# Part 1: Responses to Hanke Moritz

We thank Dr. Moritz Hanke for the comments and suggestions. We have modified the manuscript accordingly. In the following, we will reply them one by one.

1. Additionally, I would suggest getting this paper checked by someone with very good English language skills, as I have the feeling that there are still some issues.

Response: Thanks for your suggestion. A native speaker has been invited to improve this manuscript.

2. L15: "couplers such as MCT". I would not call MCT a coupler.

Response: We think that both MCT and C-Coupler can be classified as coupling software. The corresponding statements have been modified in the revised manuscript. Please refer to P1L19 and P3L62.

3. L15: "inefficient global implementation". Depending on a number of factors like problem seize, number of processes, and MPI implementation being used, the global implementation may have good performance. Therefore, instead of generally saying that the global implementation is bad, you could for example point out, that your algorithm has significantly better performance characteristics especially for higher processor counts.

Response: The abstract has been modified accordingly. Please refer to the abstract (P1L20).

4. L28-29: "weights that are from an offline file or from online calculation". What is an offline file? How about the following? "weights that read from a file or are calculated online"

Response: The corresponding statement has been modified accordingly. Please refer to P2L32.

5. L73-87: The analysis of the complexity does not take into account, that MCT allows the use of a compressed global index description, which can significantly reduce memory consumption and time required to detect common grid cells. Maybe, do the time complexity analysis only for C-Coupler and mention that MCT should be similar but that is also supports compressed indices (I am not exactly sure about the internals of MCT). L75-76: "corresponding to MCT (as well as CPL6/CPL7 and OASIS3-MCT that employ MCT for data transfer)" Unless you are very familiar with the internal implementation (I am not), you should refrain from making such explicit statements.

Response: The corresponding context has been modified accordingly. Please refer to P3L76~P3L85.

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# Part 2: Responses to Anonymous Referee #3

We thank Anonymous Referee #3 for the comments and suggestions. We have modified the manuscript accordingly. In the following, we will reply them one by one.

1. I suggest making one more pass with a native English speaker to clean up some rough sections.

Response: Thanks for your suggestion. A native speaker has been invited to improve this manuscript.

2. It would be helpful if the DiRong lines on figure 4 were clearer. The scaling is completely obscured in 4a and largely obscured in 4b. If the plots cannot be improved, a table might be better. I would also appreciate results on greater than 1600 processor cores, especially for the larger grid sizes. For high resolution cases, the coupler may be run on many more processors than 1600 and it would be good to know whether the performance of the DiRong algorithm rolls over at some processor count as is shown in Figure 4b for the Global results. Results at higher processor counts in at least Figure 4c would improve the paper significantly.

Response: Figure 4 has been replaced by new tables 7 to 10 (P21-P25), where new results corresponding to a grid of 32,000,000 points or 3200 cores for each component model are added. We are sorry of that we can only use a maximum of 6400 cores, while we failed to find a supercomputer in China with more cores available after a lot of efforts in the past four weeks.

Part 3: a marked-up manuscript version

# DiRong1.0: Aa distributed implementation for improving routing network generation in model coupling.

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**Abstract.** ~~It is a~~A fundamental functionality of model coupling ~~a coupler~~ in an~~for~~ Earth system model~~ing~~ is to efficiently handle data transfer between component models. A~~s a~~n approach of *MxN* communication following a routing network has been used widely used ~~in existing couplers~~ for ~~achieving~~ data transfer, and routing network generation ~~is~~ becomes ~~generally~~ a major step ~~for~~ required to initializ~~e~~ing ~~the~~ data transfer functionality. Some existing coupl~~ers~~ing software such as the Model Coupling Toolkit (MCT) and the Community Coupler (C-Coupler) employ a~~n inefficient~~ global implementation ~~for~~of routing network generation that relies on gather/broadcast communications, which can be very inefficient under a case of a large number of processes. ~~That's~~This is an important reason why the initialization cost of a coupler increases ~~when using more~~with the number of processor cores. In this paper, we propose a **D**istributed **i**mplementation for **Ro**uting **n**etwork **g**eneration, version 1.0 (DiRong1.0), which does not introduce any gather/broadcast communication. ~~The e~~Empirical evaluations show that DiRong1.0 is much more efficient than the global implementation. DiRong1.0 has already been implemented in C-Coupler2~~.~~, and ~~W~~we believe that some other couplers can also benefit from it.

## 1 Introduction

A cCoupled model regarding Earth system Mmodelsling and numerical weather forecasting models generally highly dependss on existing couplers (Hill et al., 2004; Craig et al., 2005; Larson et al., 2005; Balaji et al., 2006; Redler et al., 2010; Craig et al., 2012; Valcke, 2013; Liu et al., 2014; Hanke et al., 2016; Craig et al., 2017; Liu et al., 2018)., each of whichA coupler can combines different component models into a whole system, and handles data interpolation between different model grids and data transfer between component models (Valcke, 2012).

The functionalityprocess of data interpolation generally takes requires two major steps,: i.e., preparing remapping weights, that are read from an offline file or are calculated onlinefrom online calculation when initializing the coupler, and conducting parallel interpolation calculations based on the sparse matrix-vector multiplication with the remapping weights throughout the coupled model integration. CouplersThe functionality ofperform data transfer of couplers isby transferring scalar variables or fields on a model grid (hereafter called gridded fields hereafter) from one component model to another via Message Passing Interface (MPI) (Message Passing Interface). A cComponent models are generally has beenoften parallelized throughby decomposing the cells of a model grid into distinct subsets, each of which is assigned to an MPI process for cooperative concurrent computation, (e.g., the sample parallel decompositions in Fig. 1a and 1b). To efficiently transfer gridded fields in parallel, Jacob et al. (2005) proposed an approach of *MxN* communication (called the *MxN* approach) following a routing network, where each pair of processes from the two component models should have a communication connection only when they sharehave a common grid cells (for example, Fig. 1c). Theis *MxN* approach has already been used in existing couplers for more than ten years. As the parallel decompositions of component models generally remainkeep constant throughout the whole integration, a routing network can also keepremain constant. Thus, the *MxN* approach can be achievedis realized throughwith two major steps: generating the routing network when initializing the coupler, and transferring gridded fields based on the routing network throughout the coupled model integration.

In responseDue to the trend in model development towards higher grid resolutions and the resulting more and moreincreased computation resulting from higher and higher resolutions in model development, the parallel efficiency of a coupled model on modern high-performance computers has becomes more and more critical. Any module in a coupled model, including the coupler, can impact the parallel efficiency of the whole coupled model. Most existing couplers achieve scalable data transfer and data interpolation throughout the coupled model integration, i.e., the data transfer and data interpolation generally can beisare generally faster when using more processor cores., However, while experiences from experiences withstudies with OASIS3-MCT and C-Coupler2 have shown that the initialization cost of a coupler can increase rapidly when using more processor cores (Craig et al., 2017; Liu et al., 2018). A further investigation in Fig. 2 based on MCT shows that the initialization of data transfer, (i.e., generating routing networks,) is an important source of the initialization cost (see Fig. 2).

~~In t~~This paper s ~~we make a~~explores the first step toward~~sTo~~ lowering the initialization cost of a coupler~~, this paper tries to make a first step~~ by~~through~~ focusing on the generation of routing networks, and propose~~s~~s a new **D**istributed **i**mplementation for **Ro**uting **n**etwork **g**eneration, version 1.0 (DiRong1.0). The evaluation based on C-Coupler2 shows that~~,~~ it is much faster than the existing approach. The remainder of this paper is organized as follows. We investigate the existing implementations of routing network generation in Section 2, present and then evaluate DiRong1.0 in Sections 3 and 4, respectively, and conclude ~~and discuss~~with a discussion of this work in Section 5.

## 2 Existing implementations of routing network generation

In some existing coupling software~~ers~~ such as MCT and C-Coupler, the global information of a parallel decomposition is originally distributed among all processes of a component model.~~,~~ This is because~~where~~ a process only records its local parallel decomposition ~~corresponding to~~on the grid cells assigned to it. Th~~us~~erefore, these couplers generally use the following four~~4~~ steps for generating a routing network between the parallel decompositions of a source (*src*) and a destination (*dst*) component model.

1) Gathering global parallel decomposition: the *src*/*dst* root process gathers the global information of the *src*/*dst* parallel decomposition from all *src*/*dst* processes.
2) Exchanging global parallel decomposition: the *src*/*dst* root process first exchanges the *src*/*dst* global parallel decomposition with the *dst*/*src* root process, and then broadcasts the *dst*/*src* global parallel decomposition to all *src*/*dst* processes.
3) Detecting common grid cells: each *src*/*dst* process detects its common grid cells with each *dst*/*src* process based on its local parallel decomposition and the *dst*/*src* global parallel decomposition.
4) Generating the routing network: each *src*/*dst* process generates its local routing network according to the information about common grid cells.

Given that each of the *src* and *dst* component models uses *K* processes ~~and the corresponding~~on a grid of size~~ is~~ *N* (i.e., the grid has *N* cells), the first and second steps when using C-Coupler correspond to gather/broadcast communications with a~~the~~ time complexity of at least $O(N*logK)$ and a~~the~~ memory complexity of $O(N)$. The average time complexity of the third step ~~corresponding to~~ is $O(N)$, as C-Coupler first generates a map corresponding to the global parallel decomposition and then~~next~~ detects common cells ~~based on~~by looking at~~up~~ the map. Although this implementation tries to~~can~~ lower the time complexity, it~~but~~ introduces inefficient and irregular memory access~~es~~. As the last step does not depend on any global parallel decomposition, its average time complexity is $O(N/K)$. MCT (as well as CPL6/CPL7 and OASIS3-MCT, which employ MCT for data transfer) has similar complexities to C-Coupler, while a compressed global index description is further used to reduce the memory and time required to detect common grid cells corresponding to regular parallel decompositions (the compressed description may not work for irregular (such as round-robin) parallel decompositions).

Given~~Determined by~~ the gather/broadcast communications and the corresponding time complexity of $O(N*logK)$, and the time complexity of ~~$O(N*N/K)$ or~~ $O(N)$ corresponding to common grid cell~~s~~ detection, such existing implementations of routing network generation are of course inefficient ~~under the increment of~~with an increasing number of processor cores. Moreover, due~~in response~~ to the memory complexity of $O(N)$, more memory ~~will be~~is consumed ~~when~~as the model grid~~s~~ becomes~~get~~ finer.

In the following~~ context~~, the existing implementations relying on gather/broadcast communications ~~are~~will be called "global routing network generation".

**3 Design and implementation**

**3.1 Overall design**

The design and implementation of DiRong1.0 significantly benefits from the general~~ly~~ idea of distributed director~~y~~ies (Pinar and Hendrickson, 2001), ~~that~~which ha~~s~~ves already been used in coupler development (Theurich et al., 2008~~,~~; Hanke et al., 2016)~~,~~. ~~and d~~ Another different kind~~Different kinds~~ of specific distributed directories ~~are~~ is defined and used in DiRong1.0.

Each cell of a grid can be numbered with a unique index from 1 to $N$ ~~(~~called the "global" cell index~~)~~, while each grid cell assigned to the same process can ~~also~~ be numbered with a unique "local" cell index. Thus, the information of a given parallel decomposition can be recorded as a Cell Local~~-~~_Global Mapping Table (CLGMT), each element of which is a triple of global cell index, process ID, and local cell index. For example, Tables 1 and 2 are the CLGMTs corresponding to the parallel decompositions in Fig. 1a and ~~Fig.~~ 1b, respectively.

Generally, the CLGMT entries of a parallel decomposition are distributed among the processes of a component model, which means a process only stores ~~a~~ part of the CLGMT. The key idea of~~ the~~ existing global implementations ~~can be summarized as~~is to reconstruct~~ing~~ the global CLGMT of the peer parallel decomposition in each process for routing network generation. To be an efficient solution though, DiRong1.0 should be fully based on a distributed CLGMT without reconstructing any global CLGMT. E~~The reason why the e~~xisting global implementations ~~have to~~ depend on global CLGMTs ~~is~~ because the distribution of the CLGMT entries is determined by a model, and thus a coupler generally has to view any distribution as random.

Motivated by the above analysis, the key challenge in~~to~~ DiRong1.0 is~~becomes~~ ~~how to~~ achieving efficient~~ly~~ rearrangement of the original distribution of the CLGMT entries of a given parallel decomposition into a regular intermediate distribution, and ~~how to~~ efficiently generating~~e~~ the routing network based on the intermediate distribution. Specifically, we employ a regular intermediate distribution that evenly distributes the CLGMT entries among processes based on the ~~ascending order of the~~ global cell indices~~ex~~ placed in ascending order. Such an intermediate distribution is not only simple, but it also enables ~~to easily achieve the~~a straightforward rearrangement of the CLGMT entries into the intermediate distribution via a sorting procedure similar to distributed sort. With ~~the above preparations~~that, DiRong1.0 ~~is designed with~~takes the following major steps to~~for~~ generate~~ing~~ a routing network between the *src* and *dst* component models.~~:~~

1) The *src*/*dst* component model rearranges the original distribution of the CLGMT entries of the *src*/*dst* parallel decomposition into the regular intermediate distribution.
2) The *src* and *dst* component models exchange the CLGMT entries ~~based on~~in the intermediate distributions.
3) Based on the *src* and *dst* CLGMT entries in the intermediate distributions, ~~E~~each *src*/*dst* process generates table entries of the sharing relationship, which describes~~about~~ how each grid cell is shared between the processes of the *src* and *dst* component models~~, based on the *src* and *dst* CLGMT entries on the intermediate distributions~~.
4) The *src*/*dst* component model rearranges the intermediate distribution of the entries in~~of~~ the sharing relationship table (SRT) into the original distribution of the CLGMT entries of the *src*/*dst* parallel decomposition.
5) Each *src*/*dst* process generates its local routing network based on the local SRT entries.

~~In t~~The ~~following context~~remainder of this section~~, we will~~ details the implementation of each major step, except the last one because it is similar to the last major step in the global implementation.

### 3.2 Rearranging CLGMT entries within~~intra~~ a component model

~~Such~~ The rearrangement of CLGMT entries within a component model is achieved via a divide-and-conquer sorting procedure, ~~that is~~ similar to a merge sort ~~with the keyword of~~using the global cell index as the keyword. This procedure first sorts the CLGMT entries locally in each process, and then~~next~~ iteratively conducts a distributed sort via~~by~~ a main loop of *logK* iterations, ~~(~~where *K* is the number of processes of the *src*/*dst* component model~~)~~. In each~~an~~ iteration, processes are divided into distinct pairs and the two processes in each pair swap the CLGMT entries based on a point-to-point communication. Figure 3 shows an example of the distributed sort corresponding to the CLGMT entries in Table 1, and Table 3 shows the distributed CLGMT after rearranging the CLGMT entries in Table 2. As shown in Fig. 3, the distributed sort employed in DiRong1.0 uses a similar butterfly communication pattern ~~as~~ to the optimized MPI implementations of various collective communication operations (Brooks, 1986; Thakur et al., 2005).

### 3.3 Exchanging CLGMT entries between component models

After the rearrangement of the CLGMT in a component model, the CLGMT entries are sorted into~~ an~~ ascending order based on their~~of the~~ global cell index~~es~~ and are evenly distributed among processes. The CLGMT entries reserved in each process therefore have a determinate and non-overlapping range of global cell indic~~ex~~es, and such a range can be easily calculated from the grid size, the total number of ~~total~~ processes, and the process ID. Thus, it is straightforward~~easy~~ to calculate the overlapping relationship of the global cell index range between a *src* process and a *dst* process. As it is only necessary to exchange CLGMT entries between a pair of *src* and *dst* processes with overlapping ranges, point-to-point communications ~~only~~ ~~are enough for~~suffice to handle~~ing~~ the exchange of the CLGMT entries.

### 3.4 Generation of SRT

~~After~~ Following the previous major step, each process reserves two sequences of CLGMT entries corresponding to the *src* and *dst* parallel decompositions~~ respectively~~. Given that the two sequences contain *n1* and *n2* entries, respectively, the time complexity of detecting the sharing relationship is *O*(*n1*+*n2*), because the entries in each sequence have already been ordered by~~in~~ ascending global cell index~~es~~, and a procedure similar to the kernel of merge sort, which~~that~~ merges two ordered data sequences, can handle such a detection.

To record the sharing relationship, an SRT entry is designed as a quintuple of global cell index, *src* process ID, *src* local cell index, *dst* process ID, and *dst* local cell index. Given a quintuple $<q_1,q_2,q_3,q_4,q_5>$, the data on global cell $q_1$ in the *src* component model, corresponding to local cell $q_3$ in process $q_2$, is transferred to local cell $q_5$ in process $q_4$ in the *dst* component model. ~~it means that number $q_3$ local cell in number $q_2$ process of the *src* component model is number $q_1$ global cell, and the data on it will be transferred to number $q_5$ local cell in number $q_4$ process of the *dst* component model.~~ Table 4 shows the SRT in the *src* component model~~,~~ calculated from the rearranged, distributed CLGMT entries in Fig. 3 and Table 3.

It is possible that multiple *src* CLGMT entries correspond to the same global cell index. In~~Under~~ such a case, any *src* CLGMT entry can be used for generating the corresponding SRT entries~~.~~, because the *src* component model ~~should~~ guarantees that the data copies on the same grid cell are ~~exactly the same~~identical. Given a *dst* CLGMT entry, if there is no *src* CLGMT entry with the same global cell index, no SRT entry will be generated. ~~Given~~ In the case that multiple *dst* CLGMT entries correspond to the same global cell index and there is at least one *src* CLGMT entry with the same global cell index, a SRT entry will be generated for every~~ach~~ *dst* CLGMT entry.

### 3.5 Rearranging SRT entries within~~intra~~ a component model

After the previous major step, the SRT entries are distributed among processes of a component model according to the intermediate distribution. ~~-~~Because a process can only use ~~only~~ the SRT entries corresponding to its local cells for the last major step of local routing network generation, the SRT entries ~~should~~ need to be rearranged among the processes of a component model. We find that such a rearrangement can ~~also~~ be achieved via a sorting procedure similar to ~~the~~ a distributed sort ~~with~~ using the ~~keyword of~~ *src*/*dst* process ID as a keyword, or even via the sorting procedure implemented in~~for~~ the first major step ~~can be reused~~. Tables 5 and 6 show the SRT entries distributed in the *src* and *dst* component model, respectively, after the rearrangement.

### 3.6 Time complexity and memory complexity

As DiRong1.0 does not reconstruct the global CLGMT, it does not rely on any gather/broadcast communication~~,~~ and its average memory complexity is $O(N/K)$ for~~on~~ each process. Because~~As~~ the implementation of its most time-consuming ~~major~~ steps are similar to a merge sort, and the time complexity of a merge sort is $O(N*logN)$, the average time complexity of DiRong1.0 for~~on~~ each process is $O(N*(logN)/K)$, and the average communication complexity is $O(N*(logK)/K)$.

To facilitate the implementation of the sorting procedure, we force the number of processes ~~regarding~~ in the first~~1st~~ to~~∼~~ fourth~~4th~~ major steps to be the maximum power of 2 ($2^n$) no larger than the total number of processes ~~number~~ of the *src*/*dst* component model. For a process whose ID $I$ is not smaller than $2^n$, its CLGMT entries ~~will be~~are merged into the process with ~~the~~ ID ~~of~~ $I-2^n$ before the first major step, and the SRT entries corresponding to it ~~will be~~are obtained from the process with ~~the~~ ID ~~of~~ $I-2^n$ after the fourth major step. This strategy does~~will~~ not change the aforementioned~~bove~~ time complexity and memory complexity of DiRong1.0, as $2^n$ is larger than ~~a~~ half of the total number of processes ~~number~~.

## 4 Evaluation

~~For evaluating~~To evaluate DiRong1.0, we implement~~ed~~ it in C-Coupler2, which enables us to compare it with the original global routing network generation ~~in C-Coupler2~~. We develop~~ed~~ a toy coupled model for the evaluation consisting of two toy component models and C-Coupler2 ~~for the evaluation~~, which ~~enable~~allows us to flexibly change the model settings in terms of grid size and number of processor cores (processes). The toy coupled model is run on a supercomputer, where each computing node ~~on the supercomputer~~ includes two Intel Xeon E5-2678 v3 CPUs (Intel(R) Xeon(R) CPU, ~~(~~24 processor cores in total~~)~~), and all computing nodes ~~we~~are connected with an InfiniBand network. The codes ~~we~~are compiled by an Intel Fortran and C++ compiler at the optimization level O2~~,~~ using an Intel MPI library (2018 Update 2). A maximum~~ number~~ of ~~3200 ~~6400 cores are used for running the toy coupled model, and~~.~~ a~~A~~ll test results are from the average of multiple runs~~ of the toy coupled model~~.

In Table 7 to Table 10, ~~Fig. 4, ~~we evaluate the effect of varying the number of processes; ~~We made an evaluation under the variation of process numbers (Fig. 4; ~~the two component models use the same number of processor cores~~)~~. For a~~the~~ grid size of 500,000 (Table 7~~Fig. 4a~~), the execution time of DiRong1.0 does not significantly~~really~~ decrease when using more processor cores. This result is reasonable~~,~~ although it does not match the time complexity of DiRong1.0. The communication complexity of DiRong1.0 is O(*N*(logK)/K*), where *logK* stands for the number of point-to-point communications in each process and *N/K* stands for the average message size in each communication. The average message size corresponding to Table 7~~Fig. 4a~~ is small (about 160 KB ~~under ~~with 60 cores ~~while ~~and about 6 KB ~~under ~~with 1600 cores for each toy component model), ~~while~~ but the execution time of point-to-point communication ~~cannot keep ~~does not vary linearly with~~to~~ ~~the ~~message size and may be unstable when the message size is small. ~~Different from~~In contrast to DiRong1.0, the execution time of the global implementation increases rapidly with ~~the increment of~~increasing number of cores~~ number~~. As a result, DiRong1.0 outperforms the global implementation more significantly when using more cores. When the grid size ~~gets larger~~increases (e.g., from 4,000,000 in Table 8~~Fig. 4b~~ ~~and~~to ~~1~~32~~6~~,000,000 in Table 10~~Fig. 4c~~), DiRong1.0 still significantly outperforms the global implementation~~, while with~~and also has better scalability.

Considering that a model can use more processor cores for acceleration when its resolution becomes~~gets~~ finer, we further evaluate~~d~~ the weak scalability of DiRong1.0~~, where we~~ by concurrently increasing~~ed~~ the grid size and number of cores~~ number~~ to achieve similar numbers of grid points per process. As shown in Table ~~7~~11, the execution time of DiRong1.0 increases slowly, whereas~~ile~~ the execution time of the global implementation increases rapidly with ~~the increment of~~larger grid sizes and increasing number of cores~~ number~~. This demonstrates that DiRong1.0 achieves much better weak scalability than the global implementation.

## 5 Conclusion and discussion

~~In t~~This paper~~, we have ~~ proposes~~d~~ a new distributed implementation, DiRong1.0, for routing network generation. It is much more efficient than the global implementation a~~A~~s it does not introduce any gather/broadcast communication and it achieves much lower complexity in terms of time, memory, and communication~~ than the global implementation, it is of course much more efficient than the global implementation~~. This conclusion is demonstrated by our~~The~~ evaluation results~~ further demonstrate this conclusion~~. DiRong1.0 has already been implemented in C-Coupler2. Its code is publicly available in a C-Coupler2 version and will be further used in future C-Coupler versions. We ~~do ~~believe that some existing couplers such as

MCT, OASIS3-MCT, and CPL6/CPL7, can also benefit from DiRong1.0, as itfor acceleratesing the routing network generation as well as the coupler initialization.

We did not evaluate the impact of DiRong1.0 on the total time of a model simulation,, because this impact can be relative. The overhead of routing network generation as well as coupler initialization will beis trivial under for a long simulation (e.g., hundreds of model days or even hundreds of model years), but may be significant for a short simulation (e.g., several model days or even several model hours in weather forecasting (Palmer et al., 2008; Hoskins, 2013)). In a dData assimilation for weather forecasting, it maycan be required to performstart a model to run just for only several model hours or even less timeshorter. Regarding In an operational model, there is generally a time limitation onf producing forecasting results (for example, finishing a 5five-day forecasting in two hours), and thus developers always have to carefully optimize various software modules, especially when the model resolution gets becomes finer. In fact, one of the primary motivations for the development of DiRong1.0 was we have been asked to accelerate the initialization of C-Coupler2 for an operational coupled model used in China.

, and that's a main reason why we developed DiRong1.0.

Another main reason why we for developinged DiRong1.0 is that, routing network generation will become more important along with the developmentin later versions of C-Coupler. Recently, a new framework was developed for weakly coupled **e**nsemble **d**ata **a**ssimilation (EDA) based on C-Coupler2, named DAFCC1 (Sun et al., 2020), was developed. DAFCC1 will be an important part ofin C-Coupler3, the next version of C-Coupler. Given a coupled EDA system and thatFor users wanting the atmosphere component of a coupled system to perform EDA, DAFCC1 will automatically generate an ensemble component corresponding to all ensemble members of the atmosphere component for calling the DA algorithm, and will automatically conduct routing network generation for the data transfers between the ensemble component and each ensemble member. Thus, routing network generation will be more frequently used in EDA with DAFCC1. For example, given that there are 50 ensemble members, the routing network generation with the ensemble component will be conducted at least 50 times.

We note that, the current sequential read of a remapping weight file is another bottleneck drawback of C-Coupler2. Similar to Hanke et al. (2016), we will design a specific distributed directory for reading in the remapping weights in parallel, while which will enable to efficiently redistributeallow the remapping weights to be efficiently redistributed among processes based on DiRong1.0. Currently, C-Coupler2 employs a simple global representation for horizontal grids, which means that each process keeps retains all points of a horizontal grid in memory. The global representation will become a bottleneck in at least two aspects. First, it will consume too much memory to run a model simulation. For example, given a horizontal grid with 16,000,000 points, the memory for keepingrequired to keep it in each process is large: will be about 1.3 GB, (givenprovided that each point has four verticexes and the data type is double precision), which is a large memory requirement. Second, the initialization of the data interpolation functionality requires exchanging model grids to be exchanged between different component models, which introduces global communications (e.g., broadcast) for the global grid representations. To address this bottleneck, we will design and develop a distributed grid representation that can be viewed as a specific distributed directory, and will enable ~~to efficiently redistribute~~an efficient redistribution of horizontal grid points among processes based on DiRong1.0.

*Code availability*. The source code of DiRong1.0 can be viewed and run with C-Coupler2 and the toy coupled model via https://doi.org/10.5281/zenodo.3753217.

*Author contributions.* HY was responsible for code development, software testing, and experimental evaluation of DiRong1.0, and co-led paper writing. LL initiated this research, was responsible for the motivation and design of DiRong1.0, supervised HY, and co-led paper writing. CS, RL, XY, and CZ contributed to code development and software testing. ZZ and BW contributed to the motivation and software testing. All authors contributed to the improvement of ideas and paper writing.

*Competing interests.* The authors declare that they have no conflict of interest.

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**References**

Balaji, V., J. Anderson, I. Held, M. Winton, J. Durachta, S. Malyshev, and R. J. Stouffer: The Exchange Grid: a mechanism for data exchange between Earth System components on independent grids. In: Proceedings of the 2005 International Conference on Parallel Computational Fluid Dynamics, College Park, MD, USA, Elsevier, 2006.

E. D. Brooks,: The Butterfly Barrier. Int. J. Parallel Program.,15(4):295–307, 1986.

Craig, A. P., M. Vertenstein, and R. Jacob: A New Flexible Coupler for Earth System Modelling developed for CCSM4 and CESM1. Int. J. High Perform. Comput., 26-1, 31–42, 2012.

Craig, A. P., R. L. Jacob, B. Kauffman, T. Bettge, J. W. Larson, E. T. Ong, C. H. Q. Ding, Y. He: CPL6: The New Extensible, High Performance Parallel Coupler for the Community Climate System Model. Int. J. High Perform. Comput. Appl., 19(3): 309–327, 2005 .

Craig, A., Valcke, S., and Coquart, L.: Development and performance of a new version of the OASIS coupler, OASIS3-MCT_3.0, Geosci. Model Dev., 10, 3297–3308, https://doi.org/10.5194/gmd-10-3297-2017, 2017.

Hanke, M., Redler, R., Holfeld, T., and Yastremsky, M.: YAC 1.2.0: New aspects for coupling software in Earth system modelling, Geosci. Model Dev., 9, 2755–2769, https://doi.org/10.5194/gmd-9-2755-2016, 2016.

Hill, C., C. DeLuca, V. Balaji, M. Suarez, and A. da Silva: Architecture of the Earth System Modelling Framework. Comput. Sci. Eng., 6, 18–28, 2004.

Hoskins, B.: The potential for skill across the range of the seamless weather-climate prediction problem: a stimulus for our science, Q. J. Roy. Meteor. Soc., 139, 573–584, 2013.

Jacob, R., J. Larson, and E. Ong: M x N Communication and Parallel Interpolation in Community Climate System Model Version 3 Using the Model Coupling Toolkit, Int. J. High. Perform. Comput., 19, 293–307, 2005.

Larson, J., R. Jacob, and E. Ong: The Model Coupling Toolkit: A New Fortran90 Toolkit for Building Multiphysics Parallel Coupled Models. Int. J. High Perform. Comput. Appl., 19, 277–292, 2005.

Liu, L., Yang, G., Wang, B., Zhang, C., Li, R., Zhang, Z., Ji, Y., and Wang, L.: C-Coupler1: a Chinese community coupler for Earth system modeling, Geosci. Model Dev., 7, 2281–2302, doi:10.5194/gmd-7-2281-2014, 2014.

Liu, L., Zhang, C., Li, R., Wang, B., and Yang, G.: C-Coupler2: a flexible and user-friendly community coupler for model coupling and nesting, Geosci. Model Dev., 11, 3557–3586, https://doi.org/10.5194/gmd-11-3557-2018, 2018.

Palmer, T. N., Doblas-Reyes, F. J., Weisheimer, A. and Rodwell, M. J.: Toward seamless prediction: Calibration of climate change projections using seasonal forecasts, Bull. Am. Meteorol. Soc., 89, 459–470, 2008.

Pinar, A. and Hendrickson, B.: Communication Support for Adaptive Computation, Proceedings of the Tenth SIAM Conference on Parallel Processing for Scientific Computing, Portsmouth, Virginia, USA, 12–14 March 2001, SIAM, 2001.

R. Redler, S. Valcke and H. Ritzdorf. OASIS4 - a coupling software for next generation earth system modeling. Geosci. Model Dev.,3: 87–104, https://doi.org/10.5194/gmd-3-87-2010, 2010.

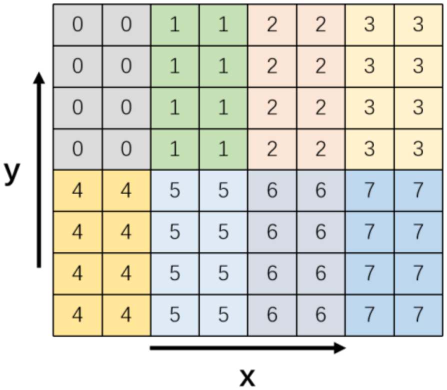
Sun, C., Liu, L., Li, R., Yu, X., Yu, H., Zhao, B., Wang, G., Liu, J., Qiao, F., and Wang, B.: Developing a common, flexible and efficient framework for weakly coupled ensemble data assimilation based on C-Coupler2.0, Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2020-75, in review, 2020.

Thakur, R., Rabenseifner, R., Gropp, W.. Optimization of Collective Communication Operations in MPICH. The International Journal of High Performance Computing Applications, 19(1), 49–66. https://doi.org/10.1177/1094342005051521, 2005.

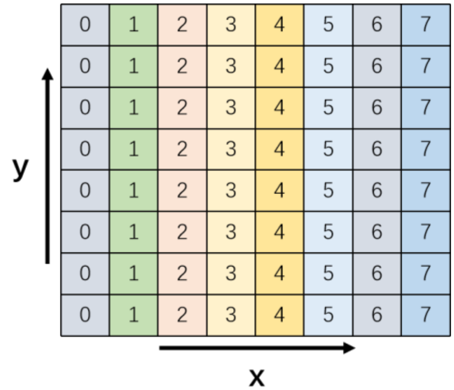
G. Theurich, ESMF Core Team: Performance Optimization of ESMF. https://www.earthsystemcog.org/site_media/projects/esmf/pres_0812_board_gerhard.pdf, 2008.

Valcke, S.: The OASIS3 coupler: A European climate modelling community software. Geosci. Model Dev., 6, 373–388, doi:10.5194/gmd-6–373-2013, 2013.

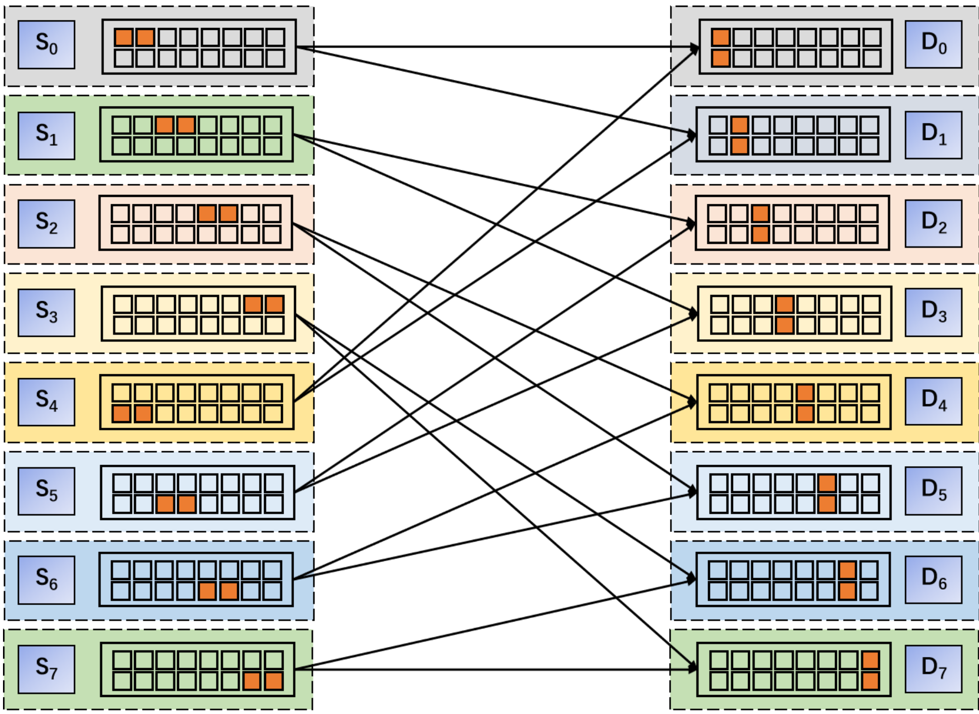
Valcke, S., Balaji, V., Craig, A., Deluca, C., Dunlap, R., Ford, R. W., Jacob, R., Larson, J., Okuinghttons, R., Riley, G., Vertenstein, M: Coupling technologies for Earth System Modelling, Geosci. Model Dev., 5, 1589–1596, 2012.




(a) A regular 2-D parallel decomposition in both X and Y directions.




(b) A regular 1-D parallel decomposition in only the X direction.




(c) The routing network from the parallel decomposition in Fig. 1a (**S**ource) to the parallel decomposition in Fig. 1(b) (**D**estination).

**Figure 1. Two sample parallel decompositions of an 8 × 8 grid under eight processes (Fig. 1a and 1b) and the routing network between them (Fig. 1c). Each color corresponds to a process.**

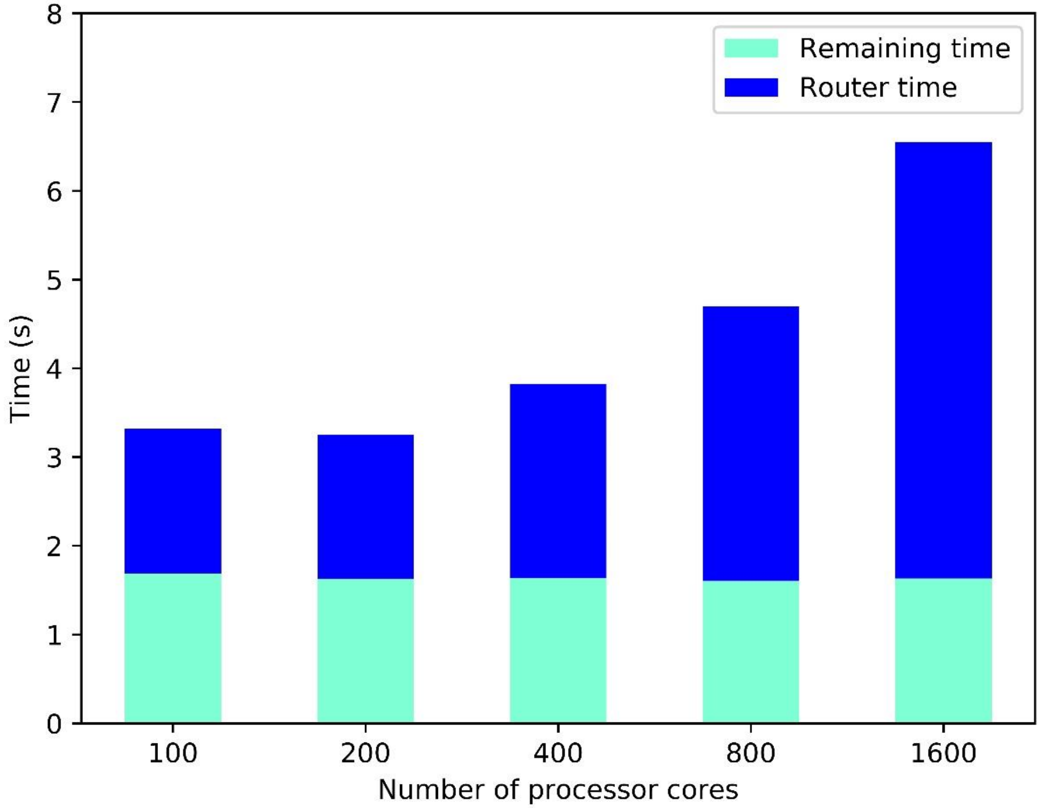



**Figure 2. -The total time of routing network generation (router time) and the remaining time for initializing a two-way MCT coupling between two toy component models. One toy component model uses a longitude_–latitude grid with 4 million points and a regular 2-D parallel decomposition, while the other uses a cubed-sphere grid with a resolution of 0.3 degreesat 0.3 degree and a round-robin- parallel decomposition. The time for reading an offline remapping weight file has been taken into account in the remaining time, and a regular 1-D parallel decomposition is designed for the data interpolation. The supercomputer as well as the corresponding software stacks described in Section 4 areis used for this test.**

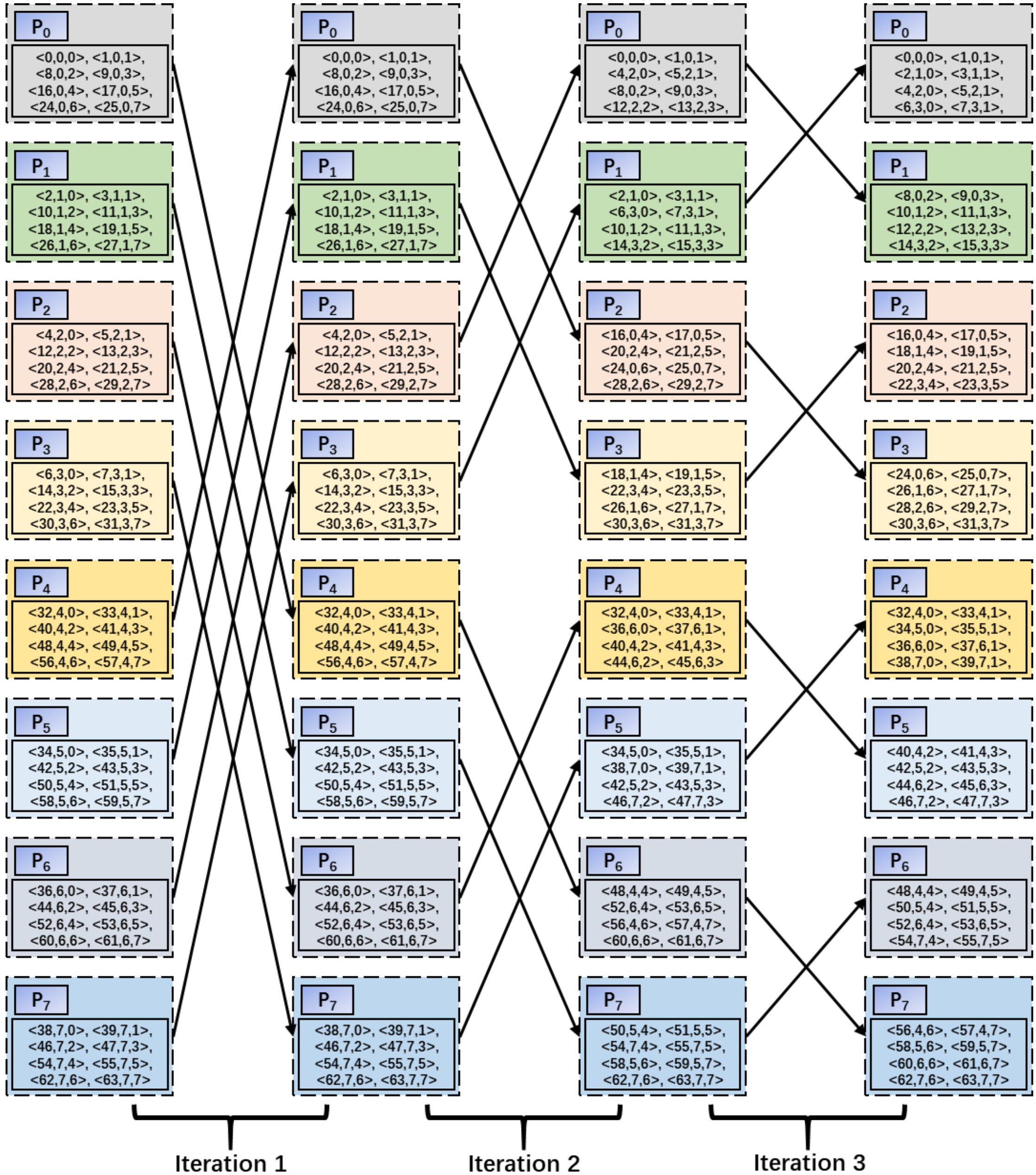
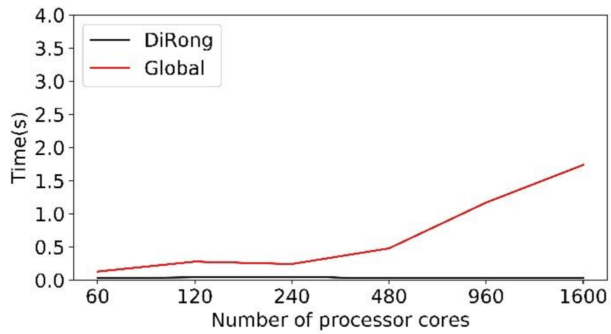
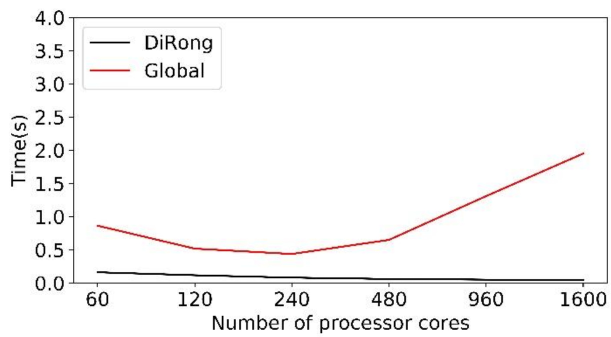


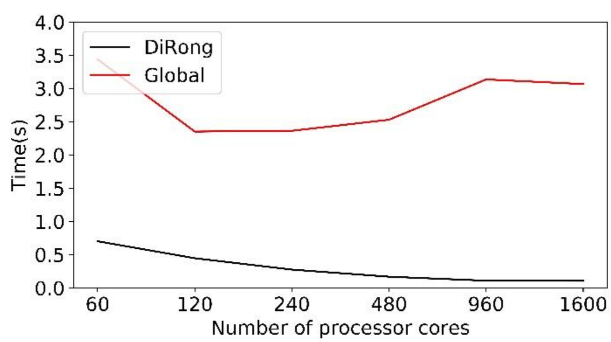

**Figure 3. The distributed sort corresponding to the CLGMT entries in Table 1. Each iteration makes the CLGMT entries, with larger global cell indices reserved in the processes with larger IDs. For example, after the first iteration, the CLGMT entries with global cell indices between 0 and 31 are reserved in P0–P3, while the remaining CLGMT entries are reserved in P4–P7.**




(a) . The execution time of DiRong1.0 and the global routing network generation under using different numbers of cores numbers and athe grid size of 500,000..




(b) The execution time of DiRong1.0 and the global routing network generation usingunder different numbers of cores numbers and athe grid size of 4,000,000..




(c) The execution time of DiRong1.0 and the global routing network generation under using different numbers of cores numbers and the a grid size of 16,000,000. .

**Figure 4. Performance of DiRong1.0 and the comparison with the original global routing network generation (Global) usingunder different numbers of cores numbers and grid sizes. Two toy component models use the same number of**

processor cores in each test case. The comparison of the two algorithms in these figureshere shows that the acceleration effect of DiRong1.0 is more obvious when the number of gridsgrid size and the number of processes is larger,: that isi.e., DiRong1.0 has higher parallel efficiency and better scalability.

**Table 1. The Cell Local–Global Mapping Table (CLGMT) of the parallel decomposition in Fig. 1a**

| Process ID | Cell Local–Global Mapping Table entries |
|---|---|
| 0 | <0,0,0>, <1,0,1>, <8,0,2>, <9,0,3>, <16,0,4>, <17,0,5>, <24,0,6>, <25,0,7> |
| 1 | <2,1,0>, <3,1,1>, <10,1,2>, <11,1,3>, <18,1,4>, <19,1,5>, <26,1,6>, <27,1,7> |
| 2 | <4,2,0>, <5,2,1>, <12,2,2>, <13,2,3>, <20,2,4>, <21,2,5>, <28,2,6>, <29,2,7> |
| 3 | <6,3,0>, <7,3,1>, <14,3,2>, <15,3,3>, <22,3,4>, <23,3,5>, <30,3,6>, <31,3,7> |
| 4 | <32,4,0>, <33,4,1>, <40,4,2>, <41,4,3>, <48,4,4>, <49,4,5>, <56,4,6>, <57,4,7> |
| 5 | <34,5,0>, <35,5,1>, <42,5,2>, <43,5,3>, <50,5,4>, <51,5,5>, <58,5,6>, <59,5,7> |
| 6 | <36,6,0>, <37,6,1>, <44,6,2>, <45,6,3>, <52,6,4>, <53,6,5>, <60,6,6>, <61,6,7> |
| 7 | <38,7,0>, <39,7,1>, <46,7,2>, <47,7,3>, <54,7,4>, <55,7,5>, <62,7,6>, <63,7,7> |

**Table 2. The Cell Local–Global Mapping Table (CLGMT) of the parallel decomposition in Fig. 1b**

| Process ID | Cell Local–Global Mapping Table entries |
|---|---|
| 0 | <0,0,0>, <8,0,1>, <16,0,2>, <24,0,3>, <32,0,4>, <40,0,5>, <48,0,6>, <56,0,7> |
| 1 | <1,1,0>, <9,1,1>, <17,1,2>, <25,1,3>, <33,1,4>, <41,1,5>, <49,1,6>, <57,1,7> |
| 2 | <2,2,0>, <10,2,1>, <18,2,2>, <26,2,3>, <34,2,4>, <42,2,5>, <50,2,6>, <58,2,7> |
| 3 | <3,3,0>, <11,3,1>, <19,3,2>, <27,3,3>, <35,3,4>, <43,3,5>, <51,3,6>, <59,3,7> |
| 4 | <4,4,0>, <12,4,1>, <20,4,2>, <28,4,3>, <36,4,4>, <44,4,5>, <52,4,6>, <60,4,7> |
| 5 | <5,5,0>, <13,5,1>, <21,5,2>, <29,5,3>, <37,5,4>, <45,5,5>, <53,5,6>, <61,5,7> |
| 6 | <6,6,0>, <14,6,1>, <22,6,2>, <30,6,3>, <38,6,4>, <46,6,5>, <54,6,6>, <62,6,7> |
| 7 | <7,7,0>, <15,7,1>, <23,7,2>, <31,7,3>, <39,7,4>, <47,7,5>, <55,7,6>, <63,7,7> |

**Table 3. The distributed CLGMT after rearranging the CLGMT entries in Table 2**

| Process ID | CLGMT entries |
|---|---|
| 0 | <0,0,0>, <1,1,0>, <2,2,0>, <3,3,0>, <4,4,0>, <5,5,0>, <6,6,0>, <7,7,0> |
| 1 | <8,0,1>, <9,1,1>, <10,2,1>, <11,3,1>, <12,4,1>, <13,5,1>, <14,6,1>, <15,7,1> |
| 2 | <16,0,2>, <17,1,2>, <18,2,2>, <19,3,2>, <20,4,2>, <21,5,2>, <22,6,2>, <23,7,2> |
| 3 | <24,0,3>, <25,1,3>, <26,2,3>, <27,3,3>, <28,4,3>, <29,5,3>, <30,6,3>, <31,7,3> |
| 4 | <32,0,4>, <33,1,4>, <34,2,4>, <35,3,4>, <36,4,4>, <37,5,4>, <38,6,4>, <39,7,4> |
| 5 | <40,0,5>, <41,1,5>, <42,2,5>, <43,3,5>, <44,4,5>, <45,5,5>, <46,6,5>, <47,7,5> |
| 6 | <48,0,6>, <49,1,6>, <50,2,6>, <51,3,6>, <52,4,6>, <53,5,6>, <54,6,6>, <55,7,6> |
| 7 | <56,0,7>, <57,1,7>, <58,2,7>, <59,3,7>, <60,4,7>, <61,5,7>, <62,6,7>, <63,7,7> |

**Table 4. The Sharing Relationship Table (SRT) calculated from the rearranged distributed CLGMT entries in Fig. 3 and Table 3.**

| Process ID | Sharing Relationship Table entries |
|---|---|
| 0 | <0,0,0,0,0>, <1,0,1,1,0>, <2,1,0,2,0>, <3,1,1,3,0>, <4,2,0,4,0>, <5,2,1,5,0>, <6,3,0,6,0>, <7,3,1,7,0> |
| 1 | <8,0,2,0,1>, <9,0,3,1,1>, <10,1,2,2,1>, <11,1,3,3,1>, <12,2,2,4,1>, <13,2,3,5,1>, <14,3,2,6,1>, <15,3,3,7,1> |
| 2 | <16,0,4,0,2>, <17,0,5,1,2>, <18,1,4,2,2>, <19,1,5,3,2>, <20,2,4,4,2>, <21,2,5,5,2>, <22,3,4,6,2>, <23,3,5,7,2> |
| 3 | <24,0,6,0,3>, <25,0,7,1,3>, <26,1,6,2,3>, <27,1,7,3,3>, <28,2,6,4,3>, <29,2,7,5,3>, <30,3,6,6,3>, <31,3,7,7,3> |
| 4 | <32,4,0,0,4>, <33,4,1,1,4>, <34,5,0,2,4>, <35,5,1,3,4>, <36,6,0,4,4>, <37,6,1,5,4>, <38,7,0,6,4>, <39,7,1,7,4> |
| 5 | <40,4,2,0,5>, <41,4,3,1,5>, <42,5,2,2,5>, <43,5,3,3,5>, <44,6,2,4,5>, <45,6,3,5,5>, <46,7,2,6,5>, <47,7,3,7,5> |
| 6 | <48,4,4,0,6>, <49,4,5,1,6>, <50,5,4,2,6>, <51,5,5,3,6>, <52,6,4,4,6>, <53,6,5,5,6>, <54,7,4,6,6>, <55,7,5,7,6> |
| 7 | <56,4,6,0,7>, <57,4,7,1,7>, <58,5,6,2,7>, <59,5,7,3,7>, <60,6,6,4,7>, <61,6,7,5,7>, <62,7,6,6,7>, <63,7,7,7,7> |

**Table 5. The SRT entries distributed in the *src* component model after rearranging the SRT in Table 4**

| Process ID | Sharing Relationship Table entries |
|---|---|
| 0 | <0,0,0,0,0>, <1,0,1,1,0>, <8,0,2,0,1>, <9,0,3,1,1>, <16,0,4,0,2>, <17,0,5,1,2>, <24,0,6,0,3>, <25,0,7,1,3> |
| 1 | <2,1,0,2,0>, <3,1,1,3,0>, <10,1,2,2,1>, <11,1,3,3,1>, <18,1,4,2,2>, <19,1,5,3,2>, <26,1,6,2,3>, <27,1,7,3,3> |
| 2 | <4,2,0,4,0>, <5,2,1,5,0>, <12,2,2,4,1>, <13,2,3,5,1>, <20,2,4,4,2>, <21,2,5,5,2>, <28,2,6,4,3>, <29,2,7,5,3> |
| 3 | <6,3,0,6,0>, <7,3,1,7,0>, <14,3,2,6,1>, <15,3,3,7,1>, <22,3,4,6,2>, <23,3,5,7,2>, <30,3,6,6,3>, <31,3,7,7,3> |
| 4 | <32,4,0,0,4>, <33,4,1,1,4>, <40,4,2,0,5>, <41,4,3,1,5>, <48,4,4,0,6>, <49,4,5,1,6>, <56,4,6,0,7>, <57,4,7,1,7> |
| 5 | <34,5,0,2,4>, <35,5,1,3,4>, <42,5,2,2,5>, <43,5,3,3,5>, <50,5,4,2,6>, <51,5,5,3,6>, <58,5,6,2,7>, <59,5,7,3,7> |
| 6 | <36,6,0,4,4>, <37,6,1,5,4>, <44,6,2,4,5>, <45,6,3,5,5>, <52,6,4,4,6>, <53,6,5,5,6>, <60,6,6,4,7>, <61,6,7,5,7> |
| 7 | <38,7,0,6,4>, <39,7,1,7,4>, <46,7,2,6,5>, <47,7,3,7,5>, <54,7,4,6,6>, <55,7,5,7,6>, <62,7,6,6,7>, <63,7,7,7,7> |

**Table 6. The SRT entries distributed in the *dst* component model after rearranging the SRT in Table 4**

| Process ID | Sharing Relationship Table entries |
|---|---|
| 0 | <0,0,0,0,0>, <8,0,2,0,1>, <16,0,4,0,2>, <24,0,6,0,3>, <32,4,0,0,4>, <40,4,2,0,5>, <48,4,4,0,6>, <56,4,6,0,7> |
| 1 | <1,0,1,1,0>, <9,0,3,1,1>, <17,0,5,1,2>, <25,0,7,1,3>, <33,4,1,1,4>, <41,4,3,1,5>, <49,4,5,1,6>, <57,4,7,1,7> |
| 2 | <2,1,0,2,0>, <10,1,2,2,1>, <18,1,4,2,2>, <26,1,6,2,3>, <34,5,0,2,4>, <42,5,2,2,5>, <50,5,4,2,6>, <58,5,6,2,7> |
| 3 | <3,1,1,3,0>, <11,1,3,3,1>, <19,1,5,3,2>, <27,1,7,3,3>, <35,5,1,3,4>, <43,5,3,3,5>, <51,5,5,3,6>, <59,5,7,3,7> |
| 4 | <4,2,0,4,0>, <12,2,2,4,1>, <20,2,4,4,2>, <28,2,6,4,3>, <36,6,0,4,4>, <44,6,2,4,5>, <52,6,4,4,6>, <60,6,6,4,7> |
| 5 | <5,2,1,5,0>, <13,2,3,5,1>, <21,2,5,5,2>, <29,2,7,5,3>, <37,6,1,5,4>, <45,6,3,5,5>, <53,6,5,5,6>, <61,6,7,5,7> |
| 6 | <6,3,0,6,0>, <14,3,2,6,1>, <22,3,4,6,2>, <30,3,6,6,3>, <38,7,0,6,4>, <46,7,2,6,5>, <54,7,4,6,6>, <62,7,6,6,7> |
| 7 | <7,3,1,7,0>, <15,3,3,7,1>, <23,3,5,7,2>, <31,3,7,7,3>, <39,7,1,7,4>, <47,7,3,7,5>, <55,7,5,7,6>, <63,7,7,7,7> |

**Table 7. Performance of DiRong1.0 and the comparison with the original global routing network generation (Global) using different numbers of cores numbers and the grid size of 500,000.**

| **Core number of each toy component model** | **DiRong1.0** | | **Global** | | **Global/DiRong1.0** |
|---|---|---|---|---|---|
| | **Time (s)** | **Speedup** | **Time (s)** | **Speedup** | |
| 60 | 0.031 | 1.000 | 0.129 | 1.000 | 4.110 |
| 120 | 0.040 | 0.774 | 0.278 | 0.462 | 6.888 |
| 240 | 0.047 | 0.671 | 0.243 | 0.530 | 5.205 |
| 480 | 0.029 | 1.076 | 0.478 | 0.269 | 16.461 |
| 960 | 0.033 | 0.943 | 1.169 | 0.110 | 35.224 |
| 1600 | 0.034 | 0.912 | 1.737 | 0.074 | 50.641 |
| 3200 | 0.036 | 0.862 | 2.573 | 0.050 | 70.900 |

**Table 8. Performance of DiRong1.0 and the comparison with the original global routing network generation (Global) using different numbers of cores numbers and the grid size of 4,000,000.**

| Core number of each toy component model | DiRong1.0 | | Global | | Global/DiRong1.0 |
|---|---|---|---|---|---|
| | Time (s) | Speedup | Time (s) | Speedup | |
| 60 | 0.161 | 1.000 | 0.863 | 1.000 | 5.349 |
| 120 | 0.117 | 1.375 | 0.517 | 1.668 | 4.409 |
| 240 | 0.081 | 1.990 | 0.437 | 1.974 | 5.391 |
| 480 | 0.060 | 2.669 | 0.649 | 1.329 | 10.737 |
| 960 | 0.051 | 3.184 | 1.308 | 0.660 | 25.811 |
| 1600 | 0.045 | 3.548 | 1.949 | 0.443 | 42.858 |
| 3200 | 0.039 | 4.098 | 2.623 | 0.329 | 66.598 |

**Table 9. Performance of DiRong1.0 and the comparison with the original global routing network generation (Global) using different numbers of cores numbers and the grid size of 16,000,000.**

| Core number of each toy component model | DiRong1.0 | | Global | | Global/DiRong1.0 |
|---|---|---|---|---|---|
| | Time (s) | Speedup | Time (s) | Speedup | |
| 60 | 0.702 | 1.000 | 3.437 | 1.000 | 4.899 |
| 120 | 0.447 | 1.571 | 2.351 | 1.462 | 5.263 |
| 240 | 0.276 | 2.547 | 2.363 | 1.455 | 8.575 |
| 480 | 0.169 | 4.163 | 2.529 | 1.359 | 15.006 |
| 960 | 0.109 | 6.429 | 3.135 | 1.097 | 28.721 |
| 1600 | 0.106 | 6.628 | 3.065 | 1.121 | 28.956 |
| 3200 | 0.098 | 7.133 | 3.242 | 1.060 | 32.960 |

**Table 10. Performance of DiRong1.0 and the comparison with the original global routing network generation (Global) using different numbers of cores numbers and the grid size of 32,000,000.**

| Core number of each toy component model | DiRong1.0 | | Global | | Global/DiRong1.0 |
|---|---|---|---|---|---|
| | Time (s) | Speedup | Time (s) | Speedup | |
| 60 | 1.438 | 1.000 | 6.878 | 1.000 | 4.782 |
| 120 | 0.960 | 1.499 | 4.206 | 1.635 | 4.383 |
| 240 | 0.554 | 2.597 | 4.739 | 1.451 | 8.557 |
| 480 | 0.340 | 4.234 | 5.083 | 1.353 | 14.964 |
| 960 | 0.199 | 7.222 | 6.098 | 1.128 | 30.616 |
| 1600 | 0.176 | 8.182 | 5.758 | 1.195 | 32.756 |
| 3200 | 0.165 | 8.704 | 5.500 | 1.251 | 33.286 |

**Table ~~7~~11. Performance of DiRong1.0 and the comparison with the original global routing network generation (Global) when concurrently increasing the grid size and number of cores~~ number~~.**

| Core number of each toy component model | Grid size | Execution time (s) of DiRong1.0 | Execution time (s) of Global | Global/ DiRong1.0 |
|---|---|---|---|---|
| 250 | 500,000 | 0.032 | 0.262 | 8.19 |
| 450 | 1,000,000 | 0.034 | 0.492 | 14.47 |
| 900 | 2,000,000 | 0.041 | 1.158 | 28.24 |
| 1600 | 4,000,000 | 0.045 | 1.949 | 43.31 |
| 3200 | 8,000,000 | 0.063 | 2.850 | 45.24 |