Planning of VHF Radio Networking Based on Tabu Search

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Abstract. In order to solve the problem of frequency planning of VHF radio network, the constraint relation of VHF radio network is analyzed, the inter-network interference optimization model including interference matrix and cost function is established, and a frequency planning method based on tabu search is proposed. Finally, the model and algorithm are analyzed and verified with examples.

1. Introduction
VHF radio network is an important means of wireless communication. Traditional radio network mostly adopts asynchronous frequency hopping network. There is no uniform time reference and frequency hopping pattern is not orthogonal, which inevitably leads to frequency collision and serious interference. With the development of synchronous equipment, synchronous frequency hopping networking without frequency collision has become the mainstream. However, due to the complex application scenarios, large number and centralized distribution, and limited available frequency resources, the interference problem still exists in the actual networking process. Frequency planning is an effective means to solve the problem of spectrum resource shortage and frequency interference. In reference [1], a multi signal interference model is designed for the mutual interference problem, and an improved algorithm combining simulated annealing algorithm and genetic algorithm is proposed to solve the radio frequency assignment problem. In reference [2-4], the author applied genetic algorithm, ant colony algorithm to radio network frequency planning, and achieved some research results. However, the above-mentioned planning method is based on the optimization algorithm of interference control, without realizing the frequency assignment without interference, and when the number of networks increases, the performance of the algorithm drops sharply and even can not complete the frequency planning. How to realize the non-interference frequency assignment of complex VHF radio network is a problem worth studying.

In order to realize non-interference frequency assignment in complex networks, this paper introduces TS(Tabu Search) algorithm, which is famous for its flexibility and efficiency in the field of artificial intelligence. Firstly, the constraints are analyzed according to the application scenarios, and the inter network interference optimization model is established. Then, the frequency assignment algorithm of VHF radio network based on TS and the related elements are designed. Finally, the algorithm is verified by simulation.
2. Interference Optimization Model

2.1. Constraints
When multiple VHF station networks are organized in a limited region, improper frequency configuration will produce interference phenomenon, which will seriously make communication unable to carry on normally. Based on the sub-network relationship, this paper studies and summarizes VHF frequency assignment constraints of radio network as follows:

It is known that the available frequency points of VHF radio network are M and the frequency point interval is 0.1 MHz.

(1) Co-frequency interference constraint. In order to avoid the co-frequency interference caused by frequency collision, each radio subnet in the same area can not use the same frequency point, that is, the frequency point number interval should be greater than 1.

(2) Co-address interference constraint. In order to prevent interference from adjacent frequencies, a frequency interval of at least 0.4MHz should be maintained between each radio subnet with the same address, that is, the frequency point interval should be greater than 4.

(3) Co-vehicle interference constraint. According to the technical requirements of the antenna sharing system, the subnet of multiple stations in the same vehicle should maintain at least 2.5MHz frequency interval, that is, the frequency point interval should be greater than 25.

According to the characteristics of organization and application of VHF radio network, its network topology structure is complex, generally divided into general line, star, tree, network, etc. According to relevant research, the relationship between VHF radio network can be abstracted as undirected graph, as shown in Figure 1:

![Figure 1. Diagram of the relationship between VHF radio networks.](image)

Each VHF station subnet is abstracted as the vertex of the undirected graph, the frequency constraint relation of the subnet is the edge of each vertex. The dotted line between the vertices represents the existence of two subnets with the same address, and the solid line between the vertices represents the existence of Co-vehicle interference constraint in the two subnets, and the default is the existence of the co-frequency interference constraint in each subnet in the same region. Transforming the undirected graph into a subnet constraint matrix, which can be expressed as:

\[
D = \begin{bmatrix}
D_{11} & D_{12} & \cdots & D_{1n} \\
D_{21} & \ddots & \cdots & \vdots \\
\vdots & \ddots & \ddots & \vdots \\
D_{n1} & \cdots & D_{nj} & D_{nn}
\end{bmatrix}
\]

Each element in the D matrix represents the constraint relationship between the i-th subnet and the j-th subnet, n is the number of radio subnets. According to the undirected graph property, only the upper half angle matrix of the matrix can be used to represent the constraint relationship of each subnet completely. The elements on the diagonal line have no practical significance. \(D_{ij} = 1\) means that the i-th and j-th subnets only have co-frequency interference constraint, \(D_{ij} = 4\) indicates that the i-th and j-th subnets have co-address interference constraint and \(D_{ij} = 25\) indicates that the i-th and j-th subnets have co-vehicle interference constraint.
2.2. Interference Matrix
The interference matrix is affected by two aspects, one from the subnet relation constraint, the other from the frequency assignment. Subnet relationship constraints can be represented by the subnet constraint matrix discussed in the previous section. Frequency assignment factors are determined by the frequency assignment scheme \( F \):

\[
F = \{ f_1, f_2 \cdots f_i \cdots f_n \}, \quad i = 1, 2 \cdots m
\]

which represents the frequency assigned by the i-th subnet.

The frequency interval matrix \( G \) can be generated by frequency assignment scheme \( F \):

\[
G = \begin{bmatrix}
G_{11} & G_{12} & \cdots & G_{1n} \\
G_{21} & \ddots & \cdots & \vdots \\
\vdots & \ddots & \ddots & \vdots \\
G_{n1} & \cdots & \cdots & G_{nn}
\end{bmatrix}, \quad G_{ij} = |f_i - f_j|
\]

Each element in the G matrix represents the absolute value of the frequency interval between the i-th subnet and the j-th subnet.

From the subnet constraint matrix \( D \) and the frequency interval matrix \( G \), co-frequency interference matrix \( A \), co-address interference matrix \( B \) and co-vehicle interference matrix \( C \) can be obtained:

\[
A = \begin{bmatrix}
A_{11} & A_{12} & \cdots & A_{1n} \\
A_{21} & \ddots & \cdots & \vdots \\
\vdots & \ddots & \ddots & \vdots \\
A_{n1} & \cdots & \cdots & A_{nn}
\end{bmatrix}, \quad B = \begin{bmatrix}
B_{11} & B_{12} & \cdots & B_{1n} \\
B_{21} & \ddots & \cdots & \vdots \\
\vdots & \ddots & \ddots & \vdots \\
B_{n1} & \cdots & \cdots & B_{nn}
\end{bmatrix}, \quad C = \begin{bmatrix}
C_{11} & C_{12} & \cdots & C_{1n} \\
C_{21} & \ddots & \cdots & \vdots \\
\vdots & \ddots & \ddots & \vdots \\
C_{n1} & \cdots & \cdots & C_{nn}
\end{bmatrix}
\]

The elements in the matrices are determined by the following formulas:

\[
A_{ij} = \begin{cases} 
1, & D_{ij} < 1 \text{ AND } D_{ij} \neq 0 \\
0, & \text{others}
\end{cases} \quad (1)
\]

\[
B_{ij} = \begin{cases} 
1, & G_{ij} - D_{ij} < 0 \text{ AND } D_{ij} = 4 \\
0, & \text{others}
\end{cases} \quad (2)
\]

\[
C_{ij} = \begin{cases} 
1, & G_{ij} - D_{ij} < 0 \text{ AND } D_{ij} = 25 \\
0, & \text{others}
\end{cases} \quad (3)
\]

Formula (1), (2) and (3) indicates that if the i-th subnet and the j-th subnet have the co-frequency interference constraint \( D_{ij} \neq 0 \), the co-address interference constraint \( D_{ij} = 4 \) or the co-vehicle interference constraint \( D_{ij} = 25 \), their interference will be calculated when their frequency interval is less than the subnet constraint condition, otherwise, no interference will be taken into account.

2.3. Optimization Model
The inter-network interference optimization model transforms the factors affecting frequency allocation into operable mathematical description. The core of the optimization model is the interference matrix and cost function.

The design of cost function plays an important role in the quality of matching results. Cost function \( S \) is obtained by multiplying the number of subnets that violate the co-frequency interference constrain, co-address interference constraint and co-vehicle interference constraint by the sum of their respective penalty factors. It reflects the magnitude of the interference of the frequency assignment scheme \( F \), as shown in the following formula:

\[
S = \alpha A + \beta B + \gamma C \quad (4)
\]

It is known that the upper half angle matrix of the matrix can be used to represent the subnets completely, so the optimization model can be obtained as follows

\[
S = \alpha \sum_{i=1}^{n} \sum_{j=i+1}^{n} A_{ij} + \beta \sum_{i=1}^{n} \sum_{j=i+1}^{n} B_{ij} + \gamma \sum_{i=1}^{n} \sum_{j=i+1}^{n} C_{ij} \quad (5)
\]

In Formula (4) and (5), \( n \) is the number of radio subnets, and \( \alpha, \beta, \gamma \) are the penalty factors of the co-frequency interference, co-address interference and co-vehicle interference respectively. Penalty factor can be set according to user requirements custom. In general, the co-vehicle interference
constraint is the strictest constraint and should be satisfied first, so the penalty factor is designed according to the $\alpha<\beta<\gamma$ rules.

3. Algorithm Design and Simulation
TS algorithm was formally proposed by American system scientist Glover professor in 1986. After continuous research and improvement, it has become an effective tool to solve the problem of combinatorial optimization. In essence, it is a local neighborhood search algorithm. By recording the search history, it consciously avoids repeatedly selecting the local optimal solution, so as to avoid the search falling into the local optimal solution and expand the search area, which is conducive to the global optimal solution.

3.1. Algorithm Flow
Step1 Set tabu table $T$. Generate initial solution $F_0$, and make the current optimal solution $F_{BST} = F_0$.

Step2 Termination criterion judgment. Outputs and stops if the termination criterion is met, otherwise the iteration executes Step3 to Step6.

Step3 Generate neighborhood solution sets. The neighborhood solution set is generated from the current solution and the cost function values of all solutions are calculated.

Step4 Select the optimal solution. A new optimal solution $F_{\text{best}}$ without taboo constraints is selected from the neighborhood solution set by using the amnesty rule.

Step5 Update $T$ and record search history. If $F_{\text{best}}$ is superior to $F_{BST}$, $F_{BST} = F_{\text{best}}$, add $F_{BST}$ to $T$. Otherwise, keep $F_{BST}$ unchanged, reset the tabu length and update the tabu length in the tabu table.

Step6 repeat Step2.

3.2. Elements Design of Algorithm
The core elements of the process include: setting tabu table, designing new solution acceptance criteria, etc. The following is a description of the design of the elements when the TS algorithm is applied to the specific frequency assignment problem:

3.2.1. Solutions

$$F = \{f_1, f_2, \ldots, f_i, \ldots, f_n\}$$

There are $n$ subnets and $m$ available frequency points, and the initial solution is $F_0$.

3.2.2. Tabu table
The element in the tabu table is $(v, f)$, $v \in \{1, 2, \ldots, i, \ldots, n\}$, $f \in \{1, 2, \ldots, j, \ldots, m\}$, which represents the radio subnet and the frequency assigned to the subnet. Whenever $f$ is assigned to $v$, insert the $(v, f)$ into the tabu table and set its tabu length to initial value. The element will be taboo for several iterations until the tabu length is reduced to 0.

In the programming implementation, an $n \times m$ dimension matrix $T$ is used to realize the tabu function. When an element is inserted into $T$, the corresponding $T(i, k)$ is given a tabu length, $T(i, k)$ records the number of iterations until the element is released. The data structure can easily determine whether an action is taboo based on the value. Tabu table length reflects the number of steps in which the current optimal solution is forbidden to search. The smaller the value, the faster the calculation, but it is easy to fall into the local optimal solution. The larger the value, the slower the calculation, but it is easy to find the global optimal solution.

3.2.3. Neighborhood solution set
Given a current solution $F_0$, its neighborhood solution set, $\text{Near}(F_k)$, is defined as follows: The new solution $F_k$ is to select one of the subnets as its change frequency on the basis of the current solution $F_0$, and the frequency of the subnet is not in the tabu table, except for this subnet, the frequency of other subnets remains unchanged.
3.2.4. Select the optimal solution
If the optimal candidate solution obtained by neighborhood search is superior to the current optimal solution, it is taken as the current optimal solution and added to the tabu table. The tabu length is set as the initial value, and the tabu length of other solutions in the tabu table is reduced by 1. If the optimal candidate solution obtained through neighborhood search is inferior to the current optimal solution, then the current optimal solution remains unchanged and its tabu length is reset, and the tabu length of the remaining solutions in the tabu table is reduced by 1.

3.2.5. Rules of pardon
The pardon rule is to avoid the algorithm losing the better solution, and continue to search the better solution locally to get the global optimal solution. The pardon rule is as follows: each better solution holds the tabu length step in the tabu table, and the tabu length decreases after each iteration. When the tabu length of the better solution is 0, it is released and can be searched again.

3.2.6. Termination criteria
When the maximum number of iterations or the cost value reaches a certain threshold, the algorithm terminates.

3.3. Simulation Analysis

3.3.1. Basic performance of the algorithm
Assuming that a pre-planned radio network has 100 radio subnets and 256 available frequency points, and the constraint relationship between networks is known.

Simulation parameters are as follows: n=100, m=256, α=3, β=5, γ=10. The termination condition is that iterative steps reaches 1000 steps or the cost function value is 0.

Figure 2 shows the change of cost function value with the number of iterative steps in the frequency assignment process.

![Figure 2. Algorithm performance simulation.](image)

It can be seen that the cost function value of initial assignment solution is 1350. With the increase of iteration times, the value decreases continuously, and finally the optimal solution is obtained to complete the non-interference frequency assignment.

3.3.2. Effect of Tabular Length
In order to explore the influence of tabu table length on the algorithm, the tabu table length is taken as 10 and 30 respectively. The interference evolution curve is obtained as follows:
Figure 3. Algorithm performance when tabu length is 10.

Figure 4. Algorithm performance when tabu length is 30.

It can be seen that when the tabu table length is 10, the iterative 435-step algorithm reaches the state of convergence, but falls into local optimal wandering until the end of the algorithm. When the tabu length is 30, the iterative 557 steps reach the convergence state, and the cost function value is reduced to 0 to obtain the global optimal solution. Conclusion: The smaller the tabu length value is, the faster the calculation is, but it is easy to fall into the local optimum. The larger the tabu length value is, the slower the calculation is, but it is easy to find the global optimal solution.

3.3.3. Frequency assignment under different network complexity

The frequency planning problem is recognized as NP hard problem, that is, the more networks to be planned, the more complex and difficult the planning is. In order to test the applicability of the algorithm to different complexity networks and obtain the optimal frequency assignment results, tabu length was selected as 30, and frequency planning was simulated when the number of networks n was 50, 100 and 150 respectively. The results are as follows:

Figure 5. Algorithm performance when network number n=50.
The results show that when the number of networks is 50, 100 and 150, the number of iterations needed to get the optimal solution is 116 steps, 167 steps and 557 steps respectively. With the increase of the number of networks, the running time and iteration steps of the algorithm also increase, but the solutions with the cost of 0 are obtained. It can be seen that the frequency planning algorithm based on TS can complete the optimal frequency index in complex networks.

4. Conclusion
In order to solve the frequency planning problem of VHF radio network, firstly, the constraint relationship of VHF radio network is analyzed, and the interference matrix and interference optimization model are constructed. Secondly, the frequency planning method based on TS algorithm is designed. Finally, the simulation results show that the algorithm can jump out of the local optimum to achieve the global optimization and complete the optimal frequency assignment.

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