Frequency Planning for Slow Frequency Hopping System

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Keywords: SFH radio system, frequency planning, local search, degradation control.

Introduction

Radio resources planning for frequency hopping military systems is very complex task due to the size of considered deployments, the radio resource limitations and the complexity of the radio phenomena to take into account[1]. In this paper, we present some aspects of the local search algorithm proposed to deal with this problem. We focus more specially on the developed degradation control mechanisms, which plays very important role in view of the perturbed nature of the objective function.

The paper is organized as follows. In section 2, we give a description of frequency assignment problem in slow frequency hopping military system. Then in section 3 we present the adopted method and we detail the tested degradation control methods. Section 4 presents a comparative study of results followed by a conclusion at the last section.

Frequency allocation for military radio-communication system

Radio systems for military deployment [4] are composed of different unities representing different decision and commandment networks such as artillery, infantry... Each network corresponds to a set of radio stations carried on special vehicles. To each network is associated a frequency plan corresponding to a subset of usable frequencies. Stations belonging to a given network communicate using only these frequencies according to frequency hopping scheme. More precisely, communication is transmitted as a sequence of bursts carried on the frequencies belonging to the network's frequency plan. A schematic example of military system is given in *Fig 1*.

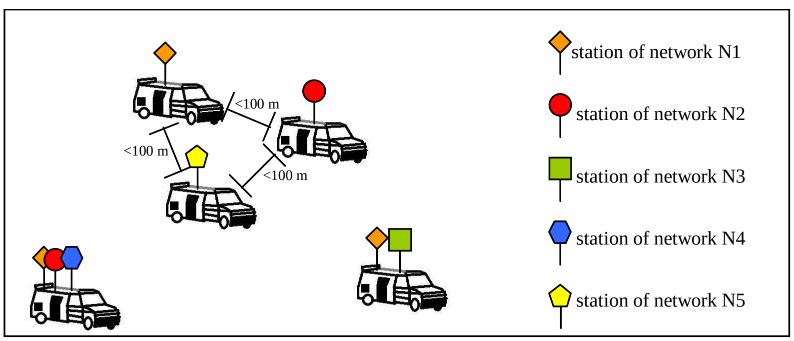

Fig 1. Military radio system architecture

A. Radio resources

The radio spectrum is composed of 2000 frequencies numerated from 0 to 1999. To each network is associated a subset of frequencies called domain corresponding to the set of frequencies available for this network. A valid frequency plan is organized into 1 to 10 sub-bands belonging to network's domain. A sub-band is a comb defined by three characteristics: a left frequency, a right frequency and a step (1, 2 or 4). To illustrate this notion let, SB, a sub-band with SB=[f_{min}, f_{max}, s]. SB corresponds then to the set of frequencies $\{f_{min}, f_{min}+s, f_{min}+2\times s, \ldots, f_{min}+k\times s\}$ where $f_{min}+k\times s \le f_{max}$ and $f_{min}+(k+1)\times s > f_{max}$. Therefore one of

[1] This work is supported by the Centre d'ELectronique de l'Armement\Délégation Générale de l'Armement

the difficult aspects of the frequency planning problem in military system is the respect of network's domains. In fact, the domains definition shows very diversified situations as presented in Fig 2 and complicate the aligning task of sub-bands into network's domain.

B. Interference constraints

The frequencies to use by each network are submitted to some constraints related to interference phenomena. These constraints express the radio perturbation due to proximity relations between radio stations. We distinguish three kinds of interference constraints:

- *Tri-station interference constraint*, which is associated to each vehicle comporting three stations. Networks associated to these stations are said connected by a tri-station link.
- *Bi-station interference constraint* corresponding to vehicles comporting two stations. Networks associated with the two stations are said connected by a bi-station link.
- *Co-site interference constraint* represents stations situated at most at 100 m one from the other. In the case where several stations (more than two) are present in the same area, the constraint is converted into pairs of co-site links.

Interferences are then modeled by pairs or triplets of networks respectively representing co-site/bi-station and tri-station links. Fig 1 depicts a deployment composed of five vehicles. The first vehicle supports three stations belonging to N1, N2 and N4 networks. The second vehicle supports two stations belonging to N1 and N3. Finally three mono-station vehicles are present into the same area and belong to N2, N1 and N5. The interferences are then modeled by the following links: TRI(N1,N2,N4); TRI(N2,N1,N4); TRI(N4,N1,N2); BI(N1,N3); BI(N3,N1); CO(N1,N2); CO(N2,N1); CO(N1,N5); CO(N5,N1); CO(N2,N5); CO(N5,N2). We denote by *L* the set of links that composes the problem. Each link is expressed as TYPE(N,I1[,I2]) expression, where [] means that the element is optional and TYPE can be either TRI, BI or CO according to the nature of the constraint. The first argument corresponds to the receptor network and the second (and eventually the third) is considered as the interferer network.

The quality of network's frequency plan is calculated as the worst interference rate undergone by the network over all links where it appears as receptor. More formally, network radio quality is calculated following the expression given here:

$$BER(N) = \underset{l=TYPE(N,I_1,[I_2])\in L}{Max}\left(BER_{TYPE}\left(FP_N, FP_{I_1}\left[, FP_{I_2}\right]\right)\right) \text{ where } FP_T \text{ is the frequency plan of } T \quad (1)$$

$BER_{TYPE}\left(FP_N, FP_{I_1}\left[, FP_{I_2}\right]\right)$ represents the *Binary Error Rate* provoked by FP_{I_1} and FP_{I_2} on FP_N. It is computed using the following formula corresponding to the average interference caused by a pair of frequencies of FP_{I_1} and FP_{I_2} on a given frequency of FP_N :

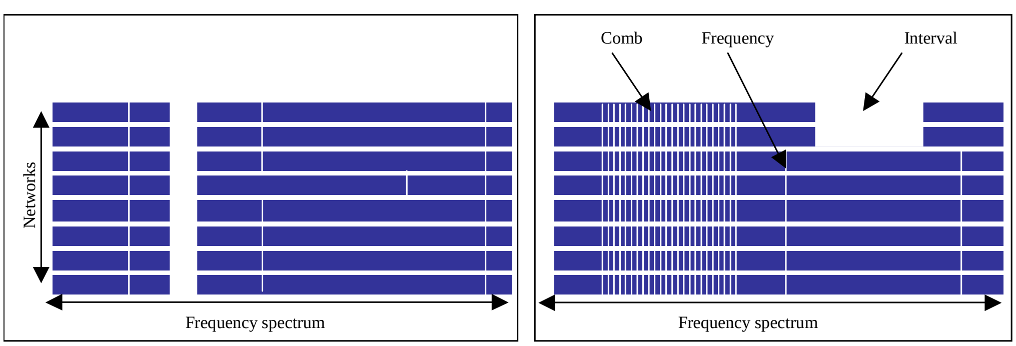

Fig 2. Examples of network's domain. White spaces designate the forbidden frequencies. Authorized frequencies could be expressed either by a set of forbidden frequencies, by a forbidden frequency combs, by a forbidden interval or a combination of these different shapes.

$$BER_{TYPE}\left(FP_N, FP_{I_1}\left[, FP_{I_2}\right]\right) = \frac{1}{\left|FP_N\right| \times \left|FP_{I_1}\right| \left[\times \left|FP_{I_2}\right|\right]} \sum_{\substack{f_N \in FP_N \\ f_{I_1} \in FP_{I_1} \\ \left[f_{I_2} \in FP_{I_2}\right]}} BER_{TYPE}\left(f_N, f_{I_1}\left[, f_{I_2}\right]\right) \tag{2}$$

$BER_{TYPE}\left(f_N, f_{I_1}\left[, f_{I_2}\right]\right)$ corresponds to the interference level provoked by the frequencies f_{I_1} and eventually f_{I_2} on the frequency f_N where f_N is used by the network *N* (receptor) and f_{I_1} and f_{I_2} frequencies are used by networks I_1 and I_2. $BER_{TYPE}\left(f_N, f_{I_1}\left[, f_{I_2}\right]\right)$ values also named elementary *BER* are given by pre-calculated data

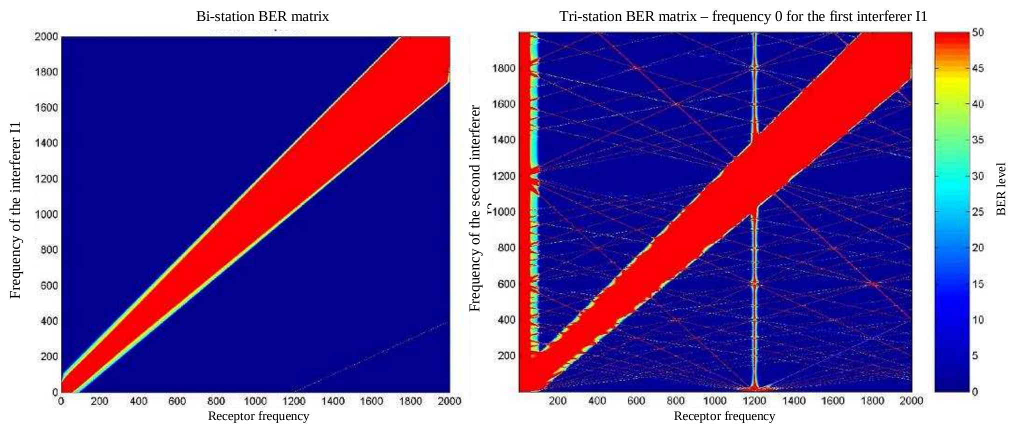

Fig 3. BER elementary matrices. Notice that when the interferer and receptor frequencies are equals, BER reaches the higher level.

matrices. In Fig 3, we give the shape of the bi-station and tri-station *BER* matrices.

The radio quality required for each network is expressed by a *BER* quality threshold denoted by ε_N. The *BER* level of the network *N* should not exceed this value or at least minimize the surplus.

C. Frequency reusing constraints

In addition to interference constraints, the radio quality of the deployment is measured in term of frequency reusing criteria. The first criterion refers to the respect of the minimum size threshold g_N of each network, *N*. The size of a network's frequency plan corresponds to the number of frequencies belonging to the plan. Secondly, the radio quality of frequency plans is measured according to the size of the shortest frequency plan over all networks (number of frequencies contained in the sub-bands composing the plan). The objective is then to maximize the size of shortest frequency plan in the deployment. Finally, the radio quality is measured by the weighted sum of frequency plans size. Weights correspond to the hierarchy level of each network h_N into the deployment, which represents the importance level of a given network.

To summarize, the frequency planning in military radio system consists in associating a frequency plan of 1 to 10 sub-bands to each network in the deployment in such manner to respect network's domain, to minimize interference and to maximize radio diversity (frequency reuse). These objectives are combined in a single objective function given as follow:

$$\begin{aligned} F = {} & \alpha \times \max_N \left(BER(N) - \varepsilon_N\right)^+ + \alpha' \times \sum_N h_N \left(BER(N) - \varepsilon_N\right)^+ + \delta \times \left|\left\{\Lambda\left(FP_N\right) < g_N\right\}\right| \\ & - \left(\gamma \times \min_N\left(\Lambda\left(FP_N\right)\right) + \gamma' \times \sum_N h_r \times \Lambda\left(FP_N\right)\right) \end{aligned} \tag{3}$$

Adaptive local search

Frequency planning in military radio system is a very complex task due to the combinatorial complexity of the problem, the noised nature of objective function and finally to the time-consuming evaluation. For these reasons, heuristic approaches appear to be the most adequate. In this case, an initial solution corresponding to a set of frequency plans (one per network) is conceived. An iterative process is then started, in which the current solution is changed each time by modifying a sub-band of one frequency plan. The noised nature of the objective function makes it difficult to identify a priori the best move, or to predict the exact impact of a change on the solution quality before real re-evaluation (objective function computing). We turned toward the use of a local search method based on a partial neighborhood exploration [3]. The main characteristics of the method reside in two points: an intelligent neighborhood extension/restriction mechanism and a powerful degradation control procedure.

A. Neighborhood extension/restriction mechanism

Two neighborhood structures are considered corresponding to two restriction levels. The first neighborhood structure, NG_1, consists in all solutions accessible by changing a sub-band of a conflicting network. A network, *N*, is said conflicting if it does not respect the ε_N quality threshold or the g_N minimum size of the frequency plan. The second neighborhood structure, NG_2, corresponds to the set of all networks. At each iteration, a conflicting network is chosen, and a sub-band of its frequency plan is modified. By opposition, when a loop is detected, the deterministic choice (among NG_1) is replaced by the selection of any network during the next iteration. This mechanism is called *neighborhood extension*. More precisely, a loop is detected when a given network is frequently selected during the *n* last iterations.

Although the extension mechanism allows diversification of the search choices, it does not offer any way to avoid that the randomly selected network be different from the source of loop detection or its selection during the next deterministic choices. Restriction mechanism based on tabu list structure consists to record networks causing loops during a given number of iterations called tabu tenure. Recorded networks are excluded from choice during this period. The synergy between these two mechanisms is analyzed in [1][2].

B. Degradation control mechanism

Noised nature of the objective function makes it necessary the adoption of a degradation control mechanism. In fact, experiments have shown that some moves can cause a very great degradation of the solution quality. Fig 4 shows objective function variation when no degradation control is made. We observe first a lot of brusque and great degradations. After each degradation, search needs lot off iterations to return to a similar quality level. By degradation control, we refer to every procedure that establishes conditions for degradation acceptation. Generally, those conditions are made on the basis of degradation amplitude, degradation frequency or the combination of the two kinds of control.

We describe hereafter some of tested techniques for degradation control:

- *Controlling the number of degradations*, implemented by a probability, $P=1/n$, of acceptance of each degradation or by a systematic acceptance of one degradation after each *n* encountered ones.

- *Controlling the amplitude of degradations*, in addition to reducing the number of accepted degradations this technique fixes a degradation threshold, *C*, corresponding to maximum tolerated degradation between the previous (or best solution) and current solution. When the degradation is below this threshold, it is accepted according to a given probability as in the first method.

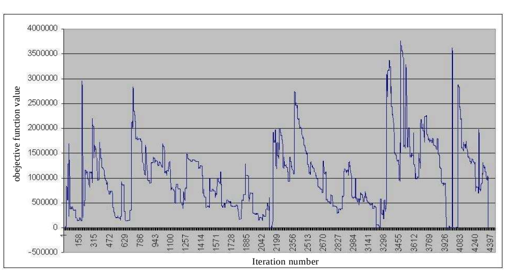

Fig 4. Objective function variation during local search iterations when no degradation control is made

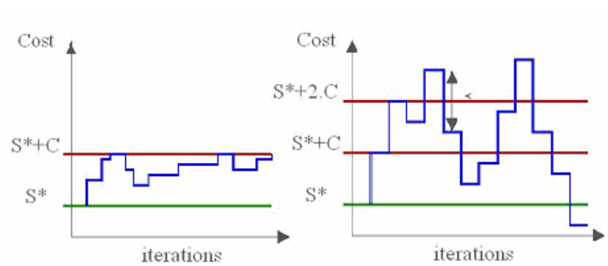

Fig 5. Left side: degradation control according to the best solution (*S) evaluation. Right side: degradation control based on precedent solution evaluation.**

Measuring the degradation amplitude compared to the best solution evaluation involves a great limitation for search exploration since cumulative degradations is forbidden as shown at left of Fig 5. By opposition, degradation measurement according to previous solution allows cumulative degradations but prevents, at the same time, from brusque variations as shown at right of Fig 5.

- *Time-varying degradation threshold,* in this case the degradation threshold (parameter C) is decreased during the search to allow more search intensification at the end of the search. Three time-varying functions were tested: A linear function represented by the expression $C_T = C_{\max} - (C_{\max} - C_{\min}) \times T$; a cubic function $C_T = C_{\max} - (C_{\max} - C_{\min}) \times T^3$ and finally a square function $C_T = C_{\max} - (C_{\max} - C_{\min}) \times \sqrt[3]{T}$. C_T represents the degradation threshold at a given instant and belongs to the interval $[C_{min}, C_{max}]$. T represents the current spent time of the search compared to the total time accorded to the run. T is equal to 0 at the beginning of search and 1 at the end.

- *Amplitude based acceptance probability:* we have tested acceptance probability variation in function of degradation amplitude. In this case, after a degrading iteration, degradation amplitude is measured and acceptation probability is attributed to the new solution. This probability is calculated in such manner that bigger is the degradation, lower is the probability to accept the new solution. We studied two kind of degradation amplitude based probability: linear function $p(x) = a \times x + b$ and exponential function $p(x) = a \times \exp(-x/b)$, where x represents the degradation amplitude.

- *Partial neighborhood exploration:* by partial exploration we mean that a sub-set of current solution neighbors are visited at each iteration. The acceptance of a given neighbor is made at the light not only of the quality of the concerned solution but also according to the other visited neighbors. We tested two kinds of partial exploration approaches. In the first case, we choose the best solution among *n* neighbors (denoted by VP_*n*). In the second approach, we choose randomly among the *n-d* best neighbors (denoted by method VP_*n_d*). In other words, we eliminate the *d* worst solutions and we select a solution among the remainder neighbors.

Experimental results

In this section, we present performed tests on CELAR's private benchmark instances. The benchmark is composed of 10 instances representing different sizes and complexity levels. We expose in Table 1 the impact of each degradation control procedure on 6 instances. The table values correspond to the fitness evaluation of the best solution find by each method. We observe first the clear results improvement for methods with degradation control mechanism. Every method provides some interesting results stressed in bold. However, there is no method that outperforms all the others, according to all instances. This observation can be explained by the sensibility of the method toward the parameter settings. In other words, the difference between the 6 tested instances make difficult to find a parameter value that fit all the situations. An example is the method VP_*n* presented in the seventh line of Table 1. We observe that the aggressive intensification performed by this method is not adapted to the second instance whereas that gives a good result for the instance 5. In the same manner, an exploration based method as the second method (third line), gives very good results for instances like 3 and 4 but presents the worst solutions for instance 5.

Method description	Parameters	SC1	SC2	SC3	SC4	SC5	SC10
Without degradation control		-10525	-23459	14e+06	-462548	-175919	24e+06
Controlling the number of degradations	*P*=1%	-39 397	-98 422	**-935 907**	**-2,48e+06**	-377 634	20e+06
Controlling the amplitude + the number of degradations	P=1%, C=30000	-40836	**-114368**	-863194	-2,31e+06	-466370	19e+06
Amplitude based acceptance – Exponential function	a=e/100, b=35 000	-39466	**-114368**	-620653	-2,40e+06	-458365	**6,9e+06**
Amplitude based acceptance – Linear function	b=e/100, a=-b/100000	**-41563**	-112969	-882070	-2,45e+06	-402937	13,6e+06
Partial neighborhood exploration – VP_*n*	VP10	-22952	-20284	-496308	-1,89e+06	**-476718**	25,4e+06
Partial neighborhood exploration – VP_*n_d*	VP10-2	-39238	-37996	-927408	-2,00e+06	-375661	18,6e+06

Table 1. Results of degradation control procedures on private CELAR's instances

In Table 2, we give results obtained by controlling the number and the amplitude of degradations (fourth line in Table 1) on CELAR's public instances [5]. The benchmark is composed of 10 instances with a number of networks varying from 10 to 400 and number of links about 500 to 30000. We give for each instance the execution time specified by the input data.

Public scenarios	**SC1**	**SC2**	**SC3**	**SC4**	**SC5**	**SC6**	**SC7**	**SC8**	**SC9**	**SC10**
Execution time (h)	0.5	0.5	1	1	1	1	1	1	1	1
Control the number and the amplitude of degradations	-14140	-1625	-12986	-32115	-8605	147315	-436779	-718703	694630	-6382

Table 2. Local search results on public CELAR's benchmark

Conclusion

In this paper, we have proposed a local search algorithm for the frequency planning problem in slow frequency hopping military systems. The problem is characterized by a great combinatorial complexity and a large neighborhood size, making impossible the complete exploration method like classical tabu search. Due to the perturbed nature of the objective function, the performance of the algorithm is very sensitive to the degradation control mechanism. We exposed here several implemented and tested procedures. These mechanisms showed a great sensitivity again the parameter setting.

As continuity of this work, we study different adaptive mechanisms, which aim to develop a free-parameter degradation control procedure. The objective is then to dynamically adapt the value of the parameters *C*, *P*, *a*, *b* according to the instance properties and search evolution.

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