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Radio Link Frequency Assignment

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Abstract. The problem of radio frequency assignment is to provide communication channels from limited spectral resources whilst keeping to a minimum the interference suffered by those whishing to communicate in a given radio communication network. This problem is a combinatorial (NP-hard) optimization problem. In 1993, the CELAR (the French "Centre d'Electronique de l'Armement") built a suite of simplified versions of Radio Link Frequency Assignment Problems (RLFAP) starting from data on a real network [16]. Initially designed for assessing the performances of several Constraint Logic Programming languages, these benchmarks have been made available to the public in the framework of the European EUCLID project CALMA (Combinatorial Algorithms for Military Applications).

These problems should look very attractive to the CSP community: the problem is simple to represent, all constraints are binary and involve finite domain variables. They nevertheless have some of the flavors of real problems (including large size and several optimization criteria). This paper gives essential facts about the CELAR instances and also introduces the GRAPH instances which were generated during the CALMA project.

Keywords: Benchmarks, radio link frequency assignment, constraint satisfaction, optimization

1. Description of the problem

1.1. An informal description

When radio communication links are assigned the same or closely related frequencies, there is a potential for interference. Consider a radio communication network, defined by a set of radio links. The radio link frequency assignment problem is to assign, from limited spectral resources, a frequency to each of these links in such a way that all the links may operate together without noticeable interference. Moreover, the assignment has to comply to certain regulations and physical constraints of the transmitters. Among all such assignments, one will naturally prefer those which make good use of the available spectrum, trying to save the spectral

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resources for a later extension of the network. Furthermore, when several bands are available, and for various reasons (for example radio wave propagation, ease of deployment etc.), the lower bands are usually most favored and one should try to assign frequencies preferably from the lower bands.

In most cases, the number of available frequencies (the spectral resource) is much smaller than the number of frequencies that have to be assigned. In the CELAR problems, a maximum of 48 frequencies are available while the largest problem requires the assignment of 916 frequencies.

Finally, the problem can occur in two forms: it may be a first or *bulk assignment problem*, where all transmitter and frequencies are assigned for the first time. Or it may be an *updating assignment problem*, where a set of new transmitters have to be assigned frequencies against a background of existing transmitters, with previously assigned frequencies. In this case, one should try, as much as possible, to avoid the modification of the background situation. So, in the most complex cases, a good assignment should avoid interference as much as possible, spare resources by using as few frequencies as possible, try to use only low frequencies and it should also avoid modifying an existing assignment.

According to the type of the communication network (e.g. mobile telephone, radio relays, air-ground-air communication etc.), the precise definitions of the problem may vary. In the sequel, we formally describe the radio link frequency assignment problem as defined by the CELAR and which also form the basis of the GRAPH instances which were later generated.

1.2. Formal definition of the CELAR problems

We are given a set X of unidirectional radio links. For each link $i \in X$, a frequency f_i has to be chosen from a finite set D_i of frequencies available for the transmitter which yield unary constraints of type

$$f_i \in D_i \tag{1}$$

Depending on the type of the problem (bulk or updating problem), some links may already have a pre-assigned frequency which define unary constraints of the type

$$f_i = p_i \tag{2}$$

Binary constraints are defined on pairs of links $\{i, j\}$. These constraints may be either of type

$$|f_i - f_j| > d_{ij} \tag{3}$$

or of type

$$|f_i - f_j| = \delta_{ij} \tag{4}$$

In the first case (equation 3), the two links i and j may interfere together. One usually distinguishes among two types of interference: co-site interference when a transmitter and a receiver are at the same location (or close together) and far-site interference, which occurs between equipment separated by some distance. In the case of the CELAR data, this distinction is useless because the same type of constraints is used to model both types of interferences[1]. d_{ij} is the minimum distance which must separate the two frequencies.

In the second case (equation 4), the two links i and j define a duplex link, one link being used for the communication from a site A to B while the other is used to communicate from B to A. The distance δ_{ij} is defined by technological constraints on transmitters. In the CELAR data, all links define duplex links using link $2i-1$ and $2i$ and the value of $\delta_{2i-1,2i}$ is independent from i (and equal to 238).

Depending on the instance considered, some of the constraints may actually be *soft constraints* which may be violated at some cost. A mobility cost m_i is defined for changing pre-assigned values, defined by constraints of type 2 and an interference cost c_i is defined for violation of soft constraints of type 3. Constraints of type 1 and 4 are always hard. The complete set of constraints C is therefore partitioned in a set H of hard constraints and a set S of soft constraints.

As sketched before, the criteria are numerous. Of first importance is the satisfaction of the interference and pre-assignment constraints. When an assignment exists that satisfies all constraints (hard and soft), secondary criteria can be considered: one is usually interested in minimizing the largest frequency used and also in using as few frequencies as possible in order to spare them for future updating problems.

So, several problems can be defined:

- Feasibility (FEAS): the problem is to find an assignment of frequencies to each link such that all constraints in C (i.e., hard and soft constraints) are satisfied. The problem is not an aim in itself, just a preliminary problem before considering secondary criteria. Obviously, the feasibility version of the RLFAP is already NP-complete since by constraints of type 1 and 3, it is possible to express the k-coloring problem.

- Minimum span (SPAN): if all the constraints in C can be satisfied together, one can try to minimize the largest frequency used in the assignment. In essence, the SPAN problem should not be much harder than the FEAS problem: it can be reduced to a short sequence of FEAS problems using dichotomic search (and can simply be cast as a Possibilistic/Fuzzy CSP by adding soft unary constraints on the domain values).

- Minimum cardinality (CARD): if all the constraints in C can be satisfied together, one can try to minimize the number of different frequencies used in the assignment. The CARD problem appears to be more difficult than the SPAN problem: it is not obvious how to reduce it to a short number of FEAS problems or how to cast the global optimization criterion in one of the soft CSP frameworks [17, 3] using only small arity soft constraints.

- Maximum Feasibility (MAX): if all the constraints in C cannot be satisfied simultaneously, one should try to find an assignment that satisfies all constraints in H and that minimizes the sum of all the violation costs (interference cost or mobility cost) for constraints in S. This is a really challenging problem, which can naturally be cast as a Partial CSP [8].

1.3. The GRAPH generator

The GRAPH generator (Generating Radio link frequency Assignment Problems Heuristically, see [20] was developed at Delft University of Technology during the CALMA project. Its initial purpose was to provide small RLFAP instances that are similar in structure and hardness to the CELAR test problems. The following guidelines were used for developing GRAPH:

- The same frequency domains as in the CELAR problems are used.
- The ratio of number of links and number of interference constraints is approximately the same as for the CELAR problems.
- The structure of the instances concerning constraints of type 4 is the same as that of the CELAR problems.
- The use of redundant information in the constraints is avoided.

Roughly speaking, GRAPH generates RLFAPs by creating an undirected graph $G = (V, E)$ containing mutually connected cliques of a certain size. In this graph, nodes correspond to communication links (so $V \equiv X$) and an edge connecting two nodes i and j represents an interference constraint concerning the corresponding communication links. Subsequently, a frequency f_i is assigned to each node i of the graph, and required frequency distances d_{ij} are assigned to its edges obviously such that $|f_i - f_j| > d_{ij}$. In the final stage of generation some edges are removed from the graph randomly.

GRAPH is capable of generating problems of each type mentioned in the previous subsection. On generation, GRAPH delivers a solution to the generated instance. For problems of type FEAS a feasible assignment is given, while for problems of type CARD and SPAN an optimal assignment is generated. To obtain instances that are conjectured to be more difficult, GRAPH provides the option to further randomize the interference constraints. The solution generated by GRAPH then is no longer guaranteed to be optimal. Finally, when generating problems of type MAX, GRAPH provides an upper bounding assignment.

The author of GRAPH conjectures [20], based on some preliminary computational results, that the instances generated by GRAPH are in general slightly harder than the CELAR instances. Since until now only few computational results on the GRAPH instances are known, no more definitive statements about the relative hardness of CELAR and GRAPH instances can be made yet.

2. Instances and results

All the RLFAP instances defined in this paper share the same file syntax described in the next section. All the instances can be downloaded from the following URL:

1. `ftp://ftp.cs.unh.edu/pub/csp/archive/code/benchmarks/FullRLFAP.tgz`
2. `ftp://ftp.cert.fr/pub/lemaitre/FullRLFAP.tgz`

For CELAR instances, most of the information found in this section can be found in the file `celar.blurb` provided with the instances and which was constantly updated when new results were communicated to T. Schiex[2].

2.1. Syntax of the data files

Each instance is described by four files that should reside in the same directory.

File 'dom.txt'

This file describes the domains that are initially allowed for the variables of the problem. Each line describes one domain. The first domain is a dummy domain which results from the union of all the other domains and which is not actually used by any variable.

Each domain is described using fixed width fields.

Field 1	Domain number
Field 2	Domain cardinality
Field 3..n	Values in the domain

The domain number is used in the 'var.txt' file.

File 'var.txt'

Each line describes a variable using fixed width fields. Fields 3 and 4 are not always present.

Field 1	Variable number
Field 2	Domain number (see dom.txt)
Field 3	Initial value (variable is assigned, optional)
Field 4	Mobility (index of cost of modification, optional)

Variable numbers are used as identifiers and are not necessarily consecutive. The mobility may be 0,1,2,3 or 4. 0 means that the value of the variable is already assigned and may not be modified. 1 to 4 means that an initial value is assigned to the variable and may be modified with a decreasing cost of modification (see cst.txt). Fields 3 and 4 are optional.

File 'ctr.txt'

Each line defines one binary constraint. A constraint is defined by the following fields:

Field 1	Number of the first variable
Field 2	Number of the second variable
Field 3	Type of the constraints (see below)
Field 4	Operator to use (see below)
Field 5	Deviation (see below)
Field 6	Weight Index (optional, see below)

Fields 1 and 2 use the variable number in file 'var.txt'. Field 3 may take value D, C, F,P or L. It is useless and refers to the original meaning of the constraint. Fields 4 and 5 define the constraint. Field 4 is the relational operator that should be used to compare the absolute value of the difference of the two variables to the integer given in field 5 (called the deviation). It can be either ">" or "=". The semantics of the constraint is therefore:

$$|Field1 - Field2|\ Field4\ Field5$$

Field 6 is optional and is used when constraint violation is allowed. It may go from 0 to 4. 0 if the constraint must be mandatory met, 1 to 4 otherwise with a decreasing weight in the optimization criterion. If the Weight Index is missing, 0 is assumed. Constraints with a non null Weight Index are said to be "soft".

File 'cst.txt'

The file defines the criterion to optimize on this instance in natural language. When applicable (i.e., MAX is considered), it also contains the four interference costs (noted $a_1, \ldots, a_4$) and the four mobility costs (noted $b_1, \ldots, b_4$) that should be used for constraints with a non zero Weight or Mobility Index.

2.2. The CELAR instances

The table 1 concisely summarizes the properties of the eleven CELAR instances. The table gives, in order, the number of links, the number of constraints, the constraint graph density, whether the set of constraints C defines a feasible problem, whether enforcing arc-consistency [14] on the set C detects infeasibility by wipe-out (WO), does nothing (AC) or simply deletes some values (number of values deleted), the criterion considered on the instance, the value of the best solution found and whether a proof of optimality has been built for this solution (if a number is given, then it is the best lower bound available).

Initially, each CELAR instance has been defined with one corresponding criterion. It is either SPAN or CARD if the instance is feasible or MAX otherwise. We suggest, in order to define more problems (and essentially open problems) that feasible instances be also tackled with the other secondary criterion. These "new" instances will be numbered 01b, 02b, 03b, 04b, 11b (SPAN criterion) and 05b (CARD criterion). No result is reported on these new problems.

Within the CALMA project, several techniques, mainly from OR, have been applied; see for a concise overview [19] and for more detailed information the CALMA reports. These techniques include

- Branch and Cut,
- Constraint satisfaction,
- Local search, including tabu search and simulated annealing,
- Genetic algorithms,
- Potential reduction.

Table 1. The CELAR instances

Inst. #	# of Var.	# of Con.	Graph Dens.	Feas.	AC Enf. result	Crit.	Best found	Opt. proof
01	916	5 548	0.0132	Yes	AC	CARD	16	Yes
02	200	1 235	0.0620	Yes	AC	CARD	14	Yes
03	400	2 760	0.0345	Yes	AC	CARD	14	Yes
04	680	3 967	0.0171	Yes	13 868	CARD	46	Yes
05	400	2 598	0.0325	Yes	12 046	SPAN	792	Yes
06	200	1 322	0.0664	No	WO	MAX	3 389	Yes
07	400	2 866	0.0359	No	WO	MAX	343 592	No
08	916	5 745	0.0137	No	WO	MAX	262	No
09	680	4 103	0.0177	No	WO	MAX	15 571	14 875
10	680	4 103	0.0177	No	WO	MAX	31 516	31 204
11	680	4 103	0.0177	Yes	AC	CARD	22	Yes

Most of these techniques proved to be efficient for problems of type FEAS, SPAN and also CARD. Problems of type MAX turned out to be more difficult. Several of the above mentioned techniques were capable of finding good quality solutions to these instances as well, but proving optimality appears to be considerably more time-consuming.

Outside of the project, the CELAR benchmarks have mainly been used in the CSP/CLP community for assessing the performance of arc-consistency enforcing algorithms [18], for satisfaction (feasibility) algorithms [1] or for the computation of lower bounds in constraint optimization problems [6]. It should be said that, as long as arc-consistency enforcing is performed as a preliminary step, all CELAR instances (except instance 11) define a trivial satisfaction problem which can be solved in a matter of seconds by a simple naive backtrack algorithm (without any constraint propagation during backtrack). Only instance 11 can be considered as a decent benchmark for FEAS[3].

2.3. The GRAPH instances

Table 2 summarizes the properties of the fourteen GRAPH instances. Most of the columns have been defined in section 2.2 for the CELAR instances. However, and because the GRAPH generator produces both an instance and a solution for the instance, we also report, in the last two columns, the value of the solution built by the generator and whether this solution was known to be optimal at generation (for non randomized CARD/SPAN instances). For MAX problems, the mobility and interference costs used are always $\{1000, 100, 10, 1\}$. It may be noted that until now, there has been considerably less work done on the GRAPH instances than on the CELAR instances.

As for CELAR instances, each GRAPH instance has been defined with one corresponding criterion. We suggest feasible instances be also tackled with the other secondary criterion. These "new" instances will be called 01b, 02b, 08b, 09b, 14b (SPAN criterion) and 03b, 04b, 10b (CARD criterion). No result is reported on these new problems.

Table 2. The GRAPH instances

Inst. #	# of Var.	# of Con.	Graph Dens.	Feas.	AC Enf. result	Crit.	Best found	Opt. proof	Gen. value	Known opt.
01	200	1 134	0.0570	Yes	AC	CARD	18	Yes	46	No
02	400	2 245	0.0281	Yes	AC	CARD	14	Yes	14	Yes
03	200	1 134	0.0570	Yes	340	SPAN	380	Yes	380	Yes
04	400	2 244	0.0281	Yes	776	SPAN	394	Yes	394	Yes
05	200	1 134	0.0567	No	WO	MAX	221	No	221	No
06	400	2 170	0.0272	No	WO	MAX	4 115	No	4 223	No
07	400	2 170	0.0272	No	WO	MAX	4 324	No	4 413	No
08	680	3 757	0.0163	Yes	AC	CARD	18	No	48	No
09	916	5 246	0.0125	Yes	AC	CARD	18	Yes	18	Yes
10	680	3 907	0.0169	Yes	386	SPAN	394	Yes	394	Yes
11	680	3 757	0.0163	No	WO	MAX	3 080	No	5 786	No
12	680	4 017	0.0174	No	WO	MAX	11 827	No	12 894	No
13	916	5 273	0.0126	No	WO	MAX	10 110	No	14 144	No
14	916	4 638	0.0111	Yes	AC	CARD	10	No[4]	8	Yes

The GRAPH instances have been used in the CALMA project as 'surprise instances'; the participants in the project were asked to report on their results on these instances within one week after receiving them. The best solutions found are reported in [19, 11, 12, 22].

2.4. *CELAR sub-instances*

While all CARD, SPAN and FEAS CELAR instances have already been solved to optimality, most MAX CELAR instances still remain unsolved. In the process of constructing lower bounds for CELAR number 6 instance, a set of small but hard sub-instances of CELAR 6 have been extracted [6]. These instances are ideal for benchmarking, being in the reach of current algorithms and yet reasonably hard to solve. Each sub-instance is simply defined by a strongly connected subgraph of the initial problem constraint graph[5].

In order to respect the structural properties of the target problem, the sub-instances extraction process can be formulated as a graph partitioning problem. Given a set X of variables, we try to separate X into K nearly equal sized disjoint subsets by removing some constraints between subsets while minimizing the total weight of removed constraints. This problem can be easily formulated as an optimization problem by defining an appropriate criterion whose minimum value corresponds to the optimal partition [15, 7]. Although finding an optimal solution to a graph partitioning problem is NP-complete, heuristic methods such as stochastic or local search methods generally yield good approximate solutions in a reasonable time.

We have selected in table 3 some properties of five sub-instances of the CELAR instance 6 obtained with this extraction process using simulated annealing [9, 7, 5]. With the exception of CELAR6-SUB0, each CELAR6-SUB$_i$ is a sub-instance of CELAR6-SUB$_{i+1}$ and is therefore presumably simpler to solve.

Table 3. The 6 CELAR sub-instances

Instance	# of Var.	# of Con.	Graph Dens.	Optimal Cost
CELAR6-SUB0	32	223	0.4697	159
CELAR6-SUB1	28	314	0.8306	2669
CELAR6-SUB2	32	369	0.7439	2746
CELAR6-SUB3	36	439	0.6968	3079
CELAR6-SUB4	44	499	0.5274	3230
CELAR6	200	1322	0.0664	3389

By combining the optimal costs of the disjoint CELAR6-SUB0 and CELAR6-SUB4 sub-instances, one may obtain a lower bound on the CELAR instance 6 optimal cost which, surprisingly, equals the best solution found so far [11], and thus proves its optimality.

3. Hints and Tricks

The Radio Frequency Assignment problem is not new and several existing results can be used. First, several lower bounds have been defined that can be used to solve the SPAN and CARD problems. The most famous result uses generalized version of the chromatic number of the constraint graph as a lower bound for CARD [13, 4]. It has been further refined in the framework of the CALMA project [10] to take into account the specificities of the CELAR instances (and the specific interaction between the constraints of type 4 and 1). The lower bound computation defines an NP-hard problem, but it is nevertheless useful because the problem it defines is in practice much simpler than the original CARD problem.

In the CELAR instances, the specific interaction between the constraints of type 4 and 1 can be exploited to actually divide the number of variables in each instance by 2. The constraints $|x_{2i-1} - x_{2i}| = 238$ that connect the two links $\{2i-1, 2i\}$, that form a duplex link are, because of the nature of the domain of the variables, actually bijective and one can simply merge the two variables in one[6]. This applies for all CELAR instances, and so for all GRAPH instances as well. As a side effect of this simplification problems, some pairs of variables may be connected by more than one constraint[7].

4. What and where to report

Just any result using the CELAR or GRAPH instances can be reported to T. Schiex[8]. Naturally, we are most interested in improved results (better solutions, better lower bounds, proof of optimality) and references to the technics used. But we are also ready to collect any reference that uses the RLFAP instances. These results and references will be made available to the public on the following URL http://www-bia.inra.fr/T/schiex/CELAR.html.

Among the 25 original problems presented here, there is probably more opportunity for improvement among the GRAPH problems, which have been the object of much less work. To these 25 problems, one can add 14 new problems, defined by applying the alternate secondary criterion to existing feasible instances. These 14 problems are completely open, the SPAN being probably the easiest ones.

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Notes

1. In some other cases, several transmitters in the co-site situation may generate "intermodulation products". In order to avoid interferences, no transmitter should use a frequency which corresponds to an intermodulation product of other frequencies used at this site. This yields additional non binary constraints.
2. People should be aware that there are several versions of this file, sometimes outdated. Pay attention to the fact that the older versions were ambiguous on how some mobility costs were to be interpreted. The last version should always be available at the USA site.
3. However, it can simply be solved using a forward-checking algorithm. A good variable ordering such as domain/degree, later popularized in [2], was crucial however.
4. The best solution found with optimization algorithms uses 10 frequencies, however, as indicated in the table, the GRAPH generator gave a solution that uses 8 frequencies when it generated the instance. Therefore this solution is known to be suboptimal.
5. When two sub-instances involve disjoint subsets of constraints, the sum of their optimal costs is still a lower bound of the target problem.
6. This can be observed using the union of all possible domains, that contains 48 values: for any frequency f chosen in the domain, there is only one value f' in the domain that satisfies $|f - f'| = 238$.
7. For the best results, these multiple edges should not be propagated independently in arc-consistency enforcing algorithms.
8. Either use e-mail to tschiex@toulouse.inra.fr or mail to the CSP mailing list at csp@www-bia.inra.fr.

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