Implementation and Evaluation of a Distributed Interactive Simulation Architecture for Group Interaction and Coordination: A Case Study in Interference Detection and Resolution in Naval Radar Units *

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Abstract: In last year's conference, a two-level architecture for the implementation of a distributed simulation environment for interference detection and frequency assignment in naval radar units [1]. In this paper, we present the current implementation and results obtained and the performance analysis of each of the three algorithms namely locally autonomous, master-slave and negotiation based algorithms for interference resolution. The locally autonomous algorithm is designed to be useful in totally chaotic conditions, while the master-slave algorithm is designed to be useful in deterministic situations. The negotiation-based approach is designed as a suitable alternative for situations that fall in between these extremes.

I. Introduction

At last year's conference, we presented a paper describing a two-level architecture for the implementation of a distributed simulation environment for interference detection and frequency assignment in naval radar units [1]. The Java-based distributed interactive simulation was designed as a two level architecture incorporating *i)* multiple radars on each ship controlled through a lower-level intra-ship interference control module and, *ii)* multiple ships in a group coordinated through a higher-level interference control module. This is shown in Figure 1. Each ship's interference detection and control mechanism would be composed of these two separate levels, called a control agent, dynamically coordinating with one another in eliminating interference problems. In addition, the control agent is a multi-threaded architecture that incorporates the maintenance of a distributed data base system that contains periodically updated radar information. In that paper, we presented a two-level distributed interactive simulation architecture for the interference resolution.

As stated in [1], the approach had the following advantages to enhance the simulation environment: *i) Intra and Inter Ship Interference:* Interference resolution is *one* of the issues addressed by a control agent that has a two-level architecture, a lower level and a higher level. The lower level resolves the interference problem if the source of interference is within the ship. If the source of interference is not from within the ship, then the lower level passes the responsibility to the higher level. The higher level of the control agent detects the source *(outside)* of interference. If the source is a radar of another ship within the group, it may resolve the interference problem in one of the following modes, viz. Master-Slave, Locally Autonomous, or the Negotiation based mode. *ii) Two-level Architecture:* A two level approach helps in balancing the local goals and the system goals and developing appropriate data structures and encapsulation techniques for addressing such concerns appropriately. Here the local goal of each control agent is to provide interference free operating frequencies to radar units on the ship and the system goal is to provide interference free operating frequencies for all radar units on all the ships within the group. *iii) Group Coordination Strategies:* Using the proposed architecture, it is easy to implement and study algorithms for group coordination. Different coordination and group management (arbitration, election of a group representative, determining group membership eligibility, rescinding / retaining group memberships, etc.) algorithms may be selectively implemented and comparatively evaluated. *iv) Localized Databases*: The two-level structure also incorporates a separate database associated with every control agent. By creating a separate thread of control for coordinating -i.e. report and maintain - database related information to legal group members, the simulation now provides for any individual control agent to assume control whenever it is decided that a group coordinator is no longer available. *v) Generic Test-bed*: The two-level implementation provides a generic test-bed for studying performance issues such as the available reaction time w.r.t. the speed of detection of an interference and its subsequent resolution, estimation of the percentage of false alarms and the consequences of subsequent actions, etc.

Each agent (ship) in the simulation is composed of one or more radars. Hence, interference for a given radar may be due to either of the following three reasons: *i)* another radar in the same ship, *ii)* radar of another ship in the same group, or *iii)* an external interference. AS in [1], in this paper the first two cases are referred to as intra-radar interference and inter-radar interference. The interference problem is resolved by either

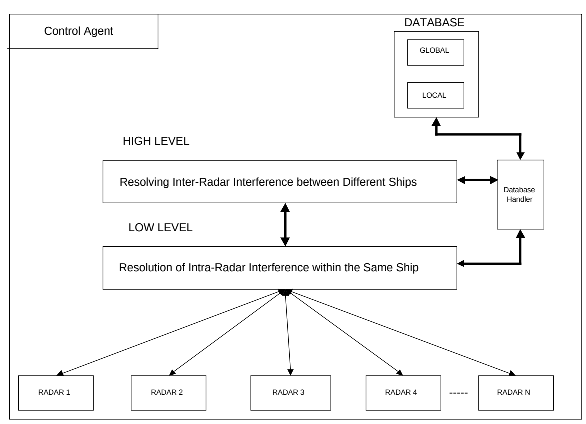

Figure 1. Two-level Control Agent Architecture

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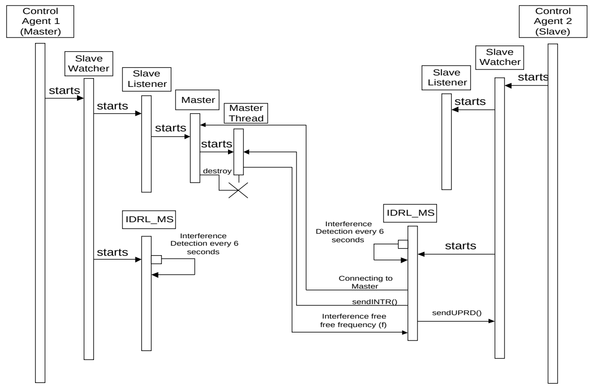


Figure 2. Interaction diagram in the Master-Slave Mode

changing the radar's frequency, bandwidth or position. The desirable alternative is for the interference resolution process to change a radar's frequency.

In this paper, the performance of each approach for interference resolution, viz. Master-Slave, Locally Autonomous, or the Negotiation, is determined by the time taken by each approach to detect, resolve the interference and update the database.

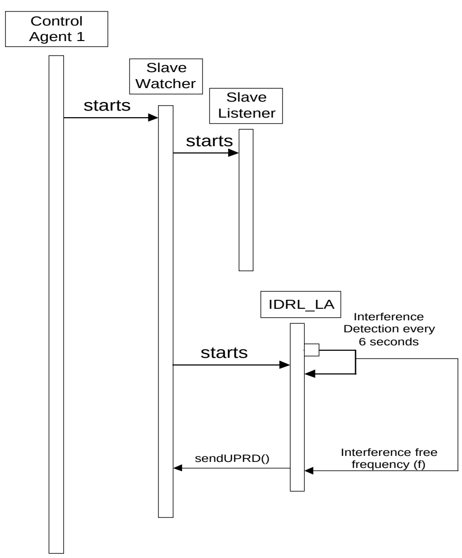


Figure 3. Interaction diagram in the Locally Autonomous Mode

The rest of this paper is organized as follows. The paper is organized as follows: Section II explains as to how each of the three algorithm viz. locally autonomous, master-slave and negotiation-based algorithms are implemented in the two-level software agent. Then each of the algorithms is evaluated based on the time taken by each algorithm to detect and resolve interference under different set of test conditions. Performance evaluation of each of the algorithm is discussed in Section III. Section IV concludes the paper.

II. The Control Agent Architecture

The control agent (ship) can be configured to operate in either of the following modes viz. Locally Autonomous, Master-Slave (Centralized) or Negotiation based modes. The following sections explain elaborately how each of the approaches mentioned above is used to detect and resolve interference using class interaction diagrams.

II. A. Master-Slave Approach

When the control agent is started in the master-slave mode the first ship that starts up becomes the master. The interaction diagram as to how interference is resolved in the master-slave mode is shown in Figure 2. The object initiating the interaction is placed at the left and increasingly more subordinate objects are placed to the right. The events that occur as time progresses are shown in increasing order of time from top to bottom along Y-axis. All the ships that join the group are slaves and the first one remains as their master until and unless it gets destroyed or leaves the group. In that case the ship that joined the group second becomes the new master control agent. This process goes on. The IDRL_MS class takes care of the detection and resolution of the interference problem. This class has two parts *i*) detection and *ii)* resolution. The detection fragment of the thread is active in all the control agents but the resolution fragment of it is active only in the current master. Hence whenever a ship detects an inter-radar interference it contacts the master and informs the master about the source causing the interference. The master randomly generates a new interference free frequency for this ship and sends it. Once the ship updates its radar and ship information in the database it acknowledges to the master. The detection algorithm checks for interference every six seconds. Thus resolution occurs every six seconds if there is interference.

II. B. Locally Autonomous Mode

In the locally autonomous mode each ship is its own master. Whenever it detects an external interference, it switches to a new interference free frequency and updates the database. The main difference between the master-slave and locally autonomous mode is that both fragments of the IDRL_LA class are active in locally autonomous mode. The interaction diagram as to how interference is resolved in the locally autonomous mode is shown in Figure 3. Then it broadcasts the new copy of the database to all the ships in the group. As in the case of the master-slave mode, the detection algorithm checks for interference every six seconds. Thus resolution occurs every six seconds if there is interference.

II. C. Negotiation Mode

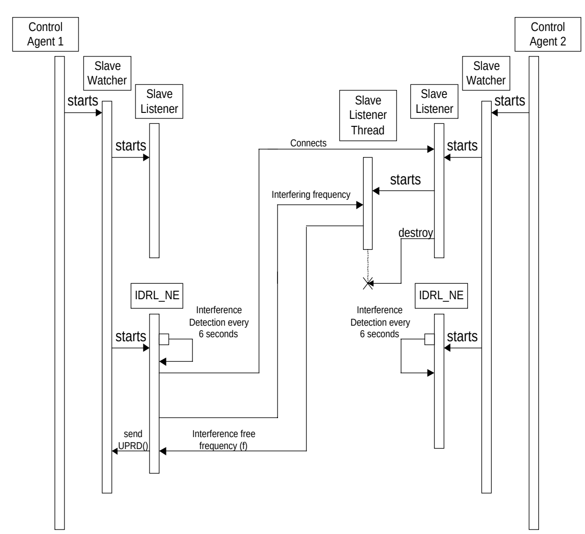


Figure 4. Interaction diagram in the Negotiation Mode

Negotiation is a process in which parties that a have conflict talk to each other in order to resolve the conflict and arrive at a solution that is mutually beneficial. Whenever there is interference between two ships the one that detects the interference first starts negotiating with the ship that is causing the interference. The interfering ship assigns a new interference free frequency to the ship that detected the interference. The ship that detected the interference then switches to this new frequency and updates the radar information in the database and broadcasts the new copy of the

Case IA: All Radar Units with 0.4 MHz Bandwith									
Locally Autonomous Mode									
	Number of Ships in the Group								
Radar/Ship	2	3	4	5	6	7	8	9	10
1	223	236	239	247	268	1234	2698	4556	8067
2	231	238	245	255	271	1943	3756	6706	9143
3	234	240	247	262	1244	2903	4223	7022	9532
4	236	243	248	268	1327	3055	4620	7537	9836
5	236	245	253	270	1521	3114	5210	8240	10057
Master-Slave Mode									
	Number of Ships in the Group								
Radar/Ship	2	3	4	5	6	7	8	9	10
1	342	411	420	423	534	745	921	1138	1169
2	421	421	426	440	576	850	950	1146	1254
3	422	453	470	518	645	778	953	1190	1287
4	427	464	555	579	712	939	1022	1220	1325
5	432	561	565	622	768	989	1085	1240	1381
Negotiation Mode									
	Number of Ships in the Group								
Radar/Ship	2	3	4	5	6	7	8	9	10
1	381	381	390	391	395	398	406	418	421
2	383	385	391	393	398	408	413	427	445
3	386	388	392	413	421	424	430	446	453
4	388	390	400	414	432	438	447	456	464
5	390	391	401	408	425	440	456	461	467

Table 1. All Radar Units with 0.4 MHz Bandwidth

database to all the ships in the group. If two ships detect that they are interfering with each other at the same time, then both of them assign a new interference free frequency to each other. As mentioned in the other modes, the detection algorithm checks for interference every six seconds. Thus resolution occurs every six seconds if there is interference. The interaction diagram of how negotiation occurs between two ships having interference is shown in Figure 4.

Case IC: All Radar Units with 1.2 MHz Bandwidth									
Locally Autonomous Mode									
	Number of Ships in the Group								
Radar/Ship	2	3	4	5	6	7	8	9	10
1	202	213	232	245	279	2508	6063	8106	10075
2	203	215	234	246	290	3352	6797	8402	11468
3	207	218	239	249	1419	4223	7242	8954	12313
4	216	218	244	255	1646	4922	7367	9476	14176
5	221	242	259	279	1819	5384	7962	10030	16021
Master-Slave Mode									
	Number of Ships in the Group								
Radar/Ship	2	3	4	5	6	7	8	9	10
1	346	425	496	513	800	1250	2652	3166	5177
2	403	433	511	547	923	1325	2836	3422	5251
3	417	461	532	556	973	1440	2912	3735	5486
4	418	508	541	591	1028	1976	2998	4091	5544
5	426	511	557	652	1101	2541	3120	4322	5628
Negotiation Mode									
	Number of Ships in the Group								
Radar/Ship	2	3	4	5	6	7	8	9	10
1	382	383	392	396	402	404	416	421	423
2	385	385	390	402	405	407	425	435	454
3	388	389	399	412	413	418	430	448	458
4	389	395	401	417	427	435	443	457	466
5	393	395	399	421	427	440	449	455	469

Table 3. All Radar Units with 1.2 MHz Bandwidth

Initially the control agent starts the SlaveWatcher class, which in turn starts the SlaveListener and the IDRL_NE classes. The SlaveListener class runs in an infinite loop ready to accept client connections. The IDRL_NE class has the interference detection and resolution algorithms in it. This thread again runs in an infinite loop and checks for interference every six seconds. Let us consider the case when control agent 1 detects that it is having interference from control agent 2. It connects to the SlaveListener of control agent 2 and starts negotiation. The SlaveListener starts a new thread SlaveListenerThread in order to negotiate with control agent 1. This way it can accept any number of client connections for negotiation at the same time. Then control agent 1 informs control agent 2 that one of its radar units is interfering and passes the interfering frequency to it. The SlaveListener thread

Case IB: All Radar Units with 0.6 MHz Bandwith									
Locally Autonomous Mode									
	Number of Ships in the Group								
Radar/Ship	2	3	4	5	6	7	8	9	10
1	201	221	230	241	261	2056	5554	7272	10034
2	200	221	233	254	266	3404	5929	7528	11339
3	196	223	237	255	704	4154	6216	8112	12250
4	201	226	238	256	1325	4529	6660	8780	13193
5	218	228	241	259	1418	5233	6948	9776	14356
Master-Slave Mode									
	Number of Ships in the Group								
Radar/Ship	2	3	4	5	6	7	8	9	10
1	347	425	496	513	578	781	907	1118	1278
2	401	433	509	553	608	821	944	1141	1337
3	414	466	531	555	673	867	974	1187	1378
4	414	501	540	595	707	903	1055	1261	1391
5	425	510	556	653	764	922	1092	1278	1421
Negotiation Mode									
	Number of Ships in the Group								
Radar/Ship	2	3	4	5	6	7	8	9	10
1	384	384	391	392	395	398	411	421	421
2	387	385	391	392	397	416	413	437	463
3	389	385	400	403	410	420	436	454	465
4	390	388	401	421	426	433	451	455	466
5	390	390	402	422	433	436	451	460	469

Table 2. All Radar Units with 0.6 MHz Bandwidth

then randomly generates a new interference free frequency and sends it to control agent 1. Control agent 1 switches it's radar to this new frequency, updates the database and propagates the new copy of the database to all the ships in the group.

III. Performance Evaluation

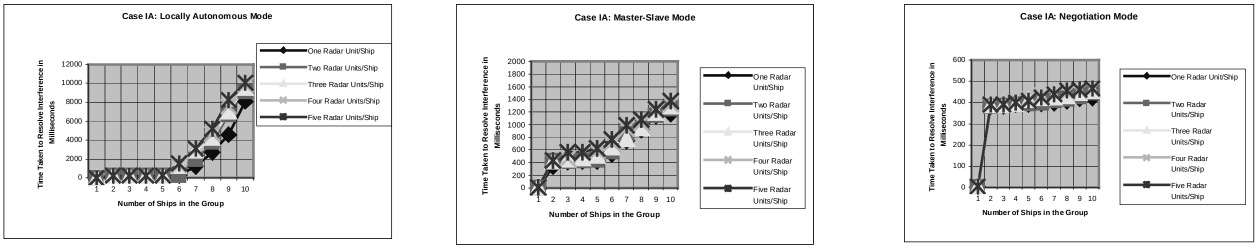
In order to evaluate the performance of each of the three approaches viz. locally autonomous, master-slave and negotiation based approaches, based on the time taken by each of the approaches to detect, resolve the interference and update the database, a test code is plugged individually into each of these modules. The test module that is used is the same for all three modes. It writes the ship name and time into the report file whenever interference is detected and resolved by any of the ships in the group.

Interference is created between ships by manual entry between two or more ships having more than one radar unit on each of them. Whenever interference is detected by any of the ships in the group, the time at which the interference was detected is written into a report file using a file output stream by the test module that is plugged into the code. Similarly the time at which interference is resolved and the database is updated is also logged into the report file.

The following assumptions are experimental assumptions that are made while evaluating the performance of each of the

Case II: Homogeneous Distribution, All radars on same ship have same bandwidth									
0.4 MHz -2 Ships, 0.6 MHz- 2 Ships, 1.2 MHz - 2 Ships, 2.4 MHz - 2 Ships, 5 MHz - 2 Ships									
Locally Autonomous Mode									
	Number of Ships in the Group								
Radar/Ship	2	3	4	5	6	7	8	9	10
1	223	236	239	247	268	1234	2698	4556	8067
2	231	238	245	255	271	1943	3756	6706	9143
3	234	240	247	262	1244	2903	4223	7022	9532
4	236	243	248	268	1327	3055	4620	7537	9836
5	236	245	253	270	1521	3114	5210	8240	10057
Master-Slave Mode									
	Number of Ships in the Group								
Radar/Ship	2	3	4	5	6	7	8	9	10
1	342	411	420	423	534	745	921	1138	1169
2	421	421	426	440	576	850	950	1146	1254
3	422	453	470	518	645	778	953	1190	1287
4	427	464	555	579	712	939	1022	1220	1325
5	432	561	565	622	768	989	1085	1240	1381
Negotiation Mode									
	Number of Ships in the Group								
Radar/Ship	2	3	4	5	6	7	8	9	10
1	381	381	390	391	395	398	406	418	421
2	383	385	391	393	398	408	413	427	445
3	386	388	392	413	421	424	430	446	453
4	388	390	400	414	432	438	447	456	464
5	390	391	401	408	425	440	456	461	467

Table 4. Radar Units within the ship with Same Bandwidth

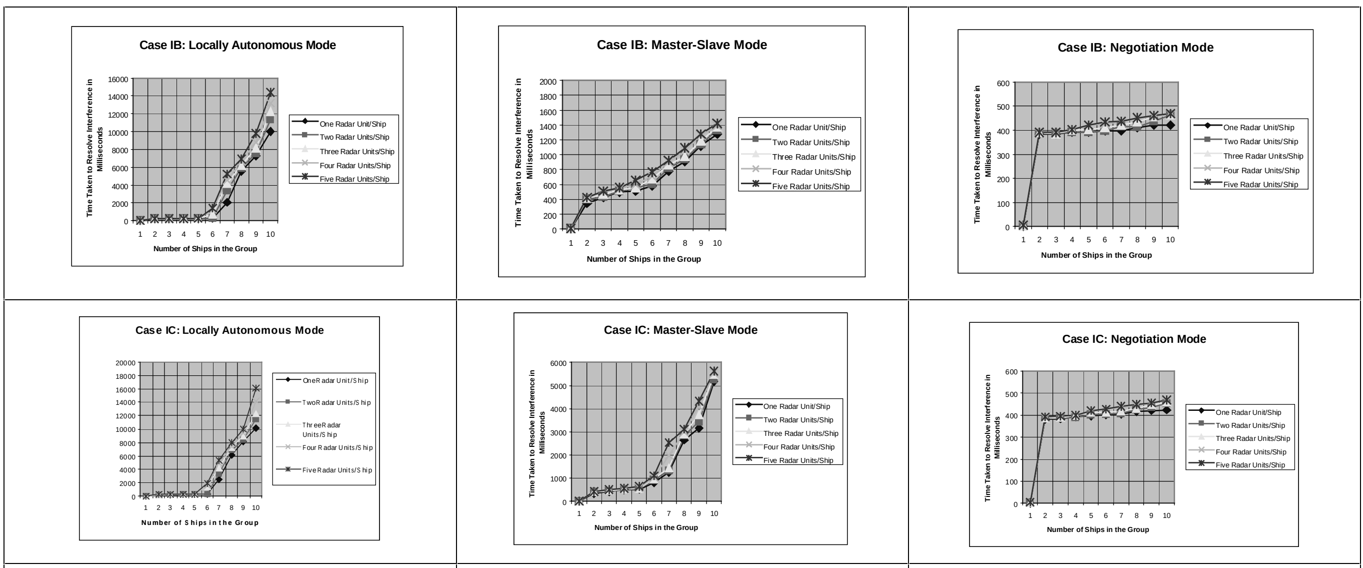


Locally Autonomous | Master-Slave | Negotiation

Figure 5. Performance Plots for Case IA

above-mentioned approaches:

- All radar units in all the ships in the group have the same receiver threshold power of –70 dB.
- All radar units in every ship in the group have the same peak transmitting power and threshold.



Locally Autonomous	Master-Slave	Negotiation

Figure 6. Performance Plots for Case IB and IC

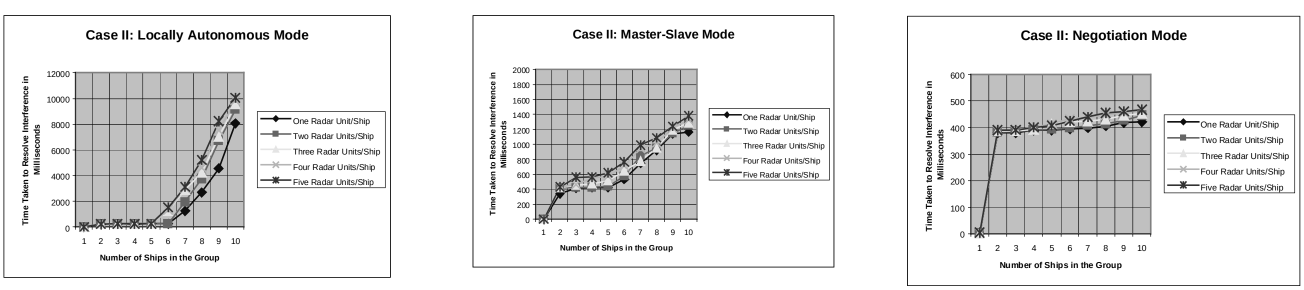
- In all the test cases the moderate ducting factor is used while calculating the propagation factor

III. A. Case I

This case involves three sub-cases: Case IA - where all radar units have 0.4 MHz bandwidths, Case IB - where all radar units have 0.6 MHz bandwidhs, and Case IC - where all radar units have 1.2 MHz bandwidths. Table 1 provides the observed performance data for Case IA, while Figure 5 plots the performance data. Similarly, Table 2 and Table 3 provide the observed performance data for Cases IB and IC, while Figure 6 plots their respective performance data. The frequency range is 1300 MHz to 1400 MHz for cases IA and IB while the frequency range for case IC is 1300 MHz to 1450 MHz. In each of the above three cases all radar units in every ship have the same bandwidth. This way the performance of the three algorithms can be evaluated with the bandwidth remaining invariant.

Interference is created between ships and the time taken to resolve interference is calculated in the above three cases using each of the three algorithms viz. locally autonomous, master-slave and negotiation-based algorithms.

It can be evidently noticed from the tables and plots



Locally Autonomous | Master-Slave | Negotiation

Figure 7. Performance Plots for Case II - Heterogeneous Ships, Homogeneous Radar Units

that the negotiation based approach for detecting and resolving interference is much more efficient compared to the master-slave and locally autonomous based approaches for Case I.

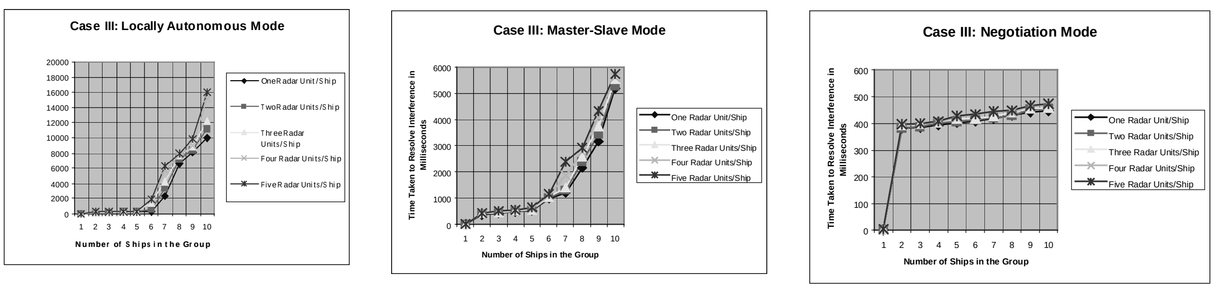
III. B. Case II

Case III: Heterogeneous Distribution, All Radar Units on same Ship have Different Bandwidths									
0.4 MHz, 0.6 MHz, 1.2 MHz, 2.4 MHz, 5 MHz - Radar Units in Each Ship									
Locally Autonomous Mode									
	Number of Ships in the Group								
Radar/Ship	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	213	215	225	245	265	2418	6555	8098	10067
2	215	217	239	252	560	3444	7142	8378	11241
3	216	218	248	258	1418	4334	7581	8776	12148
4	217	224	256	262	1749	5665	7717	9005	15078
5	221	238	260	278	1964	6282	7937	9882	16090
Master-Slave Mode									
	Number of Ships in the Group								
Radar/Ship	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	355	416	482	516	991	1204	2155	3166	5177
2	395	430	502	552	1004	1295	2394	3422	5276
3	415	452	523	560	1043	1395	2588	3735	5533
4	417	497	529	590	1106	1866	2764	4091	5615
5	425	514	545	642	1164	2393	2916	4322	5735
Negotiation Mode									
	Number of Ships in the Group								
Radar/Ship	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	383	384	394	403	410	418	431	443	446
2	382	386	402	407	413	420	429	453	455
3	394	398	403	418	418	427	441	458	458
4	396	399	404	423	432	446	442	465	471
5	397	400	408	429	434	446	449	467	475

Table 5. Radar Units within the ship with same bandwidth

In this case, all radar units in every ship have the same peak power and threshold. In order to study the effectiveness of the three chosen algorithms in a heterogeneous environment, radar units with different bandwidths are used for each ship. That is, while all radar units within the ship have the same bandwidth, radar units in other ships have other bandwidths. For example, all units on Ship1 may have a bandwidth of 0.4 MHz, while all units on another ship, Ship2, may have a bandwidth of 1.2 MHz.

The bandwidths of radar units in the ten ships is as follows: 0.4 MHz –two ships, 0.6 MHz-two ships, 1.2 MHz – two ships and 5 MHz-two ships. The chosen frequency range for this case was 1300 MHz to 1530 MHz. As in case I, interference is created between radar units in different ships and the time taken to detect and resolve interference is calculated using each of the three algorithms.



Locally Autonomous Master-Slave Negotiation

Figure 8. Performance Plots for Case III - Homogeneous Ships, Heterogeneous Radar Units

III. C. Case III

In this case, each ship has radar units with different bandwidths. The bandwidth of the five radar units in each of the ten ships is as follows: 0.4, 0.6, 1.2, 2.4, 5 MHz respectively. The frequency range for this case is 1300 MHz to 1450 MHz. In order the study the effectiveness of the three algorithms in a heterogeneous environment, radar units with different bandwidths are used in used in a single ship. Thus each ship has five radar units of the same kind with five different bandwidths. Interference is created between ships and the time taken to resolve interference is determined using each of the three algorithms and plots are made with the results obtained.

Cases I-III are used in order to obtain the performance and effectiveness of the algorithms. Here by performance we mean the time taken by the algorithm to detect, resolve and update the database when there is interference between radar units.

Case IVA: Overloading, All Radar Units with 2.4 MHz Bandwidth									
Locally Autonomous Mode									
	Number of Ships in the Group								
Radar/Ship	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	221	223	344	712	2110	8191	16233		
2	217	225	379	1065	3230	8756	17425		
3	198	216	423	1163	4745	9178			
4	195	245	512	244	6771	10163			
5	230	234	620	1450	7189	12578			
Master-Slave Mode									
	Number of Ships in the Group								
Radar/Ship	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	350	445	481	640	843	1517	2320		
2	355	411	537	656	975	1628	2651		
3	367	424	528	750	1056	1777			
4	344	450	585	789	1178	1845			
5	410	466	633	810	1221	1978			
Negotiation Mode									
	Number of Ships in the Group								
Radar/Ship	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	390	396	409	438	460	466	521		
2	395	428	415	429	456	477	525		
3	411	430	427	440	445	421			
4	420	445	454	442	478	456			
5	433	405	441	460	465	478			

Table 6. Case IV a: Overloading Available Frequency Range with 2.4 MHz Radar bandwidths

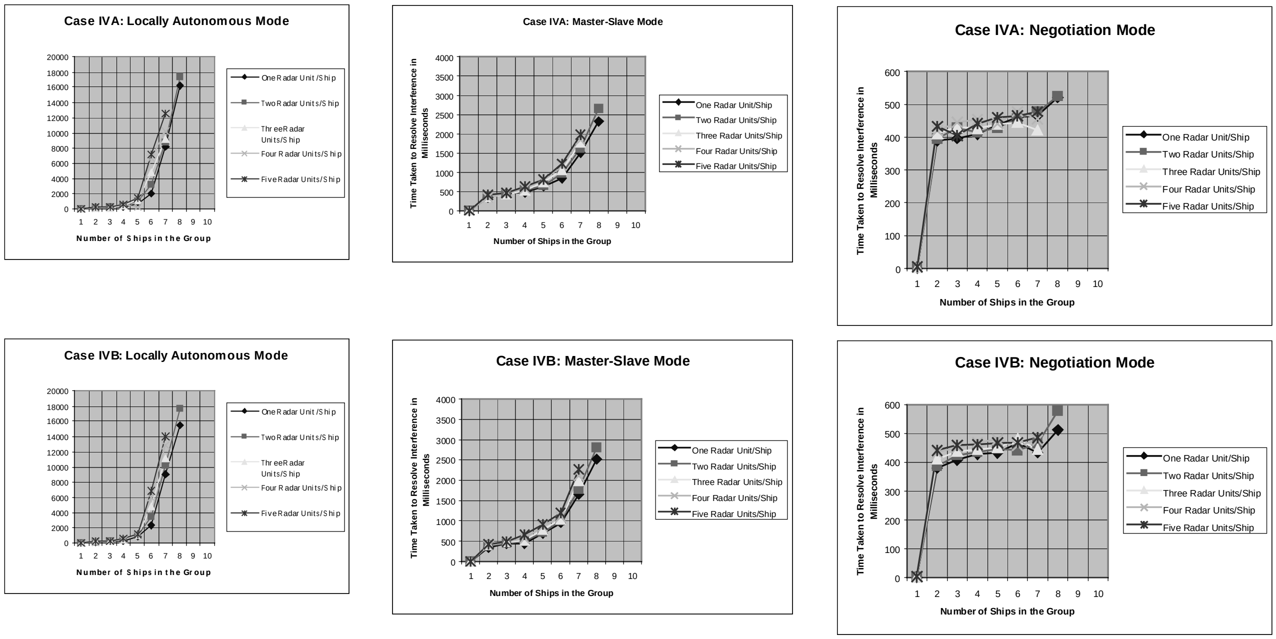
From cases I, II, III it can be observed that the time taken by the negotiation based approach is extremely better compared to the master-slave and locally autonomous based approaches. An important point to note here is that the scale used for the time taken to resolve interference on y-axis is different for the three algorithms in the different cases.

Case IVB: Overloading, All Radar Units with 5 MHz Bandwidth									
Locally Autonomous Mode									
	Number of Ships in the Group								
Radar/Ship	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	198	228	306	814	2265	9033	15442		
2	205	231	377	978	3451	10171	17621		
3	221	219	445	985	4783	11045			
4	206	265	437	1032	5972	12855			
5	242	290	625	1170	6911	14033			
Master-Slave Mode									
	Number of Ships in the Group								
Radar/Ship	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	341	435	441	696	948	1649	2519		
2	395	445	499	716	1004	1781	2802		
3	412	476	513	781	1035	1987			
4	398	481	568	865	1102	2114			
5	423	486	665	914	1195	2270			
Negotiation Mode									
	Number of Ships in the Group								
Radar/Ship	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	380	408	428	432	466	433	512		
2	386	424	436	447	441	464	578		
3	412	437	445	451	480	445			
4	434	451	468	479	457	477			
5	441	459	461	467	468	485			

Table 7. Case IV b: Overloading Available Frequency Range with 2.4 MHz Radar bandwidths

III. D. Case IV

This case has two sub-cases: Case IVA and Case IVB. This case is used to overload the algorithms by narrowing the



Locally-Autonomous | Master-Slave | Negotiation

Figure 9. Case IV - Tolerance Analysis

frequency range and introducing more radar units than possible into the system and study whether each of the algorithms provide the theoretically optimal solution. In Case IVA, all radar units in all the ships have the same peak power and threshold. All radar units are set to 2.4 MHz bandwidths. In theory, radar units operating on a 2.4 MHz bandwidth need a minimum frequency separation of 5 MHz in order to avoid interference. Therefore the frequency range is set to 1300 to 1500 MHz and all five radar units in the ten ships are set at the above mentioned radar parameters. Thus the algorithms must be able to fit forty out of the fifty radar units at their desired interference-free frequencies. Our objective is to study and find out how many radar units each of the algorithm can provide with interference free frequencies. This measure gives the tolerance of each of the algorithm.

Similarly, in Case IVB, all radar units have 5 MHz bandwidths. The minimum frequency separation required between radar units order to avoid interference is 10 MHz. Therefore the frequency range is set to 1300 MHz to 1700 MHz and all five radar units in the ten ships are set at the above mentioned radar parameters. Again, theoretically each of the algorithms must be able to fit forty of the fifty radar units at their desired frequencies. The measure of how many radar units each of the algorithm is able to provide interference free frequencies provide the tolerance of the algorithm.

It was found that all three approaches used for interference detection and resolution viz. locally autonomous, master-slave and negotiation based approaches fit 37 out of the 40 radar units that could theoretically fit in the given frequency range. The algorithms are thus found to be 92.5% efficient in finding interference free frequencies for their radar units.

III. E. Conclusions

The three different algorithms for radar interference detection and resolution viz. locally autonomous, master-slave and negotiation based algorithms were implemented in the two-level software agent program. Under different sets of tests, the negotiation based algorithm proved to performing better compared to master-slave and locally autonomous modes with regards to the time taken by each algorithm to detect and resolve the interference and update the database. Then finally a stress analysis was done on the three interference resolution algorithms by narrowing the frequency range and introducing more radar units than possible into the system and the point each of the algorithm fails was determined. In cases IVA and IVB, all the three algorithms fit 37 out of the 40 radar units into the frequency range. All the three algorithms were found to be 92.5% efficient in finding interference free frequencies for its radar units within a specified frequency range.

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V. References

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