsilon(y_{i(k\%3)}, y_{j(k\%3)}) < \dfrac{y_{i(k\%3)} + y_{j(k\%3)}}{2} \\ \varepsilon \in \{0, 1\} \end{cases} \tag{14}$$

3. Optimizing PCI Allocation via Monte Carlo and Simulated Annealing

Since the relationship between the coefficient matrix C^T and the decision variables x_{kj} in the integer programming model is difficult to represent linearly, this paper first attempts to use the Monte Carlo method to solve it. The Monte Carlo method is a numerical calculation method based on random sampling, which is used to solve probability statistics and numerical integration problems[7,8]. Its basic principle is to estimate the solution of a mathematical problem through random sampling, and a large number of random sampling can obtain relatively accurate results.

The steps of the Monte Carlo method involve generating random samples based on a specified distribution, then calculating the function value for each of these samples. Afterward, the average of all the function values is computed and used as the estimated solution to the problem.

Figure 1 below shows the results of solving the integer programming model based on the Monte Carlo method. Comparing the fitting results in Figure 1 with the sum of the MR data in the appendix, the MR data in the data set is on the order of 1010, and the result obtained by the Monte Carlo method is even larger than the original data, so the solution effect of this method is not good. After further analysis, this paper adopts the simulated annealing algorithm for solution.

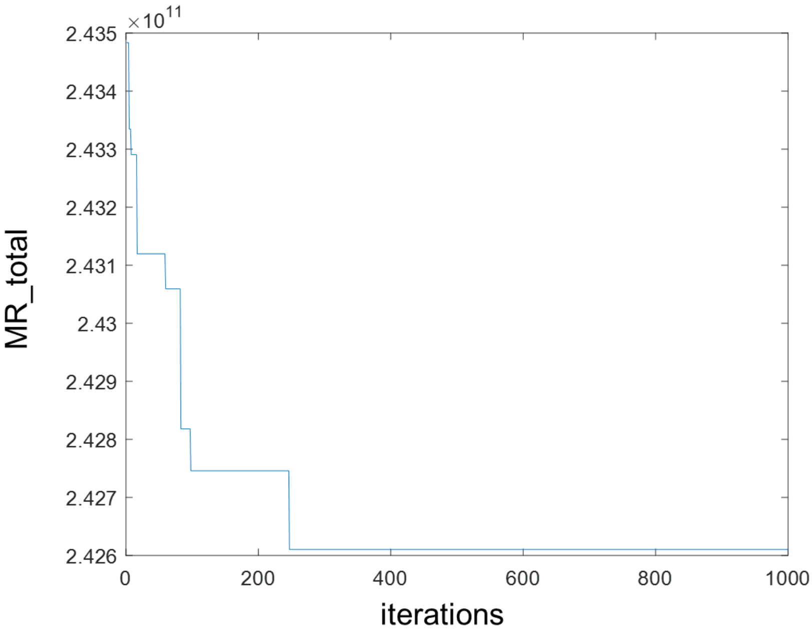

Figure 1. Monte Carlo method based integer programming results

Simulated annealing is a probabilistic optimization technique inspired by the annealing process in solids[9]. It starts with a high initial temperature and gradually cools, using random sampling to explore the solution space. At each step, it may accept worse solutions with a certain probability, helping it find the global optimum[10]. Unlike traditional methods, simulated annealing doesn't require gradients, making it simpler and faster than mathematical programming techniques. Compared to other intelligent algorithms like genetic algorithms, it requires fewer parameters and often converges faster. The key challenge is efficiently evaluating the objective function. The results are shown in figure 2.

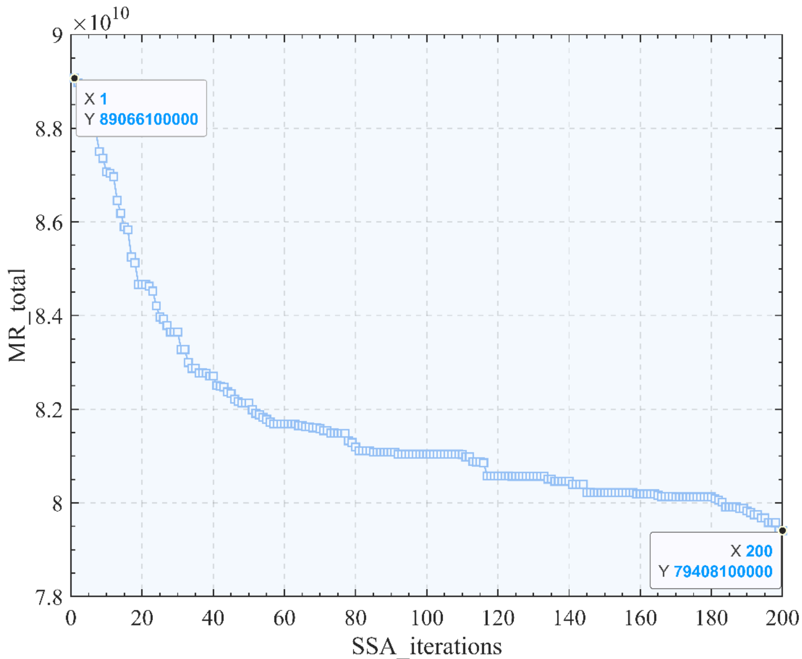

Figure 2. Simulated annealing algorithm solution results

Some of the allocation results are shown in Table 2:

Table 2. Partial allocation results

community number	Reassigned PCI
62613	775
62614	680
62615	163
62616	504
62617	543
62618	773
62622	417
62623	75
62624	300
62625	17
62626	524
62627	145
62628	718
62629	42

The comparison between the original PCI planning frequency chart and the PCI reallocation frequency chart is shown in Figure 3.

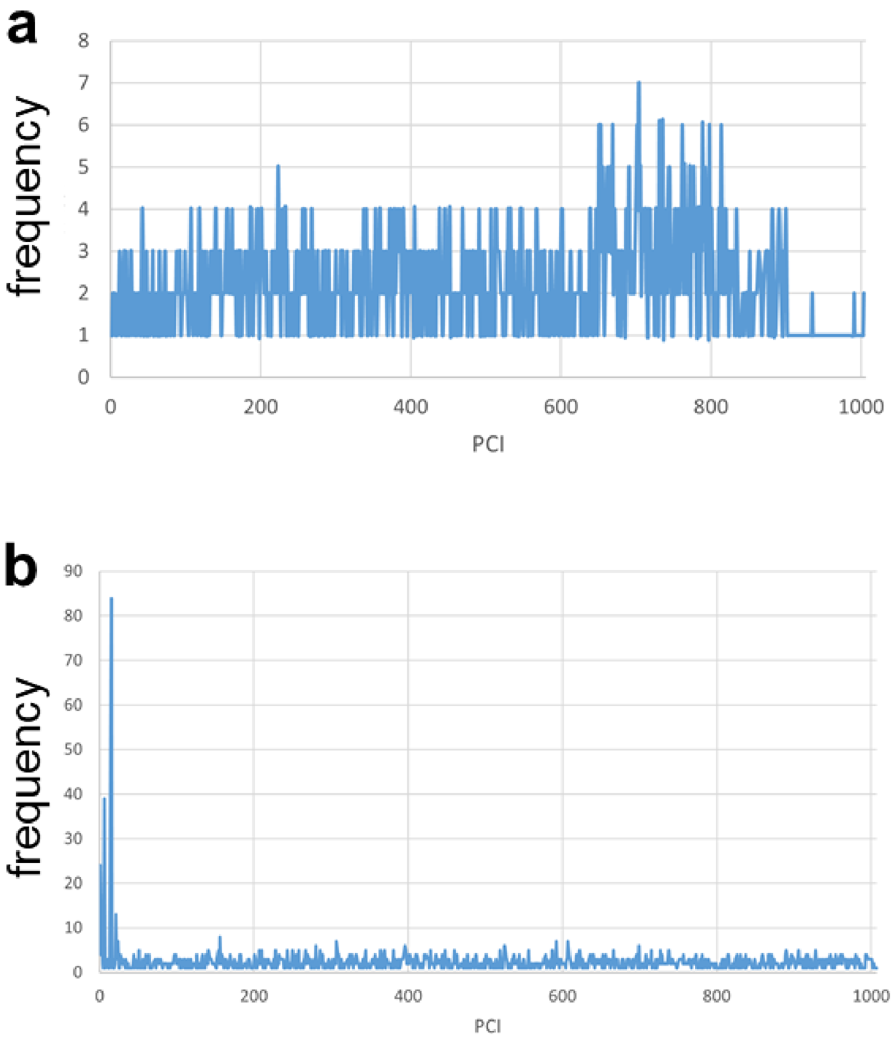

Figure 3. Comparison chart before and after planning. (a) Original PCI planning frequency. (b) PCI re-planning frequency

Figure 3a illustrates the frequency distribution of the original PCI data, which was derived by conducting a statistical analysis on the raw PCI data provided in the appendix. Figure 3b depicts the PCI frequency distribution after re-planning through the simulated annealing algorithm, aiming to minimize the objective function. By comparing the frequency distributions in Figures a and b, it is evident that the original PCI distribution is relatively uniform. In contrast, the PCI distribution after re-planning exhibits a loss of uniformity, with frequencies becoming concentrated around a few specific PCI values. This distribution leads to a significant reduction in the objective function compared to the original data, thereby indicating that the model possesses a higher degree of reliability.

4. Conclusion

This paper presents an optimization framework for PCI allocation in wireless networks, focusing on minimizing conflicts, confusion, and mod-3 interference. By cleaning the raw data and simplifying the problem to 2,067 communities, the model's efficiency is significantly improved. The integer programming approach, initially explored with the Monte Carlo method, was found to be less effective. In contrast, the simulated annealing algorithm provided a more practical solution, delivering improved results in terms of optimal PCI reassignment. The reallocation significantly reduced interference, demonstrating the algorithm's effectiveness in optimizing PCI planning. he results highlight the potential of simulated annealing for large-scale optimization problems in network planning, offering a robust and efficient approach to PCI allocation.

This research lays a solid foundation for future advancements in wireless network optimization, offering a flexible approach that can be adapted to various large-scale allocation problems and inspiring further exploration of probabilistic algorithms in this field.

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