Performance Evaluation Study of Route Scheduling in Predictable Intermittent Networks

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I. Introduction

In this document, we present the performance evaluation study of the route scheduling solver for predictable intermittent networks. This study aims to evaluate the performance of the route scheduling solver presented by [1] against two know polynomial-time algorithms: ED and EDAQ [2].
This study is organized into three simulation groups. In each group, a simulation experiment is performed on 10 different graphs. The first group is conducted on six-node graphs, the second is conducted on eight-node graphs and the last is conducted on 10-node graphs.
According to the solver architecture [1], we considered solution the following five solver configurations, each described by five parameters: H1, H2, F_1 and F_2 functions.
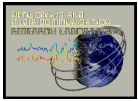
Configuration	H1	H2	F_1	F_2
ED	FCFS	N/A	ED	**Hopped**
EDAQ	FCFS	N/A	EDAQ	**Hopped**
CRP-Hopped	FCFS	MIN-HOP	RIB	**Hopped**
CRP-Overlapped	FCFS	MIN-HOP	RIB	**Overlapped**
CRP-Eager	FCFS	MIN-HOP	RIB	**Eager**

Table 1: The Five solver configurations

It has to be pointed that the simulation results reflect P1 problem specifications. Simulation results are presented by three performance metrics: overall solution (route schedule) earliness, task earliness and task throughput. Moreover, the throughput of the task t_i routed via r_i is $(s_i/(a(r_i) – o_i))$ (bps), while the task demanded throughput is $(s_i/(dl_i – o_i))$ (bps).

II. Simulation Experiment Group-1

In this group, ten simulation experiments are conducted on 10 different six-node graphs. The task set of this group is given by the Table 2. The link intermittency is chosen to be periodic. Therefore, for each edge $e_i \in E$, λ_i denotes the periodic active duration (the contact duration) between the nodes (n_u, n_v) (in seconds), μ_i denotes the periodic inactive duration (in seconds), and α_i denotes the duration shift prior to λ_i (in seconds). Based on the edge temporal attributes, β_i denotes the effective bandwidth of the edge e_i

As given in the edge (link) definition, the temporal modeling of the edge $e_i \in E$, is described by the function in Fig.1 The periodic active duration $[\alpha, (\alpha + \lambda))$, where the periodic inactive durations are $[0, \alpha)$ and $[(\alpha + \lambda), (\alpha + \lambda + \mu))$.

i	u_i	v_i	o_i (Sec)	dl_i (Sec)	s_i (MB)
1	6	3	98	**9314**	16
2	4	2	188	**10778**	15
3	2	5	263	**13013**	25
4	3	4	357	**14337**	20
5	1	5	444	**11172**	18

Table 2: The Task Set
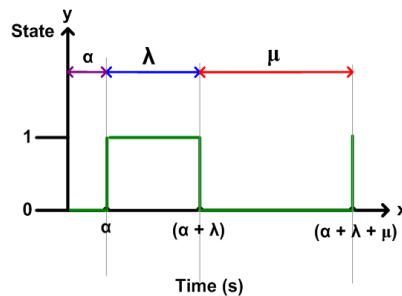
Fig.1: The periodic link intermittency characterizing the attributes α, λ, and μ.

Next, we provide the ten network topologies examined by this group as follows. In each network topology figure, the green captions represent the node service rate (bps), red captions represent the link capacity and the blue captions represents link temporal attributes. It has to be further noted that the link bandwidth (capacity) denotes the bidirectional; hence it is assumed to be on half at each direction. For instance, if the bandwidth of link is 4 Mbps, then its will be 2 Mbps at each direction.
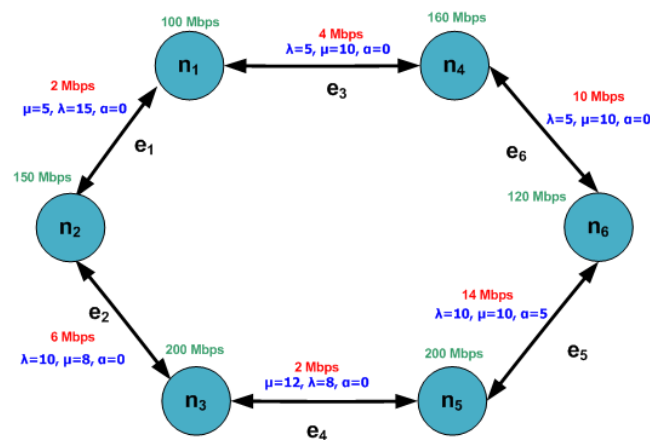
Fig.2: The Exp-1-1 Network Topology
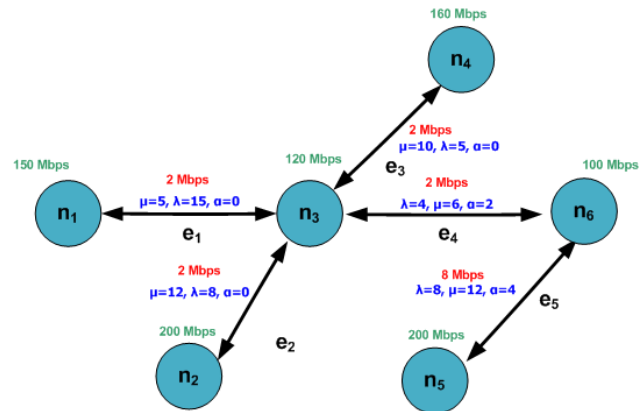
Fig.3: The Exp-1-2 Network Topology
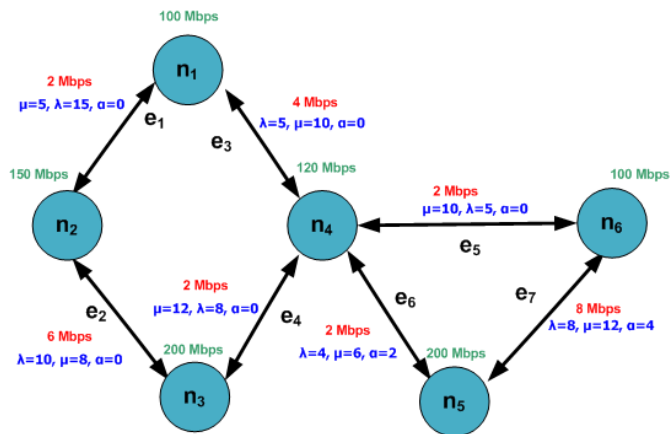
Fig.4: The Exp-1-3 Network Topology
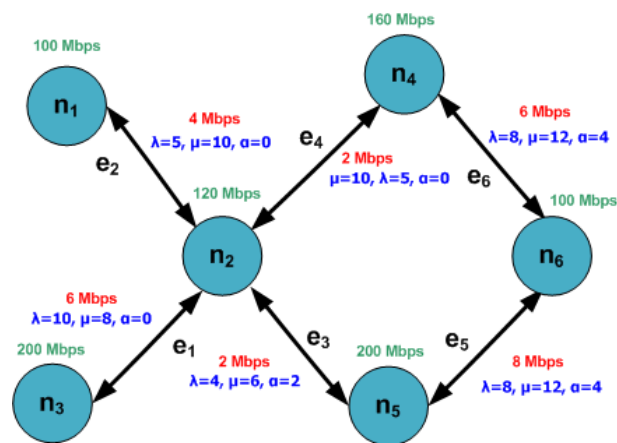
Fig.5: The Exp-1-4 Network Topology
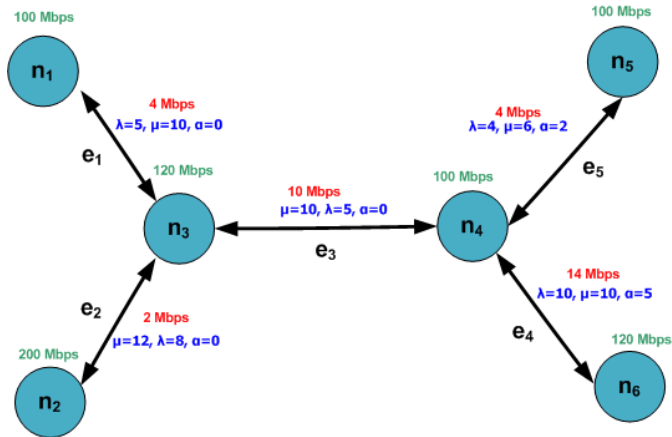
Fig.6: The Exp-1-5 Network Topology
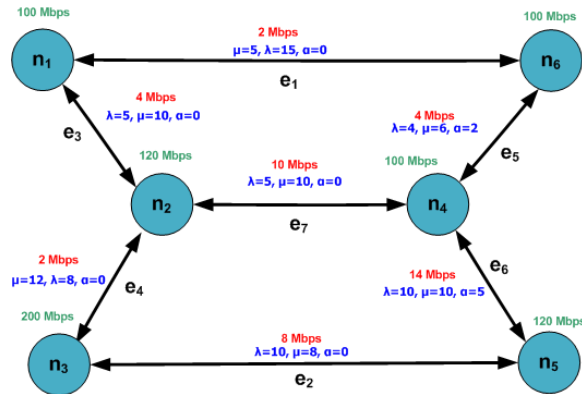
Fig.7: The Exp-1-6 Network Topology
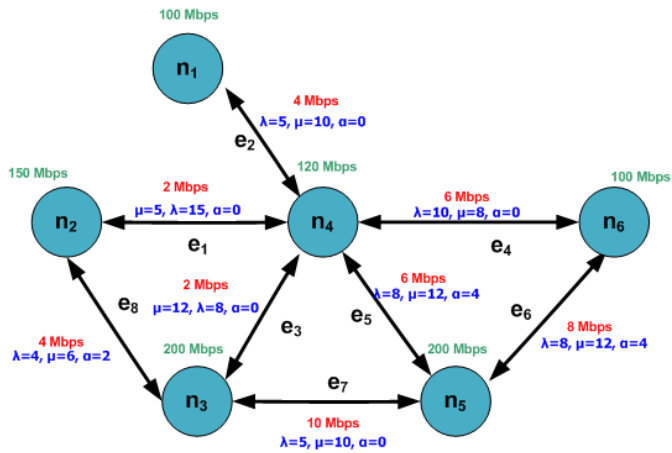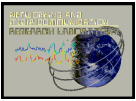
Fig.8: The Exp-1-7 Network Topology
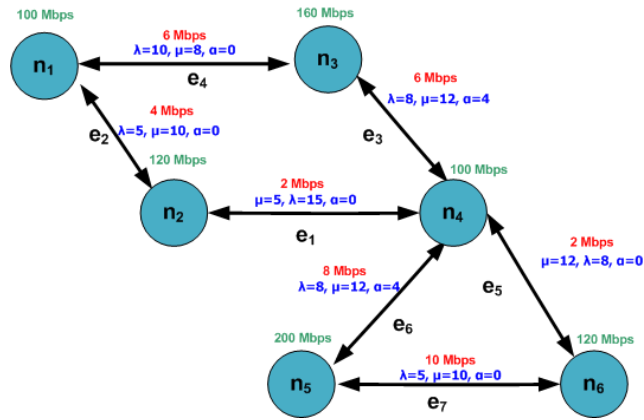
Fig.9: The Exp-1-8 Network Topology
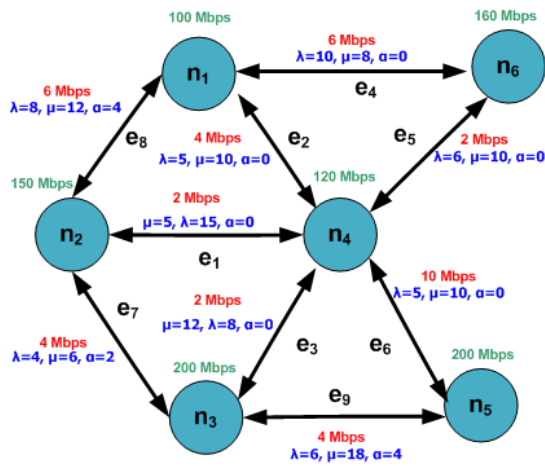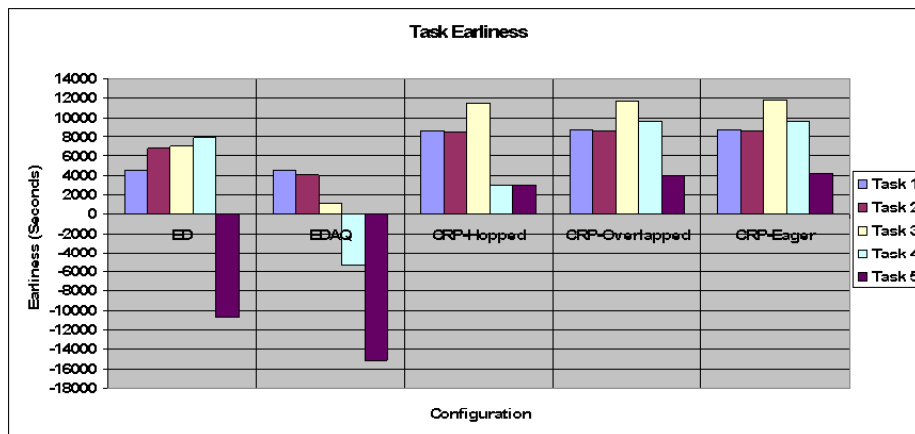

Fig.10: The Exp-1-9 Network Topology
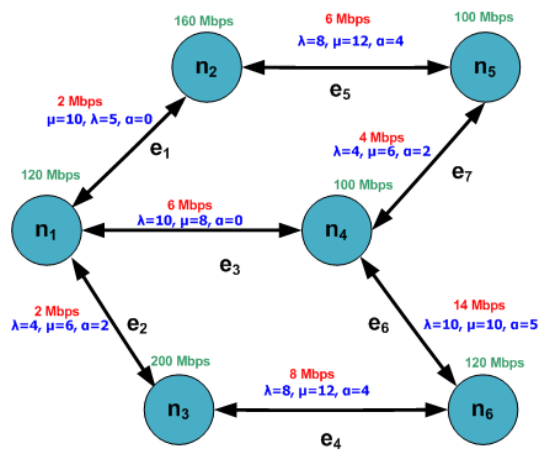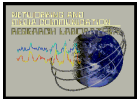
Fig.11: The Exp-1-10 Network Topology

III. Group-1 Experiments Simulation Results
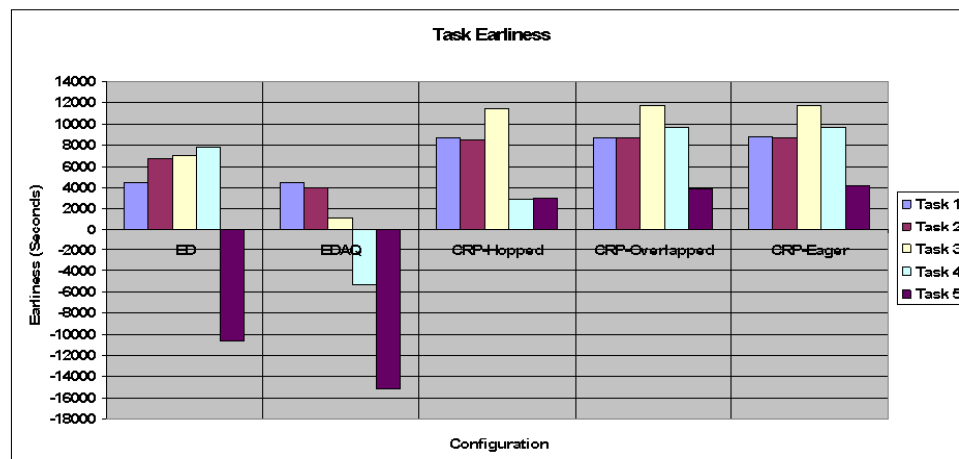
A. Simulation Experiment 1-1
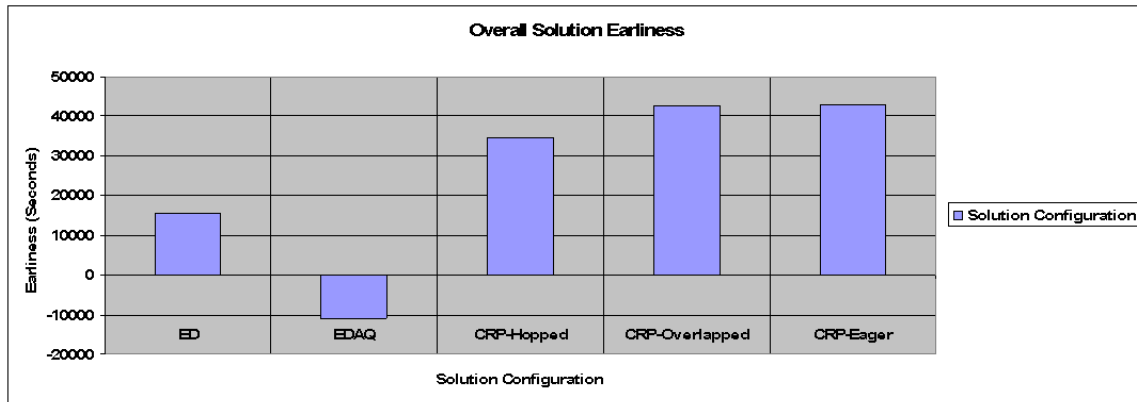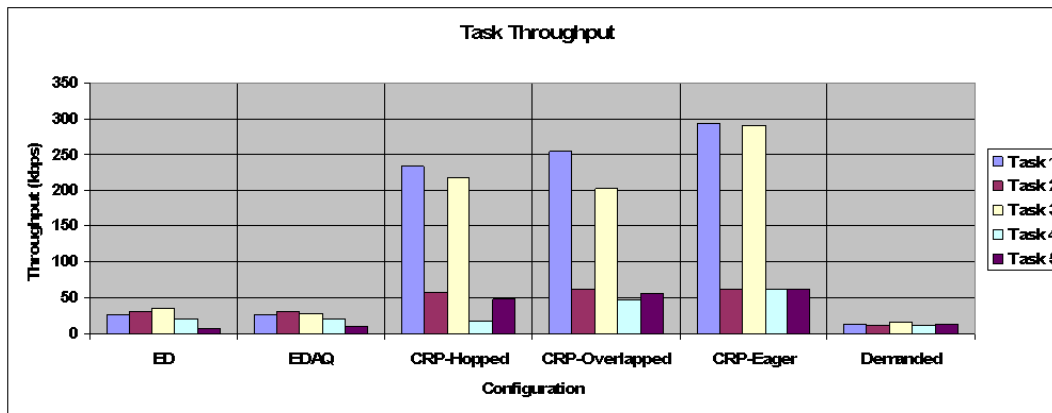
Fig.12: Exp. 1-1 Results: (a) Overall Solution Earliness, (b) Task Earliness, and (c) Task Throughput
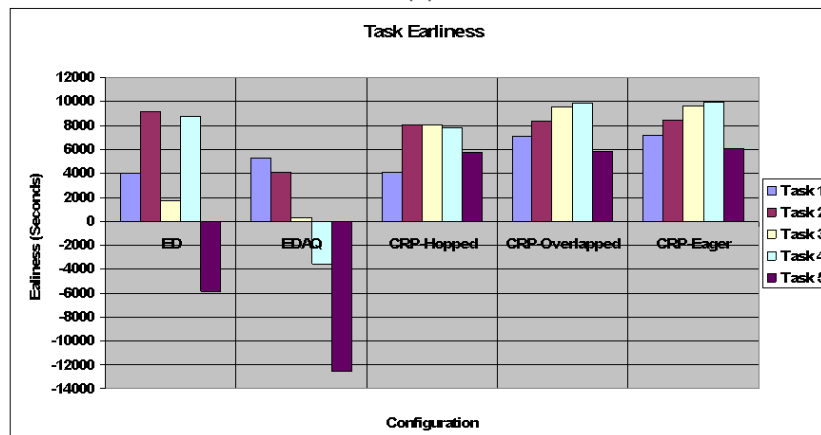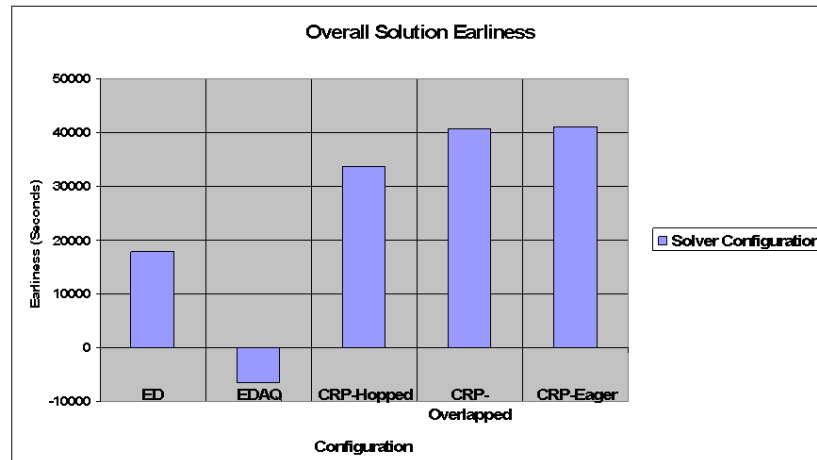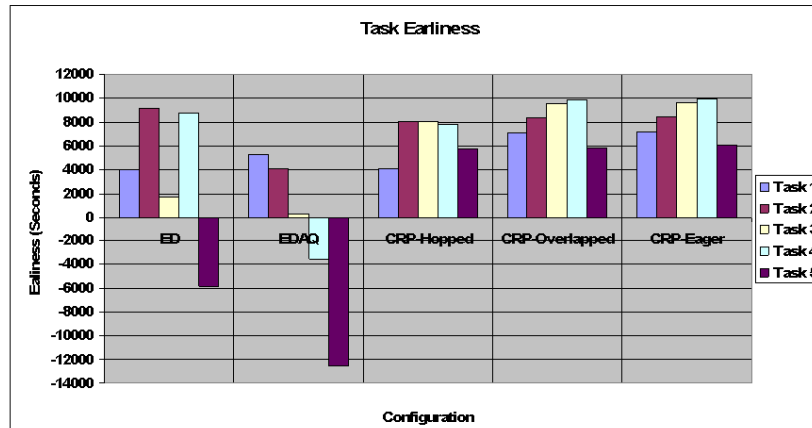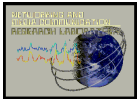
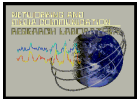## B. Simulation Experiment 1-2
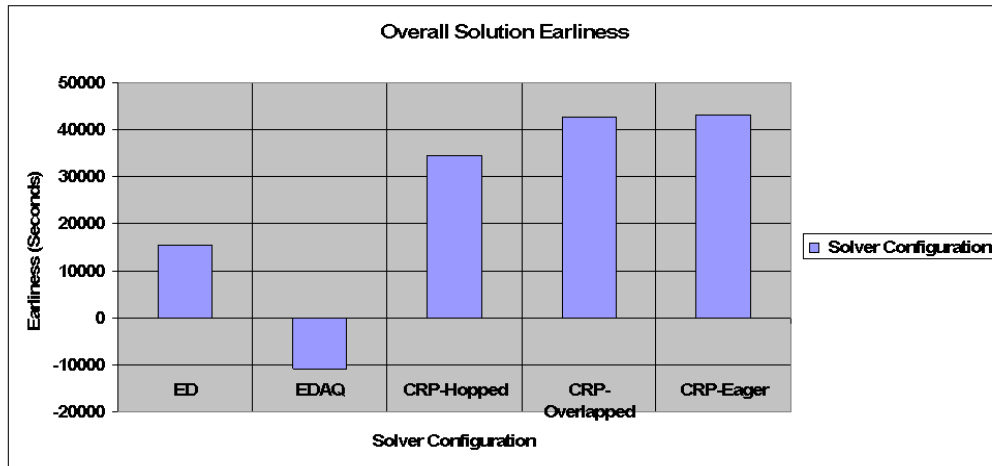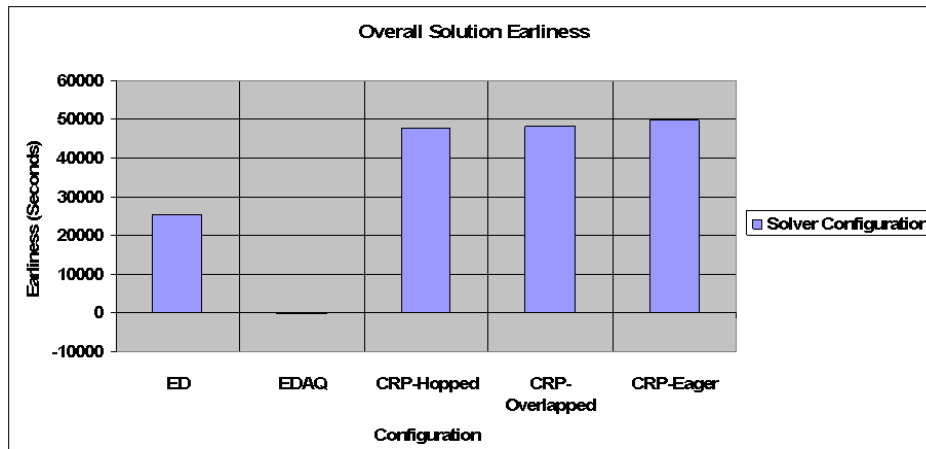
(a)
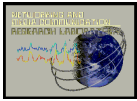
(b)
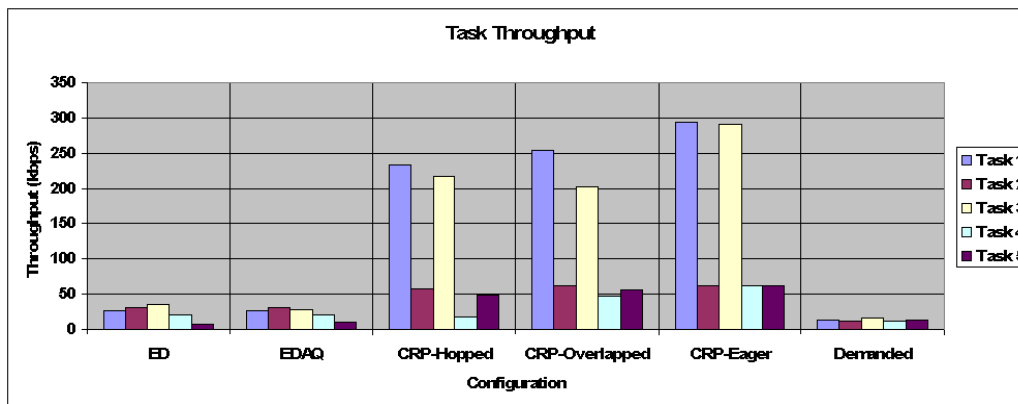
(c)

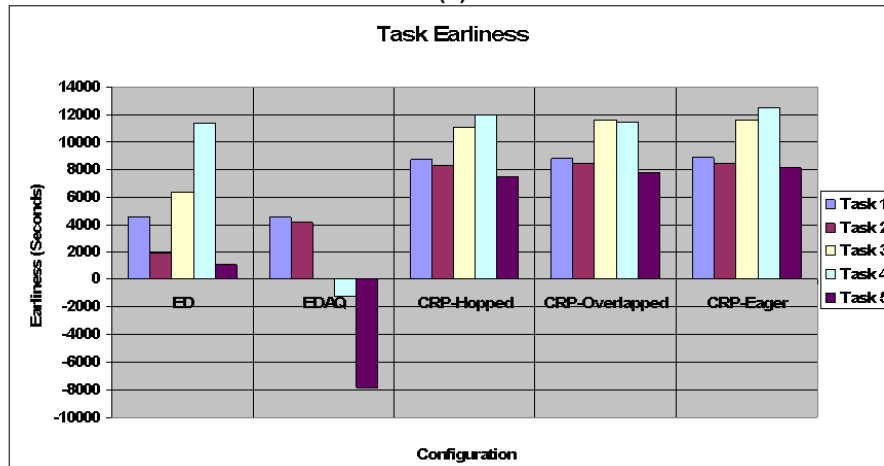**Fig.13: Exp. 1-2 Results: (a) Overall Solution Earliness, (b) Task Earliness, and (c) Task Throughput**

C. Simulation Experiment 1-3
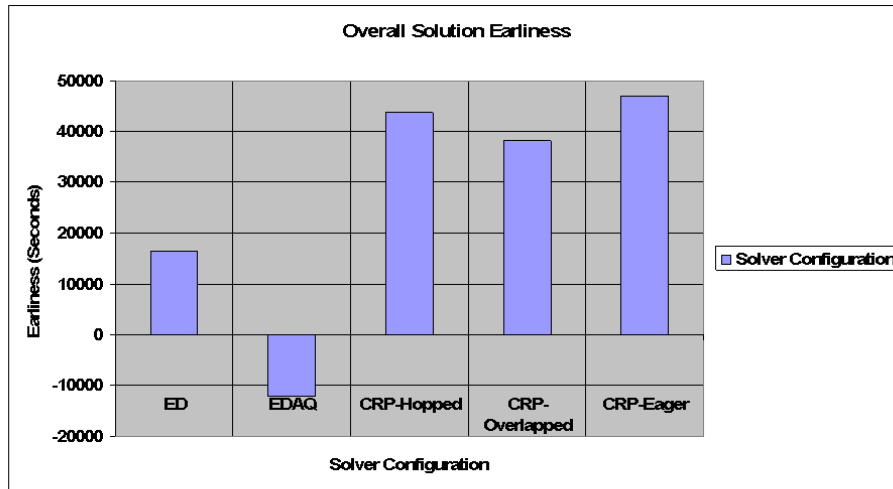
(a)
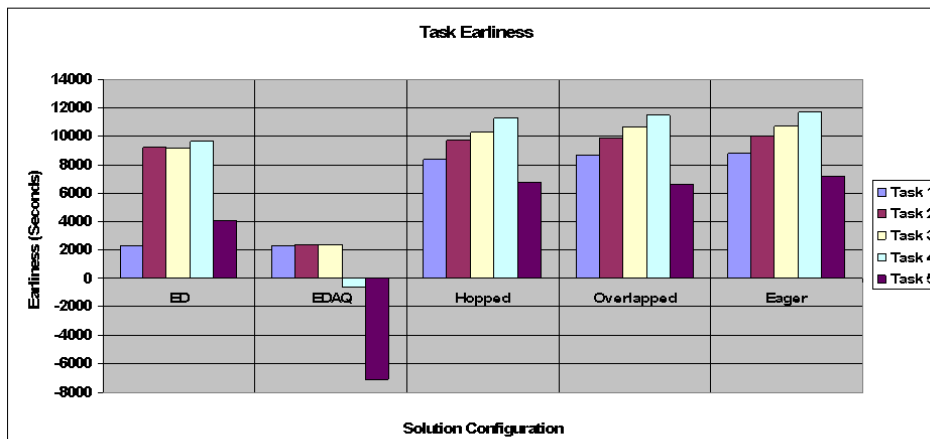
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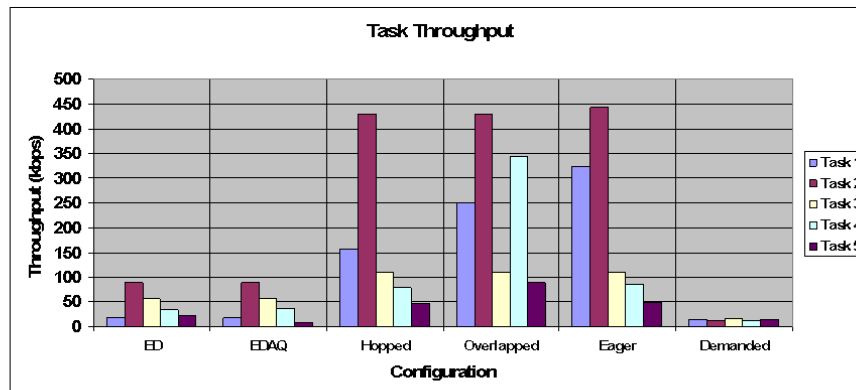
(c)

Fig.14: Exp. 1-3 Results: (a) Overall Solution Earliness, (b) Task Earliness, and (c) Task Throughput

D. Simulation Experiment 1-4
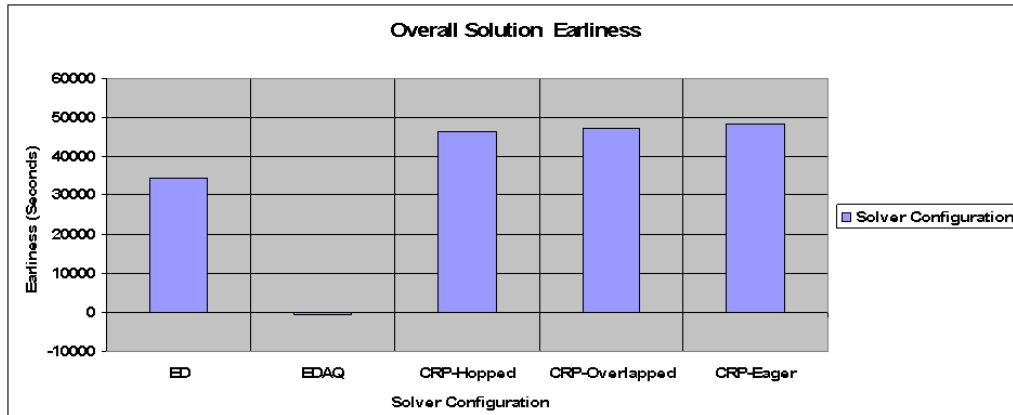
(a)
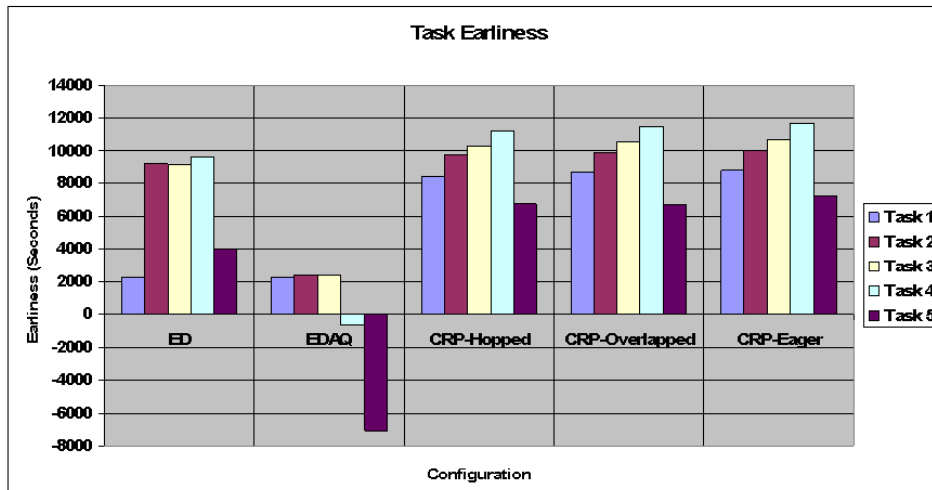
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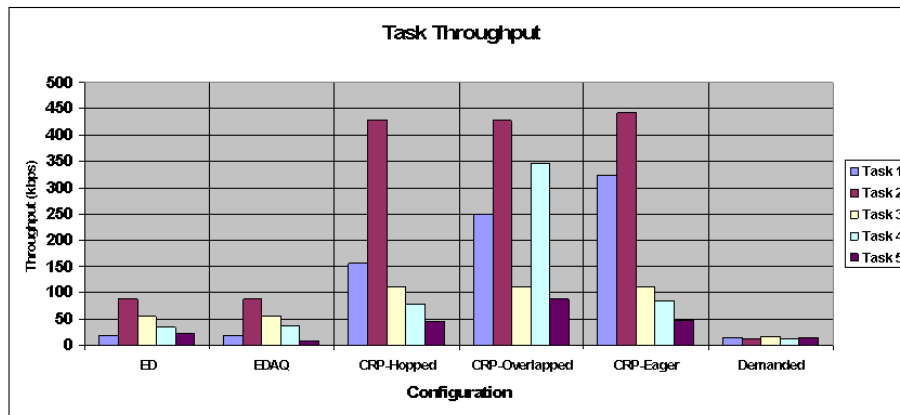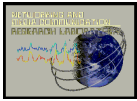
(c)
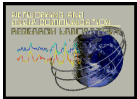
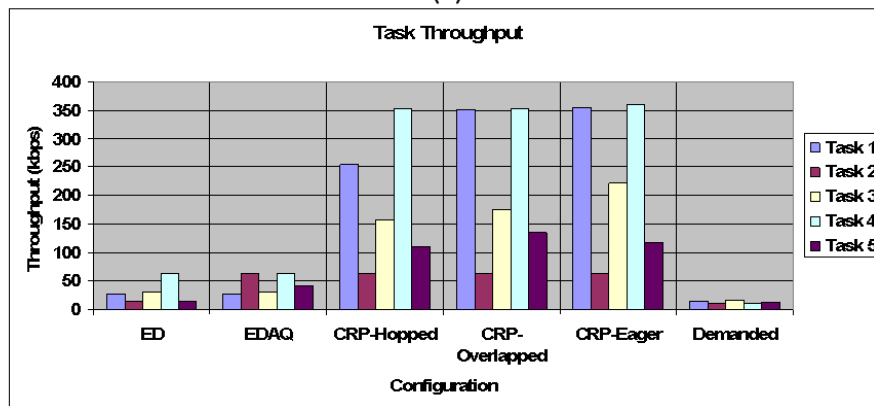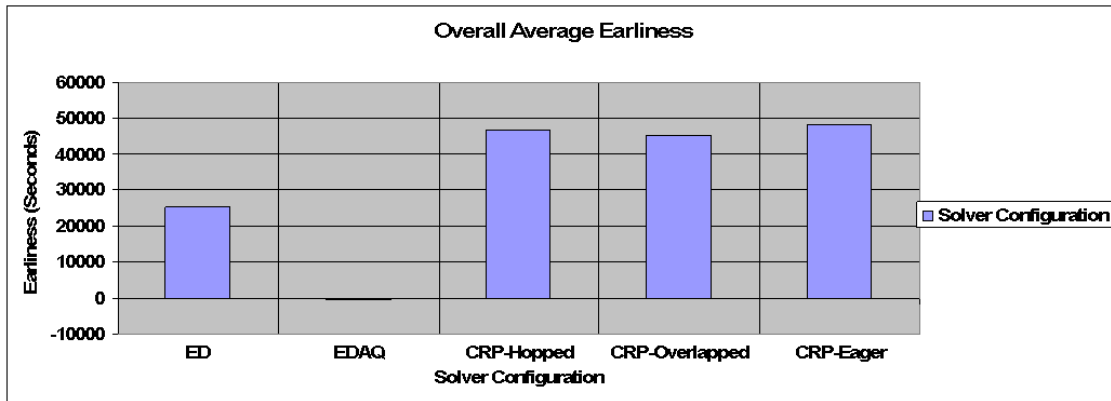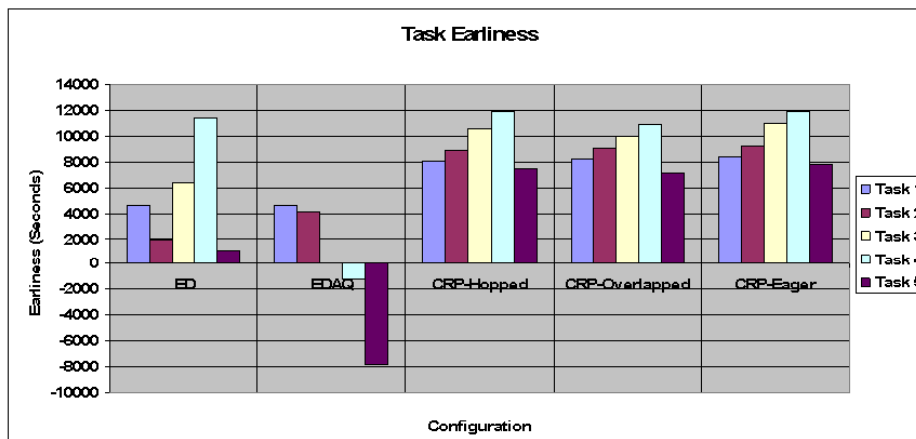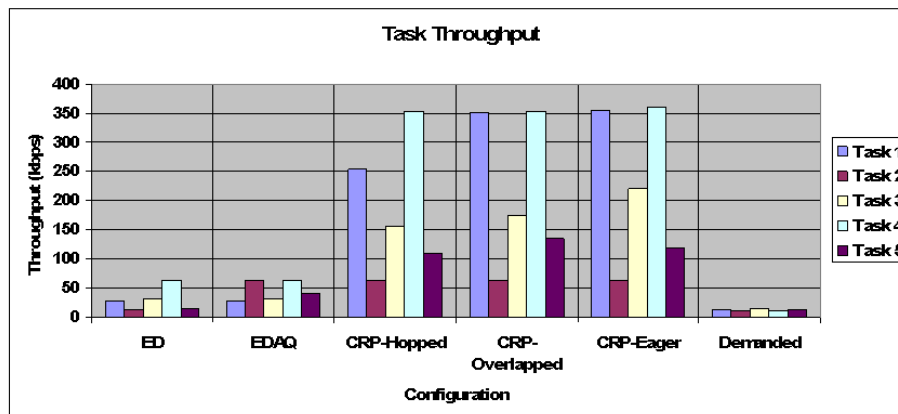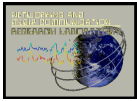**Fig.15: Exp. 1-4 Results: (a) Overall Solution Earliness, (b) Task Earliness, and (c) Task Throughput**

E.   Simulation Experiment 1-5
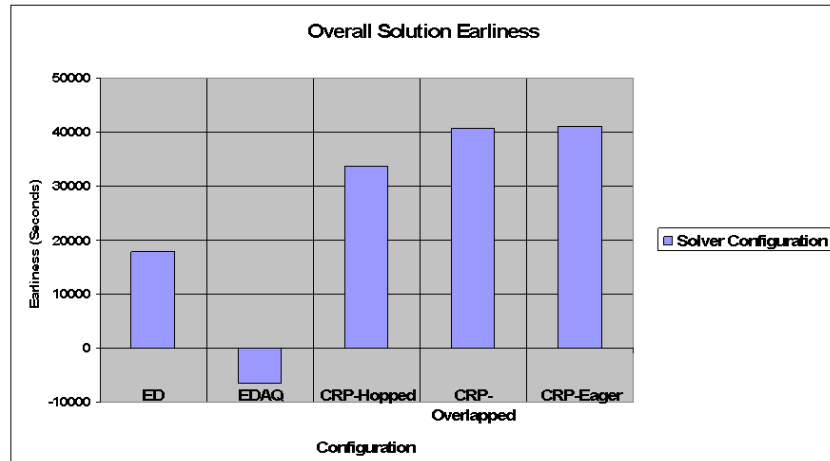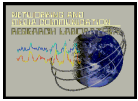
(a)
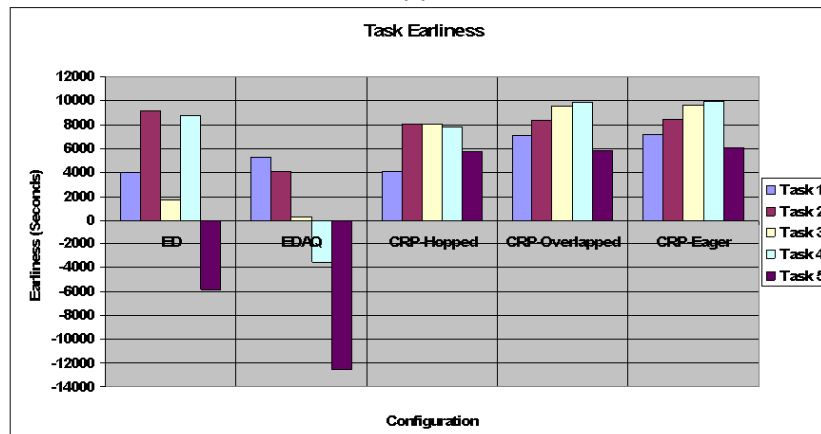
(b)

(c)

Fig.16: Exp. 1-5 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

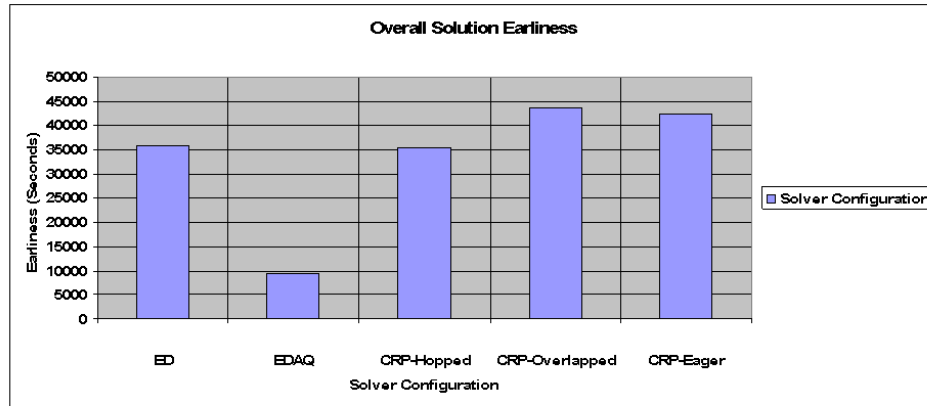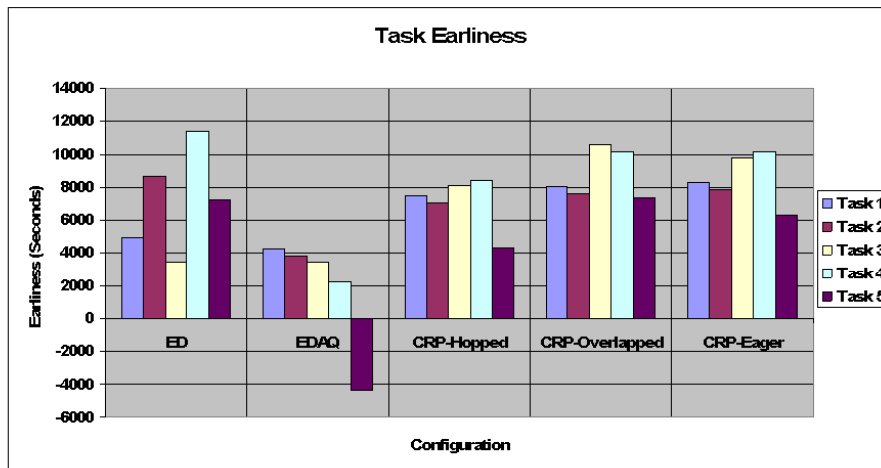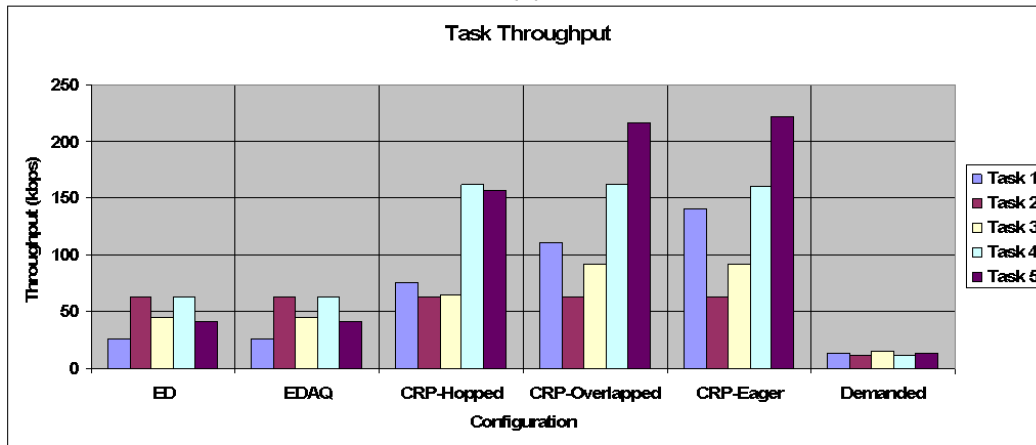## F. Simulation Experiment 1-6

(a)

(b)

(c)

Fig.17: Exp. 1-6 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

G. Simulation Experiment 1-7
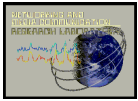

(a)

(b)

(c)

Fig.18: Exp. 1-7 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

H. Simulation Experiment 1-8

(a)

(b)

(c)

Fig.19: Exp. 1-8 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

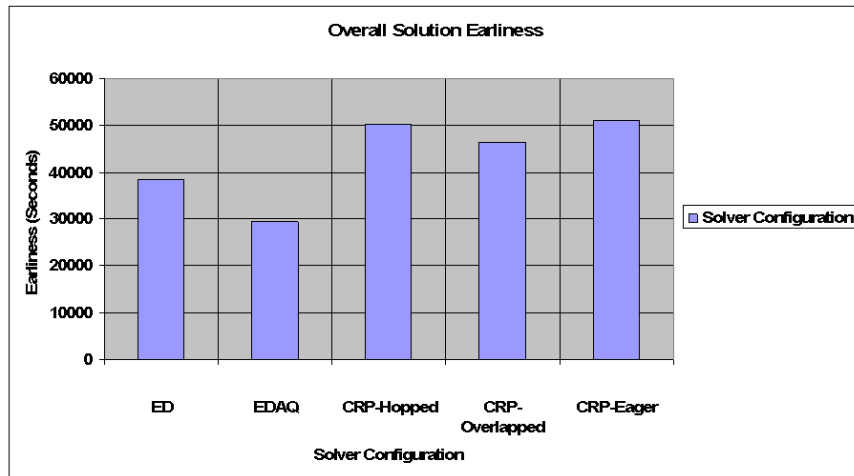## I. Simulation Experiment 1-9
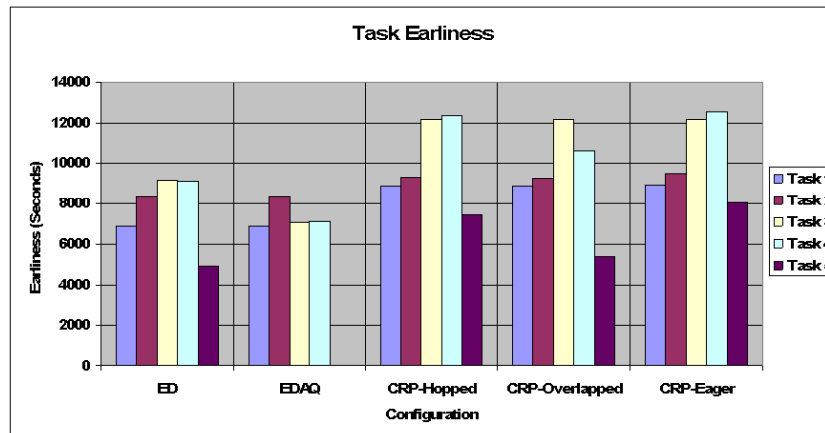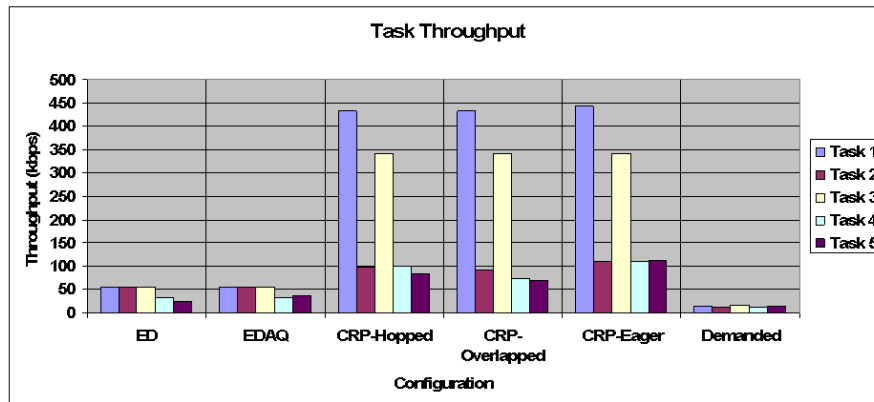

(a)

(b)

(c)

Fig.20: Exp. 1-9 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

J.   Simulation Experiment 1-10

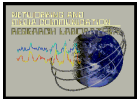**(a)**

(b)

(c)

Fig.21: Exp. 1-10 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

K. Group-1 Simulation Experiments Summary

The simulation results obtained from the ten experiments are summarized in Fig. 22-24. Te overall solution earliness of the five solver configurations are given by Fig. 22 as the average earliness over the ten experiments. Similarly to solution earliness, the overall task earliness and throughout are given by Fig. 23 and 24.
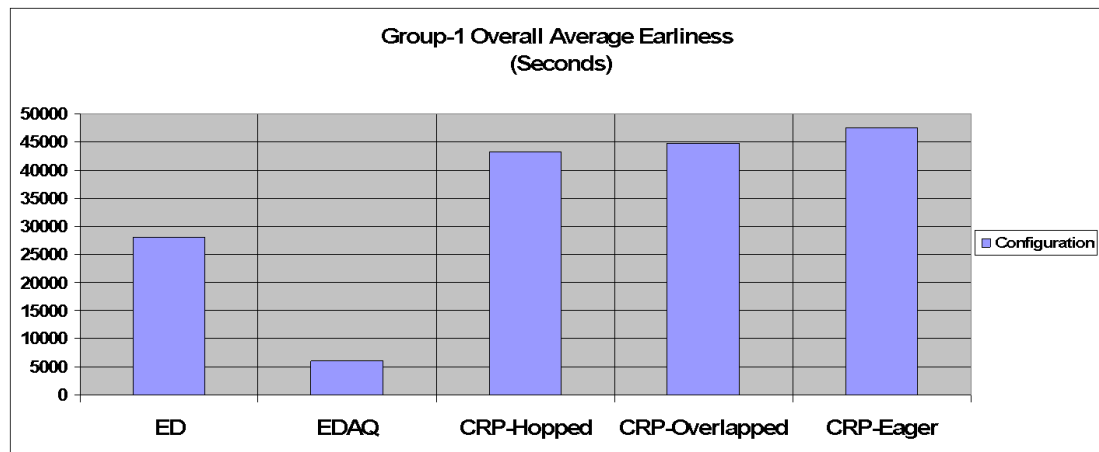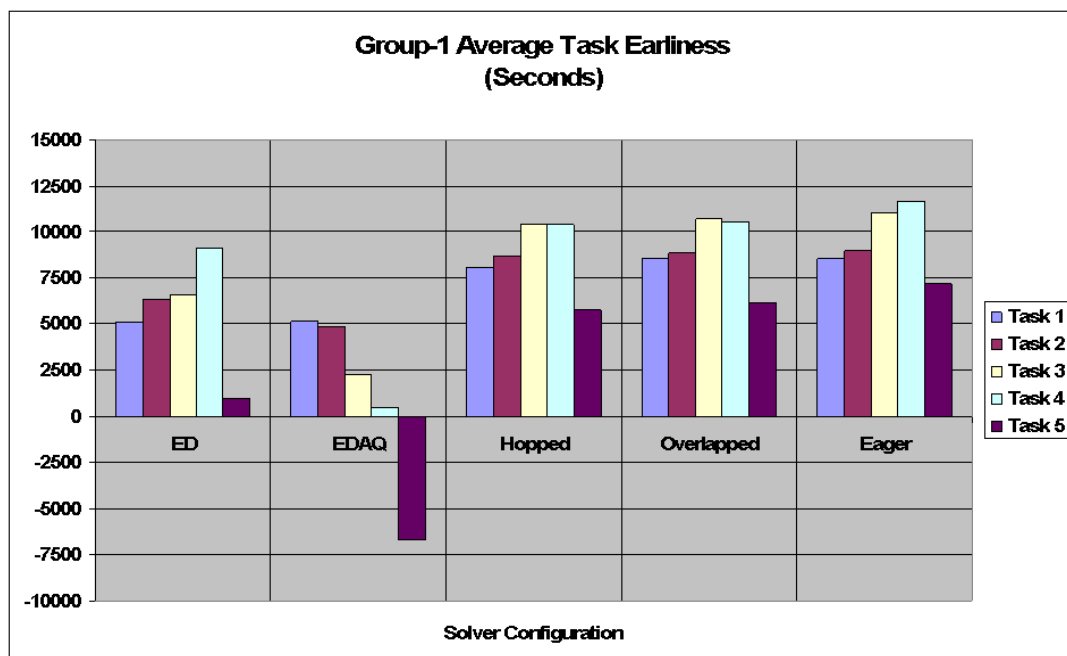

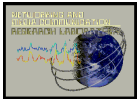**Fig.22: Overall Average Earliness of Group-1 Experiments**

Fig.23: Overall Average Task Earliness of Group-1 Experiments

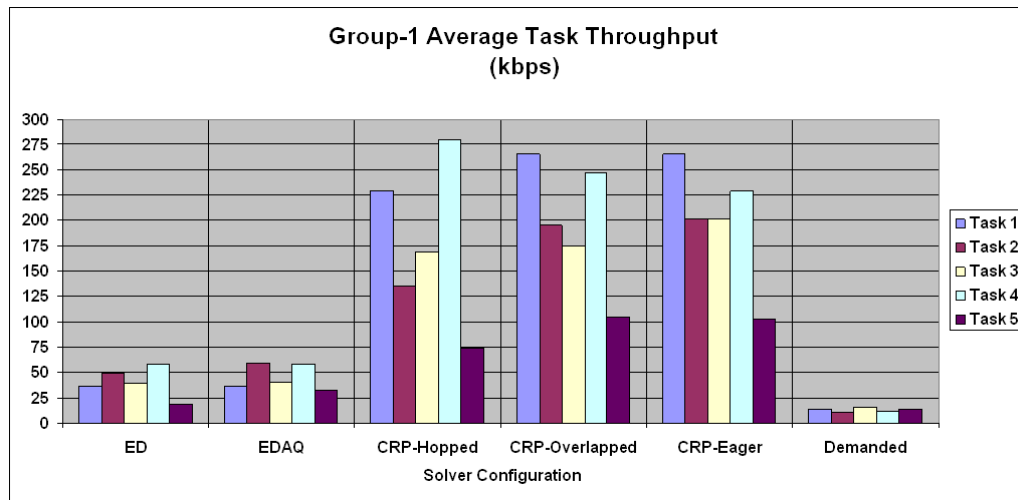**Group-1 Average Task Throughput (kbps)**

Fig.24: Overall Average Task Earliness of Group-1 Experiments

IV. Simulation Experiment Group-2

In this group, ten simulation experiments are conducted on 10 different eight-node graphs. The task set of this group is given by the table shown below.

i	u_i	v_i	o_i (Sec)	dl_i (Sec)	s_i (MB)
1	8	3	98	**9314**	16
2	6	1	188	**10778**	15
3	5	7	263	**13013**	25
4	5	2	357	**14337**	20
5	4	6	444	**11172**	18

Table 2: The Task Set
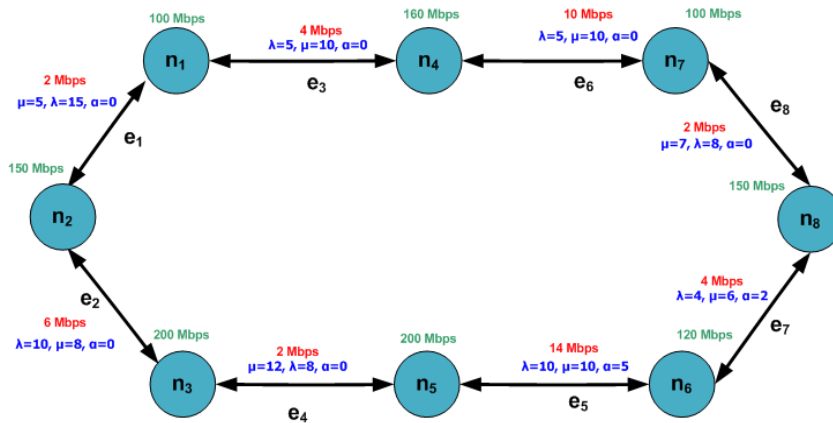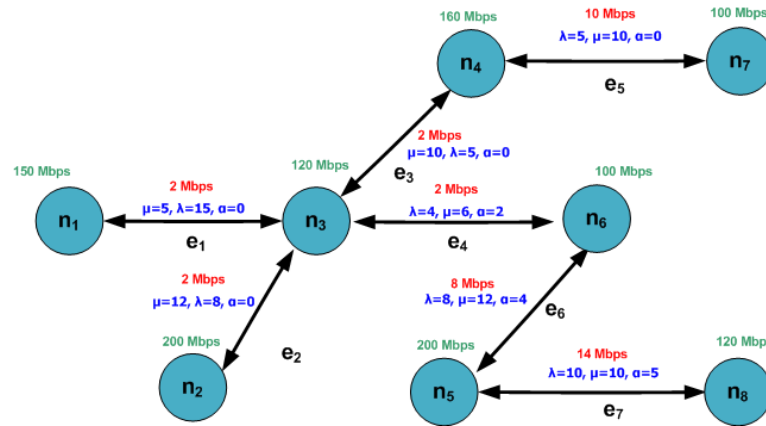
Fig.25: The Exp-2-1 Network Topology
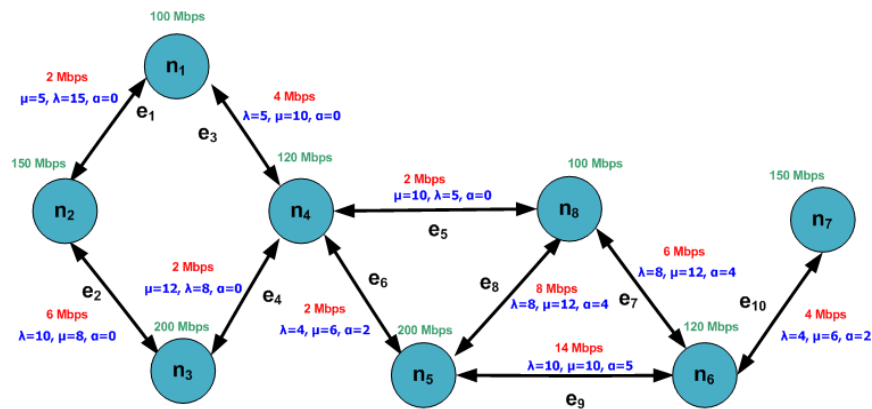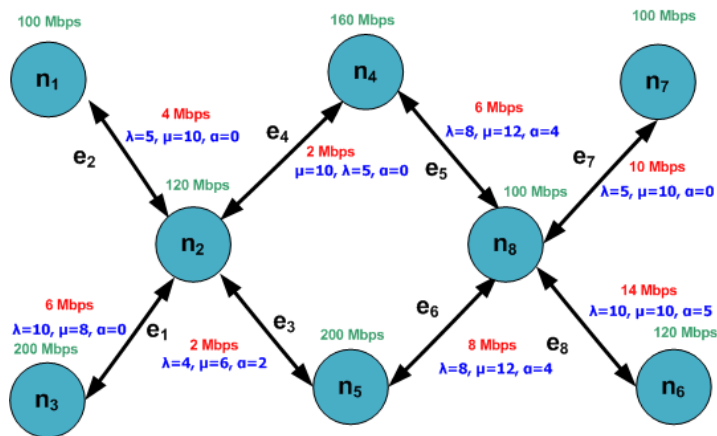

Fig.26: The Exp-2-2 Network Topology
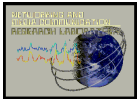

Fig.27: The Exp-2-3 Network Topology
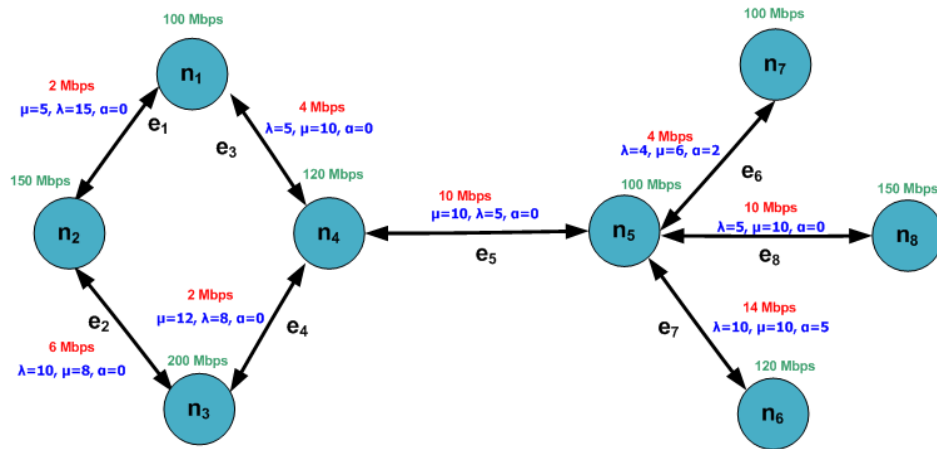
Fig.28: The Exp-2-4 Network Topology
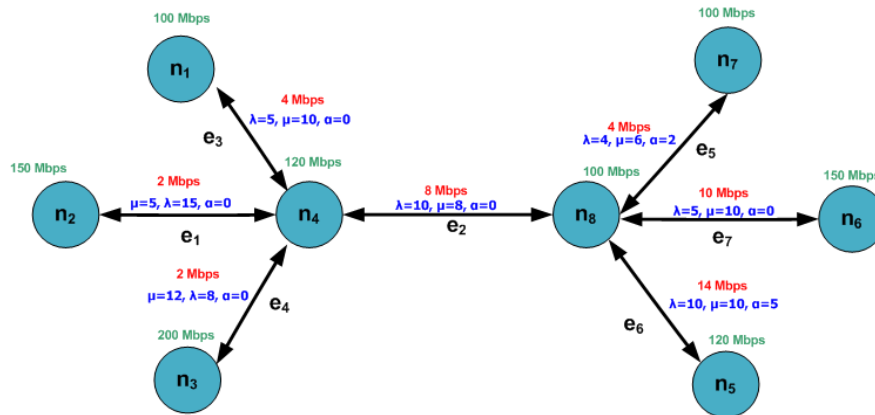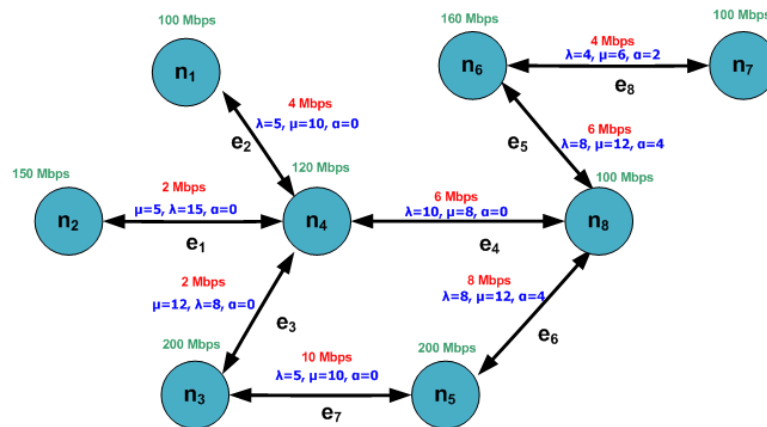

Fig.29: The Exp-2-5 Network Topology
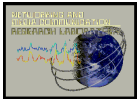

Fig.30: The Exp-2-6 Network Topology

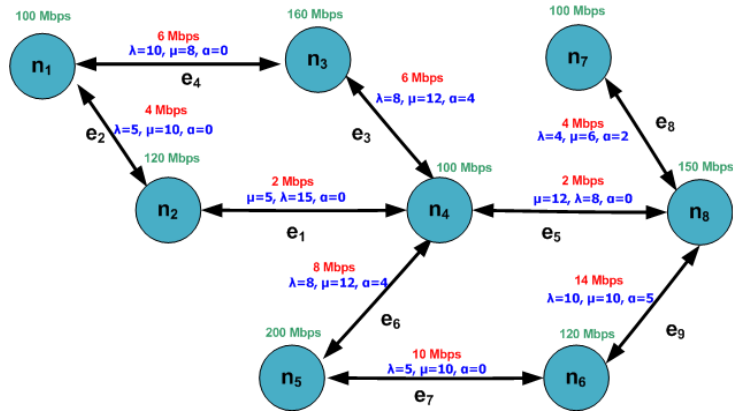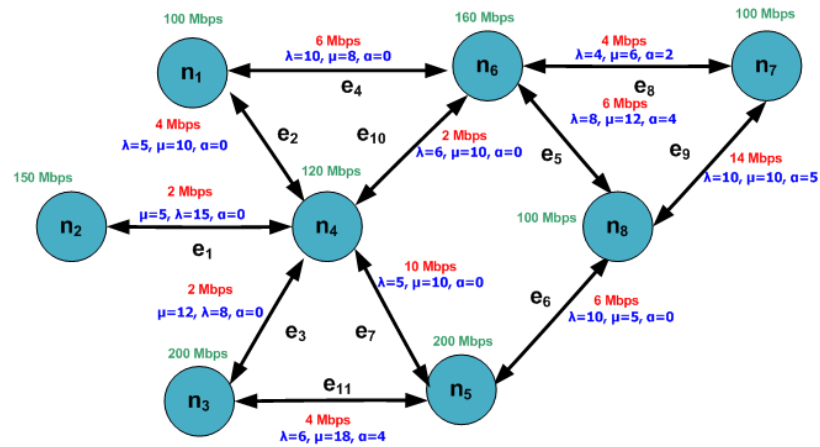**Fig.31: The Exp-2-7 Network Topology**
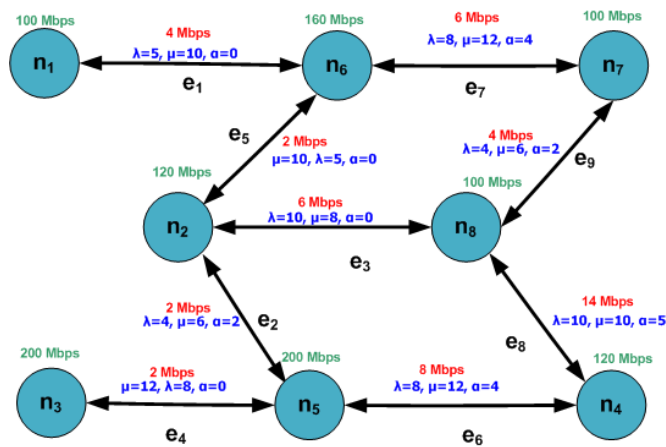

Fig.32: The Exp-2-8 Network Topology

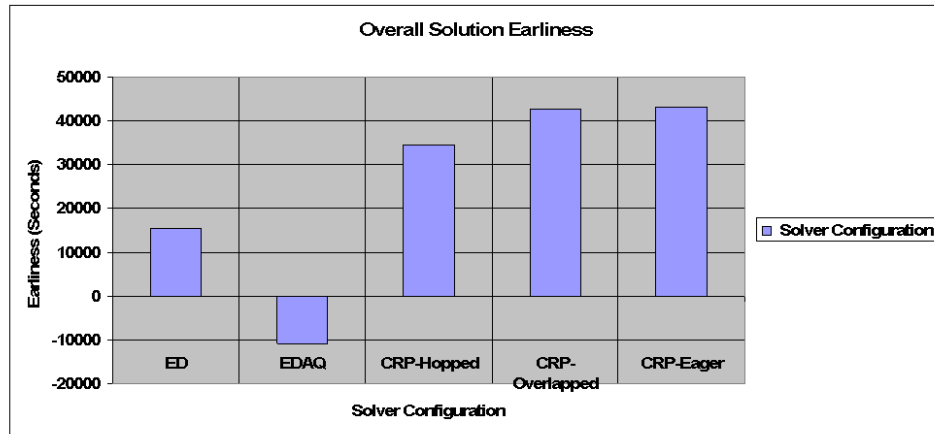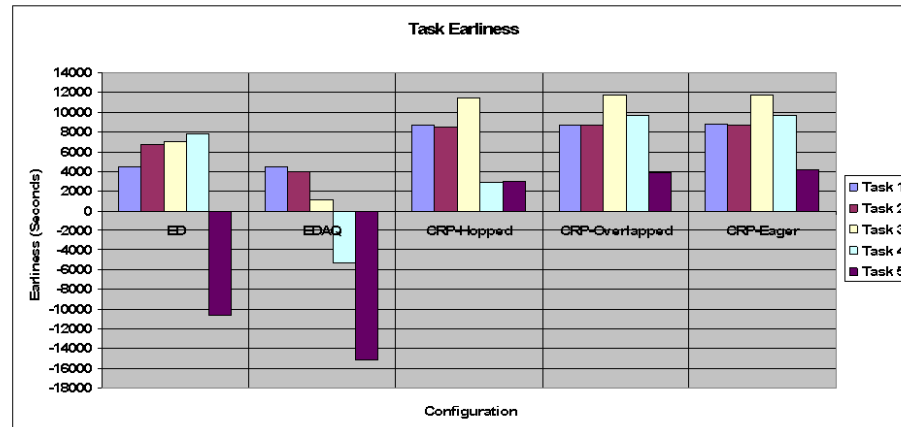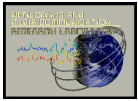**Fig.33: The Exp-2-9 Network Topology**

Fig.34: The Exp-2-10 Network Topology
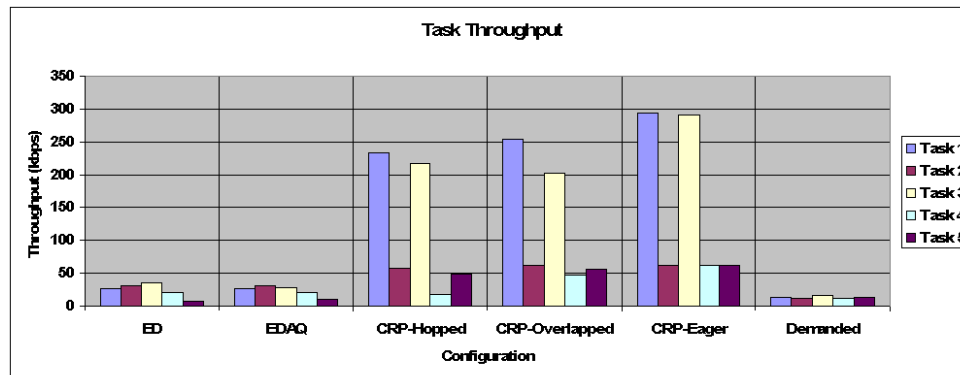
V. Group-2 Experiments Simulation Results

A. Simulation Experiment 2-1
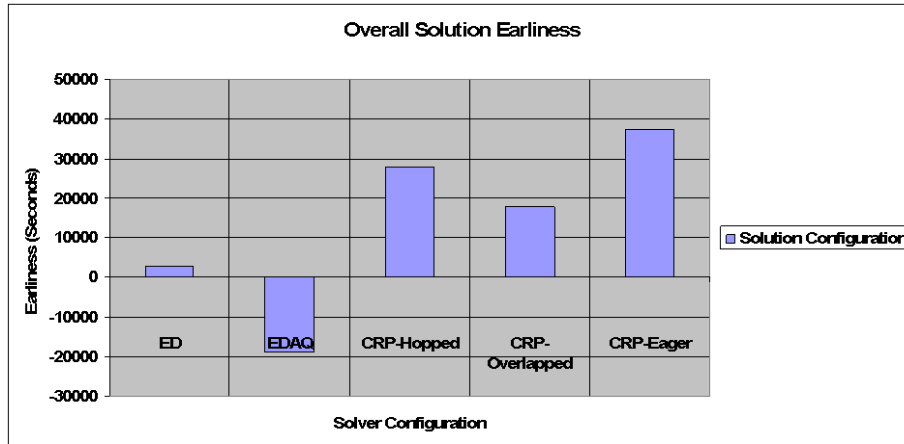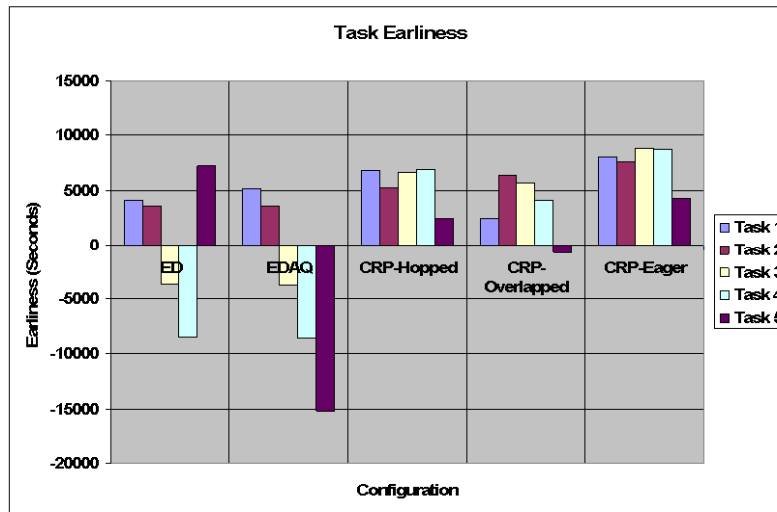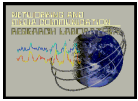

(a)

(b)

(c)

Fig.35: Exp. 2-1 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

B. Simulation Experiment 2-2

(a)

(b)
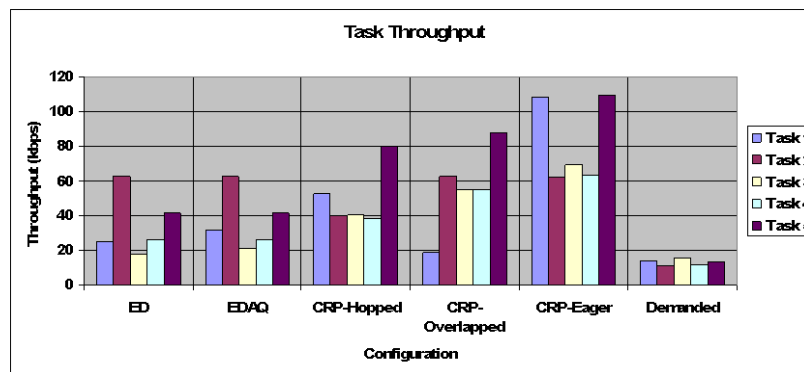
(c)

Fig.36: Exp. 2-2 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

C. Simulation Experiment 2-3

(a)

(b)

(c)
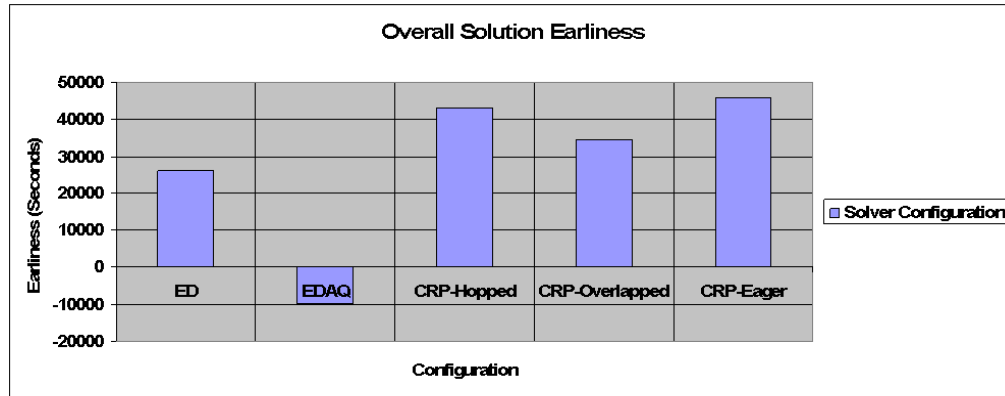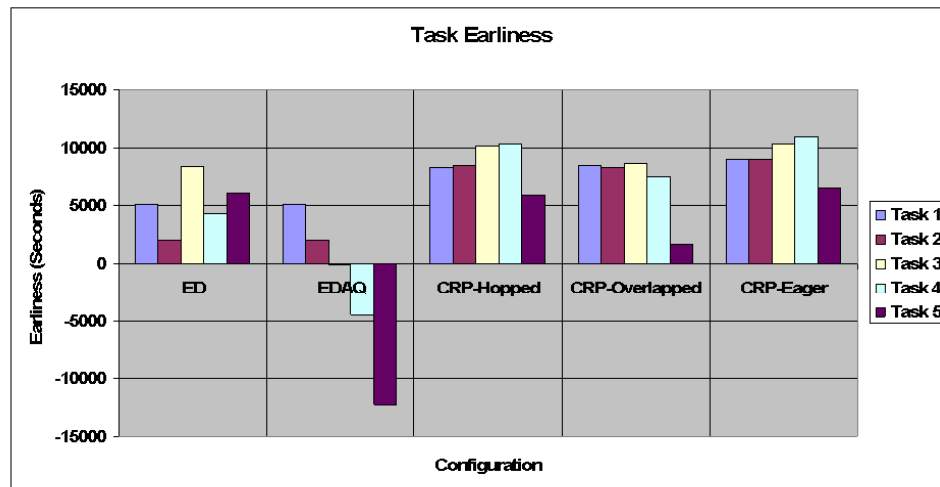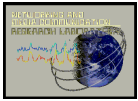
Fig.37: Exp. 2-3 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

D. Simulation Experiment 2-4

(a)

(b)

(c)

Fig.38: Exp. 2-4 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput
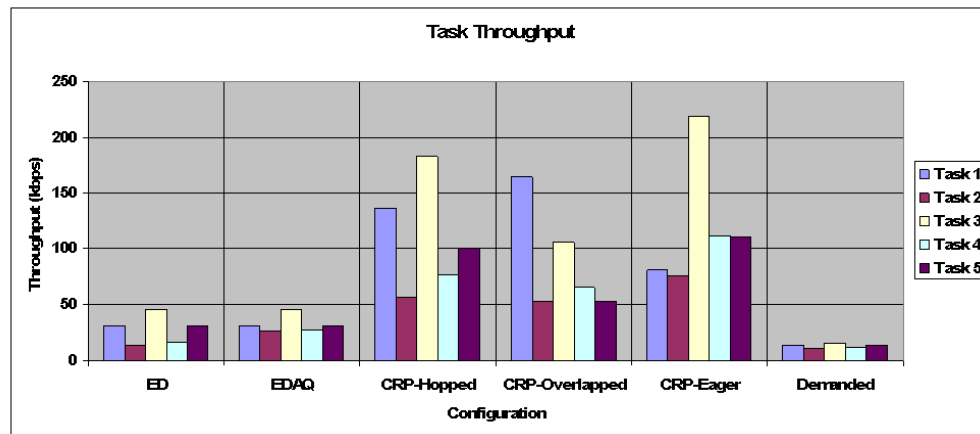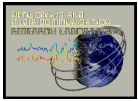
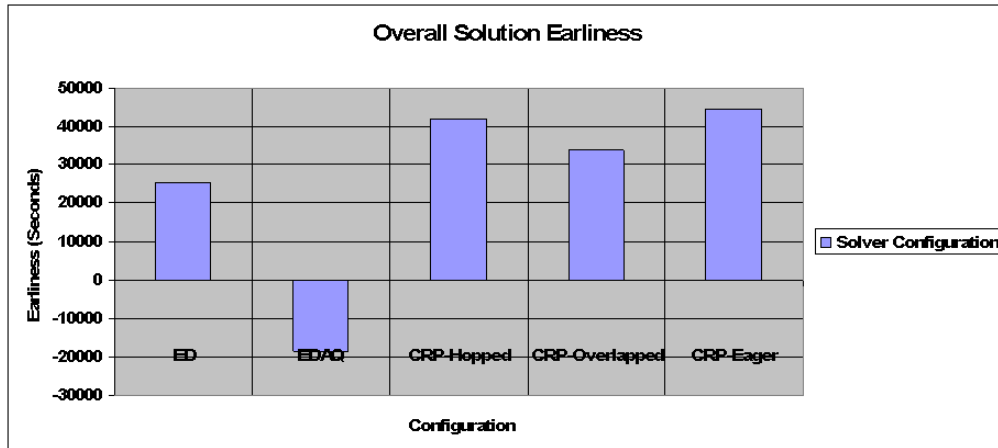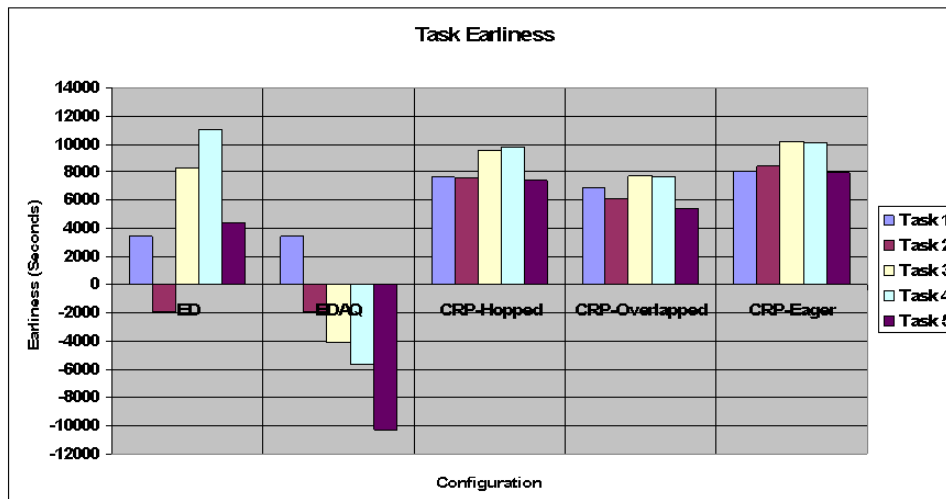### E. Simulation Experiment 2-5

(a)

(b)

(c)

Fig.39: Exp. 2-5 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

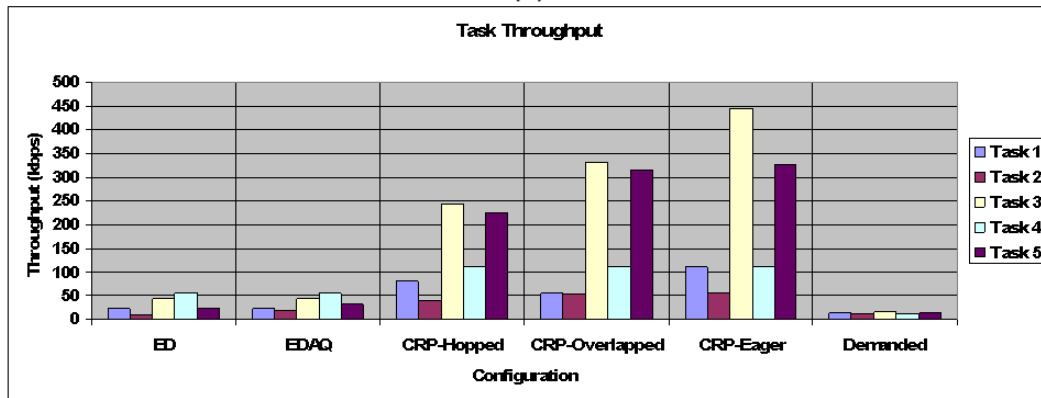## F. Simulation Experiment 2-6

(a)

(b)
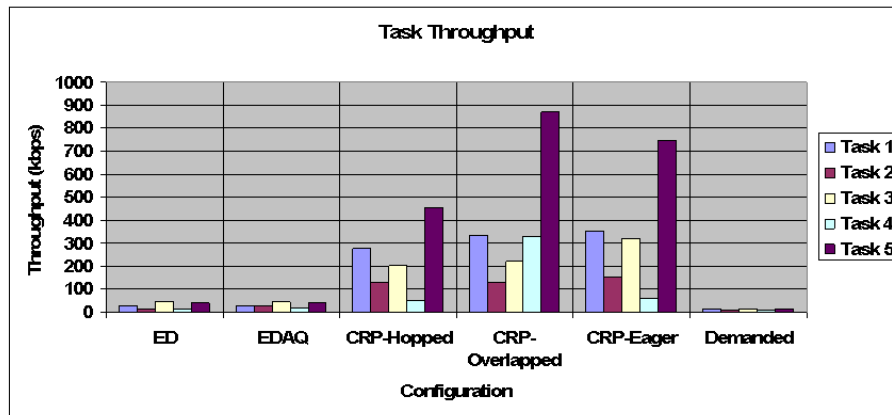
(c)

Fig.39: Exp. 2-6 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

G. Simulation Experiment 2-7
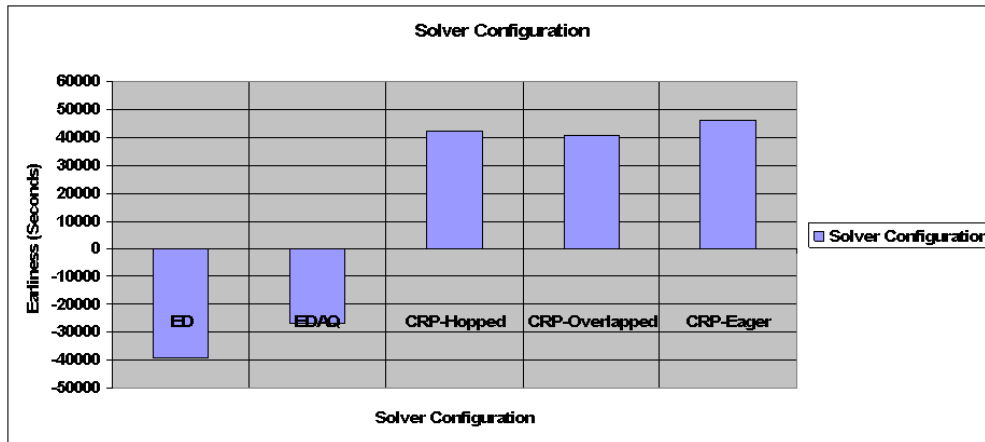
(a)
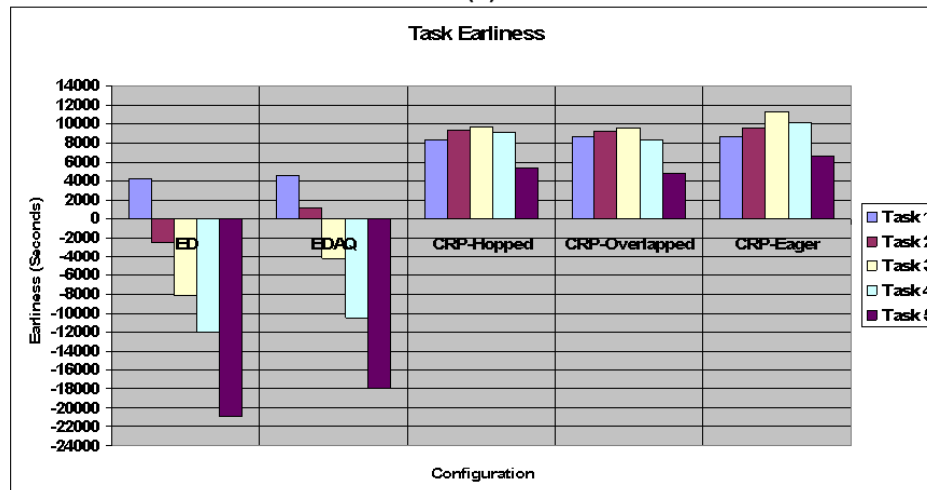
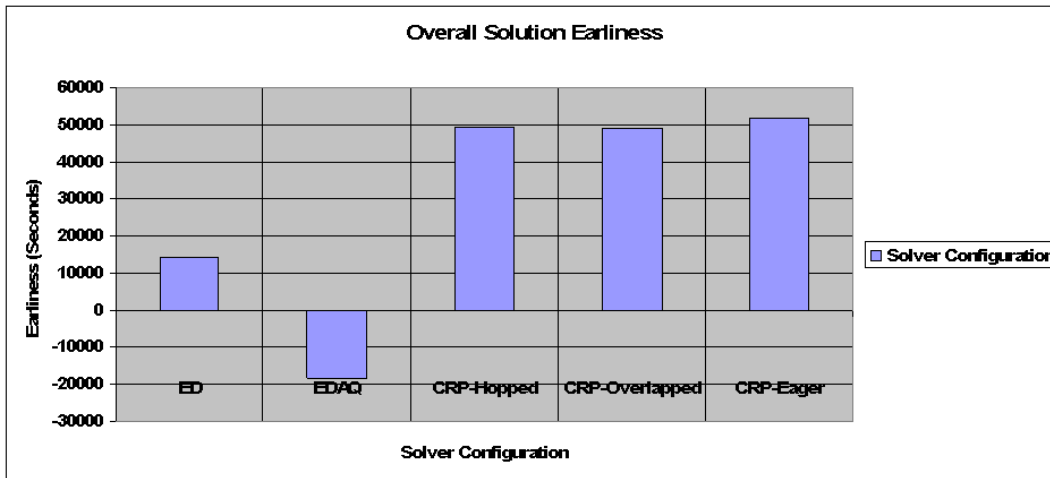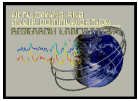**(b)**
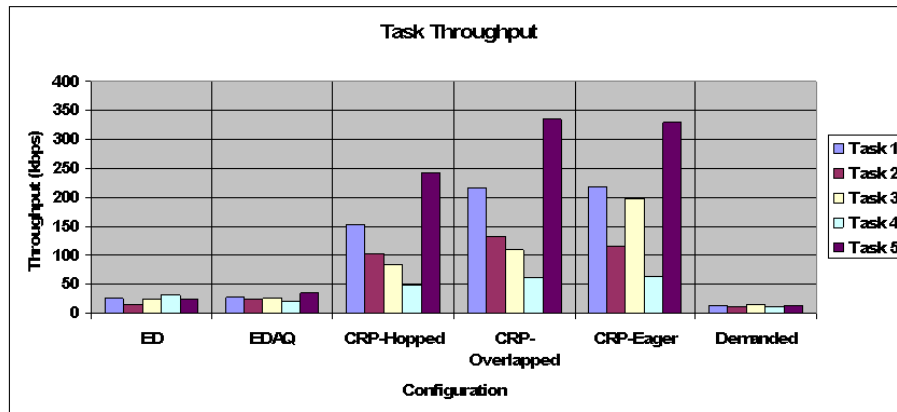
(c)

Fig.40: Exp. 2-7 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

H. Simulation Experiment 2-8

(a)
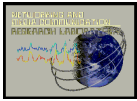
(b)

(c)

Fig.41: Exp. 2-8 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput
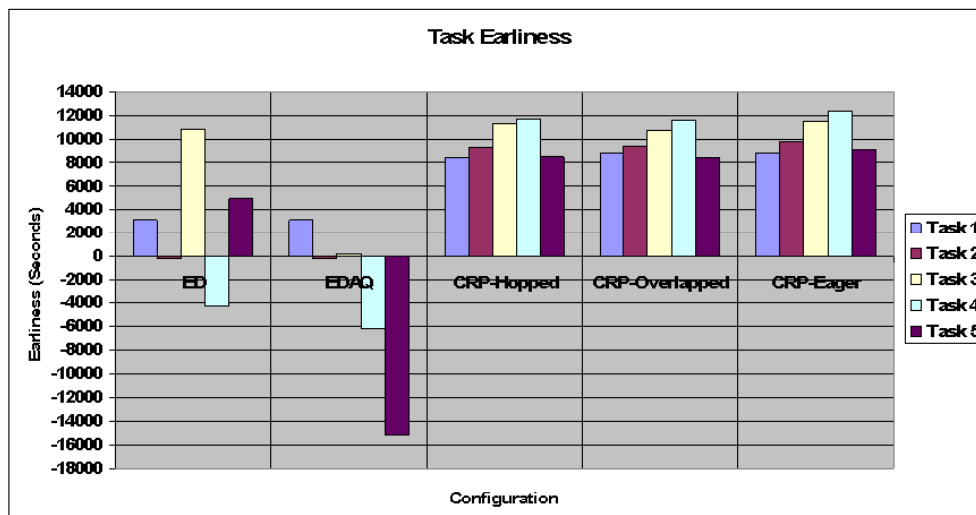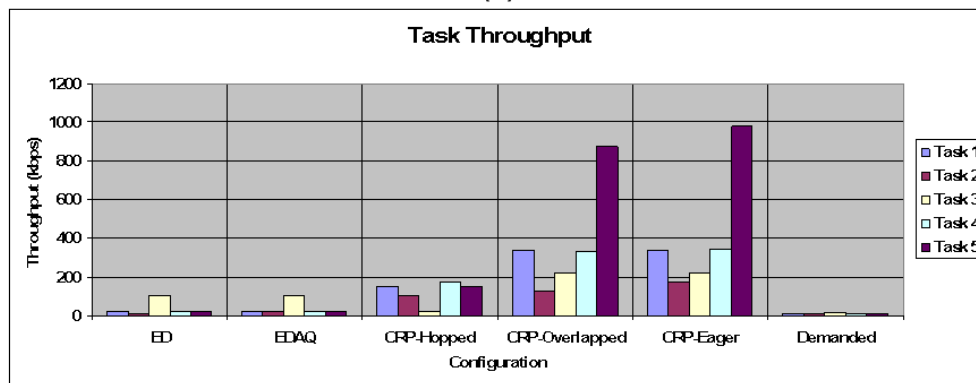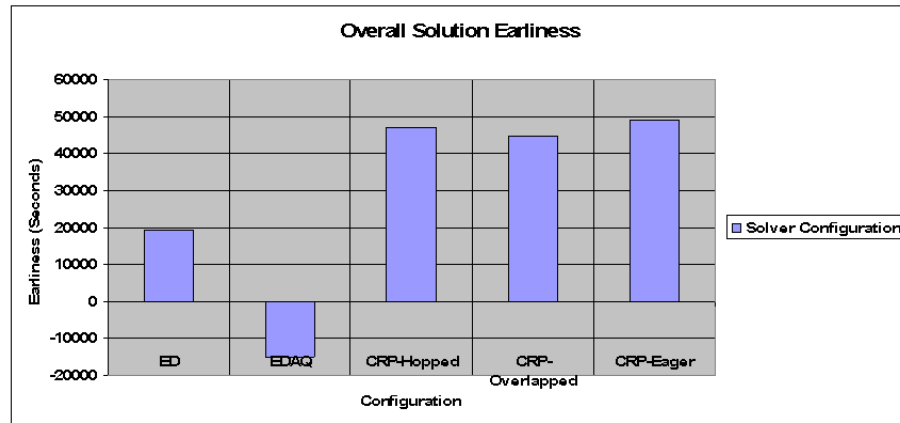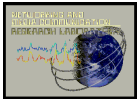
I. Simulation Experiment 2-9
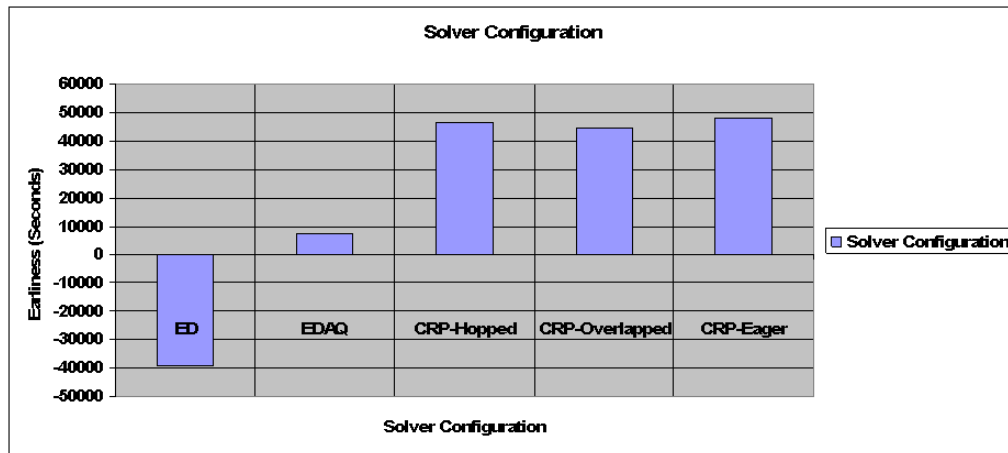
(a)

(b)
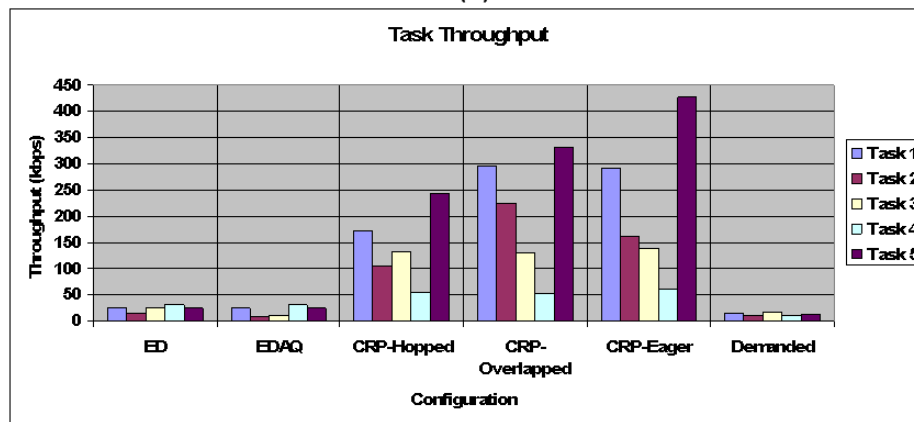
(c)

Fig.42: Exp. 2-9 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput
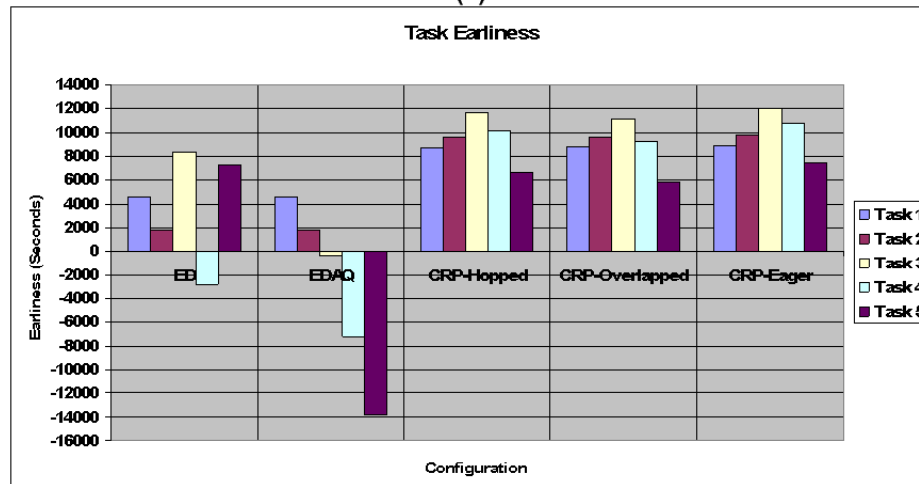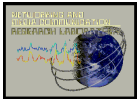
J. Simulation Experiment 2-10
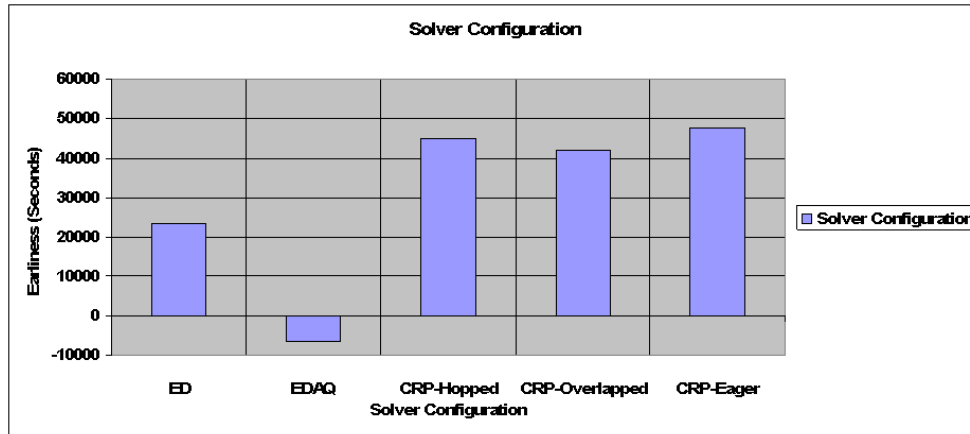
(a)
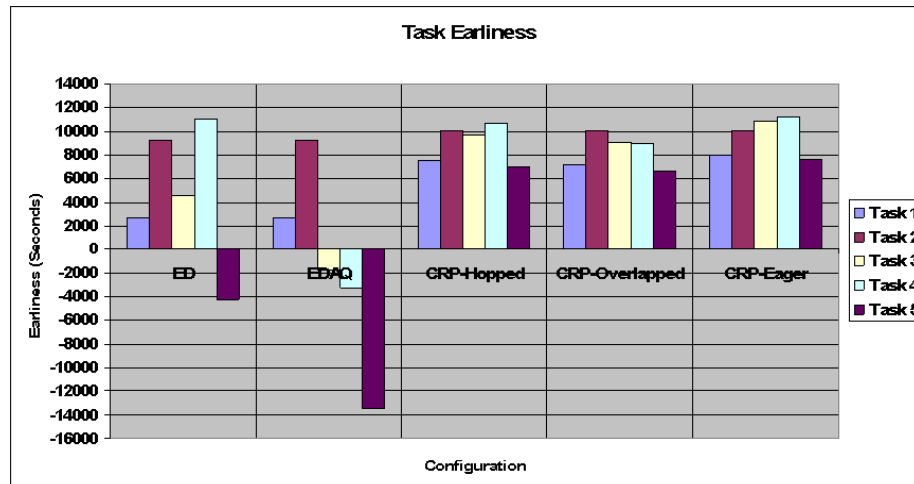
(b)
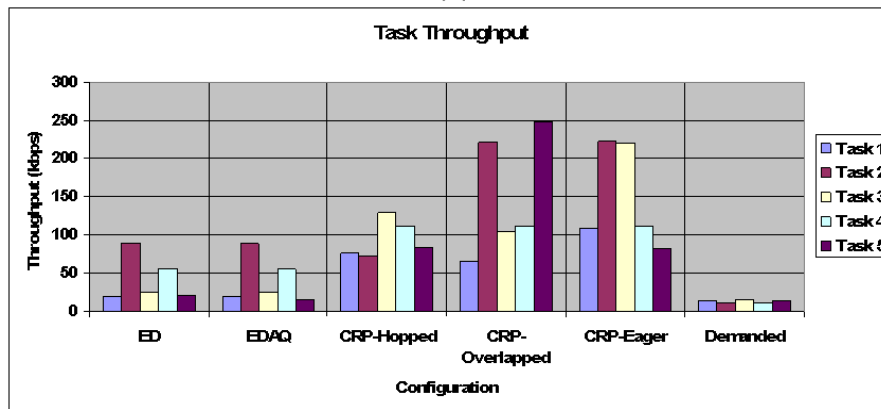
(c)

Fig.43: Exp. 2-10 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

K. Group-1 Simulation Experiments Summary
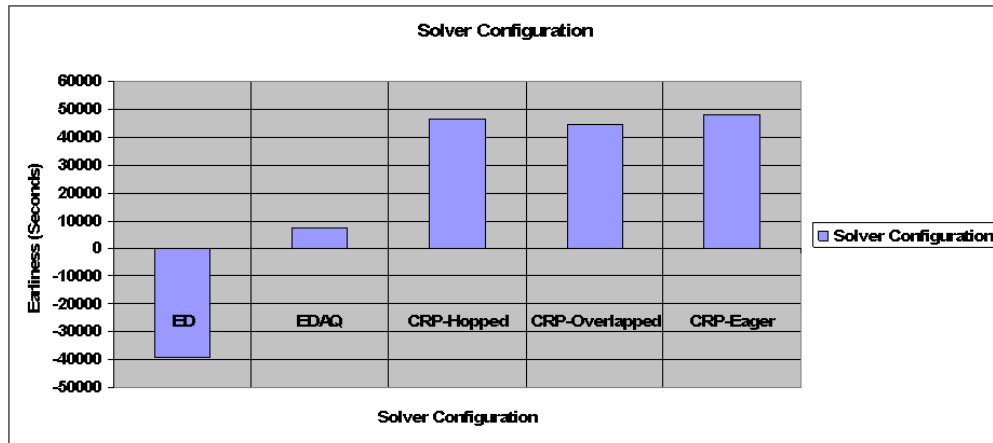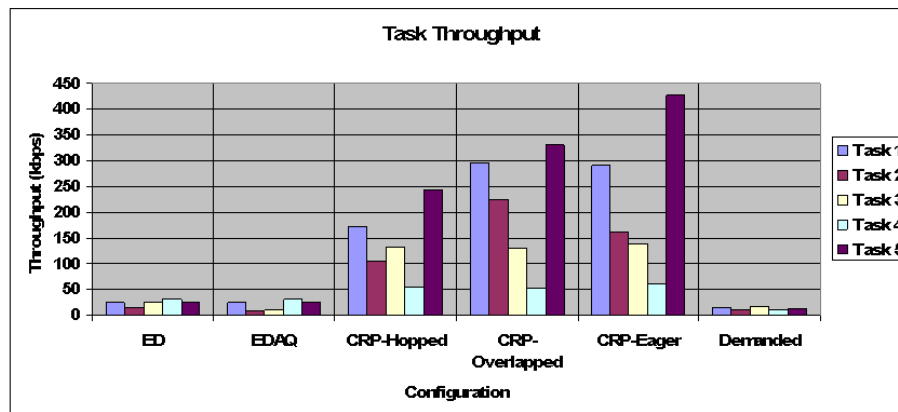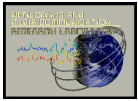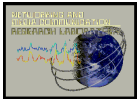
The simulation results obtained from the ten experiments are summarized in Fig. 44-46. The overall solution earliness of the five solver configurations are given by Fig. 44 as the average earliness over the ten experiments. Similarly to solution earliness, the overall task earliness and throughout are given by Fig. 45 and 46.
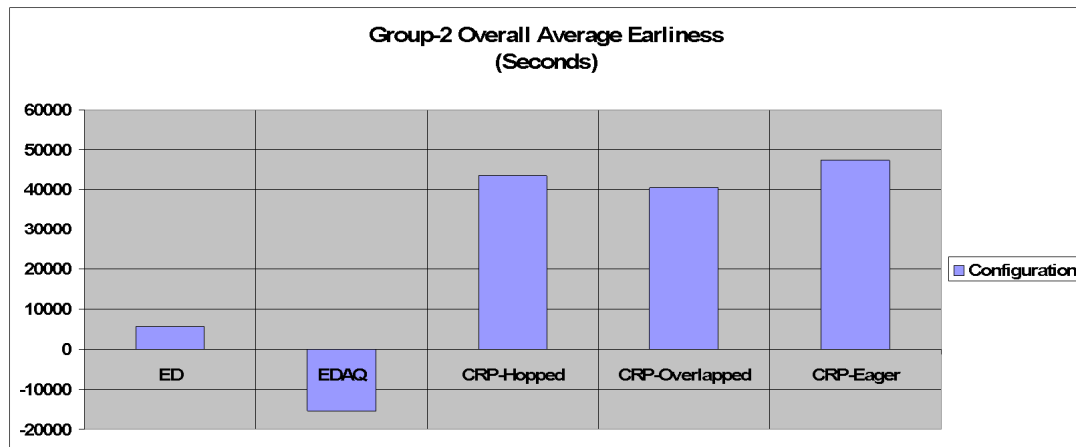
Fig.44: Overall Average Earliness of Group-2 Experiments
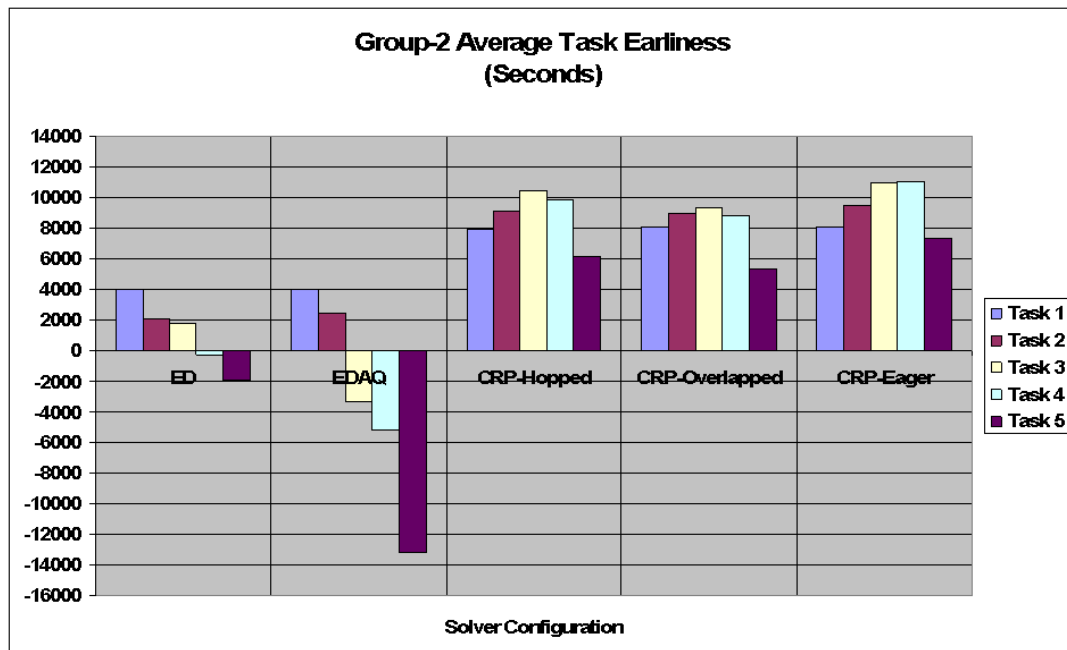
Fig.45: Overall Average Task Earliness of Group-2 Experiments
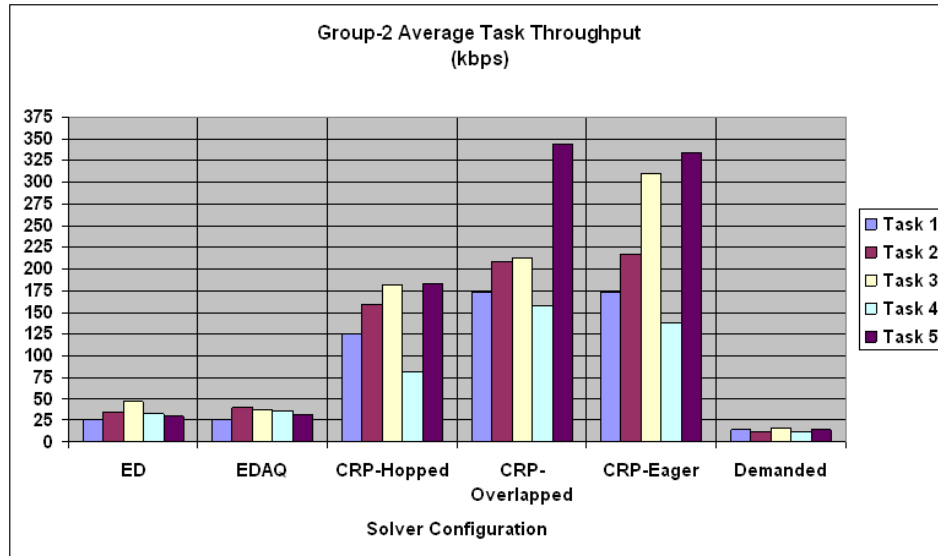
Fig.46: Overall Average Task Earliness of Group-2 Experiments

VI. Simulation Experiment Group-3

In this group, ten simulation experiments are conducted on 10 different eight-node graphs. The task set of this group is given by the table shown below.

i	u_i	v_i	o_i (Sec)	dl_i (Sec)	s_i (MB)
1	10	3	98	**9314**	16
2	8	1	188	**10778**	15
3	7	9	263	**13013**	25
4	5	2	357	**14337**	20
5	4	9	444	**11172**	18

Table 3: The Task Set

Fig.47: The Exp-3-1 Network Topology

Fig.48: The Exp-3-2 Network Topology
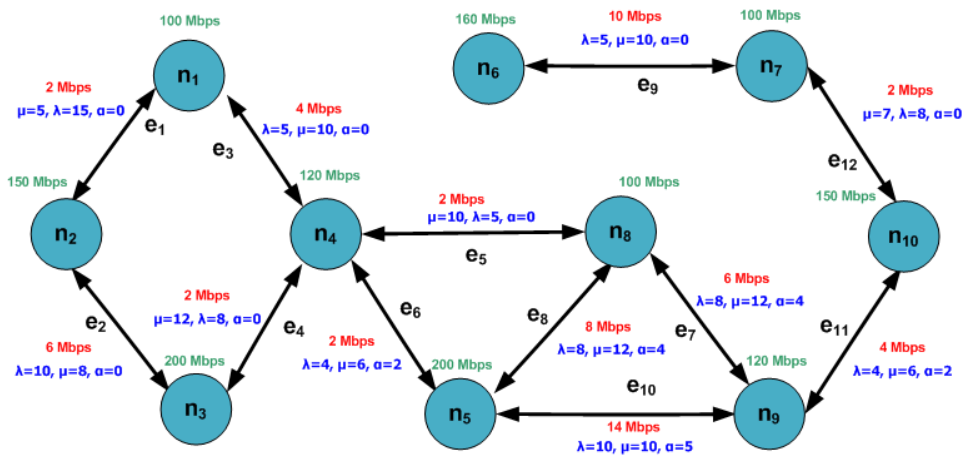
Fig.49: The Exp-3-3 Network Topology
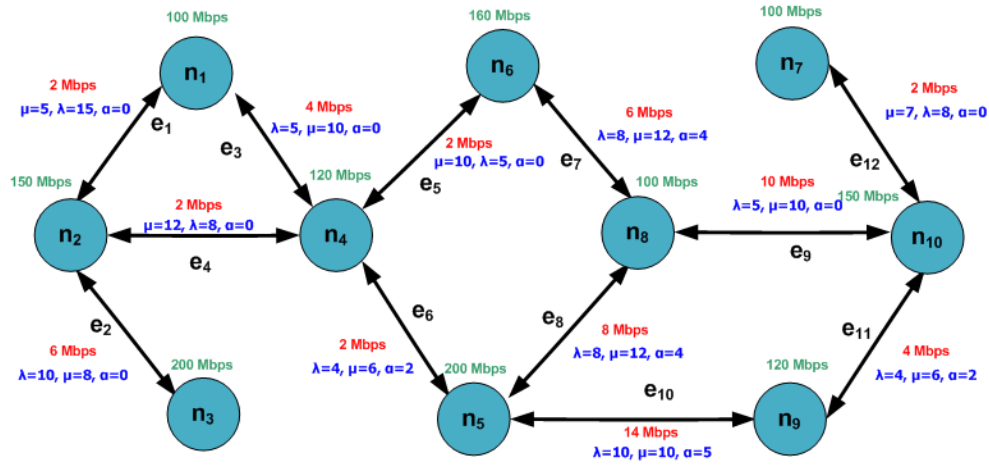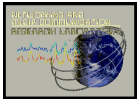
Fig.50: The Exp-3-4 Network Topology
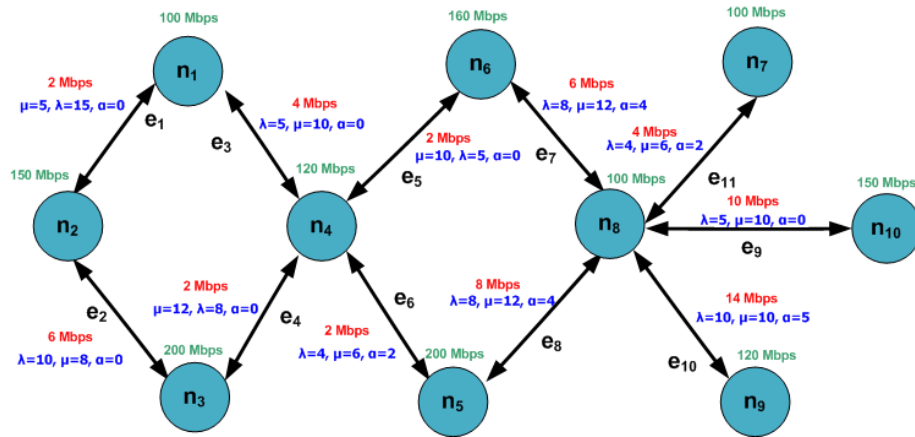
Fig.51: The Exp-3-5 Network Topology
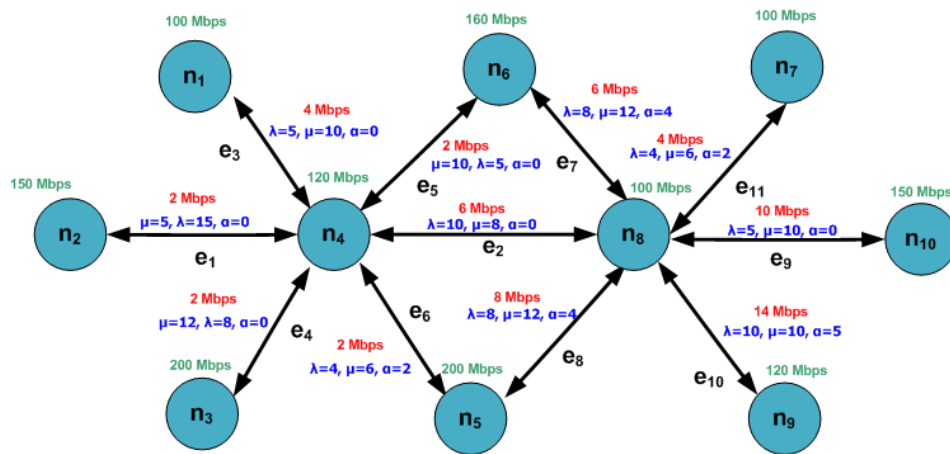
Fig.52: The Exp-3-6 Network Topology
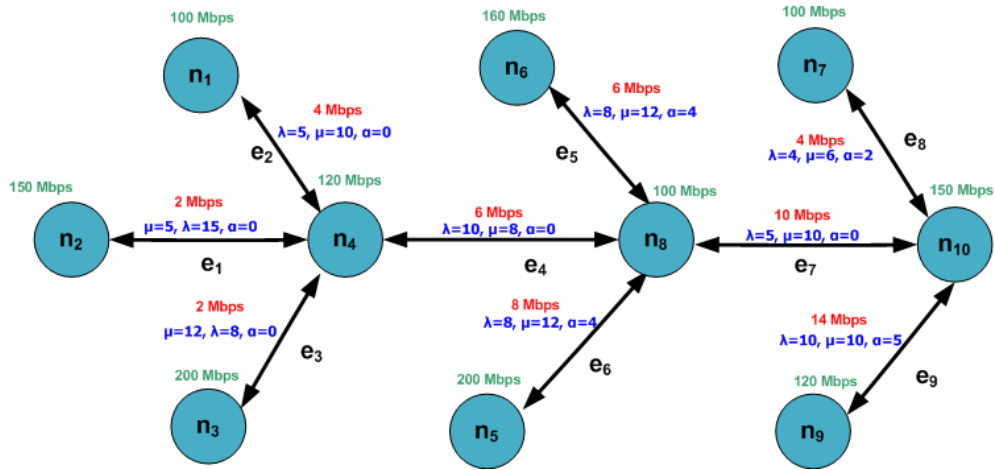
Fig.53: The Exp-3-7 Network Topology
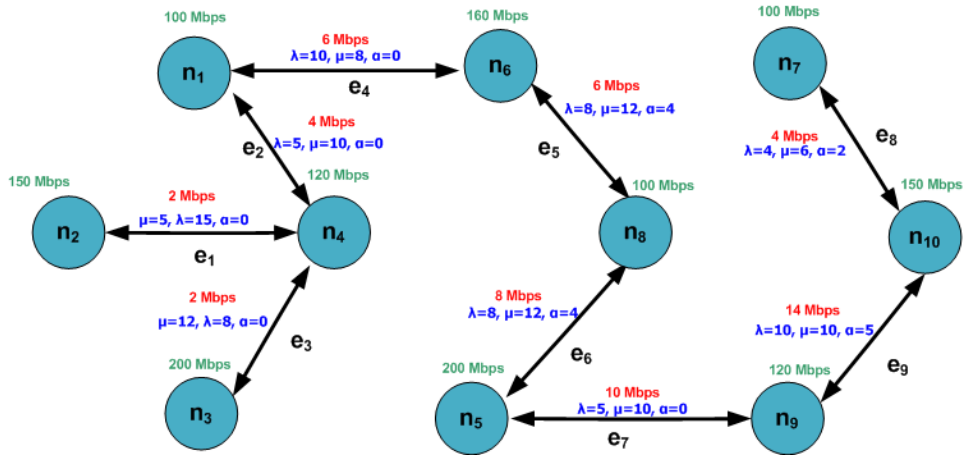
Fig.54: The Exp-3-8 Network Topology
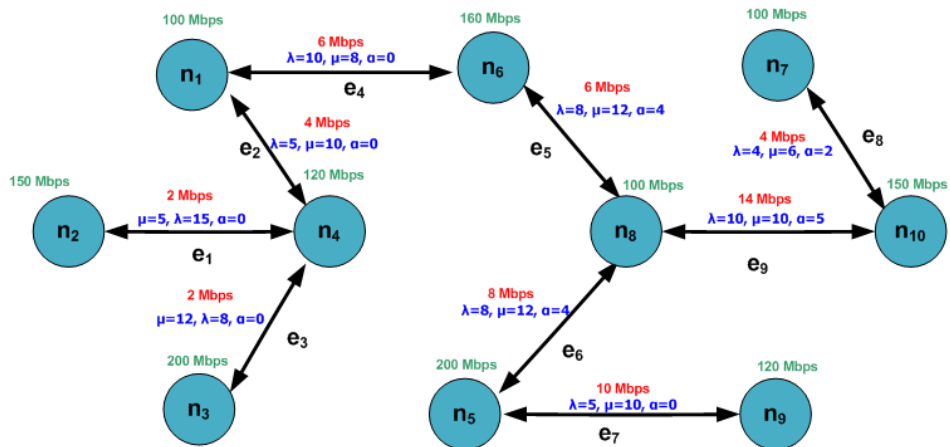
Fig.55: The Exp-3-9 Network Topology
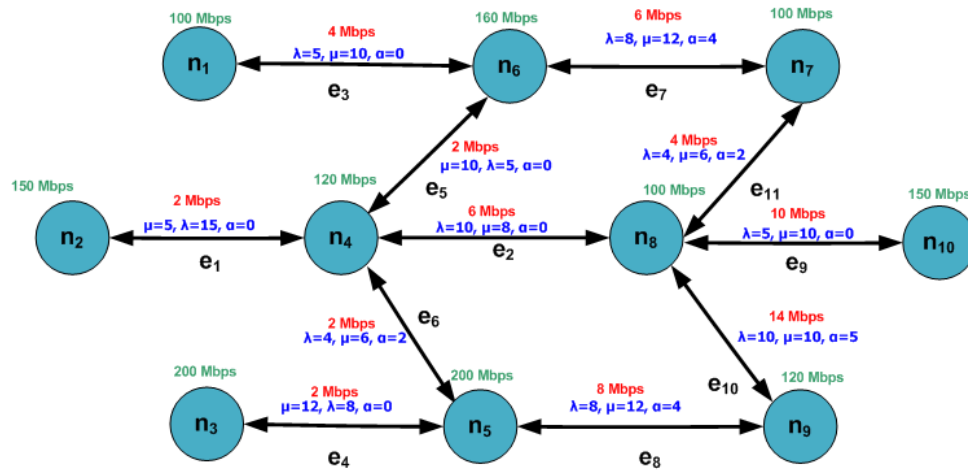
Fig.56: The Exp-3-10 Network Topology
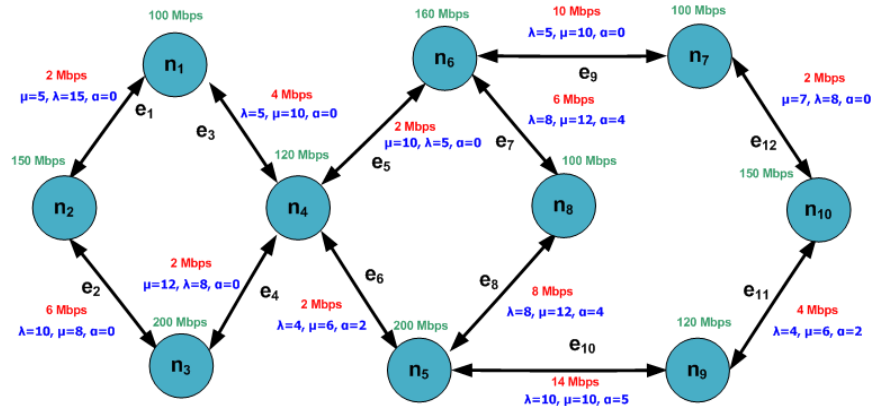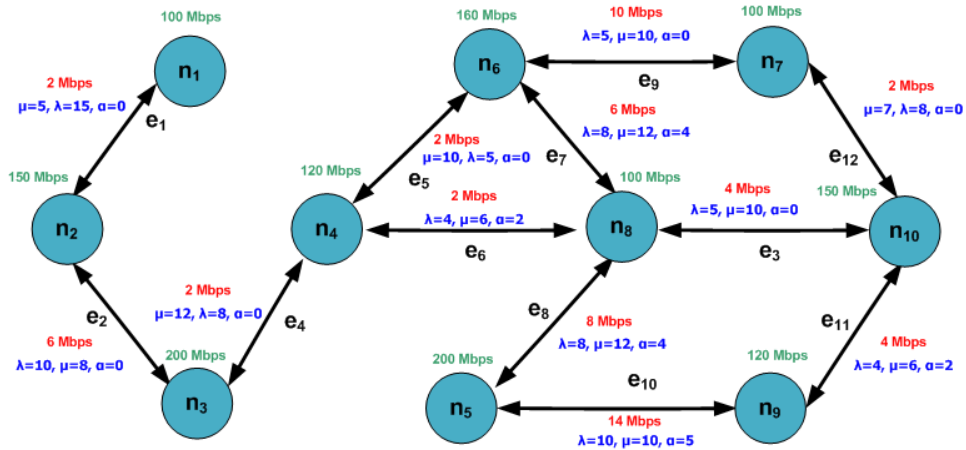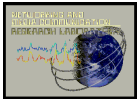
VII.   Group-3 Experiments Simulation Results

A. Simulation Experiment 3-1
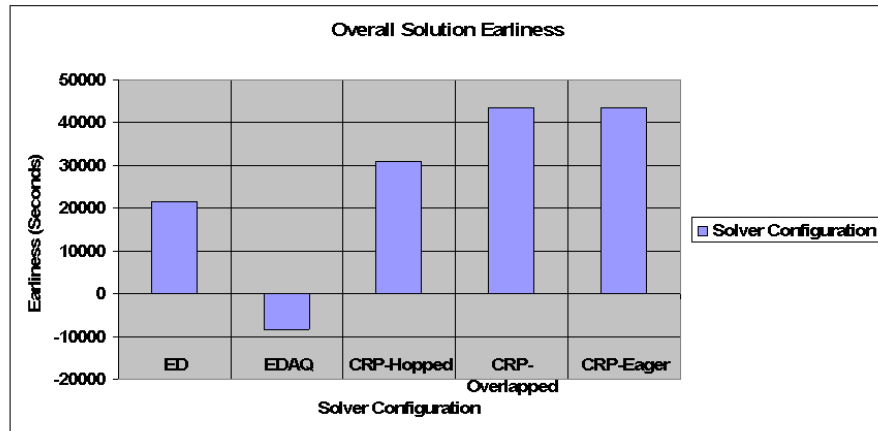
(a)
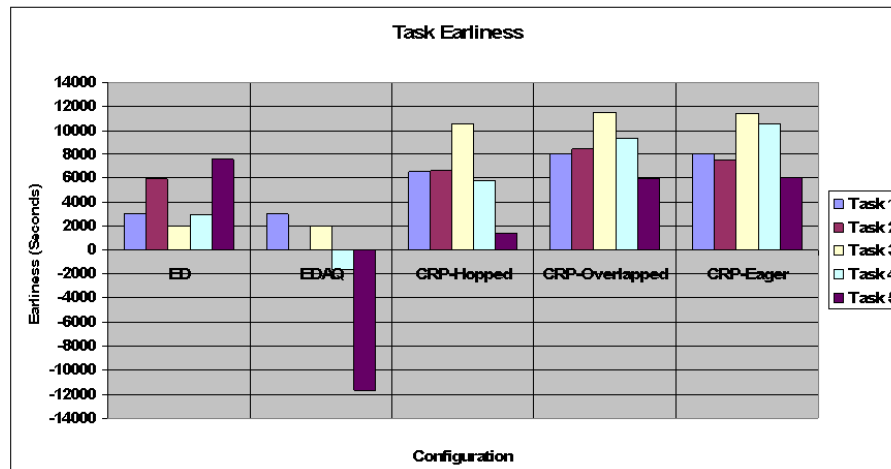
(b)

(c)

Fig.57: Exp. 3-1 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

B. Simulation Experiment 2-2

(a)

(b)

(c)

Fig.58: Exp. 3-2 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

C. Simulation Experiment 3-3

(a)

(b)

(c)

Fig.59: Exp. 2-3 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

D. Simulation Experiment 3-4
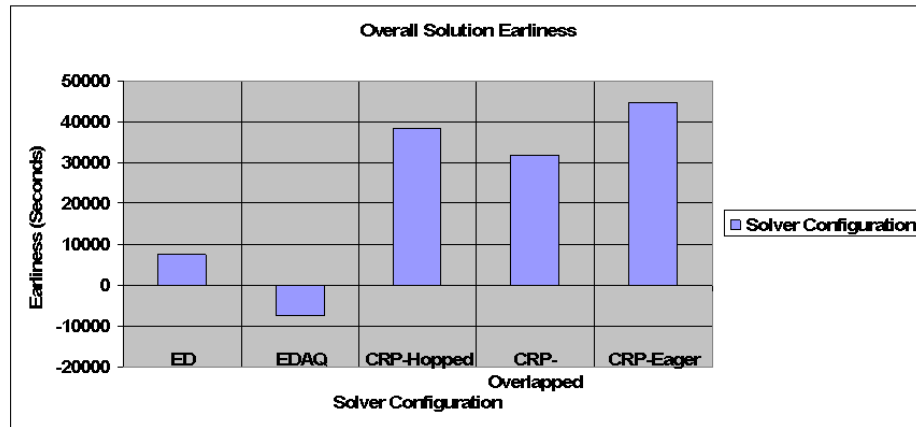
(a)
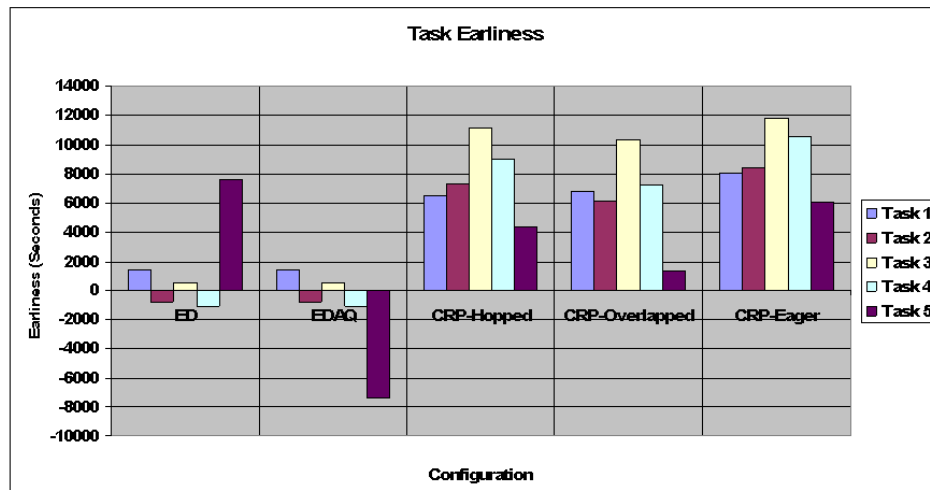
(b)
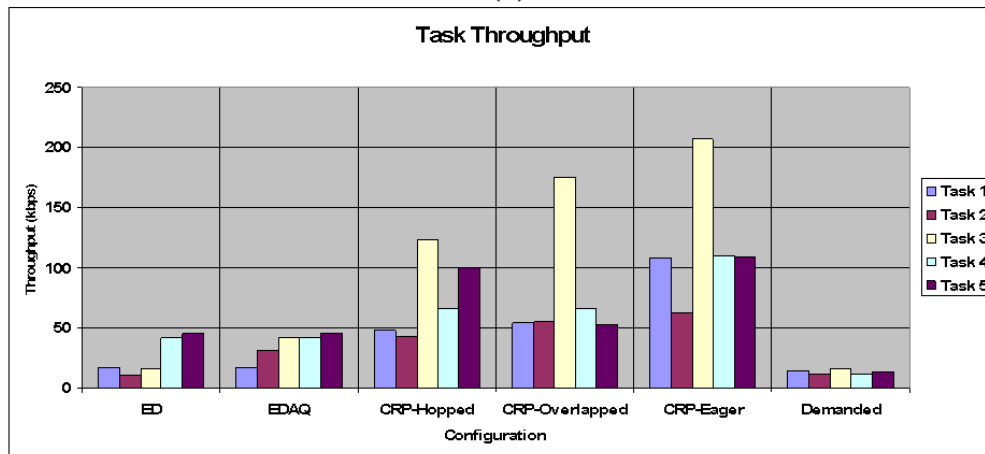
(c)

Fig.60: Exp. 3-4 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

E. Simulation Experiment 3-5
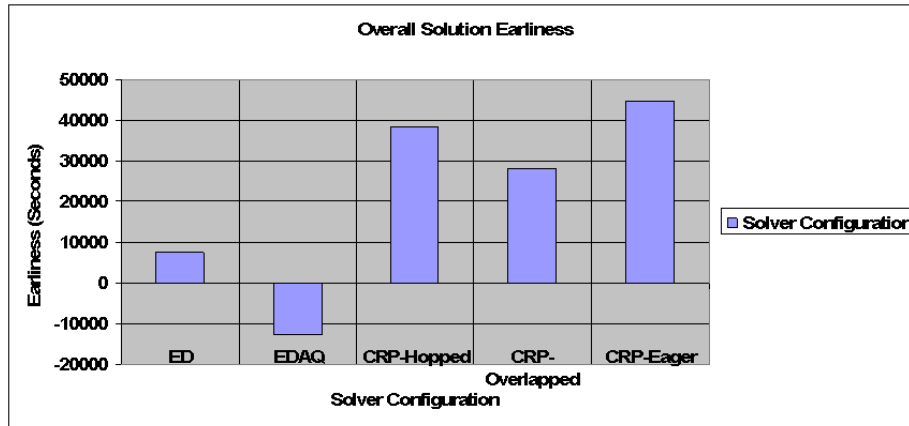
(a)
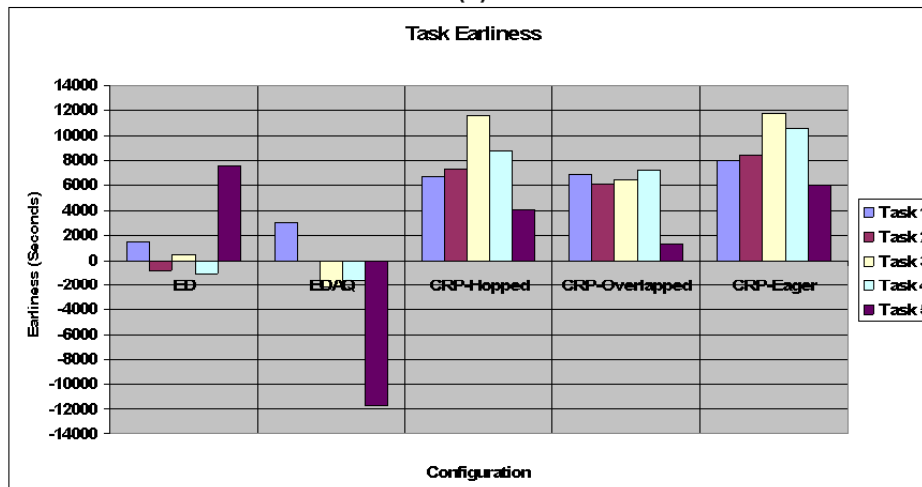
(b)
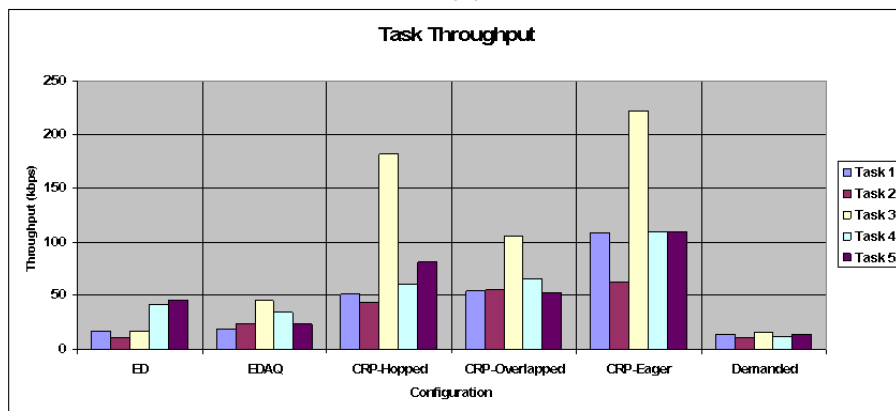
(c)

Fig.61: Exp. 3-5 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

F. Simulation Experiment 3-6
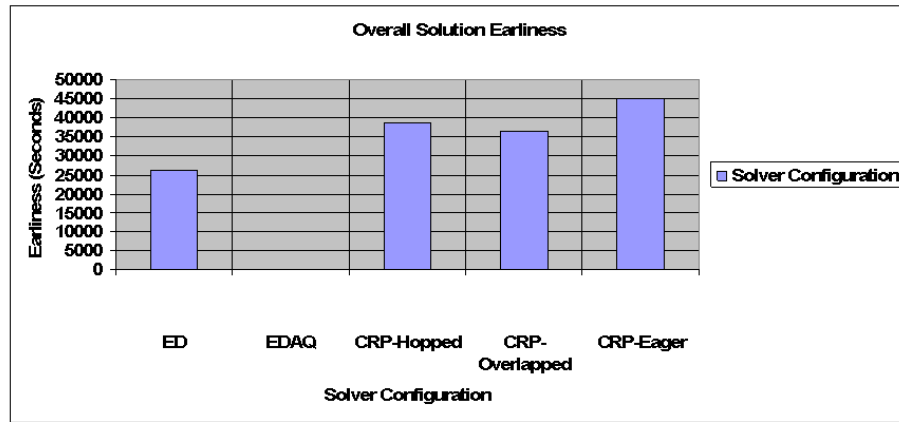
(a)
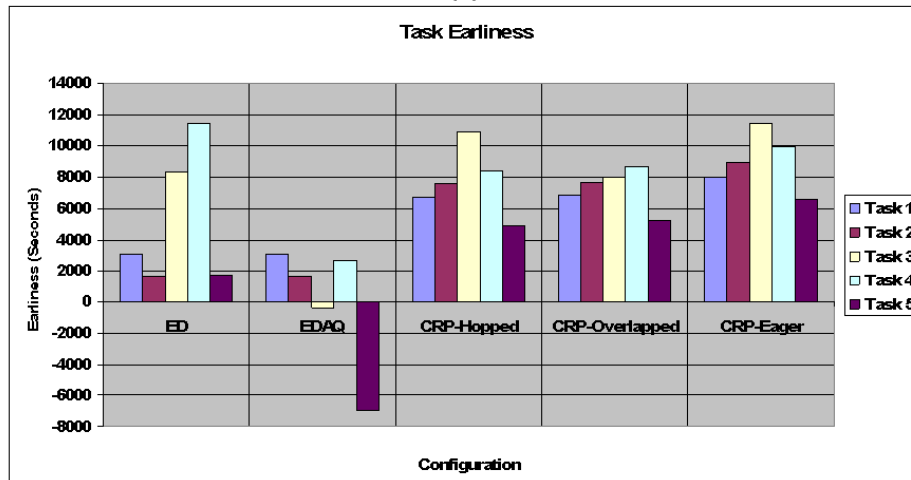
(b)
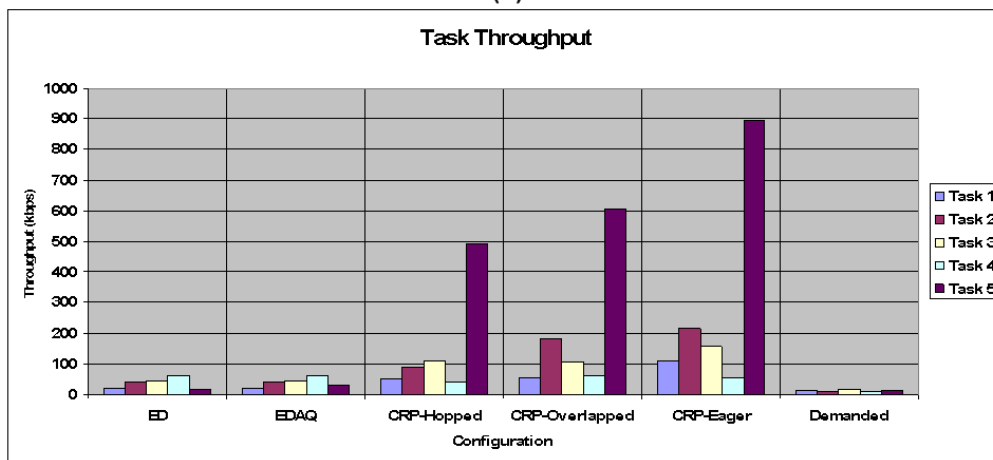
(c)

Fig.62: Exp. 3-6 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

G. Simulation Experiment 3-7
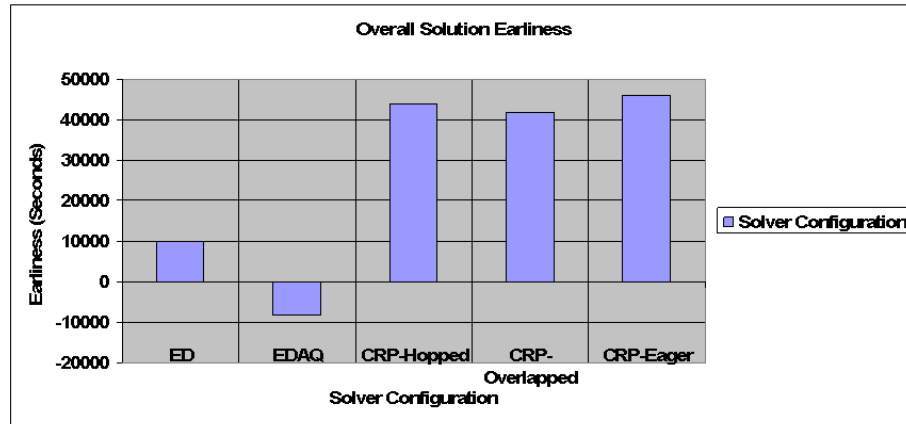
(a)
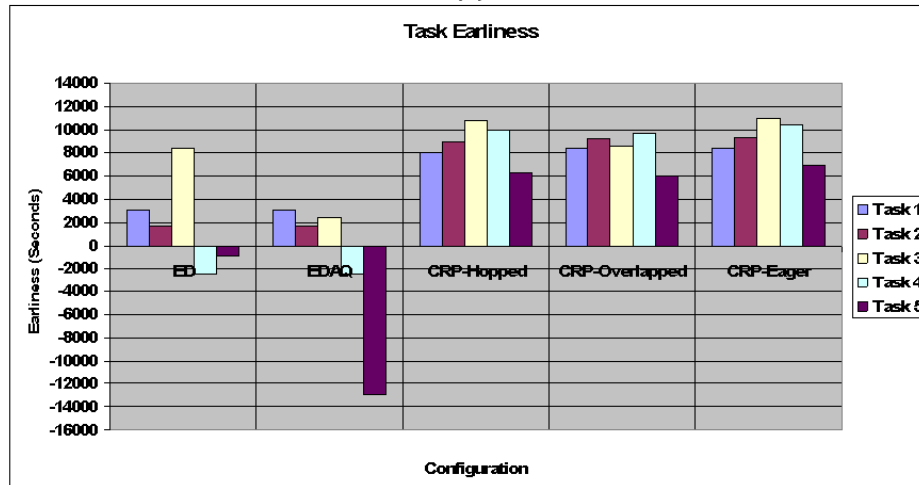
(b)
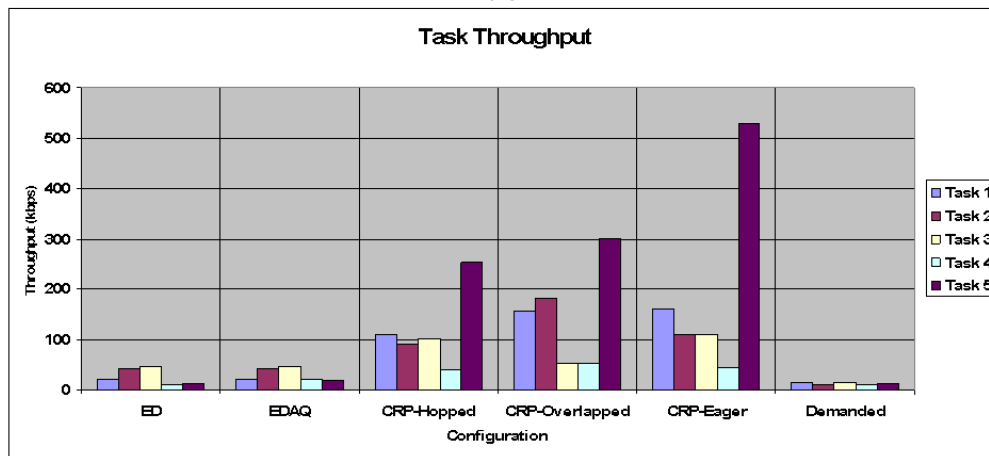
(c)

Fig.63: Exp. 3-7 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

H. Simulation Experiment 3-8
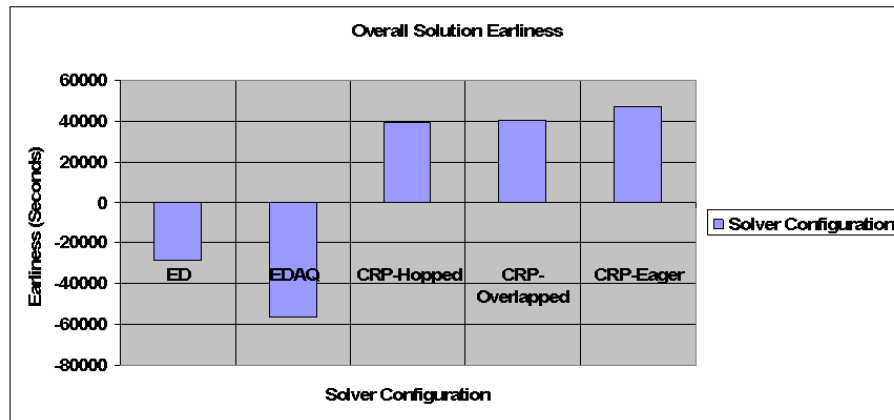
(a)
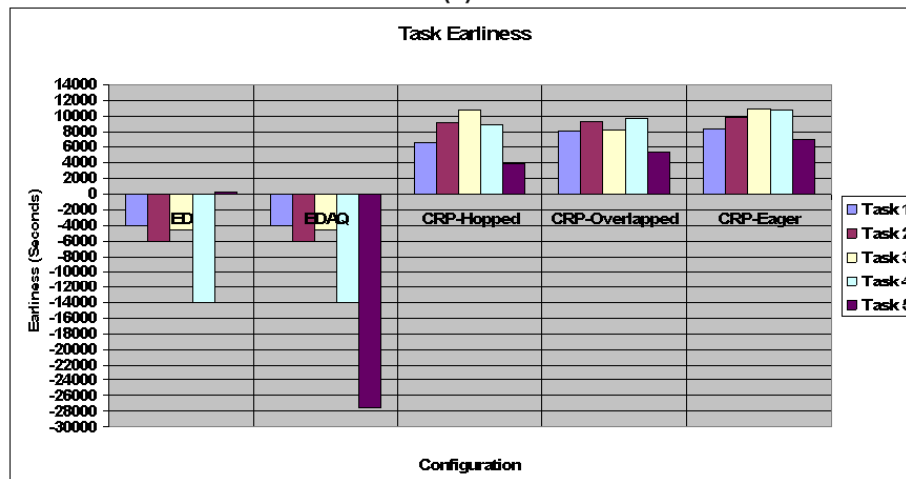
(b)
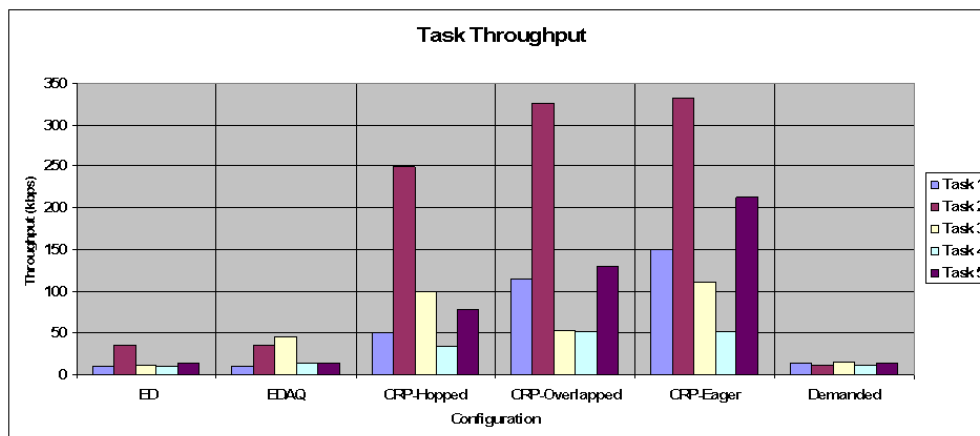
(c)

Fig.64: Exp. 3-8 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

I.   Simulation Experiment 2-9
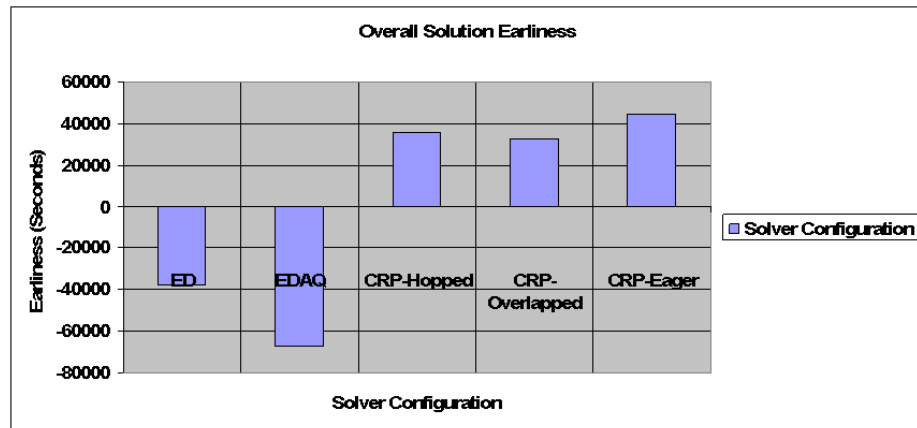
(a)
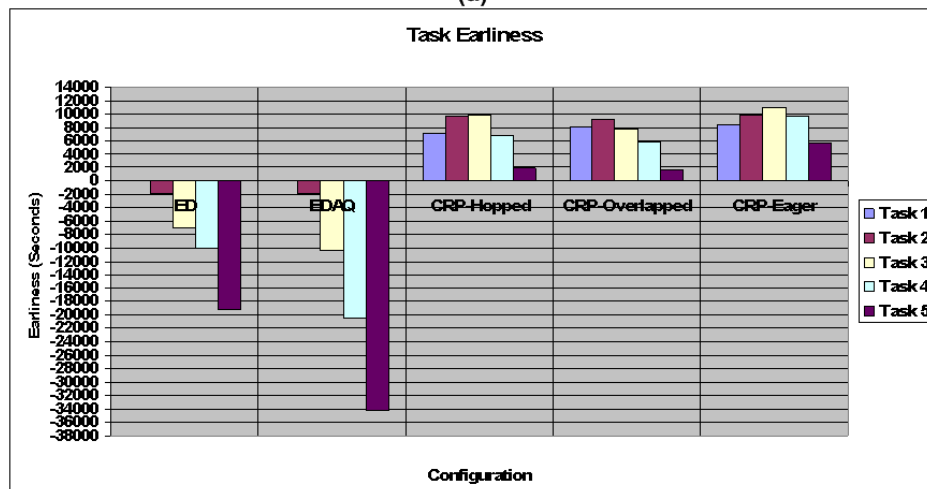
(b)
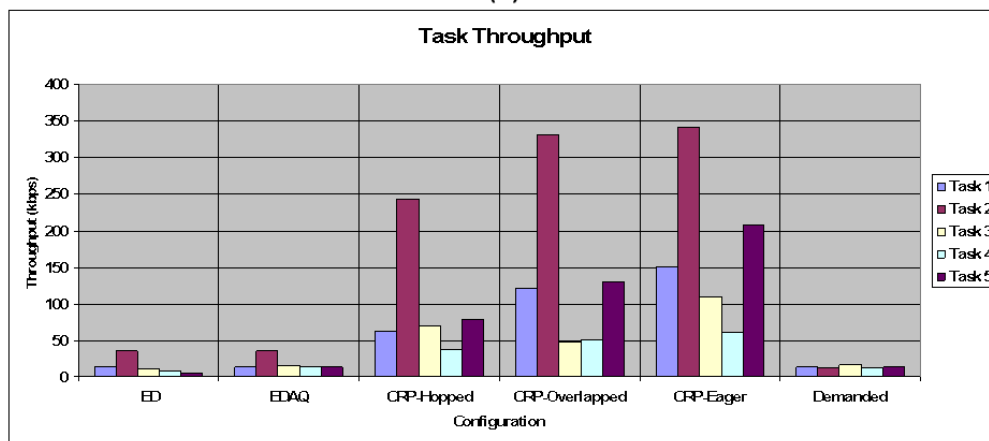
(c)

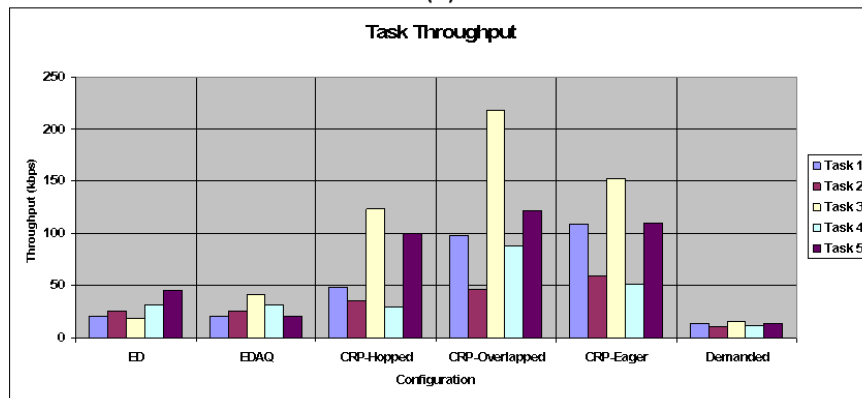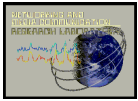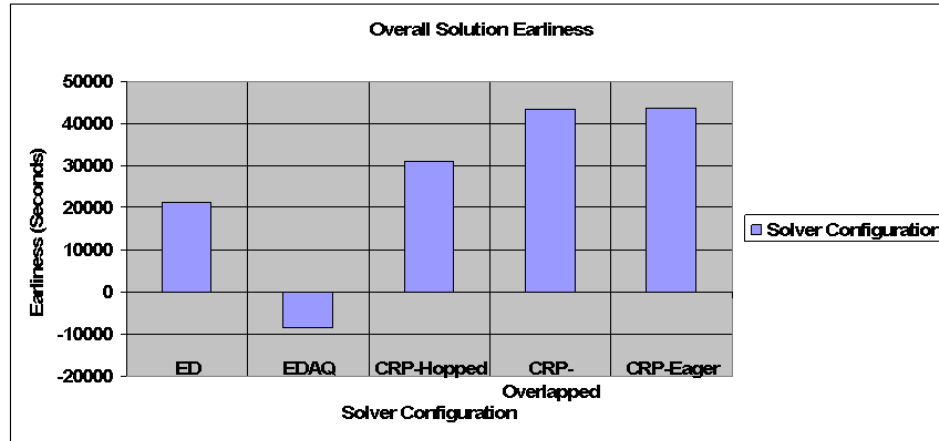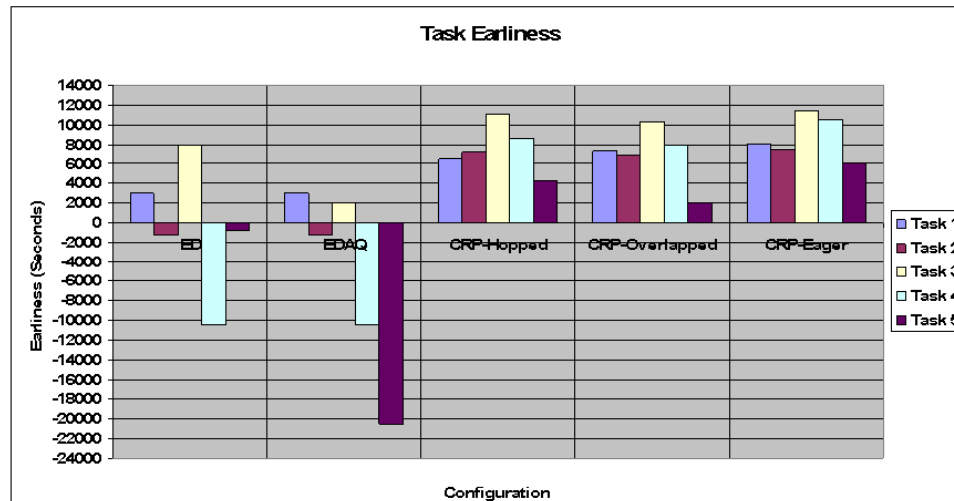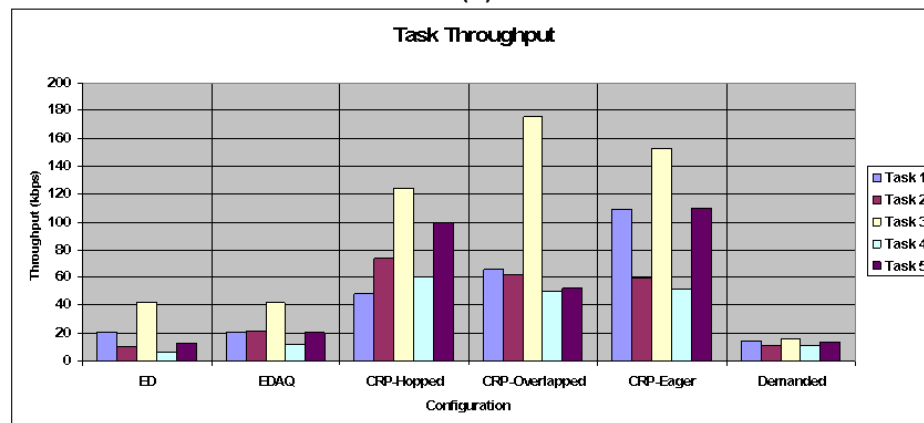**Fig.65: Exp. 3-9 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput**

J. Simulation Experiment 2-10
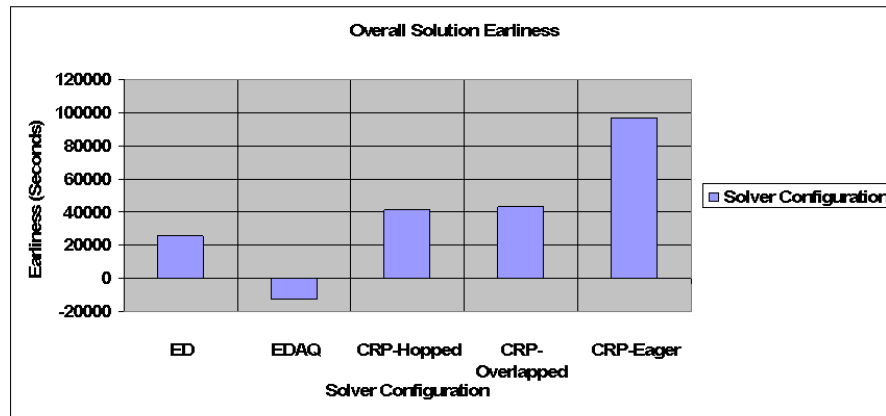
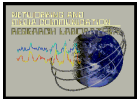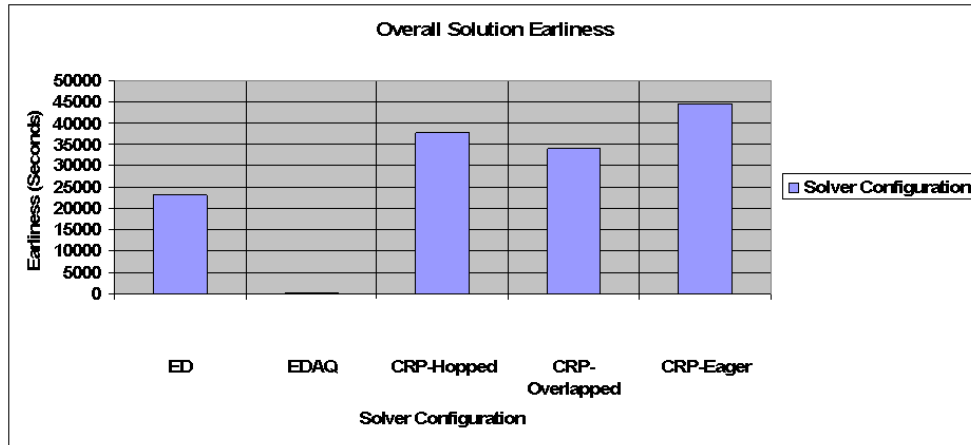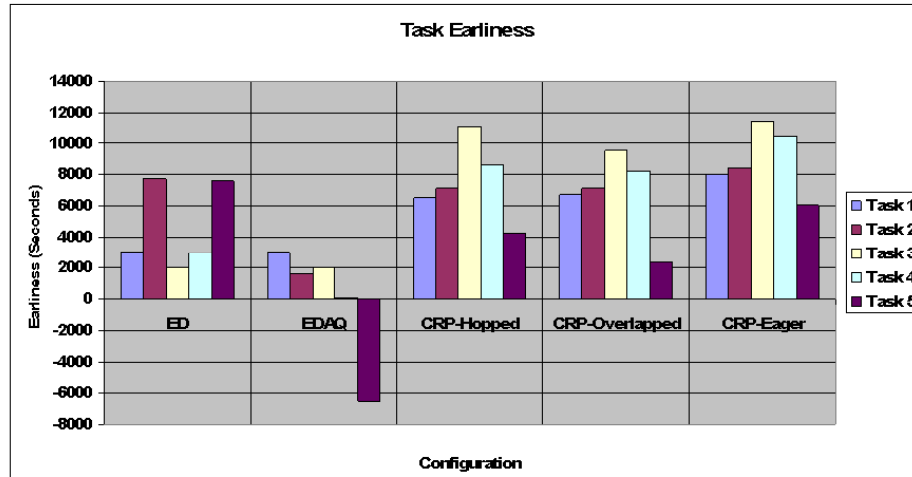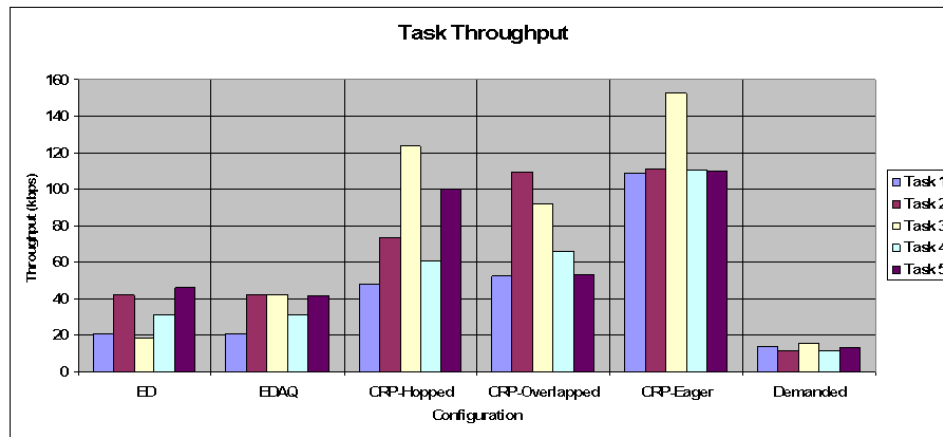

(a)
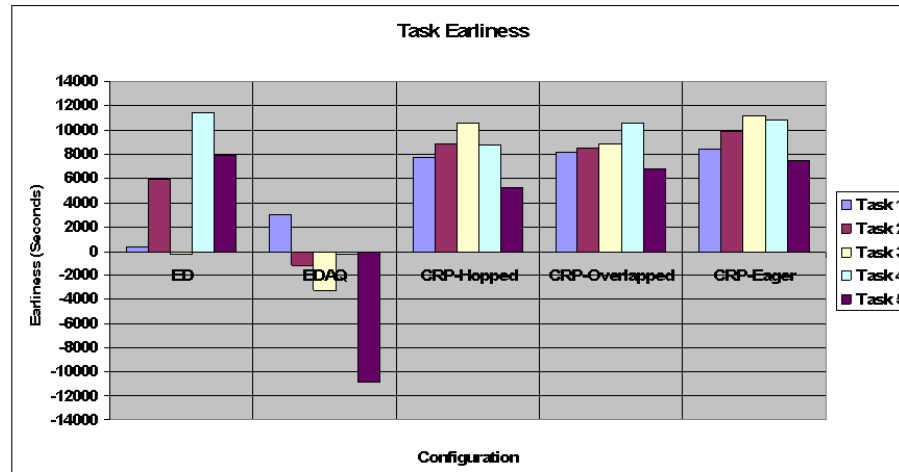
(b)
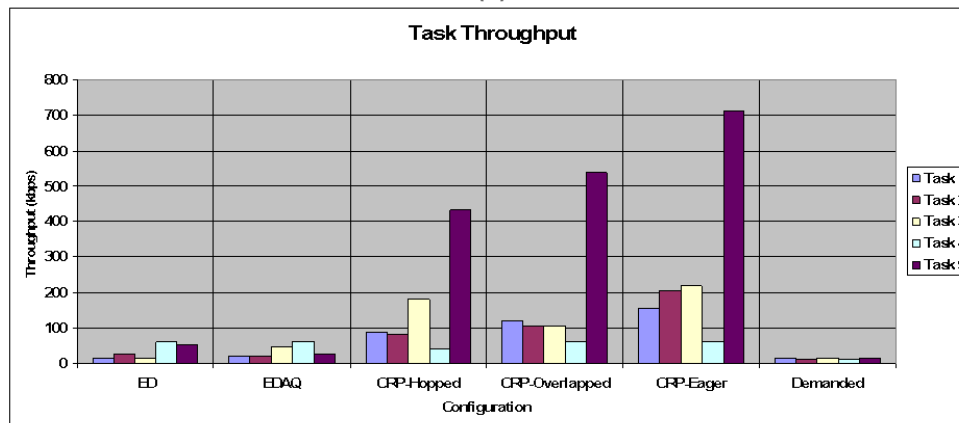
(c)

Fig.66: Exp. 2-10 Results: (a) Overall Solution Earliness, (c) Task Earliness, and (c) Task Throughput

## K. Group-3 Simulation Experiments Summary

The simulation results obtained from the ten experiments are summarized in Fig. 67-69. The overall solution earliness of the five solver configurations are given by Fig. 67 as the average earliness over the ten experiments. Similarly to solution earliness, the overall task earliness and throughout are given by Fig. 68 and 69.
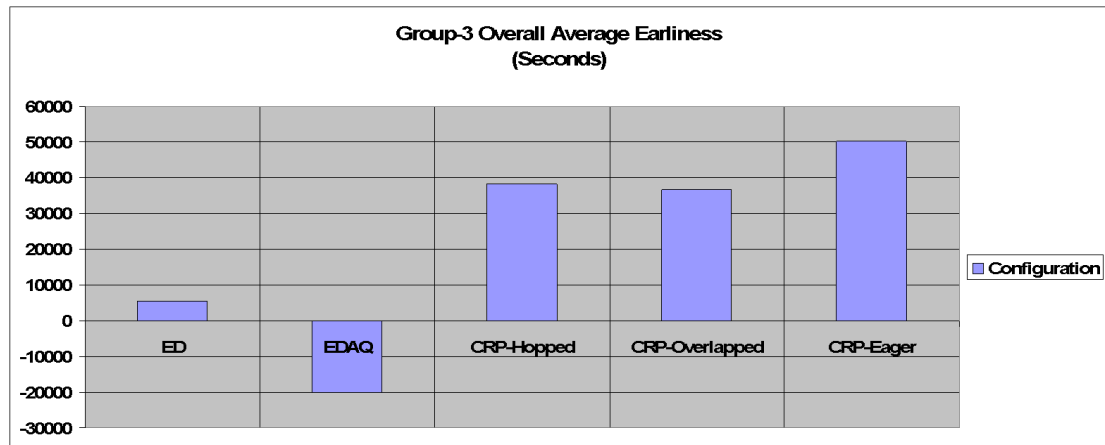
Fig.67: Overall Average Earliness of Group-3 Experiments
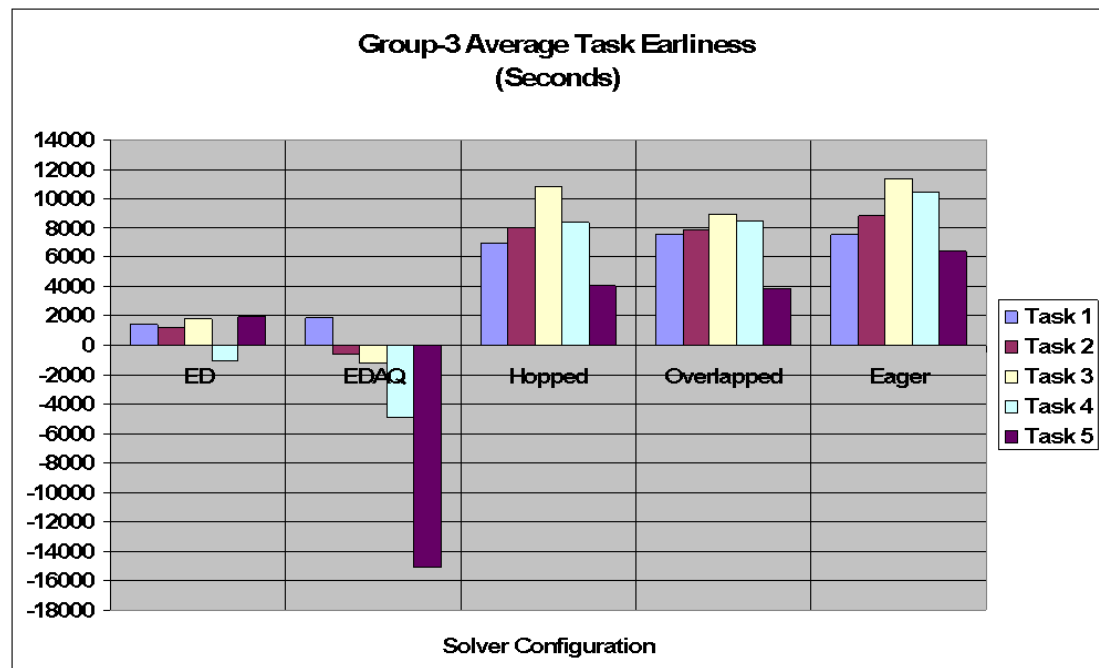
Fig.68: Overall Average Task Earliness of Group-2 Experiments
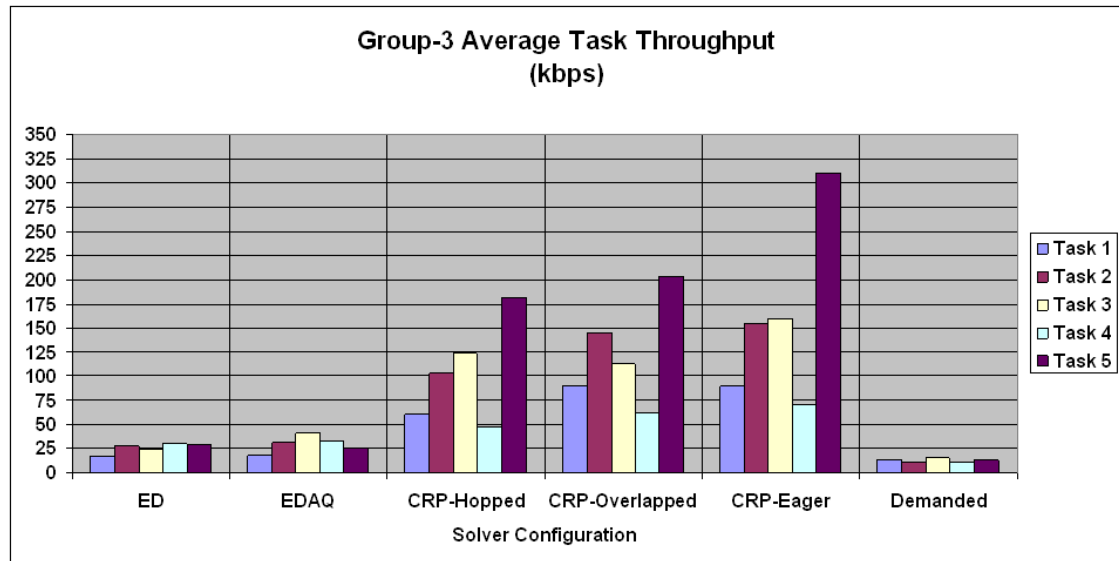
Fig.69: Overall Average Task Earliness of Group-1 Experiments

VIII. Results Discussion

In this section we discuss the results obtained from the three experimentation groups. For the purpose of clarity, we combine the performance evaluation results summaries given by sections III, V and VII. For the three experimentation groups, the overall average solution earliness is shown by Fig. 70 and the overall average task earliness and throughput are shown by Fig. 71 and 72 respectively.

From the earliness bar graphs shown below, the CRP-based configurations significantly outperform the polynomial counterparts, especially in Fig. 10 (b) and (c). The best earliness is achieved by the CRP-Eager configuration, which is clear in Fig.10 (a)-(c).The earliness of CRP-Hopped and -Overlapped is very close. In Fig. 10 (a), the CRP-Overlapped outperforms CRP-Hopped by 1500 seconds, while in Fig. (b) and (c), CRP- Hopped outperforms CRP-Overlapped by 3000 and 1500 seconds.

The per-task expansion of the overall average earliness is elaborated in Fig.72. It is clear that the average per-task earliness in the three experimentation groups is consistent with the results given by Fig.9. It can be also noted that the CRP-based configurations significantly outperform both of ED and EDAQ configurations. Moreover, CRP-based configurations achieved a complete schedulability, while ED and EDAQ failed. This is seen through the average earliness of the five tasks solved by the CRP-based configurations in the three experiments are greater than zero. Furthermore, the average per-task earliness of the CRP-Eager configuration achieved the best in the three experimentation groups, while EDAQ achieved the worst. On the other hand, a close performance is demonstrated by CRP-Hopped and –Overlapped configurations. In Grop-1, the CRP-Overlapped slightly outperforms the CRP-Hopped in Group-1, while the CRP-Hopped outperforms it in the remaining two groups.

In addition, the average task throughput of the three experimentation groups is given by Fig. 72. From the three groups, It can be noted all solver configurations satisfy the tasks throughput demands. However, the performance of CRP-based configurations still dominates both ED and EDAQ ones. This is shown by substantial throughput margin in Fig.11 (a)-(c). Moreover, the average task throughput achieved by the CRP-Eager is higher than both CRP-Hopped and Overlapped. Furthermore, both CRP-Hopped and –Overlapped still exploit a close performance.

On the basis of the performance results given by Fig. 9-11, five observations are made. First, ED outperforms EDAQ configuration. This is because ED assumes infinite node hop buffer capacities, while the rest of configurations do not. Hence, the ED configuration does not account for node buffer waiting time delays.

Second, underperformance of both ED and EDAQ is resulted due to the lack data transfer scheduling support and complete network knowledge. Both ED and EDAQ configurations are based of Dijkstra shortest path algorithm, hence both configurations are routing only. Never the less, these configurations implicitly assume hopped data forwarding mode, where the size of the data segment is limited to minimum link hop MTU along a given route, which we call bottleneck MTU. Therefore, for an arbitrary task, whose size greater than the bottleneck MTU, both of ED and EDAQ would break that task into a finite number of sub-tasks. Third, the performance achieved by the CRP-Eager configuration is attributed to nature of its data forwarding mode. As shown earlier, the eager mode does not wait until the beginning of the active period, when a task segment is ready for transfer.
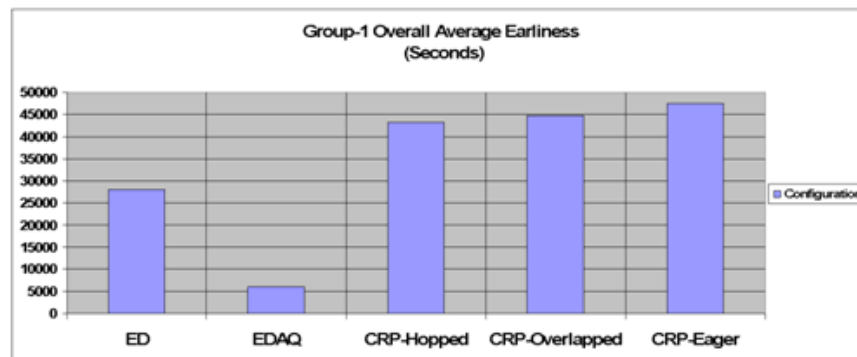
(a)
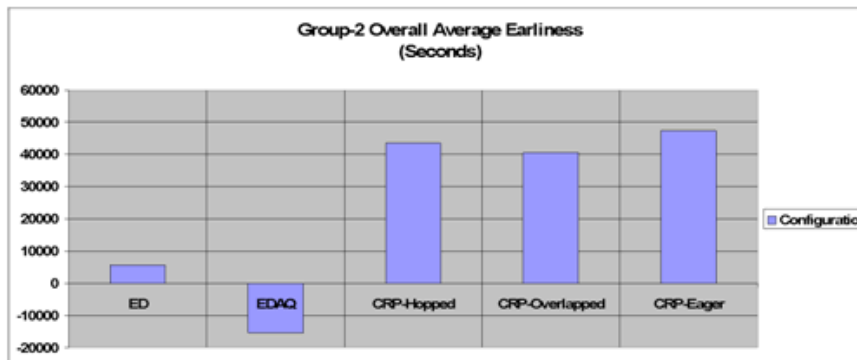
(b)
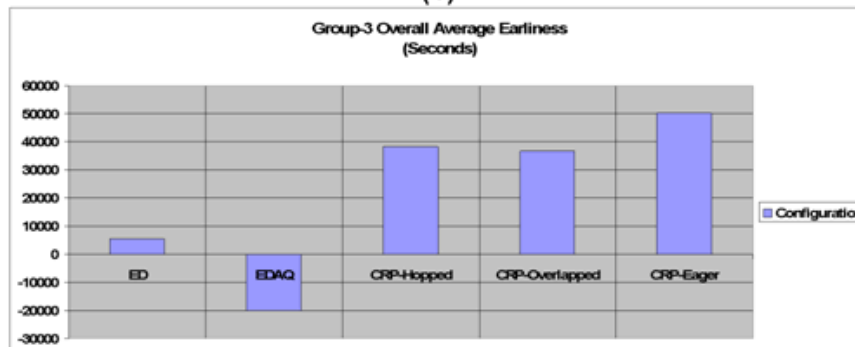
(c)

Fig.70: Overall Average Earliness, (a) Group-1, (b) Group-2 and (c) Group-3

(a)

(b)

(c)

Fig.71: Average Task Earliness, (a) Group-1, (b) Group-2 and (c) Group-3
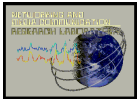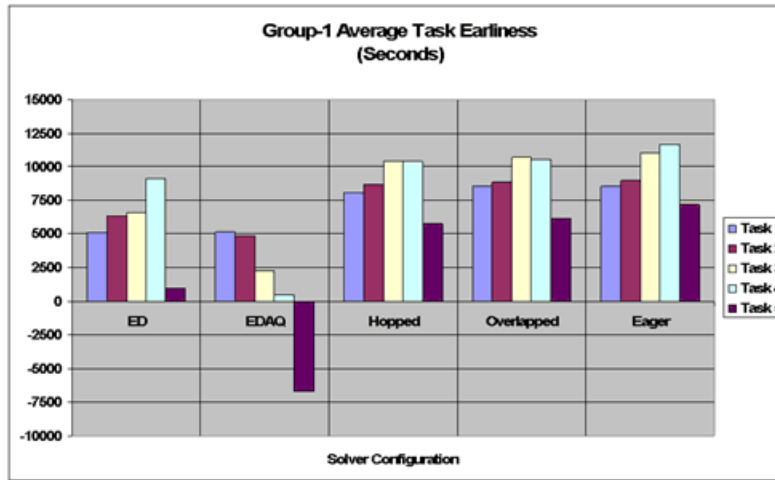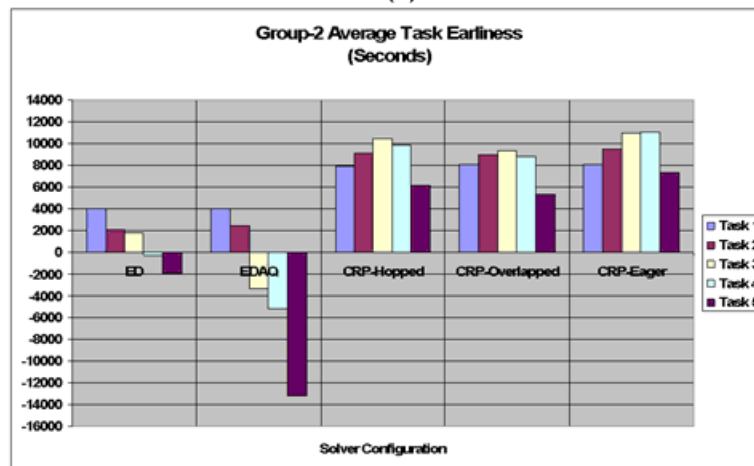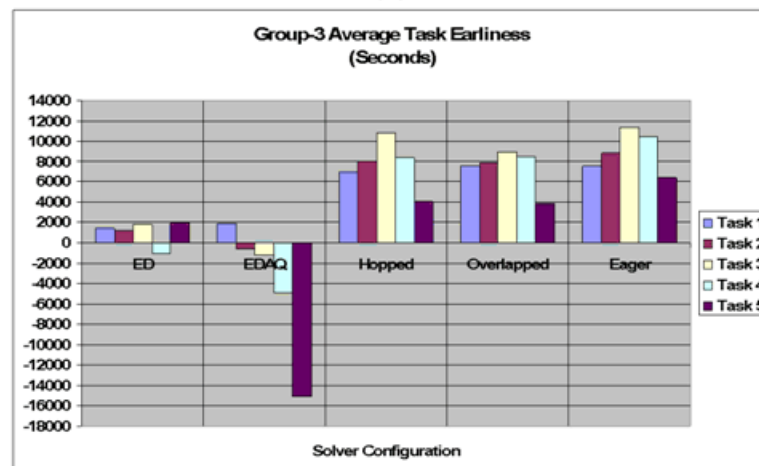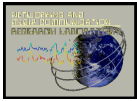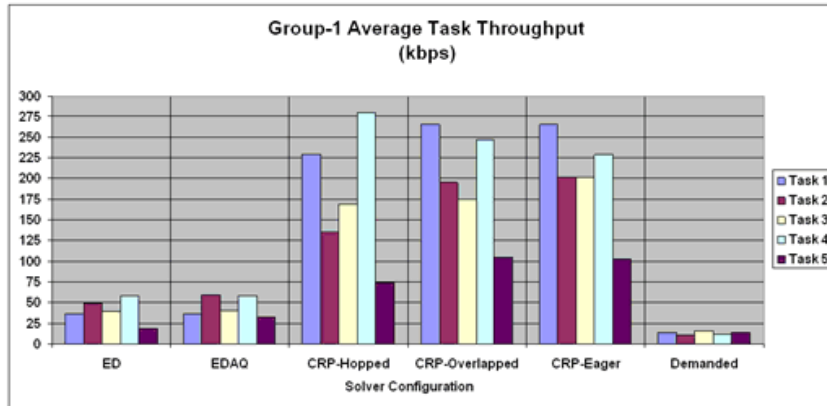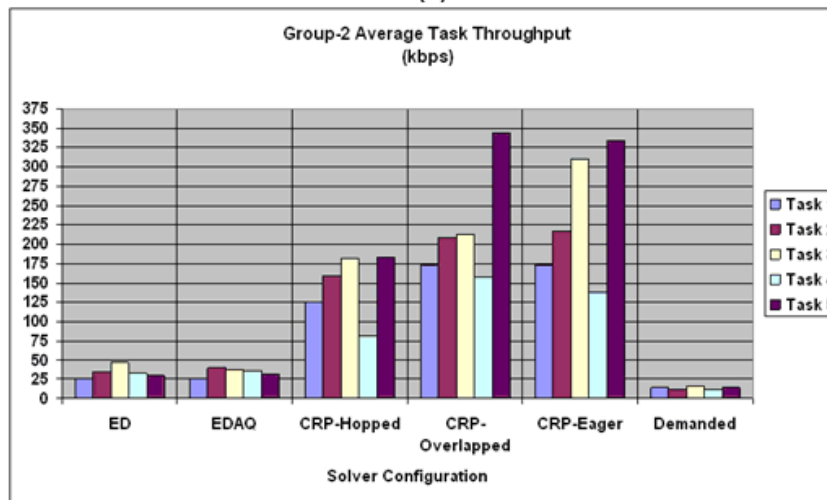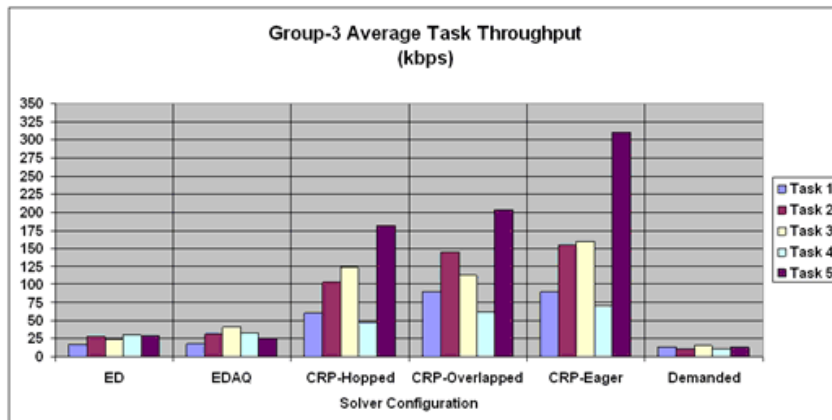
Moreover, this mode also leverages the overlapping between task segment arrival and departure between two conductive node hops.
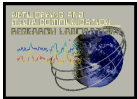

(a)

(b)

(c)

Fig.72: Average Task Throughput, (a) Group-1, (b) Group-2 and (c) Group-3

Fourth, both CRP-Hopped and –Overlapped configurations exploit a near-similar performance. Although the fact the latter leverages the task segment arrival and departure overlap, while the former does not. By carefully studying the behavior of the overlapped forwarding, it can be noted that the overlapped mode does not commence data transfer until the entire route is available. On the other hand, the hopped mode does not wait, it commence data transfer once the first link hop is available. Therefore, the hopped mode operates on partial route availability while the overlapped operates on complete.

The size each sub-task is less than or equal the bottleneck MTU and is further scheduled to be transferred to its destination. Due to the lack of complete network knowledge, ED and EDAQ are mandated to re-compute the route between the source and destination, which significantly contributes against their performance.

IX. References

[1] J. Khan, and O. Tahboub **"Routing Scheduling in Predictable Intermittent Networks"**, submitted manuscript to 9th Symposium Annual International Symposium on Applications and the Internet, Seattle, WA, 2009.

[2] S. Jain, K. Fall, R. Patra, "**Routing in a Delay Tolerant Network**", Proceedings of ACM SIGCOMM, 2004.