Adaptive Local Search for a New Military Frequency Hopping Planning Problem

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Abstract. The military radio stations with frequency hopping propose new problems of frequency assignment which must take into account the size of the deployment, the limited resources and also new interferences constraints on transmitters. This new problem is public since the publication [1] with a set of 10 instances. The computing resources and the computing times are imposed. We tackle this problem with a method based on adaptive local search coming from the graph-coloring which manages phases of intensive research and diversified research. We developed several alternatives that are tested and compared on the scenarios.

1 Introduction

The problem of frequency assignment for the radiocommunication systems with frequency hopping is a new problem exposed in 2006 [1]. Communications must be transmitted between various groups of vehicles transporting transmitter-receiver "stations". These stations are gathered in networks and are connected by the same frequency channel. The quality of the communications depends on the various situations of interferences produced by the stations. We distinguish the "Co-vehicle" electromagnetic disturbances that come from the presence of several stations on the same vehicle ("biposte" or "triposte" disturbance for two or three transmitter-receivers on the same vehicle) and the "Co-site" disturbances generated by the presence of two close stations (for example distant of less than 100 meters). These disturbances require establishing an electromagnetic constraint of compatibility between the frequencies allocated to the networks to which the stations belong in order to avoid jamming. Of a problem made up of vehicles, stations and networks, one builds a problem of optimization made up of Co-vehicle and Co-site constraints between the networks for which it is required to assign frequencies by minimizing a function of interference.

The characteristic of this system is that the stations emit with "Frequency Hopping" (FH) using sub-bands of frequency. A communication in FH is not transmitted on only one frequency but on a list of frequency called "Frequency Plan" (FP). Each frequency is used for very a short period and during a communication the whole of the frequencies of the list is used [2]. Because of assignment of a list of frequencies to each network, compared to a problem with fixed

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frequency the problem combinatory is strongly amplified. In addition, the interferences between two networks are not expressed any more in term of difference between frequencies as in the systems at fixed frequencies, but they are the result of the whole of the frequencies used by each network. Thus, one will not define the quality of the communications by the respect of separation constraints between frequencies but by a binary level of error (noted BER for *Bit Error Rate*) which results from the number of common frequencies between the lists allotted to the networks belonging to the same disturbance. Then the level of interference on each network should not exceed a maximum threshold expressed in BER.

Because of the recent publication of this problem, only [1] made state of 3 methods applied to this new problem on private scenarios (CN-Tabu, simulated annealing and our method). We thus present the first work on the scenarios made public in 2006. In the literature there exist problems which approach it: the assignment of frequencies [3, 4] and more generally the set-T-coloring. This last problem is defined as follows: given an undirected graph $G = (V, E)$ and B a whole of needs with $B = \{b_1, \ldots, b_N | \, b_i \in \mathbb{N}\}$ corresponding to the respective needs for each node x_i, the problem is to allocate a whole of b_i colors $c(x_i) = \{c_{i,1}, \ldots, c_{i,b_i}\}$ to each node x_i while respecting the constraints inside nodes: $\forall c_{i,m}, c_{i,n} \in c(x_i), m \neq n, |c_{i,m} - c_{i,n}| \notin T_{i,i}$, and the constraints between adjacent nodes: $\forall (x_i, x_j) \in E, \forall c_{i,m} \in c(x_i), \forall c_{j,n} \in c(x_j), |c_{i,m} - c_{j,n}| \notin T_{i,j}$. The problems of set-T-coloring were very largely studied in the literature [5, 6], however they do not cover the topics of organizing the colors in sub-sets and maximizing the set size per node as it is in our problem. Looking at frequency assignment problems for other communication systems (cf. http://fap.zib.de), they often are particular cases of the graph-coloring problem [3, 8]. The differences between the problems of frequency assignment are related to the various radio systems. Only the GSM system, world standard of mobile telephony, is also equipped with the frequency hopping. Unfortunately the complexity of the management of the jump makes that there is few literature on its optimization. The majority of the publications on the frequency assignment relates to the cases without hops with methods based on population of solutions [9, 10, 11], on local search [12] as Taboo Search [13, 14, 15] or constraints programming [16, 17, 18]. [19] dealt with optimization breaking up the problem into two parts: the generation of lists of frequencies per station then the modification of these lists with a simulated annealing. But the generated interferences are calculated according to the difference between the frequencies as in a problem without hops and the lists to be allocated are not structured in sub-bands.

The state of the art on the problem we deal with is thus very thin. Major specificities of this problem are the evaluation of the FP that needs a simulator to compute the BER and the concept of sub-bands which structure the frequency sets. The benchmarks combinatory is huge ($10^{28\,400}$ for a scenario with 400 networks) and the computing resources and the computing times are imposed (P-IV with 30mn or 60mn by scenario). Our work was thus guided by the adaptation of a local search method resulting from graph-coloring to profit from experiment on a theoretical problem, requiring few resources, able to provide complete solutions and rather robust. A local search method with an adaptive mechanism for diversification and intensification phases is developed for this problem. Firstly, the formulation of the problem is described in section 2. In section 3, we present the adaptive local search method. Then, in section 4 the results on public scenarios allow to compare various alternative methodologies.

2 Problem Formalization

2.1 Constraints to Satisfy

The problem constraints can be gathered in three sets: constraints related to the networks, constraints on the frequency plan and those related to interference.

Constraints linked to the networks. There are two types of networks: networks whose FP are already allocated, noted R^{hc}, and cannot be modified, and networks whose FP must be allocated, noted R^c. Each network $r \in R = R^c \bigcup R^{hc}$ is defined by: an hierarchical level h_r representing its level of priority; the minimal size NF_r^{min} of the FP to be allocated to this network knowing that the size of a FP is the number of frequencies it uses; the maximum threshold of BER of the network, noted BER_r^{max}, which defines the maximum binary error rate authorized for the network r; and a domain of resource D_r, defining the set of frequencies available for this network. The domains are various: set of contiguous frequencies, combs of frequencies, isolated frequencies...

Constraints linked to the frequency plans. The frequency planning consists in allocating to each network the list of frequencies forming the FP. The FP is a whole of frequencies structured in intervals called "sub-bands". A plan gathers a maximum number SB_{max} of sub-bands. A sub-band sb is made up of the frequencies of an interval $[f_{min}; f_{max}]$ sampled with the step δ_f and f_{min} as initial frequency. The sub-bands of the same FP cannot overlap and their number is limited. The FP pdf_r of the network r is defined by:

$$\begin{cases} pdf_r \in \mathcal{P}(S) \text{ such that } \forall sb \in pdf_r\,, sb \subset D_r \\ \forall (sb_1,\, sb_2) \in pdf_r^2,\, (max(sb_1) < min(sb_2)) \text{ or } (max(sb_2) < min(sb_1)) \\ |pdf_r|_{sb} \leq SB_{max} \text{ and } |pdf_r|_f \geq NF_r^{min} \end{cases} \quad (1)$$

with $r \in R$ one network and pdf_r the frequency plan of the network r; S, the set of sub-bands sb and $\mathcal{P}(S)$ the set of parts of S; $min(sb)$, $max(sb)$ the initial and final frequencies of sub-band sb; $|pdf_r|_{sb}$ the number of sub-bands of the frequency plan pdf_r; $|pdf_r|_f$ the number of frequencies of the frequency plan pdf_r of the network r; NF_r^{min} the minimum number of frequency the network r must have. Within the framework of the public problems we treated, the maximum number of sub-bands SB_{max} is fixed at 10, the step of a sub-band δ_f can take three values (1, 2 and 4) and the whole of the domains associated with the various networks is included in the global domain, noted D_g, of 2000 frequencies.

Constraints linked to interferences. The level of interference between several FP is calculated starting from the elementary values of interference between the frequencies of each plan. Then the binary error rate of one network will be the maximum value of BER of the network as a receiver for all the disturbances which it undergoes. To identify the scramblers, we define as a link the set of stations of various networks that disturb each other in saturated traffic condition (each transmitter is transmitting). The reference value of BER for each network is then the worst case among its whole links. The level of interference of one network, noted $BER^c(R)$, is thus:

$$BER^c(r) = \max_{l(r_r;r_{b1}[,r_{b2}])\in L} \left(BER_l\left(pdf_{r_r};pdf_{r_{b1}}[,pdf_{r_{b2}}]\right)\right) \quad (2)$$

with $BER_l(pdf_{r_r};pdf_{r_{b1}}[,pdf_{r_{b2}}])$, the BER of the link having pdf_{r_r} as receiver and disturbed by $pdf_{r_{b1}}$ and $pdf_{r_{b2}}$. It is calculated by the sum of the elementary BER generated by each triplet of frequencies, balanced by the product of the sizes of all FP. It is thus an average BER. For each network r, BER_r^{max} defines the level of radio quality to respect. The radio quality level $BER^c(R)$ of the network r should not exceed the value threshold BER_r^{max}, then:

$$\forall r \in R, BER^c(r) \leq BER_r^{max} \quad (3)$$

2.2 Objectives to Optimize

The fitness function uses two types of information to estimate the quality of the solutions: interferences and the frequency reuse.

The interferences. The first problem to deal with consists in minimizing the interferences resulting from all FP. It includes two objectives: to minimize the greatest difference between the BER of a network and the BER value threshold; and to minimize the sum of these differences for all the networks balanced by their hierarchy. These two objectives are aggregate in a function using two weights α and α' that are given input data for each scenario. Thus the function which includes the criteria of interferences is formulated by:

$$\begin{aligned} F_{BER}(S) = \alpha \times \max_{r\in R}\left(BER^c(r) - BER_r^{max}\right)^+ \\ + \alpha^{'} \times \sum_{r\in R}\left(h_r \times \left(BER^c(r) - BER_r^{max}\right)^+\right) \end{aligned} \quad (4)$$

The frequency reuse. In addition to the measurement of the interferences, the solution quality is also measured by the frequency reuse ratio. FP of big size are favored via three weighted criteria (β, γ and γ' are given input data for each scenario).

1. Minimal size of FP: the objective is to minimize the number of networks, defined by $F_{size}(S)$, whose FP does not respect the imposed minimal number of frequency used.

$$F_{size}(S) = \beta \times \left|\{\forall r \in R,\ |pdf_r|_f < NF_r^{min}\}\right| \quad (5)$$

2. Size of the smallest FP: the objective is to maximize the size of the smallest FP defined by the function $F_{min}(S)$.

$$F_{min}(S) = \gamma \times \min_{r \in R}(|pdf_r|_f) \quad (6)$$

3. The frequency reuse rate: the objective is to maximize the balanced sum of the sizes of all the FP defined by the function $F_{sum}(S)$. The hierarchy of the networks h_r is taken into account.

$$F_{sum}(S) = \gamma' \times \sum_{r \in R} (h_r \times |pdf_r|_f) \quad (7)$$

The fitness. Finally the assignment of FP in frequency hopping consists in assigning a list of frequency to each network of the deployment by respecting the constraints of a maximum number of sub-bands SB_{max} and non-covering of the sub-bands of the same FP; on the one hand by minimizing the interference between the FP $F_{BER}(S)$ and the number of networks having a too small FP $F_{size}(S)$; and in addition by maximizing the size of the smallest FP $F_{min}(S)$ and the frequency reuse rate $F_{sum}(S)$. The fitness function to minimize is:

$$F(S) = F_{BER}(S) + F_{size}(S) - (F_{min}(S) + F_{sum}(S)) \quad (8)$$

NB: This function does not have physical reality; a multi-objective approach would be more suitable but is not on the current specifications of the problem.

3 Adaptive Local Search

The scanty means imposed in the benchmark, the complexity of the problem and the combinatory of the scenarios do not make it possible to use an exact method or a population based method as starting algorithm even if they could be relevant in the further study. The local search having proven its reliability in set-T-coloring, we defined a local search method with neighborhood extension and restriction control. It is based on two complementary mechanisms: a detection of loop and a Taboo list which are employed respectively to extend and restrict the neighborhood of the current solution. The mechanism of loop detection uses a history of research in order to diversify this one by extending the set of the candidate neighborhood solutions in case of search blocking. The Taboo list limits the set of the candidate neighborhood solutions of the current solution to prevent repetitive choices of variables at the next iterations. In both cases, one iteration is defined by successive operations whose finality is to modify the list of frequency which constitutes the FP of a network: the choice of the network; the choice of the sub-band; and the choice of the modification to apply to the sub-band.

The mechanisms of loop detection and Taboo list are only applied to the network choice. The choices of the sub-band, randomized, and on the frequencies, the best ones, do not depend on these two mechanisms. The neighborhood that we used issues from graph-coloring [7]. It is the neighborhood based on the graph nodes (here the networks) which modifies the colors (here the frequencies) of the nodes in conflict (here the networks whose at least one constraint is unsatisfied). This structure is the most used in literature of graph-coloring. The extension or the restriction of the lists of candidate neighbors will act on the selection of the networks among the more in conflict, all those in conflict or those without conflict. The motivations and the principles are explained hereafter.

Network weighting. In order to select the network to be modified, a weight function $P_c(R)$ is employed for each network r estimating the quality of the associated FP. This weight shows the influence of each FP on the evaluation of the total solution according to the level of BER reached by the network and its deficit in frequencies compared to the required minimal width. The formula (9) used to define this weight takes into account the parameters of the fitness function of the solution according to the notations defined previously.

$$\begin{aligned} P_c(r) = h_r \times \Big(&\alpha' \times (BER^c(r) - BER_r^{max})^+ \\ &+ \beta \times (NF_r^{min} - |pdf_r|_f)^+ \\ &+ \gamma' \times |pdf_r|_f\Big) \end{aligned} \tag{9}$$

Restriction of candidate networks with Taboo list. Initially, we defined a local search based on the modification of the FP of worse quality. This first method was used with and without Taboo list on the choice of the network. The network of the most important weight is selected. In the event of equality, the network is randomly selected among the networks of the most important weight. This *deterministic* choice of the network is carried out with each iteration. However, the purely deterministic character may involve premature convergence towards a local optimum. The option with Taboo list forces the algorithm to choose the network not taboo of the most important weight. The selected network becomes taboo for one T duration randomly taken in the interval DT defined in equation (10) as for a dynamic Taboo list [6].

$$T = rand(DT) \text{ with } DT = \left[0.5 \times \frac{\sqrt{|R|}}{2}; 1.5 \times \frac{\sqrt{|R|}}{2}\right] \tag{10}$$

Extension of candidate networks with loop detection. Up to now, we have a local search algorithm without or with Taboo list according to a model very frequently used in literature: the algorithm works on the variables which contribute more to the degradation of the solution performance. A second method based on diversification in the choice of the network is added by the use of a mechanism of loop detection. The objective of the loop detection is to detect the occurrences of choice of networks during the iterations. It is based on the list of the last visited networks that represents a temporal window updated after each iteration. The observation of the repetition of the choice of a network is characteristic of a blocking of research in spite of the taboo status of certain variables.

The loop detection allows the method to react by modifying the behavior of the local search during research. The choice of the network will not be made any more in a *deterministic* way according to the higher weight but in a *diversifying* way by a random choice among the set of networks not taboos of non null weight. The parameters of the loop detection are identical to those applied in graph-coloring [20]. When the number of visits of a network r is higher than a value threshold representing a number of authorized occurrences $nbOcc$ during the m last iterations, then a loop of repetition is detected and one iteration of *diversifying* type is carried out. The memory size m of the last iterations observed is defined according to the number of variables of the problem. Here, the full number of networks (target and out-targets) of the problem is used, $m = \frac{|R|}{2}$. The number of authorized occurrences $nbOcc$ is defined by a percentage of the memory size fixed empirically at 5%: $nbOcc = 0.05 \times m$.

The method and its variants. The general operation of the method is the following. At each iteration the loop detection is evaluated: for each variable there is a checking of the number of occurrence compared to the threshold. Two types of iterations can then be used; they differ by the selection of the network to modify. If the algorithm does not turn round (the occurrences are lower than the threshold), a deterministic iteration is applied: the choice of network of the highest weight is selected. If the algorithm turns round (the occurrences are higher than the threshold for at least a variable), a diversifying iteration is applied: the network is randomly selected among all. The method is known as adaptive since it dynamically adapts the list of the candidate neighbors according to the state of research. If we combine the Taboo list principle with this general operation, only the networks not taboos can be selected whatever the type of iteration. With the Taboo list, two options are considered for the management of the taboo status: all the selected networks become taboos or only the networks detected in loop become taboos. To summarize, we thus have five concurrent methods tested in the following section to manage the iterative process: deterministic local search based on the networks weight; local search with Taboo list; local search with detection of loop; and local search with combination of loop detection and Taboo list of all the nodes or only nodes in loop.

4 Results and Analysis on Public Scenarios

This section compares the five methods of local search. All the methods have the same global architecture but differ by the management of the variable access. First of all the table 1 presents the evaluation of the best solutions obtained on only one run for the 10 public scenarios. The first two methods in column do not use a mechanism of loop detection; they are methods based on the use of iterations of the local search driven by the resolution of conflicts. The selected network is always that of higher weight (deterministic step). The difference between the two methods rests on the use or not of a Taboo list defined dynamically according to equation (10). The three other methods are based on the mechanism of loop detection with the combination of determinist and diversifying methods: without Taboo list on the networks (4th column), with a Taboo list on all the networks having started a loop (5th column) and with a Taboo list on all the visited networks (6th column).

Table 1. Comparison of five local search algorithms

problems	higher conflict		loop detection		
	without	with	without	with taboo	
	taboo	taboo	taboo	networks in loop	all networks
PUB01	-10 426	-10 827	-13 764	**-13 892**	-12 111
PUB02	-928	-961	-1 353	-1 436	**-1 447**
PUB03	-8 110	-9 516	-13 932	-13 952	**-14 574**
PUB04	-15 843	-17 515	**-27 866**	-27 837	-27 786
PUB05	-7 309	-9 654	-10 720	**-12 144**	-10 912
PUB06	515 417	95 906	71 738	96 314	**70 360**
PUB07	-23 554	-53 777	-478 471	-476 693	**-484 297**
PUB08	-194 435	-336 741	**-887 354**	-869 292	-878 640
PUB09	1 667 459	962 109	876 409	755 753	**684 699**
PUB10	-5 672	-7 541	**-10 731**	-10 624	-10 680

A first comparison can be made between both methods without mechanism of loop detection. For all the scenarios, the addition of the dynamic Taboo list improves the preceding results; the use of medium-term diversification by restriction of the vicinity is thus effective. Then, a comparison can be made with the detection of loop. The use of loop detection without Taboo list improves considerably the results on all the scenarios. The loop detection to diversify by extension of the vicinity is thus more effective than the Taboo list. Lastly, combining the Taboo list with the loop detection improves the best results for 7 cases out of 10. The best run for each example (in fat) was obtained with one of the three methods using the loop detection mechanism.

The preceding results relate to only one run. The table 2 presents final results for all the methods with loop detection with the average scores on 5 runs. The dark cells of the table correspond to the best results. Thus, it is observed that the first method (without Taboo list) obtains the best result three times, it is classified second for two problems and last for the five others. The second method is classified first five times, second three times and last for two scenarios. The last method is the best for two cases, second for five others and three times last. All in all, on five runs the second method obtains the best performances. The adaptive combination of the deterministic and diversifying iterations done dynamically via the loop detection gave the best performances. In particular it

Table 2. Combination of loop detection and Taboo list (on 5 runs)

	loop detection		
	without	with taboo	
problems	taboo	networks in loop	all networks
PUB01	-13 981	-14 359	-14 828
PUB02	-1 538	-1 507	-1 543
PUB03	-13 466	-13 905	-13 625
PUB04	-32 485	-32 839	-32 512
PUB05	-9 669	-10 025	-9 562
PUB06	240 937	141 303	145 587
PUB07	-474 565	-474 072	-472 030
PUB08	-863 941	-828 613	-819 019
PUB09	895 716	810 793	826 828
PUB10	-10 139	-9 207	-10 017

has been better than an intensive method with Taboo list what shows than the taboo status is sometime not enough efficient to diversify the research.

5 Conclusion and Perspectives

This paper presented studies on an adaptive local search implemented for the problem of assignment of lists of frequencies for military networks of radiocommunications with frequency hopping. The assignment of lists of frequencies with frequency hopping is a new optimization problem with constraints whose objective is to allocate to each network a frequency plan which is a structured list while minimizing a fitness which incorporates several criteria. The ideal models of set-T-coloring are closest to our problem however this one has major differences: the interferences are not represented into frequency constraints spacing as in set-T-coloring but as average BER values; the frequency plan must be organized in non-overlapping sub-bands of the spectrum; and the fitness is made up of aggregate and balanced criteria which combine radio quality and plan size data. We explained the general outline of an adaptive local search method to deal with this problem. A procedure of loop detection on the networks and adaptive choice of the intensifying or diversifying local search framed it. We defined a function to weight the networks in order to classify them according to their conflict. We also carried out a version of the method with and without Taboo list to evaluate the contribution of this combination in this applicative context. The results obtained by various alternatives of the method were provided on public scenarios which are available. The adaptive method based on the combination of two local searches by the loop detection gave better scores that an intensive method with Taboo list. In addition the association of loop detection with a Taboo status on the networks detected in loop is the most powerful option. We must now develop other methods of research in collaboration with other teams for better evaluating this problem. Also a multi-objective approach would be very interesting to identify the compromise solutions independently of the weights on the criteria which are currently given as scenario inputs.

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