**Supplementary Materials**

Hybrid Hierarchical Particle Swarm Optimization with Evolutionary Artificial Bee Colony Algorithm for Task Scheduling in Cloud Computing

Shasha Zhao1,2,3\*, Huanwen Yan1,2, Qifeng Lin1,2, Xiangnan Feng1,2, He Chen1,2 and Dengyin Zhang1,2

1 College of Internet of Things, Nanjing University of Posts and Telecommunications, Nanjing, 210003, China

2 Jiangsu Key Laboratory of Broadband Wireless Communication and Internet of Things, Nanjing University of Posts and Telecommunications, Nanjing, 210003, China

3 Tongding Interconnection Information Co., Lt, Suzhou 215000, China

The task-dependent statistical analysis results of the runtime and standard deviation of each algorithm within homogeneous and heterogeneous scheduling scenarios are shown in **Tables** S1 and S2, respectively.

**Table S1:** Statistical analysis on runtime in the homogeneous task scheduling scenario with each algorithm

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Number of tasks** | **value** | **ABC** | **PSO** | **EABC** | **HPSO** | **HPSO-EABC** |
| 200 | Worst | 11.73 | 11.82 | 11.59 | 11.78 | **11.55** |
| Best | 11.08 | 11.38 | 11.11 | 11.31 | **10.91** |
| Average | 11.45 | 11.61 | 11.41 | 11.58 | **11.34** |
| SD | 0.21 | 0.18 | **0.13** | **0.13** | 0.18 |
| 400 | Worst | 23.43 | 23.66 | 23.03 | 23.05 | **22.70** |
| Best | 22.52 | 22.37 | 22.18 | 22.36 | **22.06** |
| Average | 22.86 | 23.00 | 22.59 | 22.70 | **22.45** |
| SD | 0.29 | 0.39 | 0.23 | 0.24 | **0.21** |
| 600 | Worst | 34.66 | 35.44 | **34.36** | 34.57 | 34.46 |
| Best | 33.53 | 33.97 | 33.36 | 33.40 | **33.03** |
| Average | 34.10 | 34.59 | 33.94 | 34.01 | **33.77** |
| SD | 0.38 | 0.41 | **0.30** | 0.36 | 0.43 |
| 800 | Worst | 46.30 | 47.61 | **45.50** | 45.84 | 45.53 |
| Best | 44.55 | 45.03 | 44.31 | 44.68 | **44.15** |
| Average | 45.38 | 46.28 | 45.02 | 45.11 | **44.81** |
| SD | 0.55 | 0.76 | **0.33** | 0.39 | 0.39 |
| 1000 | Worst | 57.27 | 59.41 | 57.25 | 57.26 | **56.18** |
| Best | 56.28 | 55.76 | 55.69 | 55.69 | **55.32** |
| Average | 56.65 | 57.6 | 56.30 | 56.45 | **55.80** |
| SD | 0.34 | 1.18 | 0.44 | 0.45 | **0.30** |

**Table S2:** Statistical analysis on runtime in the heterogeneous task scheduling scenario with each algorithm

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Number of tasks** | **value** | **ABC** | **PSO** | **EABC** | **HPSO** | **HPSO-EABC** |
| 200 | Worst | 9.53 | 9.26 | 9.28 | 9.04 | **8.76** |
| Best | 6.55 | 6.65 | 6.38 | 6.47 | **6.34** |
| Average | 7.98 | 7.67 | 7.47 | 7.68 | **7.13** |
| SD | 1.13 | **0.69** | 0.93 | 0.93 | 0.75 |
| 400 | Worst | 23.47 | 18.87 | 20.59 | 18.52 | **17.01** |
| Best | 13.68 | 13.23 | 13.05 | 13.74 | **12.53** |
| Average | 19.66 | 15.67 | 16.75 | 15.88 | **14.26** |
| SD | 3.29 | 1.57 | 2.84 | 1.63 | **1.38** |
| 600 | Worst | 39.15 | 32.50 | 32.21 | 27.47 | **25.96** |
| Best | 20.84 | 19.54 | **18.92** | 19.91 | 19.20 |
| Average | 31.76 | 26.20 | 26.98 | 23.13 | **21.7** |
| SD | 5.02 | 4.06 | 4.77 | 2.63 | **2.58** |
| 800 | Worst | 65.30 | 49.00 | 47.23 | 39.52 | **34.86** |
| Best | 26.74 | 25.69 | **24.72** | 26.94 | 25.75 |
| Average | 47.81 | 37.48 | 38.01 | 32.92 | **29.77** |
| SD | 10.73 | 6.91 | 6.99 | 3.83 | **3.27** |
| 1000 | Worst | 88.28 | 68.80 | 61.38 | 52.58 | **44.15** |
| Best | 38.79 | **31.13** | 33.93 | 37.11 | 31.47 |
| Average | 61.42 | 47.52 | 49.60 | 43.27 | **36.93** |
| SD | 13.33 | 11.57 | 9.26 | 5.73 | **4.48** |

The ablation experiments were carried out on the EABC algorithm to further verify its rigor. First, only the improvement of the location update strategy in the EABC algorithm is retained, which is recorded as the EABC-A algorithm, and the operation data of the EABC-A and ABC algorithms under different number of tasks are tested in groups in homogeneous and heterogeneous environments, as shown in Table S3 and Table S4. As can be seen from Table S3 and Table S4, when only one optimized location update strategy used, the effect of EABC-A is still better than that of the original ABC algorithm. Besides the little poor processing time for of the initial less tasks in the homogeneous resource scenario, the overall runtime was reduced. It makes the load in the scheduling process more balanced.

**Table S3:** Ablation comparison experimental data of EABC-A in homogeneous resource scenario

|  |  |  |  |
| --- | --- | --- | --- |
| Number of tasks | value | ABC | EABC-A |
| 200 | Worst  Best  Average  SD | |  | | --- | | **11.73** |   **11.08**  **11.45**  0.21 | 11.91  11.36  11.60  **0.17** |
| 400 | Worst  Best  Average  SD | 23.43  22.52  22.86  0.29 | **23.40**  **22.49**  **22.82**  **0.28** |
| 600 | Worst  Best  Average  SD | 34.66  **33.53**  **34.10**  0.38 | **34.47**  33.96  34.24  **0.29** |
| 800 | Worst  Best  Average  SD | 46.30  44.55  45.38  0.55 | **46.22**  **44.50**  **45.16**  **0.50** |
| 1000 | Worst  Best  Average  SD | 57.27  56.28  56.65  **0.34** | **57.18**  **56.21**  **56.36**  0.42 |

**Table S4:** Ablation comparison experimental data of EABC-A in heterogeneous resource scenario

|  |  |  |  |
| --- | --- | --- | --- |
| Number of tasks | value | ABC | EABC-A |
| 200 | Worst  Best  Average  SD | |  | | --- | | **9.53** |   6.55  7.98  1.13 | 9.66  **6.34**  **7.91**  **1.08** |
| 400 | Worst  Best  Average  SD | 23.47  13.68  19.66  3.29 | **21.91**  **13.34**  **18.55**  **3.00** |
| 600 | Worst  Best  Average  SD | 39.15  **20.84**  31.76  **5.02** | **38.69**  21.16  **30.56**  5.17 |
| 800 | Worst  Best  Average  SD | 65.30  26.74  47.81  10.73 | **64.24**  **25.99**  **46.14**  **10.13** |
| 1000 | Worst  Best  Average  SD | 88.28  38.79  61.42  13.33 | **84.89**  **38.78**  **61.11**  **13.17** |

Then, only the honey source selection strategy is introduced into the ABC, which is recorded as the EABC-B algorithm. The ablation experiment on the EABC-B is performed, and the results are listed in Tables S5 and S6. It can be seen that, although only the honey source selection strategy of the ABC algorithm is optimized, the EABC-B algorithm is still superior to the original ABC algorithm. Different from the EABC-A, the EABC-B under homogeneous resource scheduling has a obvious improvement on the ABC algorithm.

**Table S5:** Ablation comparison experimental data of EABC-B in homogeneous resource scenario

|  |  |  |  |
| --- | --- | --- | --- |
| Number of tasks | value | ABC | EABC-B |
| 200 | Worst  Best  Average  SD | |  | | --- | | 11.73 |   11.08  11.45  **0.21** | **11.60**  **10.91**  **11.39**  **0.21** |
| 400 | Worst  Best  Average  SD | 23.43  22.52  22.86  0.29 | **23.24**  **22.28**  **22.71**  **0.25** |
| 600 | Worst  Best  Average  SD | 34.66  33.53  34.10  0.38 | **34.49**  **33.46**  **33.99**  **0.30** |
| 800 | Worst  Best  Average  SD | 46.30  44.55  45.38  **0.55** | **46.04**  **44.35**  **45.06**  0.56 |
| 1000 | Worst  Best  Average  SD | 57.27  56.28  56.65  **0.34** | **56.98**  **55.73**  **56.34**  0.41 |

**Table S6:** Ablation comparison experimental data of EABC-B in heterogeneous resource scenario

|  |  |  |  |
| --- | --- | --- | --- |
| Number of tasks | value | ABC | EABC-B |
| 200 | Worst  Best  Average  SD | |  | | --- | | 9.53 |   6.55  7.98  1.13 | **9.30**  **6.54**  **7.61**  **0.88** |
| 400 | Worst  Best  Average  SD | 23.47  13.68  19.66  3.29 | **20.36**  **13.20**  **16.80**  **2.62** |
| 600 | Worst  Best  Average  SD | 39.15  20.84  31.76  5.02 | **34.05**  **18.44**  **30.56**  **4.95** |
| 800 | Worst  Best  Average  SD | 65.30  26.74  47.81  10.73 | **50.40**  **24.85**  **40.56**  **7.19** |
| 1000 | Worst  Best  Average  SD | 88.28  38.79  61.42  13.33 | **75.53**  **36.10**  **54.22**  **10.73** |

Finally, we put the ablated algorithms EABC-A, EABC-B and EABC together for statistical analysis, and show them in Tables S7 and S8. It is obvious that the EABC algorithm has significantly improved on the basis of EABC-A and EABC-B after combining both the location update strategy and the nectar source optimization strategy.

**Table S7:** Comparison of algorithm data before and after ablation in homogeneous resource scenario

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Number of tasks | value | EABC-A | EABC-B | EABC |
| 200 | Worst  Best  Average  SD | |  | | --- | | 11.91 |   11.36  11.60  0.17 | 11.60  **10.91**  **11.39**  0.21 | **11.59**  11.11  11.41  **0.13** |
| 400 | Worst  Best  Average  SD | 23.40  22.49  22.82  0.28 | 23.24  22.28  22.71  0.25 | **23.03**  **22.18**  **22.59**  **0.23** |
| 600 | Worst  Best  Average  SD | 34.47  33.96  34.24  **0.29** | 34.49  33.46  33.99  0.30 | **34.36**  **33.36**  **33.94**  0.30 |
| 800 | Worst  Best  Average  SD | 46.22  44.50  45.16  0.50 | 46.04  44.35  45.06  0.56 | **45.50**  **44.31**  **45.02**  **0.33** |
| 1000 | Worst  Best  Average  SD | 57.18  56.21  56.36  0.42 | **56.98**  55.73  56.34  **0.41** | 57.25  **55.69**  **56.30**  0.44 |

**Table S8:** Comparison of algorithm data before and after ablation in heterogeneous resource scenario

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Number of tasks | value | EABC-A | EABC-B | EABC |
| 200 | Worst  Best  Average  SD | |  | | --- | | 9.66 |   **6.34**  7.91  1.08 | 9.30  6.54  7.61  **0.88** | **9.28**  6.38  **7.47**  0.93 |
| 400 | Worst  Best  Average  SD | 21.91  13.34  18.55  3.00 | **20.36**  13.20  16.80  **2.62** | 20.59  **13.05**  **16.75**  2.84 |
| 600 | Worst  Best  Average  SD | 38.69  21.16  30.56  5.17 | 34.05  **18.44**  30.56  4.95 | **32.21**  18.92  **26.98**  **4.77** |
| 800 | Worst  Best  Average  SD | 64.24  25.99  46.14  10.13 | 50.40  24.85  40.56  7.19 | **47.23**  **24.72**  **38.01**  **6.99** |
| 1000 | Worst  Best  Average  SD | 84.89  38.78  61.11  13.17 | 75.53  36.10  54.22  10.73 | **61.38**  **33.93**  **49.60**  **9.26** |