Frequency Assignment Optimization using the Swarm Intelligence Multi-agent Based Algorithm (SIMBA)

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Abstract: The swarm intelligence multi-agent based algorithm (SIMBA) is presented in this paper. The SIMBA utilizes swarm intelligence and a multi-agent system (MAS) to optimize the frequency assignment problem (FAP). The SIMBA optimises by considering both local and global i.e. collective solutions in the optimization process. Stigmergy single cell optimization (SSCO) is also used by the individual agents in SIMBA. SSCO enables the agents to recognize interference patterns in the frequency assignment structure that is being optimized and to augment it with frequency selections that minimized the interference. The changing configurations of the frequency assignment structure acts as a source of information that aids the agents when making further decisions. Due to the increasing demand of cellular communication services and the available frequency spectrum optimal frequency assignment is necessary. The SIMBA was used to optimize the fixed-spectrum frequency assignment problem (FS-FAP) in cellular radio networks. The results produced by the SIMBA were benchmarked against the COST 259 Siemens scenarios. The frequency assignment solutions produced by the SIMBA were also implemented in a commercial cellular radio network and the results are presented.

1 INTRODUCTION

The demand for cellular communication services is constantly growing. However, due to the limited frequency spectrum available to cellular network operators the efficiency in which the frequency spectrum is utilized is a very important issue. This is the reason why the frequency assignment problem has attracted a large amount of interest. The efficient use of radio spectrum and the minimization of interference is the main goal of any frequency assignment algorithm.

The frequency assignment problem (FAP) in its simplest form is equivalent to the generalized graph-colouring problem (Hale, 1980). Thus it is also an N-P complete problem (Hale, 1980). Searching for a solution to the frequency assignment problem increases exponentially with the number of cells in the radio network. In this paper the swarm intelligence multi-agent based algorithm (SIMBA) will be presented and discussed. SIMBA is an algorithm inspired by swarm intelligence. The SIMBA was implemented using a multi-agent system (MAS). Agents in the multi-agent system of SIMBA consider both local and global solutions when optimizing the fixed spectrum frequency assignment problem (FS-FAP). The local solution is the frequency assignment solution produced by the individual agent. The global solution is the best frequency assignment solution (solution with the least interference) produced by the collective. The design of the SIMBA as well as the MAS supporting the SIMBA will be described in depth. The results produced by the SIMBA will be compared to the COST 259 Siemens bench marks (Eisenblätter and Koster, 2008). The frequency assignment solutions produced by SIMBA were implemented in a commercial, operational cellular radio network and the results are presented in this paper.

Stigmergy single cell optimization (SSCO) was utilised by the individual agents in the SIMBA in order to make intelligent decisions on the next frequency that needed to be selected. SSCO is based on stigmergy. The actual structure that the agents are working on actually guides the agents on their future decisions. SSCO enables the agents to recognize interference patterns in the frequency assignment structure that is being optimized. These interference patterns then stimulate the agent to select a frequency that minimises this interference pattern.

The SIMBA has shown promising improvements both in the efficiency of the resultant solution and the time it took to find an acceptable solution. The efficiency of the resultant solutions has been tested against a number of cellular radio network measurement parameters. These parameters indicated the quality in a cellular radio network after a frequency assignment solution is implemented. These parameters will also be discussed briefly.

2 THE FIXED-SPECTRUM FREQUENCY ASSIGNMENT PROBLEM

The FS-FAP can be represented by a weighted, undirected graph *G* with a set of vertices *V* and a set of edges *E* (Montemanni *et al.*, 2003). Formally, it is a quadtuple FS-FAP $= \{V, E, D, P\}$ with

- Every transceiver in the frequency assignment problem is represented by a vertex v where $v \in V$. Every vertex represents a transmitter of the original frequency assignment problem (Montemanni *et al.*, 2003).
- Interference between two transceivers is represented by an edge. Edges will be written as $\{v, u\}$ (Montemanni *et al.*, 2003).
- A label on the edges will be described by D such that the edge $\{v, u\}$ is mapped to $d_{vu} \in N$ where $N=\{x|x$ is a positive integer or zero$\}$. d_{vu} will be defined as the highest separation that may cause unacceptable interference between frequencies assigned to transceivers u and v. The frequency assigned to transceiver v is denoted by $f(v)$ and similarly the frequency assigned to transceiver u is denoted by $f(u)$. If $|f(v) - f(u)| > d_{vu}$, then the interference between the frequencies on transceiver v and u is acceptable (Montemanni *et al.*, 2003).
- A label on the edges will be described by P such that the edge $\{v, u\}$ is mapped to $p_{vu} \in N$ where $N=\{x|x$ is a positive integer or zero$\}$. p_{vu} is defined as the cost to be paid if the separation between the frequencies assigned to transmitters v and u is less than or equal to d_{vu} (Montemanni *et al.*, 2003). The cost of the total interference in the frequency assignment problem is given by the following cost function:

$$Cost(S) = \sum_{\substack{\{v,u\}\in E;\\ |f(v)-f(u)|\le d_{vu}}} p_{vu} \quad (1)$$

where the solution representation of a frequency assignment *S* will be represented by using a list

$<f_s(0), f_s(1), f_s(2),\ldots, f_s(v),\ldots, f_s(|V|-1)>$

where the v^{th} element contains the frequency assigned to transceiver v.

The objective of the FS-FAP is to find an assignment that minimizes the sum of p_{vu} over all pairs for which $|f(v) - f(u)| \geq d_{vw}$ (Montemanni *et al.*, 2003).

3 STIGMERGY SINGLE CELL OPTIMIZATION

In a cellular network each cell is served by a small number of transmitters (usually 1-9). With exception of the broadcast control channel (BCCH) the constraints applied to the frequency assignment of each transceiver (TRX) in the cell may be identical. Due to the BCCH being a critical channel the constraints (frequency separation or penalties) associated with this channel are usually very high. Thus, stigmergy single cell optimization (SSCO) is an appropriate technique that can be used only in cellular telecommunication networks.

Stigmergy single cell optimization (SSCO) allows one to fix all the frequencies assigned to a single cell's interferers. The frequencies of this single cell's transceivers can then be optimized according to the interference patterns that emerge when certain frequencies are selected. If large interference patterns emerge when a frequency is selected then the frequency is discarded. If no interference or minimal interference patterns are experienced by the selection of a frequency then the frequency is accepted. The actual structure of the frequency assignments and the interference patterns created by the frequency selections is constantly influencing the decision of the agent. It is proposed that an agent will change the frequencies on the transceivers according to the structure of the current interference pattern in the frequency assignment structure. The frequency assignment working solution will represent the structure the agent is building. The agent will approach each transceiver and change its frequency to the current best frequency. The current best frequency has the least amount of interference. Once the new frequency has been assigned to the transceiver the cost of the frequency assignment solution is calculated using equation 1. The agent will be stimulated to accept a configuration change where the interference pattern (i.e. cost) was decreased and repel a change that increased the interference.

The analogy to stigmergy comes from the fact that stigmergy is the coordination of tasks and regulation of constructions (e.g. a termite mound in a termite colony) in an environment that depends not on the entities, but on the constructions themselves (Kristensen, 2000 and Valckenaers *et al.*, 2001). The entities do not direct the work but are guided by it. Structure construction e.g. nest building in social wasps is an example of this form of communication. Agents recognize patterns in a structure that is being built and are able to augment it with new components. The changing configurations of the structure act as a source of information that aids the agents when making further decisions. The agents are stimulated by the change in the configuration of the structure and respond accordingly (Bonabeau *et al.*, 1999). Social wasps have the ability to build highly organized construction i.e. nests. These structures can range from a few cells to millions of cells packed in stacked combs. Studies have shown that these building characteristics consist of a series of if-then decision loops (Bonabeau *et al.*, 1999). Each stage of the nest stimulates the wasps to respond in a certain manner.

3.1 Implementing the Stigmergy single cell optimization

The list of fixed frequencies in the network's allocated spectrum will be represented by L. Each frequency is tested using the SSCO. A priority queue will be created with the priority ranked according to the frequency causing the least amount of interference. When a frequency is requested from the priority queue the frequency with the least amount of interference is returned. This is the best current frequency that can be used.

The priority queue calculates the priority of the frequencies with minimum interference by taking as input the transceiver T. Through an iterative process the transceiver T will be set to each frequency in the fixed frequency list L, respectively. For each frequency in the list L that is set to the transceiver T the cost of the total interference is calculated i.e. an interference pattern is determined. Thus each frequency in L will have an associated interference cost. The list L is then sorted in a descending order with the frequency with the lowest interference cost at the top of list L. When requested the priority queue will return the top element or highest priority element from the list L i.e. the frequency with the lowest interference cost.

When the agent is executing the algorithm it will iterate through every transceiver in the FAP. When a certain transceiver v is selected by the agent it will select the best current frequency. The agent does this by requesting the frequency from the priority queue. The frequency is then removed from the priority queue. This process is repeated until a frequency is found that does not cause any violations (i.e. minimizes the interference pattern) and is not in the pheromone list (see section 3.2). Once a frequency is found it is assigned to the transceiver v. The cost is then calculated for the new solution S i.e. Cost(S). If the Cost(S) is less than the previous cost i.e. Cost(S_{prev}) plus a threshold value i.e. Cost(S) – Cost(S_{prev}) $\leq$ *threshold* then the frequency assigned to v is accepted. However, if Cost(S) – Cost(S_{prev}) > *threshold* then the frequency assigned to v is rejected and the transceiver v reverts back to its previous frequency.

3.2 The Analogy to Stigmergy

The structure of the frequency assignment solution influences how the agent assigns frequencies to the different transceivers. The structure seems to provide enough constraints to direct the selection of frequencies. Frequencies are not just added or changed randomly. The agent is influenced by previous frequency assignments. Assignment decisions seem to be made locally on perceived configurations in a way that possibly constrains the assignment dynamics.

The second type of stigmergy built into the algorithm is short term memory via pheromones. This is very similar to a dynamic tabu list which has been used successfully in a number of optimization algorithms (Montemanni *et al.*, 2003, Hao *et al.*, 1998). Each time a frequency is assigned to a transceiver a pheromone is created and added to the pheromone list. A pheromone is a structure containing the transceiver identity, the frequency and a duration variable. The pheromone list is a first-in-first-out queue of pheromones. The time the pheromone resides in the pheromone list is equivalent to the time it would take for the pheromone to dissolve. The pheromone is constantly dissolving in nature. To model this behavior the duration variable in the pheromone is incremented every time a frequency is assigned to a transceiver. The pheromone list is a fixed size M. If the duration variable is greater than M then the pheromone is removed from the pheromone list i.e. it has dissolved.

When the current best frequency is selected it is also checked against the pheromone list. If the current best frequency and transceiver that is busy being changed are matched against an existing pheromone in the pheromone list then that current best frequency is ignored and the next best frequency is selected from the priority queue. This technique allows the search to explore new areas in the search space and to escape local minima (Michalewicz *et al.*, 2007). The general idea behind pheromones in the algorithm is to ensure that certain changes made in the assignment solution are undisturbed for a certain amount of time or future iterations. This forces the algorithm to explore other parts of the search space and after a certain amount of time or after a number of iterations have elapsed these frequencies would become available again (Michalewicz *et al.*, 2007). A β variable was also introduced into the algorithm to reduce the size of the pheromone list M. The pheromone list will reduce over time by setting the size of the pheromone list $T_M = \beta * T_M$. The longer the algorithm executes the shorter the dissolve period for a pheromone. The reason for the reduction of the pheromone dissolve period is that the closer the algorithm moves to an optimized solution the more focused the search should be.

4 SWARM INTELLIGENCE MULTI-AGENT BASED ALGORITHM (SIMBA)

The pseudo code below describes the spectrum priority queue used in the algorithm. The purpose of the spectrum priority queue was to produce a priority queue with the best current frequencies to use. The pseudo code utilizing the spectrum priority queue would remove the first element in the priority queue to find the current best frequency to use.

```
PriorityQueue
spectrumPriorityQ(transceiver v)
 begin
  Instantiate PriorityQueue PQ
  foreach frequency f do
   begin
    oldFreq = v.getFrequency
    v.setFrequency(f)
    cost = Cost(S)
    PQ.add(KeyValuePair<f,cost>)
   end
  v.setFrequency(oldFreq)
  return PQ.sorted
 end.
```

The allow assignment pseudo code described below determines whether the current best frequency selected from the priority queue will be used or not. If the frequency is in the pheromone list then it is not allowed to be used. Similarly, if the frequency causes violating transceivers i.e. the transceivers does not obey co-site and co-cell separation constraints it is not allowed to be used. Violating transceivers cause an increase in the interference pattern. Co-site is defined as transceivers sharing the same site and co-cell is defined as transceivers sharing the same cell. The allow assignment method returns the frequency that does not cause any violating transmitters or that does not reside in the pheromone list otherwise it returns -1.

```
int AllowAssignment(transceiver v,
PriorityQueue PQ)
begin
 while (not PQ.isEmpty)
  begin
   KeyValuePair<frequency,cost>KVP =
    PQ.getFirst()
   PQ.removeFirst()
   if(not inPheromoneList
                  (v,KVP.frequency))
      AND
     (not violatingTransmitter
                  (v,KVP.frequency))
     return KVP.frequency
  end
  return -1
 end.
```

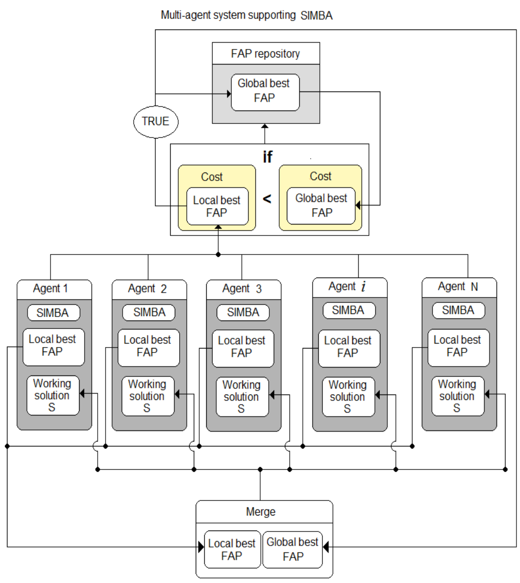

Figure 1: Multi-agent system supporting SIMBA.

The multi-agent framework for the SIMBA is comprised of the agents executing the SIMBA and a repository for the global best solution found (see figure 1). Each agent contains a working solution S for the frequency assignment problem as well as a local best solution. The local best solution is the best solution found by the individual agent. The working solution *S* is the solution that is constantly changing as the search is taking place. Each agent is able to access the repository for the best global solution. If at any time during the execution of the algorithm an agent's local best solution is better than the global best solution i.e. the total interference in the local best solution is less than the total interference in the global best solution then the global best solution is replaced with the agent's local best solution. At this point in time the remainder of the agents in the system excluding the agent that found the new global best solution will perform a transformation on their working solutions (see figure 1). The transformation process performed by the agent merges its current locally best solution with the new global best solution. The merge is dependent on two variables Φ_l and Φ_g. Φ_l is the percentage of the local solution that will be merged into the new working solution and similarly Φ_g is the percentage of the global solution that will be merged into the agent's new working solution. Selecting $\Phi_g > \Phi_l$ allows the merge to put more trust in the global solution i.e. it places more trust in the swarm solution than its own local solution. In this case more of the merged solution will be made up of the global solution than the previous local solution.

The merge method in the swarm interaction takes as input parameters the local and global frequency assignment solutions as well as the two variables Φ_l and Φ_g. $N_{local} = \Phi_l$*(total number of TRXs) and $N_{global} = \Phi_g$*(total number of TRXs). N_{local} will be the number of transceivers (including the set frequency) selected from the local solution. Similarly, N_{global} will be the number of transceivers (including the set frequency) selected from the global solution. A transceiver selected into N_{local} cannot be selected into N_{global} and similarly a transceiver selected into N_{global} cannot be selected into N_{local}. The new merged solution is $N_{global}+N_{local}$.

The Swarm Intelligence Multi-agent Based Algorithm (SIMBA) is described below.

```
SIMBA
begin
 Nit = 0;  TM = 500; Ireduce = 5*10^4;
 Φl = 30 → 40; Φg = 60 → 70;
 Threshold = 1 → 10; alpha = 0.99;
 beta =0.999;
 S = randomly generate solution for
     FAP
 foreach transceiver v do
  begin
   newFreq = AllowAssignment
            (v,spectrumPriorityQ(v))
   if (newFreq not equal to -1) then
    begin
     oldFreq = v.getFrequency()
     prevCost = Cost(S)
     v.setFrequency(newFreq)
     UpdatePheromoneList
        (new Pheromone(newFreq,v,0))
     if ((Cost(S) - prevCost)
        > Threshold) then
      v.setFrequency(oldFreq)
     else
      begin
       if(Cost(S) < Cost(localBest))
        localBest = S
       SwarmInteraction(this,Φl,Φg)
      end
    end
  end
 Nit ++;
 If (Ireduce equals Nit) then
  begin
   Nit = 0;
   TM = TM *beta;
   Threshold = Threshold*alpha
  end
end.
```

The multi-agent system is based on a social model that is based on swarm intelligence. Each agent is making use of its own local search knowledge as well as knowledge from the swarm as a whole to find an optimized solution.

```
void SwarmInteraction
          (SIBAAgent agent, Φl, Φg)
begin
 if (Cost(agent.localBest) <
    Cost(globalBest)) then
  begin
   globalBest = agent.localBest
   GlobalBest.setFound(TRUE);
  end
 if (GlobalBest.getFound())
  begin
   agent.S = Merge(agent.localBest,
                   globalBest,Φl,Φg)
  end
end.
```

5 COST 259 BENCHMARKS AUTHOR(S)

The effectiveness of the SIMBA is demonstrated by applying the SIMBA to the COST 259 benchmarks (Eisenblätter and Koster, 2008). These instances are widely used in the mobile telephone industry. The largest problem considered (Siemens

4) had 2780 transceivers. The best cost values found by the SIMBA for the Siemens instances were compared to the following:

- DTS (Glamorgan) a dynamic tabu search method (Eisenblätter and Koster, 2008).
- K-THIN(UR1) a simulated annealing combined with dynamic programming to compute local optima method (Mannino *et al.*, 2000).
- SA(TUHH) a simulated annealing (Beckmann and Killat, 1999).
- TA(RWTH) a threshold accepting method (Hellebrandt and Heller, 2000).
- TA(Siemens) a threshold accepting method (Hellebrandt and Heller, 2000).
- U(Siemens) an unknown method (Eisenblätter and Koster, 2008).
- SEMA, the Swarm Effect minimization algorithm (O'Reilly and Ehlers, 2008)

Table 1: Siemens 1, GSM 900 network with 179 active sites, 506 cells, and an average of 1.84 TRXs per cell. The available spectrum consists of two blocks containing 20 and 23 frequencies, respectively.

App	Cost	Co	Adj	TRX	TRX pairs exceeding			
					.01	.02	.03	.04
K-THIN	2.20	0.03	0.03	0.05	33	4	1	0
TUHH	2.78	0.04	0.04	0.08	60	14	6	0
RWTH	2.53	0.03	0.03	0.06	48	11	3	0
TA	2.30	0.03	0.03	0.05	43	7	2	0
U	3.36	0.05	0.04	0.12	78	25	10	3
SEMA	2.35	0.03	0.03	0.06	44	9	2	0
SIMBA	2.26	0.03	0.03	0.05	39	7	1	0

Table 2: Siemens 2, GSM 900 network with 86 active sites, 254 cells, and an average of 3.85 TRXs per cell. The available spectrum consists of two blocks containing 4 and 72 frequencies, respectively.

App	Cost	Co	Adj	TRX	TRX pairs exceeding			
					.01	.02	.03	.04
DTS	14.28	0.11	0.02	0.20	343	89	24	18
K-THIN	14.27	0.07	0.02	0.16	359	71	27	17
TUHH	15.46	0.07	0.02	0.18	404	109	42	20
RWTH	14.75	0.06	0.02	0.17	268	91	34	13
TA	15.05	0.11	0.02	0.20	381	92	37	15
U	17.33	0.08	0.02	0.20	462	148	47	18
SEMA	14.86	0.08	0.02	0.17	364	87	41	14
SIMBA	14.34	0.08	0.02	0.20	360	77	33	13

The results from these methods were obtained from the FAP website (Eisenblätter and Koster, 2008) and are presented in tables 1 to 4. The comparison of these results and the results obtained with the SIMBA are also presented in tables 1 to 4. The columns described in tables 1 to 4 are the total cost, the maximum co-channel, adjacent channel and TRX values as well as the total number TRX pairs exceeding an interference of *x* where *x€(0.01, 0.02, 0.03, 0.04)*. The emphasis was on the ultimate quality of the solution that SIMBA produced within limited time constraints. The time constraints set for SIMBA were 24 hours where many of the other algorithms ran for several days.

Table 3: Siemens 3, GSM 900 network with 366 active sites, 894 cells, and an average of 1.82 TRXs per cell. The available spectrum comprises 55 contiguous frequencies.

App	Cost	Co	Adj	TRX	TRX pairs exceeding			
					.01	.02	.03	.04
DTS	5.19	0.04	0.03	0.07	88	14	3	0
K-THIN	4.73	0.03	0.02	0.08	80	6	0	0
TUHH	6.75	0.05	0.03	0.11	137	31	9	2
RWTH	5.63	0.03	0.03	0.07	103	15	3	0
TA	5.26	0.04	0.03	0.07	87	10	3	0
U	8.42	0.05	0.04	0.12	188	47	18	6
SEMA	5.76	0.03	0.03	0.08	101	28	3	0
SIMBA	5.24	0.03	0.03	0.08	83	11	3	0

Table 4: Siemens 4, GSM 900 network with 276 active sites, 760 cells, and an average of 3.66 TRXs per cell. The available spectrum comprises 39 contiguous frequencies.

App	Cost	Co	Adj	TRX	TRX pairs exceeding			
					.01	.02	.03	.04
DTS	81.88	0.20	0.05	0.43	2161	971	547	344
K-THIN	77.25	0.19	0.05	0.36	2053	871	445	282
TUHH	89.15	0.24	0.03	0.53	2350	1056	591	368
RWTH	83.57	0.18	0.04	0.35	2251	1006	540	343
TA	80.97	0.17	0.03	0.36	2143	933	502	328
U	105.8	0.27	0.04	0.53	2644	1286	798	562
SEMA	81.96	0.21	0.05	0.48	2181	991	549	353
SIMBA	81.91	0.21	0.05	0.48	2178	990	549	353

6 CELLULAR RADIO NETWORK PARAMETER DESCRIPTION

The SIMBA was tested on a commercial mobile telecommunications network in South Africa. The frequency assignment solution produced by SIMBA was applied to an operational base station controller (BSC). There were 349 cells with an average of 3 transmitters per cell on the BSC. The available spectrum consisted of two blocks containing 24 and 31 frequencies, respectively. In order to appreciate the results produced in this paper a brief explanation needs to be given of the mobile telecommunications parameters utilized.

The %DROP (percent drop) parameter represents the percentage of abnormal disconnections (drop calls) on the BSC in a mobile cellular network. Clearly, from the description of the %DROP, a decrease in the %DROP would be very advantageous to the network, as the number of abnormal disconnections would decrease.

The idle channel measurement (ICM) was also used as an interference indicator. The idle channel measurement (ICM) parameter is explained with the use of figure 2. There are five interference bands, each marked by a limit. For example, interference band 1 ends at limit 1 and interference band 2 ends at limit 2. This continues up to interference band 5, which is the last interference band. The limits 1 to 5 are represented by the ICM parameters, namely ICM1 to ICM5, respectively. The ICM band parameters provide an indication of the level of interference in the cell. A large number of points in the ICM4 and ICM5 bands indicates a large amount of interference in the BSC and is a very unfavourable situation. From figure 2, it can be seen that the more points in band 5, the more the interference (~-47dBm), while interference band 1 has much less interference (~110dBm). Thus ICM5 is worse than ICM4 and similarly ICM4 is worse than ICM3 and so on. The ideal situation in a mobile cellular network BSC is to have all points located in ICM1 and ICM2, a smaller number of points in ICM3 and virtually no points in ICM4 and ICM5.

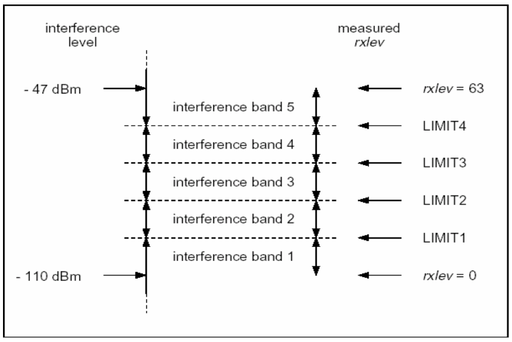

Figure 2: Interference bands 1 to 5, each interference band ends at a limit.

7 RESULTS OF IMPLEMENTATION INTO A CELLULAR RADIO NETWORK

The frequency assignments produced by the SIMBA took on average 24 hours to produce. The frequency assignment produced by the SIMBA was implemented in a cellular radio network. From figure 3 it is clear that there was a decrease in the %DROP on the BSC after the frequency assignment solution was implemented. This can be seen by studying the %DROP before and after the vertical black broken line. The vertical black broken line depicts the point at which the SIMBA frequency assignment solution was implemented into the BSC.

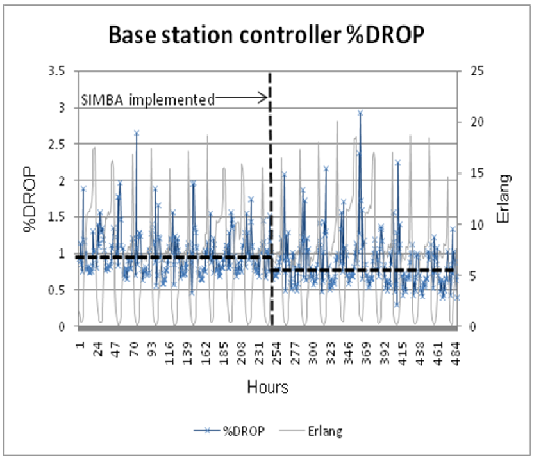

Figure 3: %DROP before and after the SIMBA frequency assignment solution was implemented.

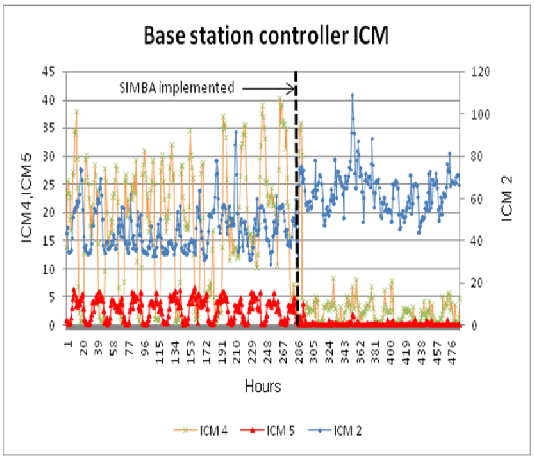

Figure 4: ICM interference bands 2, 4 and 5 before and after the SIMBA frequency assignment solution was implemented.

The decrease in the %DROP was a substantial 0.2 in figure 3 on the %DROP scale. This may not seem significant, but in terms of the %DROP on a cellular network that prides itself on its low %DROP, a decrease of 0.2 is amazing. An improvement of 0.2 on the %DROP scale on a BSC carrying a large amount of traffic can equate to a large addition in revenue. To substantiate the actual decrease of a 0.2 on the %DROP scale, the traffic (erlang rate) would have to have remained constant, since a decrease in the erlang rate would also cause a decrease in the %DROP. However, by studying figure 3 it can be seen that the erlang rate remained constant while there was a distinct decrease in the %DROP after the SIMBA frequency assignment solution was implemented.

Figure 4 depicts the actual idle channel measurements for the BSC before and after the SIMBA frequency assignment solution was implemented. Remember that the vertical black broken line represents the point at which the frequency assignments were implemented. It is apparent from the measurements in figure 4 that there was a drastic drop in ICM5 and ICM4 parameter values after the SIMBA frequency assignment solution was implemented. There was also an extensive improvement in ICM2 after the implementation. These results prove that the SIMBA frequency assignment solution has made considerable improvements to the quality on the BSC. The BSC was optimized to the ideal situation with regard to the ideal channel measurements (see section 6) as the number of points has decreased in the ICM4 and ICM5 bands, while the ICM2 band has increased considerably (see figure 4).

8 CONCLUSION

An engineering problem of high practical relevance has been addressed in this paper. An algorithm based on swarm intelligence that utilizes a multi-agent system has been proposed. The SIMBA also includes a stigmergy single cell optimization (SSCO) approach which is used during selection of the best frequencies that minimize interference patterns. This approach has a strong analogy to natural stigmergy in natural. One of the most important characteristics of the SSCO was that agents recognize interference patterns in the changing structure of the frequency assignment solution and are able to augment it with new components that minimize the interference pattern. The agents are able to make these decisions as the changing configuration of the structures acts as a source of information that aids the agents.

Another important aspect of the SIMBA was the social model created by the multi-agent system. Each agent was able to make local changes to its own local knowledge; however the agent also could gain addition knowledge from the collective giving the SIMBA its swarm intelligence characteristics.

The SIMBA was benchmarked against the COST 259 benchmarks, in particular the Siemens set of problems and the SIMBA closely match some of the best results with a search time of 24 hours. The frequency assignment solutions produced by SIMBA were also implemented into a commercial cellular radio network with good results.

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