

Frequency Assignment for Cellular Mobile Systems Using a Memetic Algorithm

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Abstract —This paper presents a novel algorithm for finding a solution to the frequency assignment problem (FAP). The algorithm proposed here is a metaheuristic approach called memetic algorithm, which uses genetic algorithm based on new crossover operator combined with a modified tabu search. The performance of our algorithm is evaluated using for the results eight well-known benchmark problems, Computational results allow us to confirm the effectiveness of the proposed algorithm.

Keywords: frequency assignment problem; genetic algorithm; tabu search; memetic algorithm, metaheuristic.

I. INTRODUCTION

Due to the insufficiency of available bandwidth resources and the increasing demand for cellular communication services, the Frequency assignment problem becomes increasingly important.

Frequency assignment is generalization of the graph coloring problem, which belongs to the class of NP-complete problems [4]. For this category of problem, there is no known algorithm that can generate a guaranteed optimal solution in an execution time that may be expressed as a finite polynomial of the problem dimension. As this reason many heuristic methods have been proposed to deal with FAP. This large production has been analyzed and organized in several surveys [1, 2, 3]. We briefly present about each of used approaches:

- genetic algorithm based approaches.
- Constructive algorithms and local searches.
- Tabu Search.
- hybrid algorithm.
- approach based on ant colony paradigms.
- Neural Network Algorithm
- Simulated annealing
- Multi agent Systems

From the experiments made by most researchers on a variety of standard benchmark problems, tabu search(TS) has been one of the most effective heuristic algorithms for the FAP especially when solution time is less important than solution quality [5]. The differences in these approaches lie in the representation of the move, in the definition of neighborhood of a move, and in the way of defining a tabu move [1]. Moreover genetic

algorithm (GA) provides for a wide exploration of the space to search. As these reasons the hybridization between the two last approaches is meant to accelerate the discovery of good solutions.

Memetic algorithms (MAs), which are similar to genetic algorithms, are good algorithms for combinatorial optimization problems [14]. Normally, a genetic algorithm combined with local search methods is called a memetic algorithm (MA) [14]. MAs have received various names throughout the literature and scientists not always agree what is and what is not an MA due to the large variety of implementations available. Some of the alternative names used for this search framework are hybrid GAs, Baldwinian EAs, Lamarckian EAs, genetic local search algorithms, and other names are not unheard of. Moscato [13] coined the name Memetic Algorithm to cover a wide range of techniques where evolutionary-based search is augmented by the addition of one or more phases of local search.

In this paper, we propose a memetic approach for solving the frequency assignment problem. We consider a general cellular radio network subjected to all three kinds of constraints [8] :

1. the cochannel constraint (CCC): the same frequency cannot be assigned to certain pairs of radio cells simultaneously;
2. the adjacent channel constraint(ACC): frequencies adjacent in the frequency domain cannot be assigned to adjacent radio cells simultaneously;
3. the co-site constraint (CSC): any pair of frequencies assigned to a radio cell must have certain distance in the frequency domain.

The rest of the paper is organized as follows. In Section 2, we formulate the frequency assignment problem. In Section 3, we present the proposed algorithm. In Section 4, experimental results are presented. Future work and perspectives are discussed in the last section.

II. PROBLEM DESCRIPTION

The problem of frequency assignment is to provide wireless communication frequencies from limited spectral resources while keeping to a minimum interference suffered by those wishing to communicate in a given radio communication network. According to [2] the here considered version of FAP is classified as a MS-FAP (minimum Span frequency assignment problem). Radio channels are represented by the positive integers. Let $M = \{1, 2, \dots, m\}$ be a set of available channels where m is the Number of available channels in the mobile network. The basic model of the channel assignment problem can be represented as follows:

1. N : The number of cells in the mobile network.
2. d_i : represents the number of frequencies that must be assigned to cell i ($1 \leq i \leq N$)
3. C : Compatibility matrix, $C=(c_{ij})_{N \times N}$ represents the Minimal channel separation between channels in cells i and j , $1 \leq i, j \leq N$.
4. $Call_{ik}$: Cell i with call k where $1 \leq i \leq N$, $1 \leq k \leq d_i$
5. f_{ik} : A radio channel is assigned to $Call_{ik}$, where f_{ik} belongs to the set of radio channel F .
6. **Frequency separation constraint** :
 $|f_{ik} - f_{jm}| \geq c_{ij}$, for all i, j, k, m ($i \neq j, k \neq m$), c_{ij} is defined in Compatibility Matrix, C . If ($i=j$), it become co-site constraint.
7. **TotalAssignCh**: the total number of required channels The total of radio channel to be assigned in the system can be shown as:

$$\text{TotalAssignCh} = \sum_{i=1}^n d(i) \quad (1)$$

Therefore, the objective is to find an assignment that minimizes the total number of violations in an assignment, Subject to:

$$\min \sum_{i=1}^n \sum_{k=1}^m \sum_{j=1}^n \sum_{l=1}^m f_{ik} \text{viol}(i,j,k,l) f_{jl} \quad (2)$$

Where: $\text{viol}(i,j,k,l) = \begin{cases} 0 & \text{if } |k-l| \geq C_{ij} \\ 1 & \text{otherwise} \end{cases}$
 and

$$f_{ik} = \begin{cases} 0 & \text{if channel } k \text{ is not assigned to cell } i \\ 1 & \text{otherwise} \end{cases}$$

for $1 \leq k, l \leq m$ and $1 \leq i, j \leq N$.

III. MEMETIC ALGORITHM

In this paper, a Memetic Algorithm (MA) is proposed for FAP. The mechanisms and operators of the MA are given below.

A. Representation and selection mechanisms

Encoding the chromosome in FAP is relatively simple, We represent a solution by a binary matrix $N \times m$. N is the number of cells and m is the number of channels. If a gene $f_{ik} = 1$, then the k^{th} channel is assigned to the i^{th} cell. Chromosomes are randomly selected from the population for crossover and mutation.

B. Population initialization

In a traditional GA, each chromosome in the initial population is generated randomly. However, many experimental results have shown that the GA does not always result in good solutions due to the random method.

the co-site constraint (CSC) may cause more interference in the real-world situation[6]. So firstly to make sure the absence of interference between two channels assigned to the same cell, we have generate the initial population with new method called (PI) inspired from[7]. Figure 1 shows the difference between the two methods: -Cell: i

- j : is random number between 1 and $m - ((d_i - 1) \times C_{ii} + 1)$

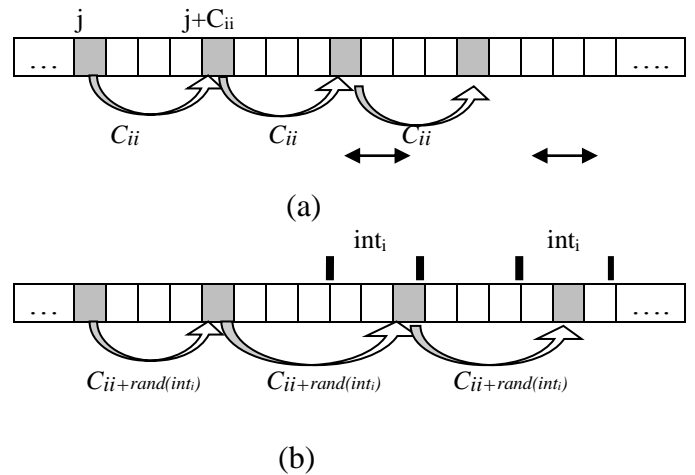


Fig.1: Frequencies assigned to cell 'i'
 (a) Cheng method [7] (b) our method(PI)

The int_i is defined by

$$\text{Int}_i = \frac{m - ((d_i - 1) \times C_{ii} + 1)}{d_i} \quad (3)$$

Where:

C_{ii} represents the Minimal channel separation between channels in cell i ;

$\text{Int}_i + C_{ii}$ is the maximum channel separation between channel in cell i ;

Int_i represents the interval of possible assignment to cell "i" without breaking the CSC constraint of all assignment in the Cell i .

The cells with a high channel demand have more difficulty obtaining an assignment that satisfies the CSC constraints. So we have generated p_i to deal with this problem. Where p_i is defined as:

$$p_i = \frac{(d_i - 1) \times C_{ii} + 1}{m} \quad (4)$$

Cells with a high value of p_i means that these cells must use the minimum separation distance (C_{ii}) between channels. For the others with low value of p_i means that these cells use the separation distance $C_{ii} + \text{random}(0, \text{int}_i)$. Figure 2 is the pseudo code of PI. Where sol_i is the assignment of cell i .

C. Proposed crossover operator

Chromosomes in the population have good genes resulting from the population initialization, It is clear that performance can be improved by transferring these good genes to the next generation.

An overview of the crossover operator is shown by figure 3. Two parents such as parent1 and parent2 are considered for the crossover process. We randomly generate a binary number mask then, we calculate P_i for each cell in the two parents where P_i is defined in (4). The value of P_i can exclusively reduce the searching space and consequently the convergence time is shortened. P_i has two roles; the first one is keeping CSC constraints for some cells verified, the other one is for the cells that do not have a high probability for improvement - optimum solution obtained - will be leaved uncrossed.

Population initialization

for each cell i

$a = \text{random}(0, 1)$

if ($a > p_i$)

for each demand d_j of cell i

$\text{sol}_i(d_j) = [\text{random}(0; \text{Int}_i) + \text{sol}_i(d_{j-1}) + C_{ii}] \text{mod } m + 1$

end

else

$s = \text{random}(m - (r_i - 1) \times C_{ii})$

$\text{sol}_i(1, \dots, d_i) = [s, s + C_{ii}, s + 2 \times C_{ii}, \dots, s + (d_i - 1) \times C_{ii}]$

endif

end for

Fig. 2: population initialization

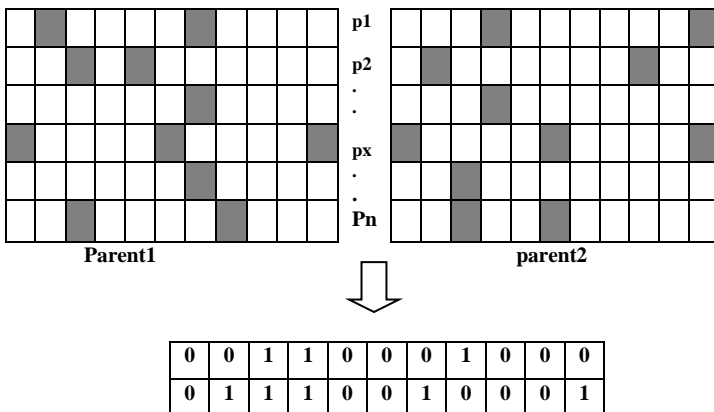
$C = \text{Random}(0, 1)$

If ($C < p_i$)

The row pairs leave uncrossed

Else

The row pairs will be crossed



1	0	0	0	1	1	1	0	1	0	1
0	0	0	0	0	0	0	0	0	0	0
1	0	1	1	0	1	1	0	1	0	0
1	1	0	0	1	1	0	1	0	0	0

($C < P_x$)

Binary mask

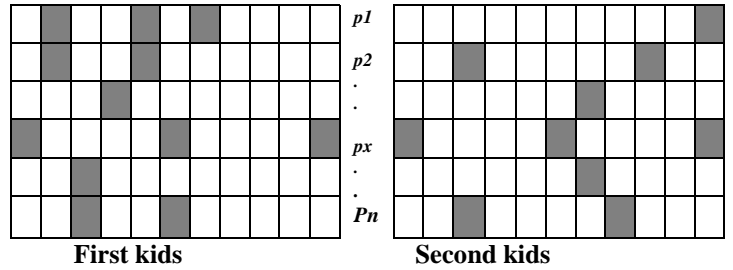


Fig. 3: Proposed crossover operator

D. Mutation operator

Our mutation operator called "mutation adapter" controls the total number of "1" in row i . we make sure that not to exceed d_i of the demand vector in any case. We do this by adding or removing a "1" randomly from the specified row. The mechanism of mutation operator is shown in figure 4.

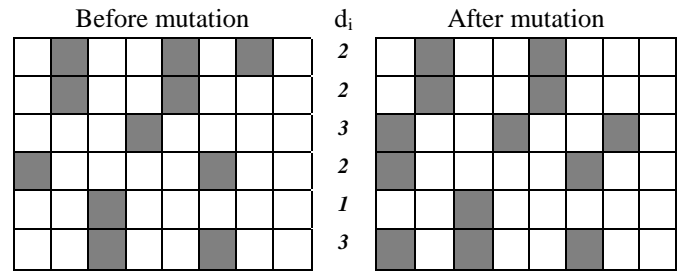


Fig. 4: mutation adapter

E. MA description

Figure 5 illustrates the MA framework followed in the implementation of the proposed algorithm. The first step of the algorithm is to create an initial population with PI and evaluate it. After that, for each generation, a pair of "parent" solutions is selected for the above methods of crossover and mutation. Two solutions are created which typically shares many of the characteristics of its "parents". After that the Tabu search and the module of restricted frequency are performed on these solutions. The mechanisms and operators of these components are given in section F and G.

Algorithm MA

	Fx	fy				
Interference ↑ cell=i ↓ cell=j
	.	1	.	.	.....	.

	.	1	.	0	.....	.

embrace more efficient and systematic forms of direction such as memorizing and learning [15].the hybridization between GA and TS is more successful in our case.

1) *Solution representation*

The representation of a frequency assignment S is obtained by using a matrix $N \times m$. where if a gene $f_{ik} = 1$, then the k^{th} channel is assigned to the i^{th} cell.

2) *Neighborhood*

The space to search or set of moves is defined in figure 6. Our basic move is then moving a 1 to a 0 entry of the same row. Thus changing the assigned channel of one cell, maintaining the number of assigned channels unchanged and keeping the result of crossover operator (co-site interference).

3) *Tabu list*

Some neighbors composed of previously encountered solutions will not be considered for the next k iterations (k, called tabu length). These neighbors are consisted in tabu list, which is one of the main mechanisms of tabu search. Tabu list is also the most important feature distinguished with other search algorithms. Thus, TS can be described as a form of neighborhood search with a set of critical and complementary components.

As shown in Figure 6, the element (j, fx) prevents the algorithm from re-visiting previously seen solutions. The element (j, fy) prevents the other individuals from re-exploring the same search area.

.
.	1	.	.	.	.....	.
.
.
.	0	.	1	.	.....	.

Begin
 Initialize population P with PI;
 Evaluate initial population,
 Repeat
 -Generate-Binary-Masks
 -Select two parents randomly
 -use the **proposed crossover**. Then get two offspring
 - **mutation adapter**(offspring1, offspring2)
 - If fitness (offspring2) better than fitness (parent)
 then Offspring will be accepted.
 - **tabu Search** (ofspring1, offspring2)
 - calculate the **unrestricted frequencies** for each cell which have interference in offspring1
 - replace the restricted frequencies with unrestricted frequencies
 -add offspring1 to population
 Until Termination criteria are satisfied;
 End;

Fig. 5: MA framework

F. *Tabu search*

After several generations, chromosomes in the population are similar enough to each other such that only local optimization may be possible. Tabu search is one of the mechanisms to avoid minimum local. Opposite to randomizing approaches such as Simulated Annealing (SA) where randomness is widely used, TS is based on the principle that intelligent search must

tabulist = (j,fx); (j,fy).

Fig. 6: Tabu search moves

G. *Restricted frequencies*

In order to improve the quality of the solution obtained, we apply the following steps to locate the free frequencies (if any exist) and resolve the maximum of conflict between cells. This

module is applied to solution obtained by tabu search that do not satisfy all the constraints of the problem.

1. determine the couples of cells which have interference between them ;
2. from the list of couples “S” ,we create list of candidate L .where L is defined by:
 $L = \{x, p_x < p_y \forall (x,y) \in S\}$ p_x, p_y defined in (4)
3. delete all frequencies assigned to L
4. Assigned={}
5. calculate” free frequencies” it means the authorization of assigning frequencies in cell x, $\forall x \in (L\text{-Assigned})$ (see figure 7) if (L-Assigned)={ } go to 7;
6. if (free frequencies) then
 $x \in (L\text{-Assigned})$ Assign the first free frequency to “x”,
 Assigned={x};
 else
 Assign a frequency randomly to x;
 Assigned={x};
 endif ;go to 5.
7. End

This approach shares some similarities in the calculation of the free frequency in Frequency Exhaustive Strategy [16].

H. Termination criteria

In traditional GA, either computation time or the number of generations or solution improved is selected as termination criterion. In this paper, all of them are considered. If a solution cannot be improved any more in consecutive generations, the algorithm terminates. However, it is very time-consuming for problems, MA terminates when any of the three conditions is true.

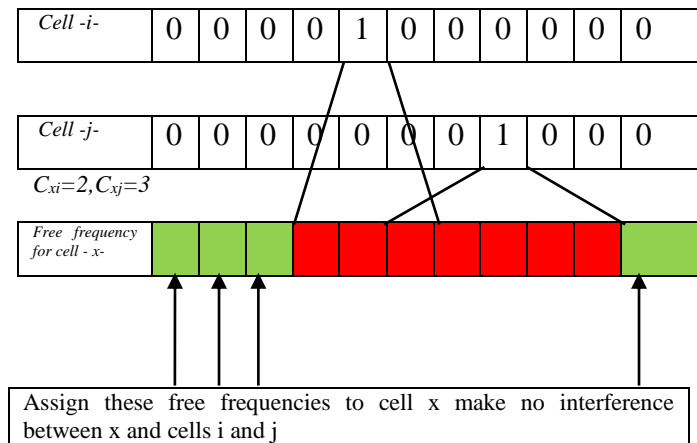


Fig. 7: Free frequencies

IV. EXPERIMENTAL RESULTS

In these experiments we used the Philadelphia problem instances [12]. These instances are widely known within problem FAP, and they are characterized by a number of hexagonal cells (habitually 21), that represent a cellular phone network of the Philadelphia city (see Figure 8).

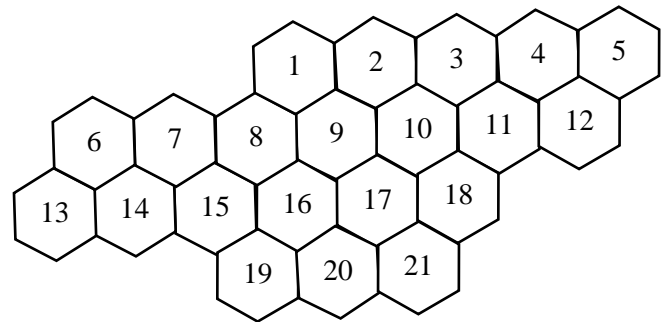


Fig. 8: Cellular geometry of test problems

The main differences among the instances correspond with the use of different interference matrices and demand vectors (see table 1). In these instances, the number of antennas (cells) varies from 4 to 25, and the number of frequencies finally used varies between 11 and 533. Figure 11 shows the different interference matrices (C) and the demand vectors (D) used.

Table I: Problem Specifications

Instance	# of Cell	Lower Bound (lb)	Compatibility matrix (C)	Demand vector (D)
P1	4	11	C ₁	D ₁
P2	25	73	C ₂	D ₂
P3	21	381	C ₃	D ₃
P4	21	533	C ₄	D ₃
P5	21	533	C ₅	D ₃
P6	21	221	C ₃	D ₄
P7	21	309	C ₄	D ₄
P8	21	309	C ₅	D ₄

To investigate the convergence frequency, Table II summarizes the simulation results, and shows the convergence to the optimum solution (the convergence frequency).

Table II: convergence rate

Inst	Approach and rate of convergence					
	Lower Bound	MA	[9] MGA	[10] NN	[11] DGuGA	[7] CSCP
P1	11	100%	100%	-	100%	100%
P2	73	100%	100%	62%	98%	100%
P3	381	100%	-	99%	-	100%
P4	533	100%	-	100%	-	100%
P5	533	100%	-	98%	-	100%
P6	221	100%	92%	97%	89%	100%
P7	309	100%	-	99%	-	100%
P8	309	100%	80%	52%	-	100%

Figure 9 shows the required generation to converge to the solution in two problems. In problem #8, our MA found the solution within 22 generation, in problem #2, our MA converge in the 36th generation.

Table 2 allows us to confirm the effectiveness of the proposed algorithm. The simulation results show that our algorithm achieved 100% convergence to solutions for all eight benchmarking problems. The results show that MA outperform the convergence results of the neural network (NN) [10], genetic algorithm (MGA) (DGuGA)[9,11]. The MA shows the same convergence results of [7]. Our algorithm identifies higher-quality solutions than other methods and it is easy to implement. For cellular systems with high number of cells, this algorithm can be efficiently applied to find the exact solution in an acceptable time of computation. Also since it is an implicitly parallel technique, it can be implemented very effectively on powerful parallel computers to solve exceptionally demanding large-scale problems.

Figure 10 shows a two-dimensional stem plot. It displays the frequency assigned to each cell for the problem #8, where the x-axis represent the cells, and the y-axis represent the frequency assigned. The full assignment of channels for a sample of the 8 benchmark problems considered in our simulations is presented in the Appendix. The results and analysis presented above indicate that our MA is certainly an effective Memetic algorithm for solving the frequency assignment problem.

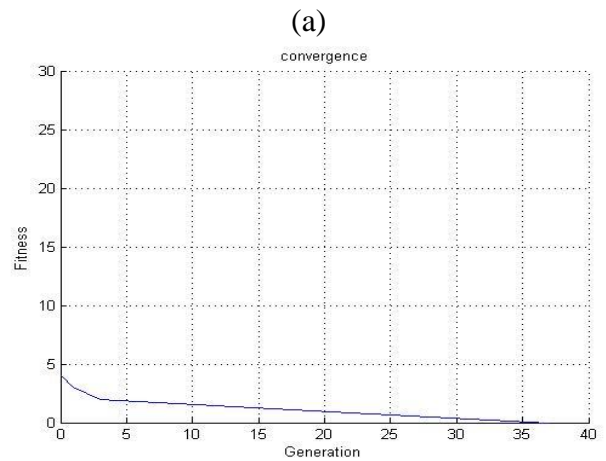
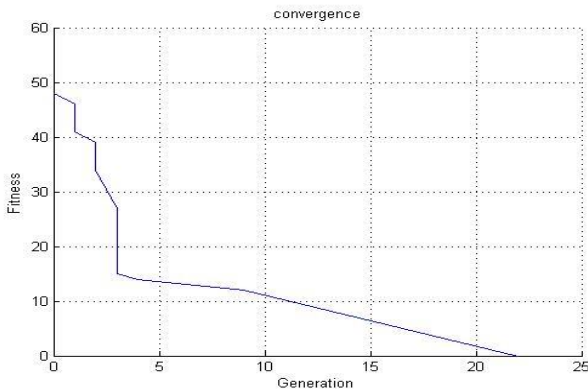


Fig. 9: (a)instance P8 convergence (b) instance P2 convergence

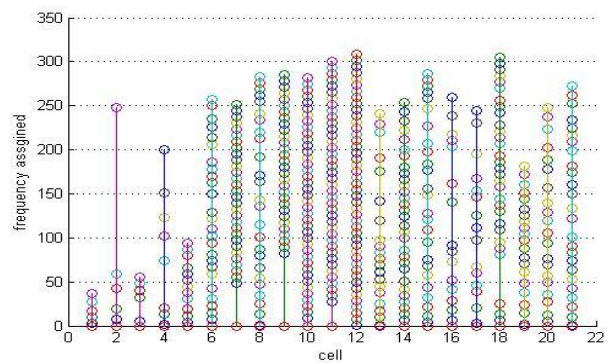


Fig. 10: two-dimensional stem plot

V. CONCLUSION

We have presented a memetic algorithm for solving the frequency assignment problem in cellular radio networks. Due the importance of CSC constraints, we have considered this in the population initialization. Problems specific information has been used into the mechanism of crossover and tabu search as to effectively bias the search process towards promising regions of the search space. After experiments with real data, optimization was achieved and the algorithm has been efficient and convergent. Our approach can find better or equivalent solutions compared with existing optimization methods. Our work presents a good perspective of managing the radio spectrum that can be intended towards a parallel implementation for implementing a pertinent strategy and effective management of resources in the future works.

Appendix:

This appendix shows the full assignments for benchmark instances No. 2, 5, and 6(see table 3-5)

Table III: Channel assignment for benchmark problem 2

Cells	Frequency
1	31,33,35,37,39,41,67,69,71,73
2	6,8,10,12,14,16,18,20,22,24,26
3	28,32,34,36,38,40,42,51,70
4	6,12,26,37,39
5	30,44,46,48,50,52,54,56,72
6	1,3,5,67
7	53,55,57,61,64
8	30,44,46,48,50,52,54
9	10,13,15,17
10	2,4,43,47,58,60,62,66
11	14,16,18,20,22,24,31,35
12	1,3,5,7,9,45,59,63,65
13	11,13,15,17,19,21,23,25,27,29
14	49,53,55,57,61,64,68
15	28,36,38,51,59,63,65
16	6,8,26,32,37,40
17	2,10,14,16
18	3,5,7,9,33
19	1,12,34,39,41
20	44,46,48,50,52,54,56
21	2,4,9,32,37,43
22	3,5,11,42
23	7,10,13,23,36
24	53,55,57,59,61,63,65
25	1,8,21,33,44

Table IV: Channel assignment for benchmark problem 5

Cells	Frequency
1	6,11,21,27,95
2	4,10,20,30,108
3	1,8,16,25,31
4	2,7,12,18,23,35,40,45
5	3,9,14,20,28,33,38,43,48,55,60,65
6	1,7,12,18,24,33,40,45,50,57,66,75,81,86,91,100,106,111,116,122,137,145,152,191,200
7	44,49,54,59,64,69,74,79,84,89,94,99,104,109,114,119,124,129,134,139,144,149,154,159,164,169,174,179,184,189
8	3,9,15,26,35,41,51,56,61,70,80,110,120,130,140,165,170,180,185,190,199,204,209,214,219
9	76,81,86,91,96,101,106,111,116,121,126,131,136,141,146,151,156,161,166,171,176,181,186,191,196,201,206,211,216,221
10	17,22,27,32,37,42,47,52,57,62,67,72,77,82,87,92,97,102,107,112,117,122,127,132,137,142,147,152,157,162,167,172,177,182,187,192,197,202,207,212
11	19,24,29,34,39,44,49,54,59,64,69,74,79,84,89,94,99,104,109,114,119,124,129,134,139,144,149,154,159,164,169,174,179,184,189,194,199,204,209,214
12	1,6,11,16,21,26,31,36,41,46,51,56,61,66,71,76,81,86,91,96,101,106,111,116,121,126,131,136,141,146,151,156,161,166,171,176,181,186,191,196,201,206,211,216,221
13	2,10,19,27,36,41,46,52,60,65,70,77,95,112,120,127,136,147,161,167
14	43,48,53,58,63,68,73,78,83,88,93,98,103,108,113,118,123,128,133,138,143,148,153,158,163,168,173,178,183,188
15	8,17,23,31,38,47,55,62,67,72,85,92,97,105,117,135,142,157,162,172,177,182,187,192,197
16	5,14,19,29,45,50,60,90,100,145,150,175,194,203,208
17	13,21,28,33,43,65,95,125,160,195,200,205,210,215,220
18	53,58,63,68,73,78,83,88,93,98,103,108,113,118,123,128,133,138,143,148,153,158,163,168,173,178,183,188,193,198
19	1,10,16,22,27,34,40,46,52,57,75,82,87,102,107,112,122,127,137,167
20	2,7,12,18,24,39,44,49,54,59,64,69,74,79,84,89,94,104,115,155
21	6,15,20,25,30,36,41,48,55,61,66,71,80,85,105,110,120,130,135,140,165,170,180,185,190

Cells	Frequency
1	10,17,31,51,61,68,89,271
2	6,19,46,59,76,96,103,118,131,139,150,164,180,187,194,201,208,220,227,234,241,248,255,262,269
3	11,26,54,62,109,122,129,167
4	7,16,42,68,142,236,272,326
5	34,83,137,170,194,220,248,286
6	1,11,22,29,45,60,69,76,88,97,161247,278,321,338
7	20,27,39,49,82,104,112,119,128,135,142,159,166,181,191,202,209,250
8	3,12,25,33,41,53,66,73,80,87,94,101,108,115,125,146,153,174,216,223,230,237,244,258,265,279,300,328,335,342,349,356,363,370,377,384,391,398,405,419,426,433,440,447,454,461,482,496,503,517,524,531
9	1,8,15,22,29,36,43,50,57,64,71,78,85,92,99,106,113,120,127,134,141,148,155,162,169,176,183,190,197,204,211,218,225,232,239,246,253,260,267,274,281,288,295,302,309,316,323,330,337,344,351,358,365,372,379,386,393,400,407,414,421,428,435,442,449,456,463,470,477,484,491,498,505,512,519,526,533
10	5,24,31,38,45,74,81,88,95,102,117,124,138,145,157,171,178,185,192,199,206,213,222,229,243,257,264,276
11	13,20,28,40,49,56,65,72,79,115,153,227,310
12	1,30,43,63,86,111,146,158,186,200,209,224,250,270,282
13	7,16,32,42,52,64,73,83,95,106,118,130,145,156,170,178,186,193,201,210,225,241,254,263,273,287,310,335,355,367,375
14	5,13,24,35,47,54,67,86,93,100,121,138,147,195,205
15	9,18,30,37,44,56,63,70,77,84,91,98,110,117,132,140,149,163,177,184,198,212,219,226,233,240,252,261,268,275,282,289,296,307,315,322,123,130,137,144,151,158,165,172,179,186,193,200,207,214,221,228,235,242,249,256,263,270,277,284,291,298,305,312,319,326,333,340,347,354,361,368,375,382,389,396,403,410,417,424,431,438,445,452,459,466,473,480,487,494,501,508,515
17	10,17,52,60,69,83,90,97,104,111,160,181,188,195,202,209,251,286,293,314,321,412,468,475,489,510,521,528
18	2,35,47,58,67,76,119,341
19	2,11,26,34,42,51,58,68,75,88
20	4,13,23,32,39,46,54,65,72,93,100,139,329
21	6,19,27,37,44,63,80,87,

Table V: Channel assignment for benchmark problem 6

C2	D2	C3	D3
2110101111011110000000000	10	511001111000011100000	8
1210101101011110000000000	11	151100111100001110000	25
1121111111111100000000000	9	115110011110000111000	8
0012001111111000000000111	5	011510001111000011000	8
1110200001111110000000000	9	001150000111000001000	8
0010021111000000000000000	4	100005110000111000000	15
1111012111111000000000000	5	110001511000111100100	18
1111011211111000000000010	7	111001151100011110110	52
1011011121110000000000011	4	111100115110001111111	77
111111112111111000001010	8	011110011511000111011	28
0011101111201111011111111	8	001110001151000011001	13
1111101111021100000000000	9	000110000115000001000	15
1111101101112111111100000	10	000001100000511000000	31
1110100001111211111100000	7	100001110000151100100	15
1100100001101121111111000	7	110001111000115110110	36
0000100001101112111100000	6	111000111100011511111	57
0000000000001111211000000	4	011100011110001151111	28
0000000000101111121100000	5	001110001111000115011	8
0000000000101111112111100	5	000000111000011110511	10
0000000000101111011211100	7	000000011100001111151	13
0000000000100010001121100	6	000000001110000111115	8
0000000001100010001112111	4		
0001000000100000001111211	5		
0001000111100000000011211	7		
0001000010100000000001112	5		

C4	D4	C5	C1	D1
711001111000011100000	5	721001221000011100000	5400	1
171100111100001110000	5	272100122100001110000	4501	1
117110011110000111000	5	127210012210000111000	0052	1
011710001111000011000	8	012720001221000011000	0125	3
001170000111000001000	12	001270000122000001000		
100007110000111000000	25	100007210000221000000		
110001711000111100100	30	210002721000122100100		
111001171100011110110	25	221001272100012210110		
111100117110001111111	30	122100127210001221111		
011110011711000111011	40	012210012721000122011		
001110001171000011001	40	001220001272000012001		
000110000117000001000	45	000120000127000001000		
000001100000711000000	20	000002100000721000000		
100001110000171100100	30	100002210000272100100		
110001111000117110110	25	110001221000127210210		
111000111100011711111	15	111000122100012721221		
011100011110001171111	15	011100012210001272122		
001110001111000117011	30	001110001221000127012		
000000111000011110711	20	000000111000012210721		
000000011100001111171	20	000000011100001221272		
000000001110000111117	25	000000001110000122127		

Fig. 11: Interference matrix (C) and demand vector (D) for the tested instances

REFERENCES

- [1] Audhya, G. K., Sinha, K., Ghosh, S. C. and Sinha, B. P. (2011), A survey on the channel assignment problem in wireless networks. *Wireless Communications and Mobile Computing*, vol. 11 pp. 583–609
- [2] K. I. Aardal, C.P.M. van Hoesel, A.M.C.A. Koster, C. Mannino, and A. Sassano, “Models and solution techniques for frequency assignment problems,” *Annals of Operations Research*, 2007, vol.153, pp.79–129.
- [3] Katzela I., and Nagshineh M., Channel assignment schemes for cellular mobile telecommunication systems, *a comprehensive survey*, *IEEE Personal Communications*, 1996, pp.10–31.
- [4] Hale WK Frequency assignment: theory and applications Proc IEEE , 1996 vol. 68(12) pp.1497–1514.
- [5] R. Montemanni, J.N.J. Moon and D. H. Smith, “An improved tabu search algorithm for the fixed spectrum frequency assignment problem”, *IEEE Transactions on Vehicular Technology*, vol. 52(4), pp.891–901
- [6] Yuanyuan Zhang; Ming Chen; , "A Metaheuristic approach for the Frequency Assignment Problem," *6th International Conference on Wireless Communications Networking and Mobile Computing (WiCOM)*, Sept. 2010, vol., no., pp.1-5, pp.23-25
- [7] Cheng R-H., Yu C. W., Wu T-K, “ A Novel Approach to the Fixed Channel Assignment Problem”. *Journal of Information Science and Engineering* 2005, 21, pp.39-58.
- [8] A.Gamst, “Homogeneous distribution of frequencies in a regular hexagonal cell system,” *IEEE Trans. Veh. Technol*, Aug. 1982, vol. VT-31, pp. 132-144
- [9] Ngo C. Y. and Li, V. O. K. “Fixed channel assignment in cellular radio networks using a modified genetic algorithm”, *IEEE Transactions on Vehicular Technology*, 1998, 47, pp.163–171.
- [10] Kim J.-S., Park S. H, Dowd P. W., and Nasrabadi N. M. “Cellular radio channel assignment using a modified hopfield network”, *IEEE Transactions on Vehicular Technology*, 1997, 46, 4, pp.957–967.
- [11] L.M. San Jose´-Revuelta “A new adaptive genetic algorithm for fixed channel assignment” *Information Sciences*, 2007 , vol. 177, pp. 2655-2678 .
- [12] Eisenblätter, A., Koster, A. Web site in which the Philadelphia instances for the FAP problem are explained <http://fap.zib.de/problems/Philadelphia>, May 2007
- [13] Moscato, P. (1989) “On Evolution, Search, ptimization, Genetic Algorithms and MartialArts: Towards Memetic Algorithms” *Caltech Concurrent Computation Program*, C3P Report 826.
- [14] N. Krasnogor and J. Smith, “A Tutorial for Competent Memetic Algorithms: Model, Taxonomy and Design Issues,” *IEEE Transactions on Evolutionary Computation*, 2005, vol. 9, no. 5, pp. 474 - 488.
- [15] Maninder Singh Kamboj, Jyotsna Sengupta, “Comparative Analysis of Simulated Annealing and Tabu Search Channel Allocation Algorithms”, *International Journal of Computer Theory and Engineering (IJCTE)*, 2009, Vol. 1, No. 5, pp. 588-591,
- [16] Sivarajan, K.N., McEliece, R.J. and Ketchun, J.W. ‘Channel assignment in cellular radio’, *Proceedings of the 39th IEEE Vehicular Technology Conference*, May 1989, pp.846–850.