

Radar Frequency Assignment in Mobile Radar Units

Robert Macfadzean, S. Ramaswamy and K. S. Barber

Naval Surface Warfare Center, Dahlgren VA
and
The Laboratory for Intelligent Processes and Systems
Electrical and Computer Engineering
The University of Texas at Austin
Austin, TX 78712
<http://www-lips.ece.utexas.edu>
barber@mail.utexas.edu
phone: (512) 471-6152
fax: (512) 471-3652

Abstract

This paper presents a case study based on a radar interference control problem using frequency assignment as the control mechanism. The results suggest that locally autonomous agents will generally not converge to an acceptable solution and a central control using a master will converge, but at a higher cost. These results drive the need for negotiation based autonomy with some form of arbitration to work on goals common to system agents.

Accepted to

Intelligent Systems: A Semiotic Perspective

Workshop: Semiotic Modeling for Sensible Agents

Workshop organizers:
K. Suzanne Barber
Electrical and Computer Engineering
The University of Texas at Austin
24th and Speedway, ENS 240
Austin, TX 78712
phone: (512) 471-6152
fax: (512) 471-3652

Srini Ramaswamy
800 Wheatley Street
School of Computer and Applied Sciences
Georgia Southwestern State University
Americus, GA 31709
Phone: (912) 931-2100
srini@gswrs6k1.gsw.peachnet.edu

October 23-25, 1996

Radar Frequency Assignment in Mobile Radar Units*

R. Macfadzean

Naval Surface Warfare Center, Dahlgren, VA

S. Ramaswamy**, K. S. Barber

Laboratory for Intelligent Processes and Systems, Electrical and Computer Engineering Department
The University of Texas at Austin, Austin, TX-78712

Abstract - This paper presents a case study based on a radar interference control problem using frequency assignment as the control mechanism. The results suggest that locally autonomous agents will generally not converge to an acceptable solution and a central control using a master will converge, but at a higher cost. These results drive the need for negotiation based autonomy with some form of arbitration to work on goals common to system agents.

I. INTRODUCTION

Many agent-based systems are designed with a fixed level of autonomy¹. Issues that determine the appropriate level of autonomy are a problem by itself. The autonomy level of an agent with respect to a goal is defined using four constructs: responsibility, commitment, authority and independence [1]. Based on these constructs, four levels of autonomy may be assigned to the agent's goals: (i) **command-driven**: An agent who is command-driven for a goal achieves this goal by accepting plans from another agent, (ii) **consensus**: Agents in consensus work cooperatively to meet their goals, (iii) **locally autonomous**: Agents that are locally autonomous for a goal can initiate their own thread of execution and can work efficiently toward this goal in an environment with unreliable global information, (iv) **Master**: The agent devices plans for this goal and the goals of other agents who are command-

driven for their respective goals. These issues are addressed in greater detail in [1].

In this paper, the actual impact of autonomy in problem-solving for radars operating in a cooperative environment is discussed. For radars (or units of which the radar is a part) operating close to one another, the issue of interference-free operation is of utmost importance if the radars are to operate efficiently and effectively. In a multi-agent architecture, each unit is considered to have a radar interference control agent (RIC agent) which deals with the assignment of correct frequencies for operation. The RIC agent has the ability to detect interference, represent the states related to the interference, reason about and understand the possible solutions that can resolve interference, and act upon this reasoning to choose a particular operating frequency.

When an RIC agent detects interference it may choose to deal with the interference in three ways: (i) change position, (ii) change frequency, or, (iii) change bandwidth. Sometimes it may be necessary use a combination of the above three methods. For simplicity, we use AND/OR graphs for representing goal trees, where the OR'ing operation indicates that any combination of these approaches may be used. Figure 1 shows a possible AND/OR representation of this goal structure.

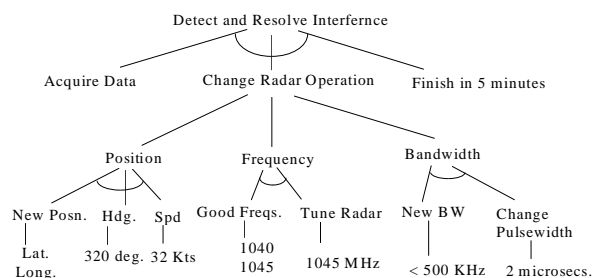


Figure 1: RIC Agent Goal Tree Representation

This paper is organized as follows. Section II presents the radar interference model. In Section III, the frequency assignment problem is discussed in detail. Section IV presents two different solution approaches. One approach presents a simulation based on local autonomy with no outside information, while another treats the RIC agent to consist of command-driven goals that are planned for by a centralized master. It has been shown that while locally autonomous operations are seemingly desirable, the use of a centralized master *always* provides a viable solution. These two approaches sufficiently demonstrate the extreme situations with respect to the various tradeoffs involved. Section V concludes the paper and discusses the results obtained.

* This research was supported in part by the Naval Surface Warfare Center, Dahlgren, VA.

** Dr. Ramaswamy is with the School of Computer and Applied Sciences, Georgia Southwestern State University, Americus, GA 31709. Between Aug. 94 and June 95 and subsequently in Summer 96, Dr. Ramaswamy has been a visiting research fellow with the Laboratory for Intelligent Processes and Systems.

¹ An agent's level of autonomy for a goal specifies the interaction framework in which that goal is planned [1].

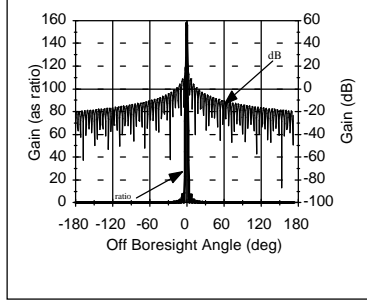


Figure 2. Antenna Gain Pattern for 4 degree beamwidth and maximum gain of 158 (22 dB)

II. RADAR INTERFERENCE MODEL

Various factors cause radar frequency interference². For this research, we are most interested in the following three major factors between the source and victim radars: (i) The off frequency rejection factor: This relates to the difference in frequencies, (ii) Bandwidth: Both bandwidths are of interest, (iii) Range: This represents the physical distance between the radars.

A. Radar Interference Model

The interference power received by a victim radar due to the transmission of a single pulse from a source radar can be modeled by the one-way radar equation:

$$P_V = \frac{P_S G_{mut} \lambda^2 F_{OFR} F_{PROP}}{(4\pi)^2 R^2} \quad (1)$$

where P_V is interference power received by the victim radar (in watts), P_S is the peak power of a single pulse transmitted by the source (in watts), G_{mut} is the product of the source antenna gain in the direction of the victim and the victim antenna gain in the direction of the source, λ is the wavelength (in meters), F_{OFR} is the normalized off-frequency rejection factor (normalized convolution of source transmitter power spectrum and receiver frequency response), F_{PROP} is the propagation factor ($F_{PROP}=1$ when both radars are within the horizon, $F_{PROP} \ll 1$ when masked by earth's curvature) and R is the range (in meters).

B. Mutual Gain

The mutual gain factor depends on the dynamic behavior of the radar antenna, and the shape of the antenna gain pattern. Here, we are interested in search radars with mechanically scanned antennas that rotate continuously in azimuth. The antenna gain pattern for such radars in azimuth and elevation can be approximated by

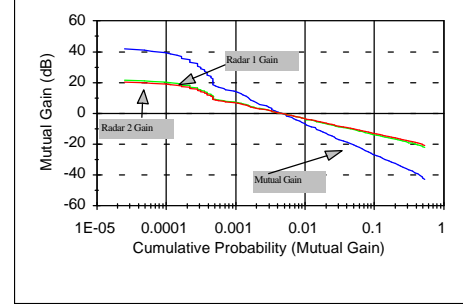


Figure 3. Representative Relationship between Mutual Gain and Cumulative Prob. that Mutual Gain Exceeds a Given Value

$$G = \left[\frac{\sin(2.78\theta / \theta_{bw})}{(2.78\theta / \theta_{bw})} \right]^2 \quad (2)$$

where G is the instantaneous value of antenna gain, G_{max} is the maximum gain of the antenna, along the antenna "boresight", θ is the angle between antenna boresight and direction of interest, (e.g. toward the other radar), θ_{bw} is the nominal beamwidth of the antenna at the -3 dB points either side of the antenna boresight (degrees). The peak gain and the beamwidth are both functions of the physical dimensions of the antenna, its shape, and the radio-frequency wavelength.

Figure 2 shows the antenna pattern for a beamwidth of 4 degrees and a maximum gain along the boresight of 158 (22 dB). These values are typical for L band radars used in air traffic surveillance, or in moderate range search radars in naval ships. The pattern is plotted as a straight ratio and in dB units. The negative spikes seen in the plot based on dB units are uneven in amplitude because a relatively coarse angle increment of about 0.5 degrees was used to generate the plot. Note that the ratio plot shows the main lobe of the function clearly, but interpretation is essentially impossible beyond the second side lobe. The use of dB units is frequently preferred in radar work because of the wide dynamic range of data encountered.

An antenna rotating at 60 RPM will sweep this entire pattern by an arbitrary point once every second. Obviously, the instantaneous value of gain in the direction of an arbitrary point varies by a wide range as the antenna rotates. The mutual gain is the product of the gain of the two antennas associated with the source and victim radars. Therefore, the maximum mutual gain is the product of the maximum gains of each antenna. This maximum mutual gain would only occur at the instant the two antennas are pointing directly toward one another. If the received power that causes damaging interference at the victim is known, and if the source power, wavelength, and mutual gain are known, it is possible to determine the relationship between frequency difference and range that just produces the

² In the following discussion, a victim radar denotes the radar that is being interfered (receiver) with and a source radar is the radar that is interfering (transmitter).

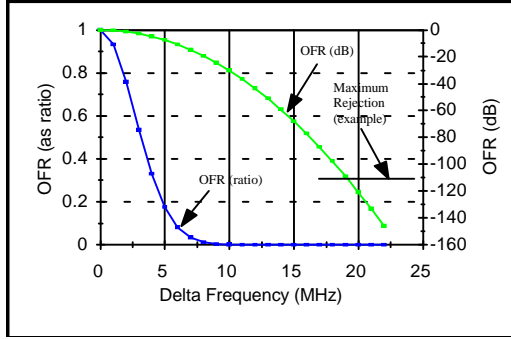


Figure 4. Off Frequency Rejection(OFR) as a Function of Freq. Difference

specified interference power. Range is also implicit in the computation of the F_{PROP} .

A simple approach is proposed in [2] to relate the mutual gain to probability of interference (PI). This is based on the cumulative probability distribution function of the mutual gain. From Figure 3 the fraction of one rotation that the gain is greater than -50 dB, -40 dB, etc., may be determined. This fraction is an estimate of the probability that the gain exceeds the specified value. Obviously, the probability that the gain exceeds 22 dB is 0, because it is the maximum gain of the antenna. If these data are determined for two antennas independently, then the product of the probabilities for a pair of gains yields the probability that the mutual gain exceeds this product. Thus, for a 0 PI, the mutual gain used in the expression for received victim power must be the product of the maximum gains of the two antennas. For a pair of identical antennas having the characteristics as in Figure 3 a PI specified to be .001 would result in a mutual gain value of about 14 dB, i.e. the probability that the mutual gain exceeds 14 dB is about .001. If this value of mutual gain is used in (1), the resulting relationship for frequency difference vs. range represents a constraint relationship such that, if satisfied, results in a PI less than or equal to .001.

C. Off Frequency Rejection

Off frequency rejection is the attenuation of received signals due to a difference in the frequency of the arriving signal and the tuned frequency of the receiver. Rejection is defined as the normalized convolution of the transmitter power spectrum and the receiver frequency response. The characteristics of these spectra vary widely, depending on the type of power device in the transmitter (e.g. magnetron, klystron, traveling wave tube), and on the design of the receiver. Off frequency rejection is usually determined numerically, based on experimental measurements of transmitter and receiver characteristics. For our simulation, we decided to model both spectra as Gaussian functions, with the mean representing the tuned frequency of the transmitter or receiver, with the standard deviation

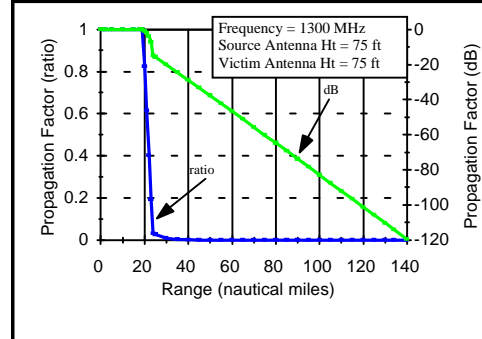


Figure 5. Propagation Factor vs. Range Shown as Ratio and in dB Units

serving as a measure of the bandwidth of the device. The Gaussian function represents the approximate shape of many spectra, and the product of two Gaussian functions has a definite integral when the limits are negative infinity to positive infinity, the basic definition of convolution. This provides an analytical expression for the convolution that can be easily calculated for any set of two frequencies and bandwidths. Thus, F_{OFR} expressed as a normalized convolution is given by

$$F_{OFR} = \frac{\int_{-\infty}^{+\infty} T(f)R(f + \Delta f)df}{\int_{-\infty}^{+\infty} T(f)R(f)df} \quad (3)$$

where $T(f)$ is the transmitter power spectrum (normalized to peak power), $R(f)$ is the receiver frequency response spectrum (normalized to maximum response). When these two spectra are approximated as Gaussian, the F_{OFR} function above can be expressed as

$$F_{OFR} = e^{-\left[\frac{1}{2\sigma_2^2} + \frac{1}{4\sigma_2^2 \left[\frac{1}{2\sigma_1^2} + \frac{1}{2\sigma_2^2} \right]} \right] \Delta f^2} \quad (4)$$

In the above, σ_1 and σ_2 represent the source and victim bandwidths respectively, Δf represents the difference in frequencies between the source and the victim radar (in MHz). For $\Delta f=5$, $\sigma_1=2.4$, and $\sigma_2=1.2$ the off frequency rejection (as a ratio) is $F_{OFR}=0.176$; in dB units, $F_{OFR}(dB) = 10\log(.176) = -7.5$ dB. Figure 4 is a plot of the off frequency rejection vs. frequency for the two above values of σ , shown both as a ratio and in dB units. Figure 4 also shows a notional maximum rejection by the receiver of approximately -130 dB. The implication of this is that no further reduction in rejection can be obtained by tuning off more than the corresponding frequency difference, about 20 MHz in this case. The character of these data is very similar to many transmitter-receiver pairs, except that many receivers have an image response at some frequency that is offset from the tuned frequency of the receiver. This results in a non-symmetrical off-frequency rejection,

meaning for example that a difference of +5 MHz has a different result than -5 MHz. Our model does not account for this factor.

D. Propagation Factor (Diffraction)

Most radar computations assume a line of sight between the radar and its intended target. Although high powered radars may detect targets beyond the horizon, the diffraction effect rapidly attenuates the power density at the target, and further attenuates the reflected power back at the radar antenna essentially making the probability of detection near zero for targets that are beyond the horizon. When interference between radars is being considered, the assumption that diffraction renders over-the-horizon effects negligible is no longer valid because of the one-way path (i.e. the attenuation only occurs during the travel from the source to victim) and the high powers involved. At the same time, the attenuation that does occur is much greater than predicted by free-space propagation, resulting in reasonable range separation for low interference given a particular frequency separation. The propagation factor model normally accounts for the diffraction effect and multipath. We consider only the diffraction effect. The diffraction model depends on an estimate of the range to the radar horizon. The radar horizon is slightly greater than the optical horizon, and is approximated under non-ducting conditions as

$$R_{hor} = 1.23(\sqrt{h_{source}} + \sqrt{h_{victim}}) \quad (5)$$

where R_{hor} is the horizon range (nautical miles), h_{source} is the height of source antenna (feet) and h_{victim} is the height of victim antenna (feet). We are using mixed units because the empirical diffraction prediction we use from Blake [3], is based on these units and we wished to maintain the same constants used in [3]. Conversion to metric or other desired units is easily done. The diffraction model is complex, requiring three range zones to define. The first range zone extends from the source radar to just shy of the horizon range computed in (5) above. We have defined zone 1 to extend from 0 to $0.95R_{hor}$. The propagation factor in zone 1 is unity, i.e. there is no attenuation due to diffraction around the curved earth in zone 1. Zone 2 is the transition zone, for which there is

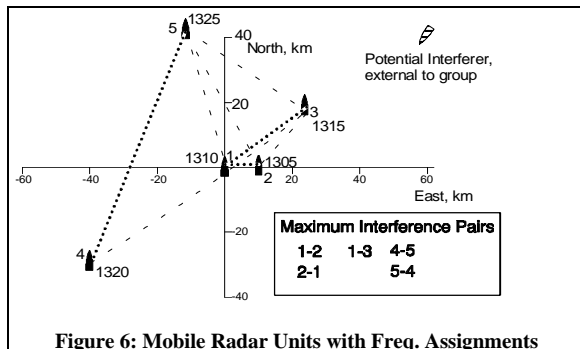


Figure 6: Mobile Radar Units with Freq. Assignments

$\ell = k1/f^{1/3}$, $k1=102.7$, f =frequency (MHz)
$H=k2/f^{2/3}$ $k2=6988$
$z1 = z1'/H$, $z1'$ = height of antenna 1 (feet)
$z2 = z2'/H$, $z2'$ = height of antenna 2 (feet)
$R_{low} = .95 R_{hor}$, $R_{high}=1.10 R_{hor}$, R = range
$Uz1 = 10^{(19.85(z1^{.47}-0.9)/20)}$
$Uz2 = 10^{(19.85(z2^{.47}-0.9)/20)}$
$VX = 2\sqrt{\prod R_1} e^{-2.02R_1}$, $R_1 = R_{high} / \ell$,

Table 1: Empirical values for calculating F_{PROP}

little data available and no suitable empirical model. In [3], it is suggested that interpolation be used between zone 1 and the full diffraction effect, defined as zone 3. Full diffraction was assumed to be active at $1.10R_{hor}$; therefore, zone 2 extends from $0.95R_{hor}$ to $1.10R_{hor}$. At the shorter range, the propagation factor is 1; at the longer range, it is forced equal to the propagation factor computed from the empirical relations from [3]. In our model, we use linear interpolation between the two ranges and do not attempt to match slopes. Table 1 gives the empirical expressions used in our calculation for F_{PROP} for zone 3. Thus, F_{PROP} for the full diffraction zone (for zone 3) is given by:

$$F_{PROP} = VX * Uz1 * Uz2 \quad (6)$$

Figure 5 shows the propagation factor due to diffraction for a typical L band radar. The frequency of this radar is assumed to be 1305 MHz. The source antenna and victim antenna are each assumed to be at a height of 75 feet, yielding a horizon range of 21.3 nautical miles. The values of R_{low} and R_{high} are 20.2 and 23.4 nautical miles, respectively. Note that this factor, which is a function of range, is multiplied by the remaining portions of equation (1) which is also a function of range. When equation (1) is being solved for range as a function of frequency difference (given a value for the interference power level), the solution must be obtained iteratively because of the propagation factor. A simple application of Newton's method results in fast and reliable convergence to the range value that balances the equation.

The above model can be used to modify propagation conditions, allowing interference control methods to be tested in the presence of uncertainty about propagation. For example, the horizon range can be artificially increased to simulate ducting. The result, in terms of interference, would be a larger frequency difference requirement at a given range to maintain an acceptable level of interference. The $k1$ term can be adjusted to change the slope of the full diffraction curve to simulate a less severe ducting condition. Increasing the $k1$ term above from its nominal value of 102.7 to 200 reduces the slope of the propagation curve such that the attenuation at 140 nautical miles decreases from -120 dB to about -60 dB.

III. RADAR FREQUENCY ASSIGNMENT

Figure 6 shows a group of five mobile units, each containing an L band radar. An identifying number and the frequency are shown opposite each unit. Complete parameter sets describing each radar are given in Table 2.

Parameter	Radar 1	Radar 2	Radar 3	Radar 4	Radar 5
Peak Power (w)	50	50	100	250	250
Freq. (MHz)	1310	1305	1315	1320	1325
Min Tuning Freq	1300	1300	1300	1300	1300
Max Tuning Freq	1340	1340	1340	1340	1340
Tuning Increment	5	5	5	5	5
Hor. Beamwidth (deg)	3.94	5.27	7.84	3.91	3.89
Ver. Beamwidth (deg)	15.75	15.81	15.69	7.81	7.78
Peak Gain (dB)	22.02	20.73	19.04	25.09	25.09
PRF (pulses/sec)	1000	1000	1000	1000	1000
Pulsewidth (μ s)	1	2	3	1	0.5
BW (MHz)	1.2	0.6	0.4	1.2	2.4
σ , used in F_{OFR} (MHz)	1.02	0.51	0.34	1.02	2.04
Easting (m)	0	10	25	-40	-10
Northing (m)	0	0	20	-30	45
Ant. Height (m)	25	25	25	25	25
Thermal Noise	-140	-140	-140	-140	-140
Int. Flr. (w)	-140	-140	-140	-146	-146
Max F_{OFR} Rejection (dB)	-130	-130	-130	-130	-130
Desired Prob. of Int.	0.001	0.001	0.0005	0.0005	0.0005
Max Int. Level	4	4	4	5	5
Max Int. level - source	2	1	1	5	4

Table 2. Radar Parameter Sets

For the data given, each of the five radars experiences interference to some degree. The table at the bottom of Figure 6 indicates which source-victim pairs exhibit the maximum level of interference. For example, radar 2 is being interfered with, and the maximum interference level is attributed to radar 1. The example radars on which Figure 5 and Table 2 are based are generally realistic, but are not based on any particular radar unit. An exhaustive search was conducted through all frequency combinations to determine which frequency assignments resulted in an acceptable interference level at each radar, i.e. one that met the probability of interference criterion for each radar. An exhaustive search would not be used in practice. It is provided here to indicate the complete solution space with which to judge other methods.

Table 3 shows the minimum frequency differences that must exist between each radar pair to meet the minimum interference probability specified in Table 2. Of course, these differences cannot be exactly met because the tuning increment for each of the radars is 5 MHz. Thus the only available frequencies are at intervals of 5 MHz between 1300 and 1340 MHz. Table 4 shows the twenty-four

Radars (i, j)	Freq. Diff	Radars(i,j)	Freq. Diff
(1, 2)	8	(2, 4)	8
(1, 3)	7	(2, 5)	14
(1, 4)	10	(3, 4)	6
(1, 5)	15	(3, 5)	14
(2,3)	5	(4, 5)	13

Table 3: Minimum Freq. Differences Between Radars

frequency assignments for the five radars that result in each radar meeting its criterion for probability of interference(PI). Note that of the twenty-four assignments, four produce global minimum interference levels, defined as the sum of the maximum interference at each of the five radars.

IV. RIC AGENT AUTONOMY

When a RIC agent detects interference, it may attempt to solve the problem using three basic approaches. These include: (i) totally on its own, i.e. using locally autonomous goals, (ii) through consensus with other agents, i.e. through negotiative autonomy, (iii) by accepting orders from a master, i.e. command-driven autonomy. Solutions based on local autonomy and an omniscient centralized master are discussed below.

A. Locally Autonomous Approach

In this situation, an agent detects interference and attempts to solve the problem with no knowledge of other agents or the environment. It *only* has information on its own interference state, available frequencies for assignment to

Seq. Number	Radar 1	Radar 2	Radar 3	Radar 4	Radar 5	FOM Total*
1	1300	1310	1315	1325	1340	-20
2	1300	1315	1310	1325	1340	-20
3	1300	1320	1325	1310	1340	-17
4	1300	1325	1320	1310	1340	-21
5	1310	1320	1325	1300	1340	-17
6	1310	1325	1320	1300	1340	-21
7	1315	1300	1305	1325	1340	-19
8	1315	1305	1300	1325	1340	-19
9	1315	1325	1330	1340	1300	-20
10	1315	1330	1325	1340	1300	-20
11	1315	1335	1340	1325	1300	-18
12	1315	1340	1335	1325	1300	-18
13	1325	1300	1305	1315	1340	-18
14	1325	1305	1300	1315	1340	-18
15	1325	1310	1315	1300	1340	-20
16	1325	1315	1310	1300	1340	-20
17	1325	1335	1340	1315	1300	-19
18	1325	1340	1335	1315	1300	-19
19	1330	1315	1320	1340	1300	-21
20	1330	1320	1315	1340	1300	-17
21	1340	1315	1320	1330	1300	-21
22	1340	1320	1315	1330	1300	-17
23	1340	1325	1330	1315	1300	-20
24	1340	1330	1325	1315	1300	-20

* FOM stands for Function of Merit

Table 4. Freq. Assignments Meeting PI. Criteria itself, and a measurement of the current frequency. A

Run #	Freq 1	Freq 2	Freq 3	Freq 4	Freq 5
1	1310*	1300	1315*	1320*	1335
2	1310*	1305*	1300	1340	1325
3	1310	1305*	1300	1340*	1325
4	1310	1305*	1300	1340	1325*
5	1340	1310	1300	1320*	1325*

*: Unable to find interference-free frequency assignment in this run

Table 5. Results of Locally Autonomous Approach

simulation was prepared based on the radar interference model described in Section II. A run in the simulation consisted of random ordering the five agents, then allowing each agent to successively test for interference and attempt to get rid of it by a frequency change. To maintain some degree of control we chose to randomize the order, then force the agents to work sequentially (*not simultaneously*) within the random order. Basically, each agent with interference increased its frequency until the maximum tuning value was reached, then set the frequency to the minimum tuning value and continued increasing until the interference was gone or until the original frequency was reached. After going through this cycle, the second randomly chosen agent performed the same steps. When all agents had no interference, the simulation halted. In all test cases attempted based on the initial conditions indicated in Table 2, no complete solution evolved. The results of five such tests are shown below in Table 5.

B. Centralized Master Based Approach

In this approach, the master is given all pertinent information about each radar, and a utility based search approach [4] was used to find frequency assignments. It resulted in an interference-free frequency assignments for all radars (within PI requirements). The utility based search approach generated a solution in every test case. The length of the search varied widely, due to the many non-global minima encountered.

The basic algorithm was to find the combination of radar and frequency change that resulted in the maximum change in the global figure of merit. After making the change, the process was repeated until the figure of merit indicated that a solution has been found or until no further reduction in the figure of merit was possible. If no further reduction in the figure of merit was possible, a random set of frequency assignments was generated for each of the five radars, and the utility-based search repeated. The number of random initializations varied from 1 to 35, with the average being about 12. Typically, rapid convergence to a near solution occurred for each set of initial frequencies, but the existence of many local minima that did not satisfy the interference criteria caused hanging. This problem might benefit from the genetic algorithm approach, but this was not attempted.

V. CONCLUSIONS

This paper presented a case study for assigning interference-free frequencies to radars working in a cooperative environment. While, the use of a locally autonomous construct seems to be intuitively appropriate, the efficiency of this approach is highly dependent on the a *good initial (random)* assignment of frequencies. In this situation, no appropriate solution was found. A possible

reason for this situation is because, for the interference-free operation of radars that are experiencing interference, a radar that is currently interference-free may have to give up its frequency and mutually resolve the interference problem. However, since the problem solving activity is completely local, this does not happen. Therefore, the radars that experience interference continue to do so (stuck in groups of 2 or 3). An easy compromise solution is to use table 4 for the initial value assignments of 3 or 4 radar frequencies and the other remaining radars find the correct operating frequency when assigned a completely *random* initial frequency. However, this implies, that the RIC's ability to find an interference-free frequency *depends* on the initial value assignment. The absence of a centralized effort in problem solving leads to two or three radars being in conflict with respect to frequency assignments. This problem is further handicapped by the absence of coordinated / negotiated consensus.

On the other hand, the centralized approach illustrates the other extreme. To its merit, it always finds a solution. However, it may require a high communication / computational overhead. Although, it is assumed that the centralized master has complete knowledge about all the other RIC agents, it might also require dynamic data from each RIC agent. The assumption that the centralized master has complete information about each agent and the propagation is too simplistic. However, this presents a valuable insight into centralized problem solving approaches. One possible solution may be to have a negotiated problem solving approach with a clear arbitrator taking the role of the centralized agent.

Finally, the simulations are entirely based on accommodating the interference problem using just one method - modification of radar frequencies. Future research remains in addressing the combination of the control methods.

VI. REFERENCES

1. C. E. Martin, K. S. Barber, "Representation of Autonomy in Distributed Agent-Based Systems", in *Workshop on "Semiotic Modeling for Sensible Agents"*, *Intelligent Systems: A Semiotic Perspective*, NIST, Gaithersburg, MD, Oct. 23-25, 1996.
2. J. Cross, "Naval Radar Frequency Management", Technical Report, Aug. 1986. Atlantic Research Corporation.
3. Lamont V. Blake, "Radar Range-Performance Analysis", Lexington Books, 1980.
4. M. Massaro, "A Multivariable Search Approach to Frequency Assignment", *Proceedings of the International Symposium on Electromagnetic Compatibility*, July 13-15, 1976. pp. 47-52.

