An Interference-Free Frequency Assignment Method Based on Hybrid Pattern

Donglei Zhang, Xiedong Hao, Hongwei Yan, and Feng Han

***Abstract*—Interference-free frequency assignment for wireless electronic equipment on the same spot is a key technology for electromagnetic spectrum management and utilization. In this article firstly study the restrictive conditions for same frequency, adjacent frequency, intermodulation and harmonic interference. And then acquire the relations between distance of stations on the same spot and interference-free frequency interval by experiments. Finally put the experiment result and the priority limit conditions into the improved frequency assignment algorithm based on hybrid pattern with sequential graph coloring algorithm and genetic and simulated annealing algorithm, and accomplish the interference-free frequency assignment on the same spot.**

***Index Terms*—Electromagnetic spectrum management, frequency assignment, genetic and simulated annealing algorithm, sequential graph coloring algorithm.**

I. Introduction

The purpose of frequency assignment is to find proper frequencies for wireless electronic equipment in order to keep them working without mutual interference, which is a kernel technology for electromagnetic spectrum management and efficient utilization [1]. Generally we will assign one frequency to stations as most as possible for increasing using efficiency of spectrum resource if interference between them can be avoid under some conditions. In early frequency assignment models the same frequency interference is mostly considered, which is turned into distance constraint conditions in those models [2]. Two stations can use the same frequency if the distance between them is above a certain threshold. When the stations have to be disposed closely, or even more, on the same spot, the frequency assignment model should also take adjacent frequency interference, intermodulation interference, and harmonic interference into account.

However, in the previous work researchers or frequency managers usually think about the same frequency problem only, and neglect the other types of interference factors. When the stations are in the same place (in the range of 1km) and the frequencies they use have adjacent relations, intermodulation relations or harmonic relations, mutual interference will take place between one another in all probability.

Furthermore, there has always been priority sequence among the communication links especially in a network with multilevel departments. For example, the communication link between upper-level departments sometimes has higher priority than others. In addition, the communication quality also has distinction between different frequencies. Therefore, all those factors need to be considered in the practical assignment work to assure that communication links with higher priorities can be assigned frequencies with better quality and less interference.

From the point of view of actual requirement in frequency assignment, in this article we firstly study the restrictive conditions for same frequency, adjacent frequency, intermodulation and harmonic. Then we acquire the relations between distance of stations on the same spot and interference-free frequency interval by experiments. Finally, we put the experiment result and the priority limit conditions into the improved frequency assignment algorithm and realize the interference-free frequency assignment on the same spot.

II. Constraints Analysis

Suppose f_{ij} is the frequency of the communication link from station i to station j in the situation of frequency assignment, i.e. the emission frequency assigned to station i.

A. Same Frequency Constraints

As long as the distance between two stations working with the same frequency is far enough, the influence of same frequency interference can be approximately neglected. Suppose N is the total number of stations. For station i, the set $L(i)$ consists of stations that form the communication link with i.

The same frequency constraints between stations i, j can be figured as:

$$\begin{aligned} f_{ik} &\neq f_{lj}, \qquad k \in L(i), l \in L(j), i \notin L(j) \\ f_{ki} &\neq f_{jl}, \qquad k \in L(i), l \in L(j), i \notin L(j) \end{aligned} \tag{1}$$

and the distance between stations i, j, i.e. $d(i, j) \le D_{CCI}$, in which D_{CCI} is the farthest distance that can cause same frequency interference. In other words, if station i and station j do not belong to the same communication network in a certain distance, any two links with station i cannot use the same emission frequency or receive frequency.

B. Adjacent Frequency Constraints

For those stations that have to be close to each other, enough frequency intervals should be kept in order to avoid adjacent frequency interference. If the distance between

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stations i, j, i.e. $d(i, j) \le D_{ACI}$, the adjacent frequency constraint between stations i, j can be figured as:

$$\left| f_{ki} - f_{jl} \right| \ge K \cdot B_{j,IF} \quad , \qquad k \in L(i), l \in L(j), i \notin L(j) \tag{2}$$

in which D_{ACI} is the farthest distance that can cause adjacent frequency interference, $B_{i,\ IF}$ is the receiver intermediate frequency bandwidth of station i, and K is the assumed multiple of the intermediate frequency bandwidth interval.

C. Intermodulation Interference Constraints

If stations i, j are quite close or even on the same spot, the frequency relationship that will cause third order intermodulation interference can be figured as:

$$\begin{aligned} f_{jl} + f_B - f_C &= f_{ki}, \quad k \in L(i), l \in L(j) \\ 2 f_{jl} - f_B &= f_{ki}, \qquad k \in L(i), l \in L(j) \end{aligned} \tag{3}$$

and the distance between stations i, j, i.e. $d(i, j) \le D_{IM}$, in which D_{IM} is the farthest distance that can cause intermodulation interference.

If the intermediate frequency bandwidth interval is taken into account, the intermodulation interference constraints can be transformed into:

$$\begin{aligned} &\left| (f_{jl} + f_B - f_C) - f_{ki} \right| > B_{i,IF} / 2, \quad k \in L(i), l \in L(j) \\ &\left| (2 f_{jl} - f_B) - f_{ki} \right| > B_{i,IF} / 2, \qquad k \in L(i), l \in L(j) \end{aligned} \tag{4}$$

D. Harmonic Interference Constraints

If stations i, j are quite close or even on the same spot, the frequency relationship that will cause harmonic interference can be figured as:

$$\left| n f_{jl} - f_{ki} \right| \le B_{i,RF} / 2, \qquad k \in L(i), l \in L(j) \tag{5}$$

and the distance between stations i, j, i.e. $d(i, j) \le D_{HI}$, in which D_{HI} is the farthest distance that can cause harmonic interference, and $B_{i,\ RF}$ is the RF front end bandwidth of station i.

E. Constraints and Protected Frequency of External Interfering Source

In the practical application environment, the ERP (Effective Radiated Power) of some wireless devices cannot exceed the given threshold in a certain range, or can just be made limited use of with some frequencies, such as radar, microwave link, wireless navigation device, e.t., near which the emission power and frequency of other devices must follow some restrictive requirement. This kind of constraints can be represented as forbidding some frequencies in a certain distance, with which some devices will not work properly due to the potential influence of same frequency, adjacent frequency, intermodulation, harmonic, and spurious interference. Forbidden frequency can only be listed one by one according to specific situation with forbidden range for each link or station. Moreover, the frequencies and their adjacent frequency used by some important devices must be protected so as to prevent potential interferences from disturbing their normal work. Otherwise, in some case frequencies need to be reserved for emergency to maintain the minimum communication. The especially protected frequencies are usually given in the form of forbidden frequency table.

F. Goal Function

The different constraints play different roles in the process of frequency assignment, which give different weight to all sorts of violation in the goal function. The relationship of emission-receive frequency is a compulsive constraint that must be satisfied. The assignment result that violates this constraint is invalid and useless. Therefore this constraint must be set the maximal weight. Among devices that work on the same spot, same frequency, intermodulation and harmonic interferences also have to be avoided, which should be set big weights either [3]. The constraints of adjacent frequency interference can be relaxed to some extent, whose violation weight can be set to a form correlative to frequency interval. In addition, different radio stations have different statuses and functions. For a station with higher priority, its interference-free state should first be assured, thus the violation relative to it ought to be set a heavier weight. In order to describe the goal function exactly, some assumption is put forward as follows:

$$p(i),\ i = 1, \ldots, N: \text{ the priority of all stations}$$

$$V_{TR}(i,j) = \begin{cases} 1, & \text{if there is emission-receive relation violation} \\ & \text{in link between sations } i, j \\ 0, & \text{if there is no emission-receive relation violation} \\ & \text{in link between sations } i, j, \text{ or there is no} \\ & \text{emission-receive relaion between stations } i, j \end{cases}$$

$$V_{CCI}(i,j) = \begin{cases} 1, & \text{if there is same frequency violation} \\ & \text{between sations } i, j \\ 0, & \text{if there is no same frequency violation} \\ & \text{between sations } i, j \end{cases}$$

$$V_{IM}(i,j) = \begin{cases} 1, & \text{if there is intermodulation violation} \\ & \text{between stations } i, j \\ 0, & \text{if there is no intermodulation violation} \\ & \text{between stations } i, j \end{cases}$$

$$V_{HMI}(i,j) = \begin{cases} 1, & \text{if there is harmonic interference} \\ & \text{violation between stations } i, j \\ 0, & \text{if there is no harmonic interference} \\ & \text{violation between stations } i, j \end{cases}$$

$$V_{ACI}(i,j) = \begin{cases} \sum_{k,l} \left[K - \dfrac{\left| f_{ki} - f_{jl} \right|}{B_{i,IF}} \right], & \text{if } d(i,j) < D_{ACI}, \left| f_{ki} - f_{jl} \right| < K \cdot B_{i,IF}, \\ & \text{i.e. there is adjacent frequency} \\ & \text{violation between stations } i, j \\ 0, & else \end{cases} \tag{6}$$

Suppose W_{TR}, W_{CCI}, W_{IM}, W_{HMI}, W_{ACI} are the weights of emission-receive violation, same frequency violation, intermodulation violation, harmonic violation, and adjacent frequency violation respectively, and their values decrease in turn.

The goal cost function is as follows:

$$\begin{aligned} C_I = {} & w_{TR} \sum_i \sum_j \max\left[p(i), p(j)\right] \cdot V_{TR}(i,j) + w_{CCI} \sum_i \sum_j \max\left[p(i), p(j)\right] \cdot V_{CCI}(i,j) \\ & + w_{IM} \sum_i \sum_j \max\left[p(i), p(j)\right] \cdot V_{IM}(i,j) + w_{HMI} \sum_i \sum_j \max\left[p(i), p(j)\right] \cdot V_{HMI}(i,j) \\ & + w_{ACI} \sum_i \sum_j \max\left[p(i), p(j)\right] \cdot V_{ACI}(i,j) \end{aligned} \tag{7}$$

The frequency assignment problem is now changed into seeking a link frequency set $\{f_{ij}\}$ that make the goal cost function above have the minimum value.

III. Interference Experiment among Stations

In order to acquire the distance bound of adjacent frequency interference, a great deal of experiments were carried out among stations disposed on the same spot (<1km), considering time, place, terrain conditions, ground conditions and weather conditions. A frequency range from 3500 kHz to 28500 kHz was selected as an example. By statistics of experiment results a set of synthetic reference value was figured out about the relations between interference-free frequency interval and the working frequency of stations with different distances, as shown in Fig. 1.

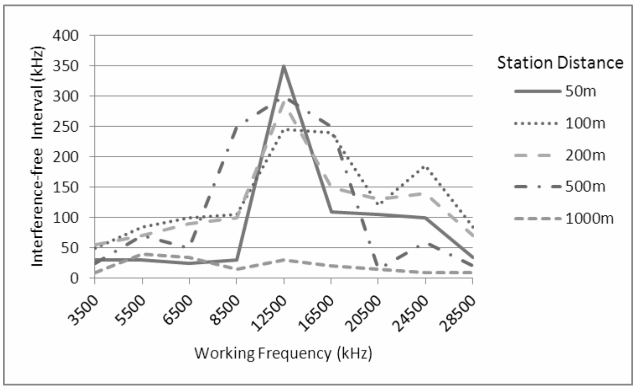

Fig. 1. Relations between interference-free frequency interval and the working frequency of stations with different distances.

IV. Frequency Assignment Algorithm Based on Hybrid Patterns

A. Improved Sequential Graph Coloring Frequency Assignment Algorithm

In the theory of frequency assignment optimization, the assignment problem is transformed into solving the problem of combination optimization under some constraints. The assignment method under same frequency interference constraint converts the assignment problem into the graph coloring problem, in which the goal of frequency assignment optimization is generally to find an assignment scheme that minimizes the amount of the required frequencies or cause the least interference.

The earliest optimization method adopted sequential assignment technique, in which there is not any direct line between the vertexes that can be assigned the same frequency or be marked with the same color since a station can be regarded as a vertex in the graph, while there is a direct line between the vertexes that cannot be assigned the same frequency or be marked with the same color [4]-[8]. The more a vertex has lines linked to it, the more difficult it is to assign a frequency to the station it represents. The process of assignment is to rank the stations on the "difficulty" at first, and then to begin assigning frequencies to the most difficult stations, and in turn to assign frequencies to the other stations that is less difficult. Meanwhile, during the process frequency reuse is tried to be maximized to reduce the number of frequencies involved. The key point of sequential assignment method is the order of assignment, and the method can get the optimal solution fast if the communication network is not very complex.

Consequently, we put forward a sequential coloring frequency assignment algorithm with improved difficulty ranking based on former algorithms, taking into account those practical factors such as the priority order of the communication link and the frequency quality. The essential thought is as follows. First of all the priorities of the stations and the qualities of the frequencies are both ranked. Secondly the algorithm starts with the highest-priority station, and tries to assign the highest-quality frequency to this station. If it does not conflict with the frequencies that have be assigned, the assignment will be really executed, or else a less high quality frequency will be inspected whether it is compatible or not until all the frequencies left have be explored according to the sequence from high frequency quality to low. And then repeat performing the above steps to the less high priority station until all the stations has been assigned. Therefore the frequency assigned to the current station always has the highest quality without interference. Besides, during the assignment process the result of interference-free frequency interval experiment should be referred to and select the optimal frequencies that satisfy the constraints according to the specific locations of the stations.

In the process of assignment if a station cannot seek out any frequencies that do not conflict with the frequencies assigned, the algorithm need to come into a regression state, i.e. the frequencies assigned must be revised so that subsequent assignment can be realized without interference. Choosing a proper difficulty calculating method can effectively reduce the times of algorithm regression. Existing algorithms usually adopt quantity of usable frequencies to enhance the veracity of difficulty ranking, while we introduce the interference violation weight and link priority etc. in our algorithm to improve difficulty ranking and to increase the convergence rate of the algorithm. The procedure of our algorithm is shown in Fig. 2.

B. Hybrid Assignment Algorithm Based on Genetic and Simulated Annealing Algorithm

When there are a large number of stations, the sequential assignment method may cause exhaustive search and the calculation work will be greatly increased, while heuristic search method can solve this problem in a better way, and thus find extensive research and application in frequency assignment problem. Among those methods genetic algorithm and simulated annealing algorithm can adapt to various optimization problems, while both of them have some limitation in practical use. Genetic algorithm has the disadvantage of low capability in local search when solving large-scale optimization problems, and has poor ability of keeping population diversity, which will not evolve the population totally and easily fall into local optimum with premature convergence. While the calculating speed of simulated annealing algorithm is too slow. Some researchers combined those two algorithms and proposed the genetic and simulated annealing algorithm, which controls the direction of searching optimum by genetic algorithm in order to speed the searching process, and solves the problem of local convergence by simulated annealing algorithm in order to improve searching accuracy [9], [10]. The algorithm takes full advantage of quick global searching capability of genetic algorithm and local searching ability of simulated annealing algorithm, which has high efficiency and wide adaptability shown by experiments.

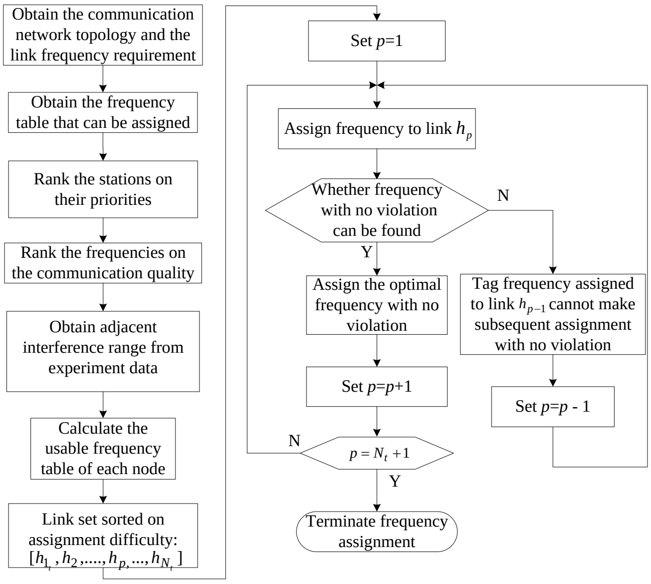

Fig. 2. Procedure of improved assignment algorithm based on sequential coloring.

Therefore, in our method hybrid assignment algorithm based on genetic and simulated annealing algorithm will be adopted when there are plenty of stations, and in the initial condition the station priority and the frequency quality constraints are thought over instead of producing initial assignment scheme randomly. The basic procedure is as follows.

1) Suppose the population scale be M, for the given N stations in the network, produce M assignment schema in the assigned frequency or frequency group in a way that priority constraints are satisfied, i.e. produce one original population v_1', v_2', …, v_M', in which the length of each chromosome is N.
2) 2) Calculate the goal function value of each member in the original population, and set the original temperature T_0=−(f_b−f_w)/lnp_r according to the original temperature formula, in which f_b and f_w are goal function values of the best and the worst members in the population respectively, and usually set p_r =0.1.
3) Calculate the adaptability value of each member in the population $e_k = \sum_{j=1}^{N} P_{kj},\ k = 1,...,M$, i.e. the total interference power of member k, and calculate the selecting probability $p_k = e_k / \sum_{j=1}^{M} e_j$ and the cumulating probability $q_k = \sum_{j=1}^{k} p_j,\ k = 1,...,M$.
4) Select M members to make up of a new population in a way as follows. Produce a random number r in interval [o, 1]. If $r \le q_1$, select the first member v_1, else if $q_{k-1} < r \le q_k$, $2 \le k \le M$, select the k th member v_k.
5) Execute intercrossing operation and simulated annealing operation to population v_1', v_2', …, v_M' with random intercrossing probability. Suppose v_1', v_2' produce offspring v_1'', v_2'' after intercrossing, calculate the goal function $f(v_i')$, $f(v_i'')$ of v_i'', v_i'', i=1, 2. If $f(v_i'') \le f(v_i')$, replace v_i' with v_i'', else accept v_i'' with the probability of min｛1, exp(−($f(v_i'')$—$f(v_i')$)/t)｝, and produce a new population.
6) Execute aberrance operation and simulated annealing operation to population v_1', v_2', …, v_M' with random aberrance probability, and the simulated annealing process is the same with 5).
7) Select M members with the most adaptability values in the offspring and the father after intercrossing and aberrance to make up of a new population, and replace the worst members with the best members in the new population.
8) If the current evolution generation is less than the most evolution generation, carry out the control of lowering the temperature. Set the annealing temperature t=T_0(α^g), in which g is the current evolution generation and α is the coefficient of temperature reduction. Here let α =0.95 experientially, and go to 3) to go on iterating genetic operating next time. Otherwise terminate the algorithm and return the current optimal solution which is the final frequency assignment scheme.

V. Conclusion

In this article we studied the restrictive conditions for same frequency, adjacent frequency, intermodulation and harmonic interference, and then acquired the relations between distance of stations on the same spot and interference-free frequency interval by experiments. We put the experiment result and the priority limit conditions into the improved frequency assignment algorithm based on hybrid pattern with sequential graph coloring algorithm and genetic and simulated annealing algorithm. We designed a kind of frequency assignment software based on this algorithm, and some users fed back that in their applications this algorithm can improve the quality of the communication links obviously.

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