RELEASE

SEVENTH FRAMEWORK PROGRAMME

ICT-287510
RELEASE
A High-Level Paradigm for Reliable Large-Scale Server Software
A Specific Targeted Research Project (STReP)

D3.4 (WP3): Scalable Reliable OTP Library Release:

Patterns for Scaling Distributed Erlang Applications

Due date of deliverable: 31st August 2014
Actual submission date: 23rd September 2014

Start date of project: 1st October 2011 Duration: 41 months

Lead contractor: The University of Glasgow Revision: 1.0

Purpose: Design, implement and validate a set of reusable reliable massively parallel programming patterns as a scalable, performance portable OTP library.

Results: The main results of this deliverable are as follows.

- We have discussed scalability recipes of distributed Erlang applications using four benchmarks.
- We have provided scalability and reliability principles, application methodology, and introduced generic patterns.
- We have briefly outlined performance portability under development for deliverable D3.5.

Conclusion: We have identified generic patterns, introduced methodology for scalable reliable SD Erlang applications, and both designed and implemented them in a number of SD Erlang benchmarks.

Project funded under the European Community Framework 7 Programme (2011-14)			
Dissemination Level			
PU	Public		✳
PP	Restricted to other programme participants	(including the Commission Services)	
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CO	Confidential only for members of the consortium	(including the Commission Services)	

Scalable Reliable OTP Library Release: Patterns for Scaling Distributed Erlang Applications

Contents

Executive Summary

In this deliverable we discuss methodology and patterns for building SD Erlang applications, as well as our plans to extend the `s_group.erl` module in the RELEASE branch of Erlang/OTP. The work is closely related to the work in WP5 on refactoring and tuning SD Erlang applications, in particular to deliverables D5.3: Systematic Testing and Debugging Tools and D5.4: Interactive SD Erlang Debugger.

The discussion and methodologies we provide in this deliverable are derived from the following four benchmarks of different types: Orbit (P2P), Ant Colony Optimisation (master/slave), Instant Messenger (server), and Sim-Diasca (multicomponent) (Section 3). We start with non-distributed Erlang versions of the applications and then refactor them first into distributed Erlang, and then into SD Erlang. This is done to show differences between the familiar *non-distributed Erlang → distributed Erlang* refactoring and the new *distributed Erlang → SD Erlang* refactoring. Using the observations from the benchmarks we discuss scalability principles of distributed Erlang applications (Section 4). We do not aim to cover scalability issues related to a single Erlang node (the single node scalability issues are discussed and dealt with in WP2 deliverables) but rather focus on scalability features of distributed applications and SD Erlang. These are replacing all-to-all connections, grouping nodes, replacing global namespaces, and eliminating single process bottlenecks. We also discuss reliability features of SD Erlang (Section 5) and briefly cover our ongoing work on portability principles (Section 6).

The reliable SD Erlang is open source and can be found in Github `https://github.com/release-project/otp/tree/dev`.

1 Introduction

The objectives of Task 3.4 are to "design, implement and validate a set of reusable Reliable Massively Parallel (RMP) programming patterns as a scalable, performance portable OTP library". The lead participant is the University of Glasgow.

The aim of this deliverable is to demonstrate approaches to scale distributed Erlang applications, and introduce application methodology and generic patterns. We start with an overview of SD Erlang (Section 2). We then provide design and refactoring techniques of four benchmarks (Section 3) and discuss scalability principles and application methodology for SD Erlang applications (Section 4). These two sections are mutually complementary, that is we first started with benchmarks, derived refactoring techniques, formalised and improved those techniques, and then we applied them back to the benchmarks. Then we discuss SD Erlang reliability features using Instant Messenger benchmark as an example (Section 5). We provide our initial measurements and findings on performance portability that will be further discussed in deliverable D3.5: SD Erlang Performance Portability Principles (Section 6). Finally, we summarise the deliverable and discuss our future plans (Section 7).

Partner Contributions to D3.4 We had a series of email exchange with the University of Kent and Erlang Solutions. The University of Kent contributed to the refactoring and tuning aspects of the benchmarks, and together with the Erlang Solutions and Ericsson teams contributed to identifying the simplest and the most efficient ways to install SD Erlang. All partners contributed to different aspects of Sim-Diasca scaling.

2 SD Erlang Overview

SD Erlang is a modest conservative extension of distributed Erlang [REL13a]. Its scalable computation model has two aspects: s_groups and semi-explicit placement.

The reasons we have introduced s_groups are to reduce the number of connections a node maintains, and reduce the size of namespaces. A namespace is a set of names replicated on a group of nodes and treated as global in that group. In SD Erlang node connections and namespace are defined by both the node belonging to an s_group and by the node type, i.e. hidden or normal. If a node is free that is it belongs to no s_group, the connections and namespace only depend on the node type. A free *normal node* has transitive connections and common namespace with all other free normal nodes. A free *hidden node* has non-transitive connections with all other nodes and every hidden node has its own namespace. An *s_group node* has transitive connections with nodes from the same s_group and non-transitive connections with other nodes. It may belong to a number of s_groups. The SD Erlang s_groups are *similar* to the distributed Erlang hidden global_groups in the following: (1) each s_group has its own namespace; (2) transitive connections are only with nodes of the same s_group. The *differences* with hidden global_groups are in that (1) a node can belong to an unlimited number of s_groups, and (2) information about s_groups and nodes is not globally collected and shared. In SD Erlang behaviour and functionality of free nodes remains the same as in distributed Erlang.

The semi-explicit and architecture aware process placement mechanism was introduced to enable performance portability, a crucial mechanism in the presence of fast-evolving architectures (Section 6).

3 Recipes for Scalability of Distributed Erlang Applications

In this section we discuss 'recipes' for refactoring non-distributed Erlang programs into distributed Erlang programs (Non2D) and then distributed Erlang programs into the SD Erlang ones (D2SD). A very simplified version of transformations is presented in Figure 1. When we want to increase scalability of a non-distributed Erlang application we refactor it into distributed Erlang by distributing functionality between multiple nodes. Then if we want to increase the scalability further we do D2SD transformation by reducing the number of connections between Erlang nodes and by providing nodes the means to communicate with each other without establishing direct connections.

To identify suitable distributed Erlang benchmarks we consulted our partners ESL and Ericsson. It turned out that the task is not a simple one because existing benchmarks are either very complicated to re-engineer or are comercial products not available as open source. Therefore, apart from Sim-Diasca that is a simulation engine developed by EDF (Section 3.4) we had to write most of the benchmarks ourselves: Orbit (Section 3.1), Ant Colony Optimisation (ACO, Section 3.2), and Instant Messenger (IM, Section 3.3). To identify refactoring patterns we discuss the above four benchmarks, and summarise the emerged patters in Section 3.5. Notations we use in the figures in this section are presented in Figure 2.

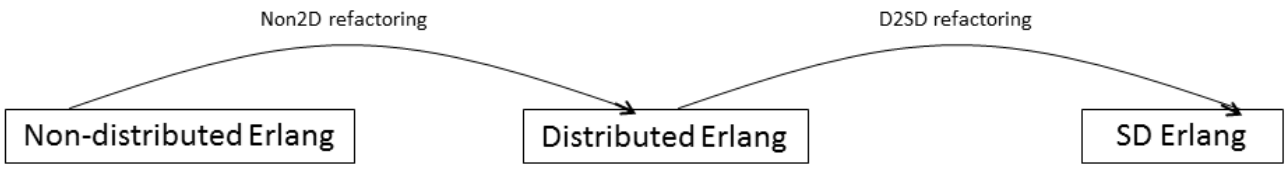


Figure 1: Refactoring Erlang Programs into SD Erlang Programs

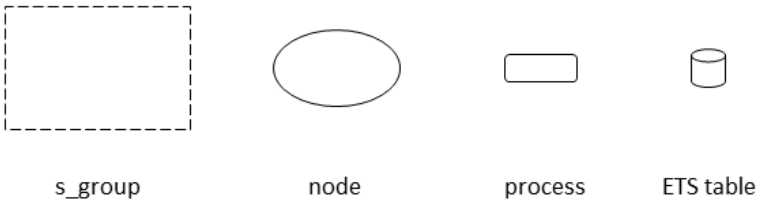


Figure 2: Legend

3.1 Orbit (P2P)

Overview. Orbit is an example of distributed hash table applications which are one of the typical class distributed Erlang applications. The Orbit's goal is to find the least subset X_{orb} such that $X_{orb} \subseteq X = \{x \mid x \in \mathbb{N}, x \leq N_1\}$ and $f1, f2, ..., fn : X \to X$ where $f1, f2, ..., fn$ are generators and X_{orb} is closed under all generators. Thus, the larger N_1 and the more complex generators are used the larger computation and storage resources the benchmark requires. The idea is that worker processes explore the space by generating new numbers and fill the table. The master process is responsible for spawning the first vertex process. The termination mechanism is implemented by using credit. That is the first process has the full credit. When a process spawns child processes it devides the credit equally between them, and terminates without a credit. In case a process terminates with no child processes it returns its credit to the master process first. The program terminates after the master process collects all the credit back.

All three versions of Orbit have been used in various experiments, and are available in the following directories of the RELEASE project github repository:

- Non-distributed Erlang: `https://github.com/release-project/RELEASE/tree/master/Research/Benchmarks/orbit-int`
- Distributed Erlang: `https://github.com/release-project/benchmarks/tree/master/D-Orbit`
- SD Erlang: `https://github.com/release-project/benchmarks/tree/master/SD-Orbit`

Non-distributed Erlang version. The whole computation is done on a single node (Erlang VM) that contains two types of processes: a master process and worker processes (Figure 3). The master process starts the computation by spawning the first worker process with full credit, and then collects statistics and credit from the worker processes, and returns the result when all credit is collected. The worker processes fill the table, spawn new processes, and either distribute the credit between child processes or return it to the master process.

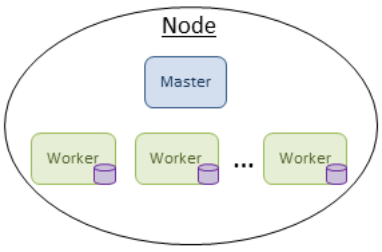


Figure 3: Orbit in Non-distributed Erlang

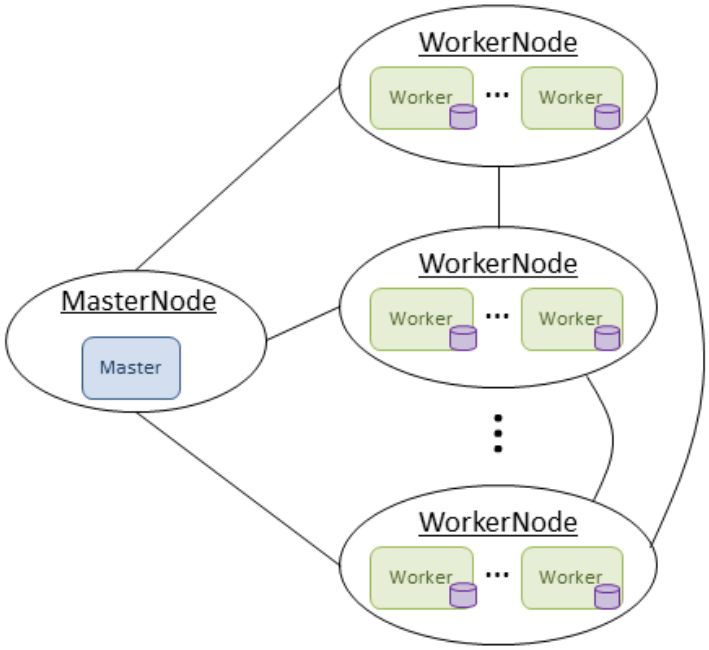


Figure 4: Orbit in Distributed Erlang

Non2D. To transform a non-distributed Erlang version of Orbit into a distributed Erlang one we introduce two types of nodes: a master node and worker nodes. Thus, worker processes are now spawned to worker nodes rather than locally (Figure 4), i.e. we replace `spawn(Module, Fun, Args)` by `spawn(Node, Module, Fun, Args)`. We also distribute the table between worker nodes. Thus, the target node to which a new worker process is spawned is defined by the hash value of the process vertex.

Types of nodes and processes. A master node has one master process that spawns worker processes to worker nodes, distributes the table between worker processes in the beginning of the computation, starts the computation, and collects statistics from the worker processes. Worker nodes keep a part of the Distributed Hash Table (DHT) and contain a number of worker processes that perform the computation, fill the table, spawn new worker processes, and distribute credit between child processes. The table is partitioned between the nodes; therefore, the target node where a new process should be spawned is defined by the value of the vertex. That is we take a hash of the vertex, and spawn the process to the node that keeps the part of the table with which the hash value is associated.

Summary. We introduce two types of nodes, replace local spawn by remote spawn, and distribute the table between worker nodes.

D2SD. Here we discuss changes required to turn the distributed Erlang version of Orbit into an SD Erlang one. We first introduce essential steps to perform the transformation, and then discuss types of nodes and processes.

1. Partitioning the set of worker nodes to reduce the number of connections between the nodes. Due to the uniform communication between nodes in Orbit the way a set of worker nodes is partitioned does not matter. However, we need to consider the size of s_groups, i.e. the number of nodes in s_groups (Figure 5).

2. Introducing submaster nodes, submaster processes, and gateway processes. The purposes of submaster processes are initial setting and supervision of worker processes (in the distributed

Erlang implementation the worker processes are supervised by the master process). The gateway processes act as routers. The submaster nodes only contain submaster and gateway processes. We have separated them for the benchmarking purpose; however, in general it may not be needed to keep submaster and gateway processes separately from worker processes.

3. Creating a submaster s_group. The submaster s_group contains the master node and all submaster nodes.

4. Hierarchical process spawning. The master process spawns submaster and gateway processes to submaster nodes. Every submaster node has one submaster process, whereas the number of gateway processes should be proportional to the following parameters to avoid gateway process bottleneck and resource wasting:

   - the number of worker processes on the worker nodes.
   - the number of nodes in the current s_group.
   - the number of s_groups.

   In turn submaster processes spawn worker processes to worker nodes. As before the target worker node is defined by the hash value of the worker process vertex.

5. Hierarchical partitioning of the DHT. The master process partitions the DHT between submaster processes, and then the submaster processes partition their parts of the DHT between their worker processes. The parts of the DHT only reside on worker nodes. Here, the first hashing of the vertex

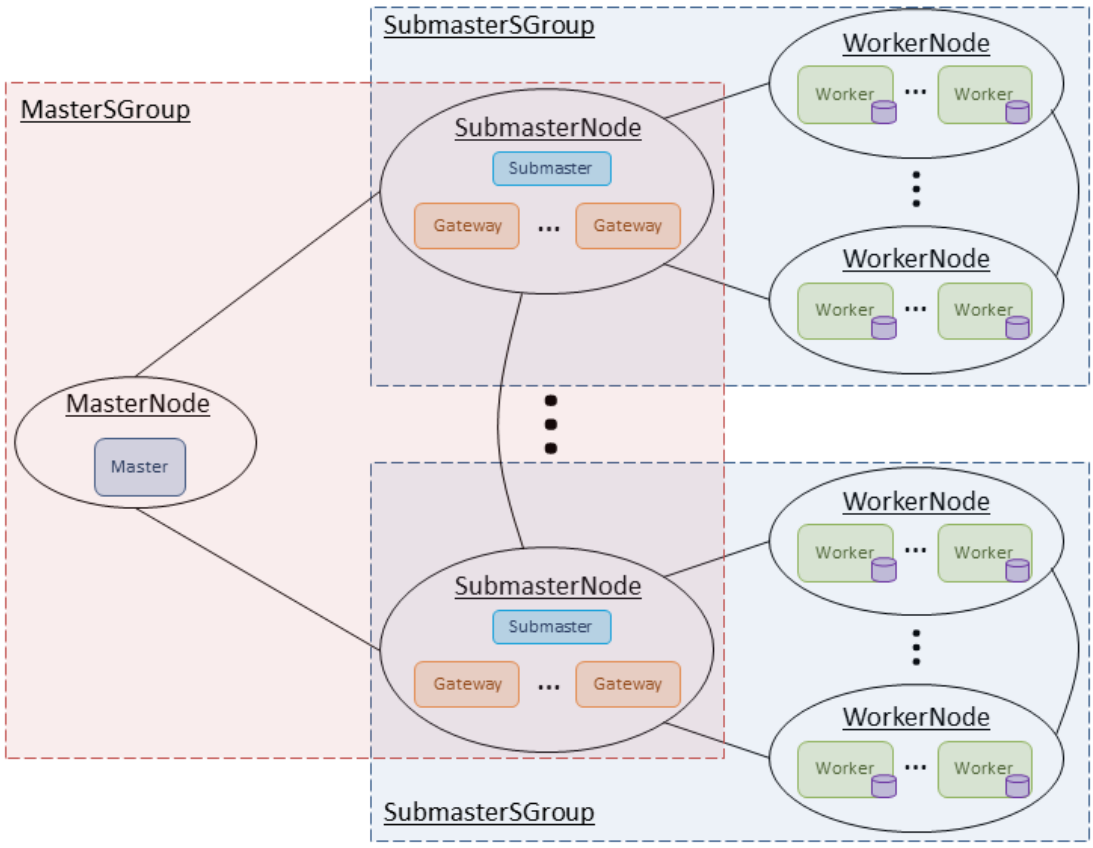


Figure 5: Orbit in SD Erlang

defines the subgroup, and the second hashing defines the node to which a new process should be spawned.

6. Indirect communication between nodes from different s_groups. The node to which a worker process spawns a new process is defined by the value of the vertex, i.e. the first hash of the vertex defines the s_group, and the second hash of the vertex defines the node. Thus, if both the initial and the target nodes are in the same s_group then the process is spawned directly to the target node; otherwise the message is sent to a gateway process on the submaster node in the current s_group (GT1), then GT1 forwards the message to a gateway process on the submaster node of the target s_group (GT2), and then GT2 spawns a process to the target node.

7. Hierarchical information collection. The worker processes return the credit to their submaster processes, and then submaster processes return the credit to the master process.

Types of nodes and processes. A master node has one master process that starts the computation and collects statistics from submaster processes. The master process also spawns submaster processes and gateway processes. Every submaster node contains a single submaster process and a number of gateway processes. The submaster processes distribute DHT to worker processes in the beginning of the computation, spawn worker processes, and collect statics from the worker processes. Gateway processes forward messages between worker processes from different s_groups. Worker nodes keep DHTs and contain a number of worker processes that perform the computation and fill the table, spawn new worker processes, and distribute credit between child processes.

Summary. The main components of refactoring are as follows: 1) grouping nodes, i.e. partitioning worker nodes and grouping them around a submaster node, and then grouping submaster nodes around a master node; 2) introducing an intermediate communication level via gateway processes on submaster nodes; 3) introducing hierarchical process spawning and information distribution/collection; 3) tuning the performance, i.e. defining the number of nodes in s_groups and the number of gateway processes on submaster nodes. The speed up of distributed Erlang and SD Erlang versions of Orbit are presented in Figure 6.

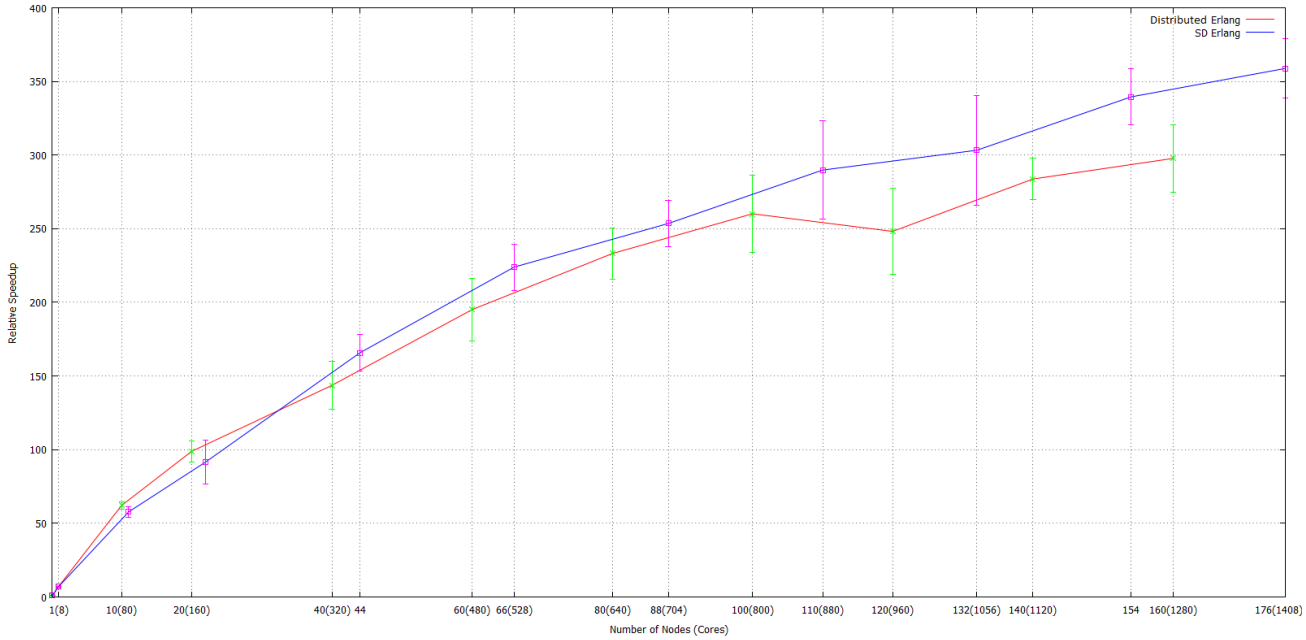


Figure 6: Speed up of Distributed Erlang and SD Erlang Versions of Orbit

3.2 Ant Colony Optimisation (Master-Slave)

Ant Colony Optimisation (ACO) is a "metaheuristic" which has proved to be successful in a number of difficult combinatorial optimisation problems, including the Travelling Salesman, Vehicle Routing, and Quadratic Assignment problems. A detailed description of the method and its applications can be found in the book [DS04][1]; a more recent overview can be found in [DS10]. There is a vast amount of research on this subject: an online bibliography at `http://www.hant.li.univ-tours.fr/artantbib/artantbib.php` currently has 1089 entries.

The ACO method is inspired by the behaviour of real ant colonies. Ants leave their colonies and go foraging for food. The paths followed by ants are initially random, but when an ant finds some food it will return to its home, laying down a trail of chemicals called *pheromones* which are attractive to other ants. Other ants will then tend to follow the path to the food source. There will still be random fluctuations in the paths followed by individual ants, and some of these may be shorter than the original path. Pheromones evaporate over time, which means that longer paths will become less attractive while shorter ones become more attractive. This behaviour means that ants can very quickly converge upon an efficient path to the food source.

This phenomenon has inspired the ACO methodology for difficult optimisation problems. The basic idea is that a (typically very large) search space is explored by a number of artificial ants, each of which makes a number of random choices to construct its own solution. The ants may also make use of heuristic information tailored to the specific problem. Individual solutions are compared, and information is saved in a structure called the *pheromone matrix* which records which records the relative benefits of the various choices which were made. This information is then used to guide a new generation of ants which construct new and hopefully better solutions. After each iteration, successful choices are used to reinforce the pheromone matrix, whereas pheromones corresponding to poorer choices are allowed to evaporate. The process finishes when some termination criterion is met: for example, when a specified number of iterations have been carried out, or when the best solution has failed to improve over some number of iterations. A detailed discussion on Erlang implementation of ACO is presented in Section A.

Thus, the goal is to arrange the sequence of jobs in such a way as to minimise the total weighted tardiness: essentially, we get penalised when jobs are finished late, and we want to do the jobs in an order which minimises the penalty. This problem is known to be NP-hard [DL90, LRKB77, Law77]. Typically, interesting problems are ones in which it is not possible to schedule all jobs within their deadlines. We have a collection of N jobs which have to be scheduled in some order. The pheromone matrix is a $N \times N$ array τ of floats, with τ_{ij} representing the desirability of placing job j in the ith position of a schedule. The algorithm involves several constants:

- $q_0 \in [0, 1]$ determines the amount of randomness in the ants' choices.
- $\alpha, \beta \in \mathbb{R}$ determine the relative influence of the pheromone matrix τ and heuristic information η (see below).
- $\rho \in [0, 1]$ determines the pheromone evaporation rate.

The algorithm performs a loop in which a number of ants each construct new solutions based on the contents of the pheromone matrix, and also on heuristic information given by a matrix η (different or each ant); however, the entries η_{ij} are only used once each, and are calculated as the ants are constructing their solutions: it is never necessary to have the entire matrix η in memory.

Each ant constructs a new solution iteratively, starting with an empty schedule and adding new jobs one at a time. Suppose we are at the stage where we are adding a new job at position i in the schedule. The ant chooses a new job in one of two ways:

[1] This can be downloaded from the internet.

- With probability q_0, the ant deterministically schedules the job j which maximises $\tau_{ij}^{\alpha}\eta_{ij}^{\beta}$. Various choices of heuristic information η have been proposed; here, we have used the *Modified Due Date* (MDD) [BBHS99a] given by $\eta_{ij} = 1/max\{T + p_j, d_j\}$ where T is the total processing time used by the current (partially–constructed) schedule. This rule favours jobs whose deadline is close to the current time, or whose deadline may already have passed.

- With probability $1 - q_0$, a job j is chosen randomly from the set U of currently-unscheduled jobs. The choice of j is determined by the probability distribution given by $P(j) = \frac{\tau_{ij}^{\alpha}\eta_{ij}^{\beta}}{\sum_{k\in U}\tau_{ik}^{\alpha}\eta_{ik}^{\beta}}$

In the sequential version of the algorithm, an ant can perform a *local pheromone update* every time it adds a new job to its schedule. This involves weakening the pheromone information for the job it has just scheduled, thus encouraging other ants to explore different parts of the solution space. In our concurrent implementation, several ants are working simultaneously, and we have omitted the local update stage since it would involve multiple concurrent write accesses to the pheromone matrix, leading to a bottleneck.

At the start of the algorithm, the elements of the pheromone matrix are all set to the value $\tau_0 = \frac{1}{MT_0}$, where M is the number of ants, and T_0 is the total weighted tardiness of the schedule obtained by ordering the jobs in order of increasing deadline, i.e. *earliest due date* schedule. After each ant has finished, their solutions are examined to select the best one based on lowest total tardiness. The pheromone matrix is then updated in two stages:

- The entire matrix τ is multiplied by $1 - \rho$ in order to evaporate pheromones for unproductive paths.

- The path leading to the best solution S is reinforced. For every pair (i, j) with job j at position i in S, we replace τ_{ij} by $\tau_{ij} + \rho/T$, where T is the total weighted tardiness of the current best solution.

To a large extent the ACO algorithm is naturally parallel: we have a number of ants constructing solutions to a problem independently, and if we have multiple processors available then it is sensible to have ants acting in parallel on separate processors rather than constructing solutions one after the other, i.e. the more resources are available the larger number of ants we can have, in turn the more ants the larger number of solutions we get and, hence, better final solution of the problem.

To date we have implemented and tested six versions of ACO: non-distributed Erlang version using ETS and DETS tables to store pheromone matrices, single- and multi-level distributed Erlang versions, a reliable non-distributed Erlang version, and SD Erlang version. The source code of non-distributed Erlang, multilevel distributed Erlang, and SD Erlang versions of the ACO can be found in the following directories of the RELEASE project github repository:

- Non-distributed Erlang: `https://github.com/release-project/RELEASE/tree/master/Research/Benchmarks/ACO/aco-smp`

- Distributed Erlang: `https://github.com/release-project/RELEASE/tree/master/Research/Benchmarks/ACO/multi-level-aco`

- SD Erlang: `https://github.com/release-project/RELEASE/tree/master/Research/Benchmarks/ACO/aco-scalable_reliable`

Non-distributed Erlang version. We run the ACO on a single Erlang node (Figure 7). The pheromone matrix is represented as an ETS table which stores each row of the matrix as an N-tuple of real numbers. This is accessible to all processes running in the Erlang VM. The program takes three

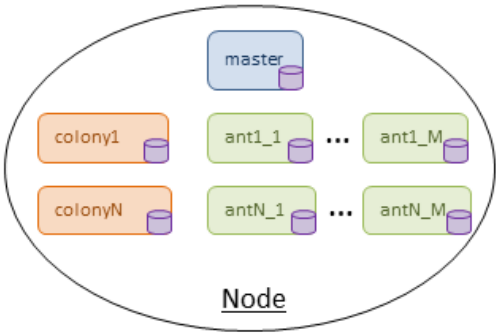


Figure 7: ACO in Non-distributed Erlang

arguments. The first argument is the name of a file containing input data: an integer N and 3 sets of N integers, representing the processing times, the weights, and the deadlines for each job. The second argument is the number M of ants which should be used, and the third argument is the number K of iterations of the main "loop" of the program, i.e. the number of generations of ants.

After reading its inputs, the program creates and initialises the table representing the pheromone matrix, then spawns M ant processes. The program then enters a loop in which the following happens:

- The ants construct new solutions in parallel.
- When an ant finishes creating its solution, it sends a message containing the solution and its total tardiness to a master process.
- The master compares the incoming messages against the current best solution.
- After all M results have been received, the master uses the new best solution to update the pheromone matrix.
- A new iteration is then started: again, each ant constructs a new solution.
- After K iterations, the program terminates and outputs its best solution.

The execution time of the program is linear in the number of iterations K and quadratic in size of the matrix N due to data allocation and also due to the fact that since the entire $N \times N$ matrix τ has to be traversed by each ant and later rewritten in the global update stage. It is more difficult to see how the execution time is influenced by the number of ants M, although it appears to vary linearly. The details can be found in Section A.3.2.

Non2D. A number of Erlang VMs are started on different machines in a network, and each of these runs a single colony (Figure 8). There is a single master node which starts the colonies and distributes information (like the input data and parameter settings) to them; each colony runs a specified number of ants for a specified number of generations, and then reports its best solution back to the master. The master chooses the best solution from among the colonies and then broadcasts it to all of the colonies, which use it to update their pheromone matrices and then start another round of iterations. Sharing only the best solution allows colonies to influence each other while retaining some individuality. This reduces the amount of data transfer significantly: instead of having to transmit N^2 floats, we only have to transfer N integers. The entire process is repeated some number of times, after which the master shuts down the colonies and reports the best result. For details see Section A.4.

Summary. We introduce two types of nodes: a master node and slave nodes. The master node contains a master process, and the slave nodes contain the colonies. Each node has its own pheromone

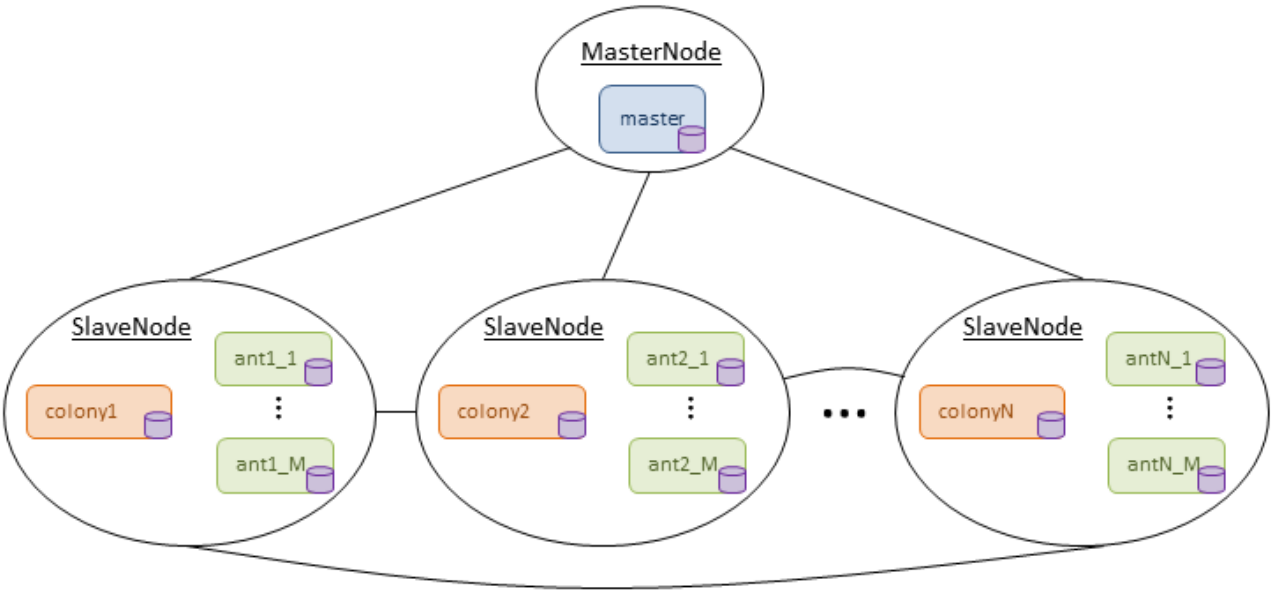


Figure 8: ACO in Distributed Erlang

matrix. The master process collects pheromone results, picks the best one, and distributes it back to the colonies. The colonies are spawned by the master process in the beginning – one colony per slave node, and during the rest of the computation no other new processes are spawned to remote nodes.

D2SD. In the SD Erlang implementation of ACO we introduce yet one more type of nodes – submaster nodes (Figure 9). We partition the set of slave nodes into groups and add a submaster node to every partition – these are submaster s_groups. The master node and submaster nodes form a master s_group. The colonies on slave nodes run computation and periodically send results to their submaster nodes. The submaster nodes collect results from their slave nodes, pick the best solution, and distribute it back to the colonies. The submaster nodes also periodically send results to the master node. The master node collects results, picks the best solution, and distributes it back to the submaster nodes, after that the submaster nodes forward the result to their slave nodes.

Summary. To refactor a distributed Erlang ACO into an SD Erlang one we do the following: (1) partition slave nodes, add submaster nodes, and group nodes into submaster and master s_groups, (2) share the master process functionality with submaster processes.

Scalability Measurements. Figure 10 compares reliable SD Erlang version of ACO with reliable and unreliable distributed Erlang versions of ACO. The measurements are done for weak scalability when no failures occur. Here, the main difference between reliable and unreliable versions is that the reliable versions have global name registration. The figure shows that SD Erlang ACO scales much better than reliable ACO due to replacing global name registration in distributed Erlang version by s_group name registration in SD Erlang version. Additionally, SD Erlang ACO scales better than the unreliable version of distributed ACO. Since the unreliable version has no global name registration we believe this better performance of SD Erlang ACO is due to a smaller number of connections between the nodes.

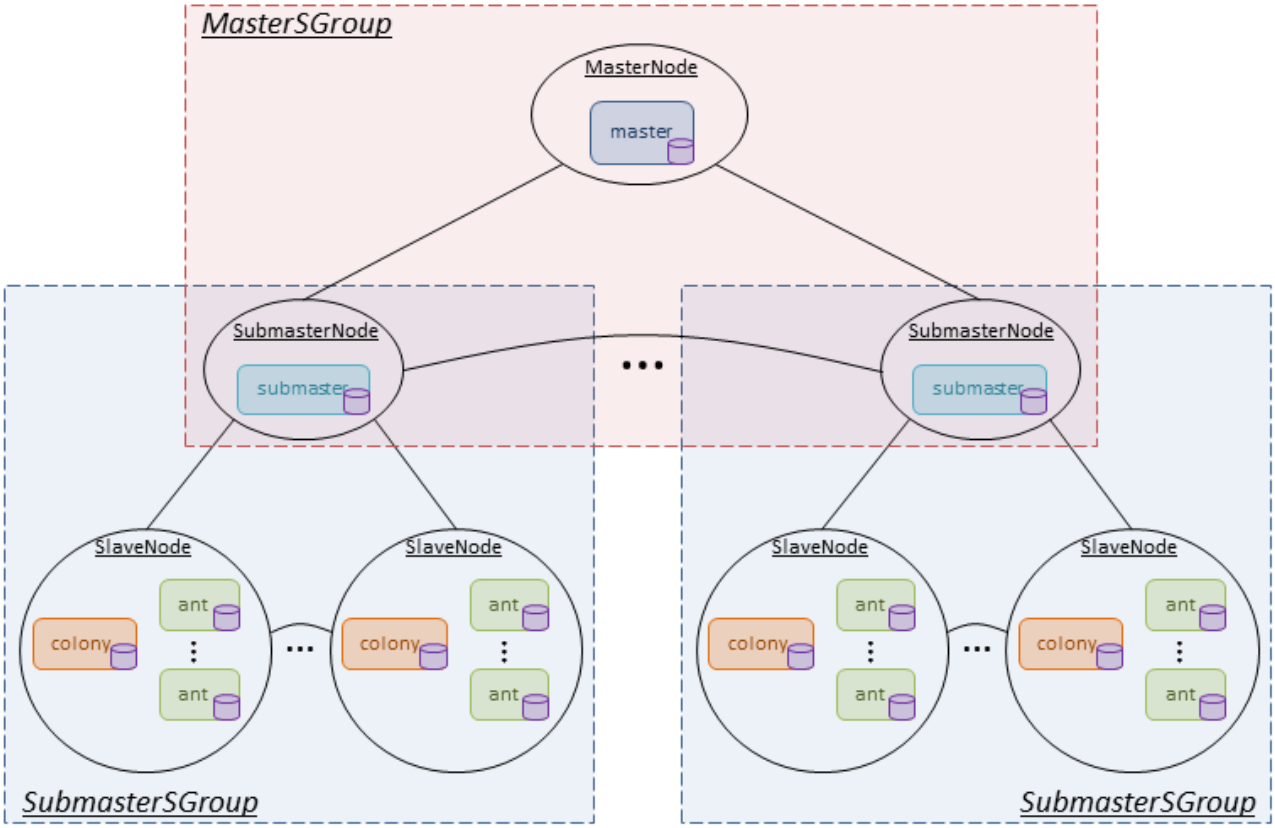


Figure 9: ACO in SD Erlang

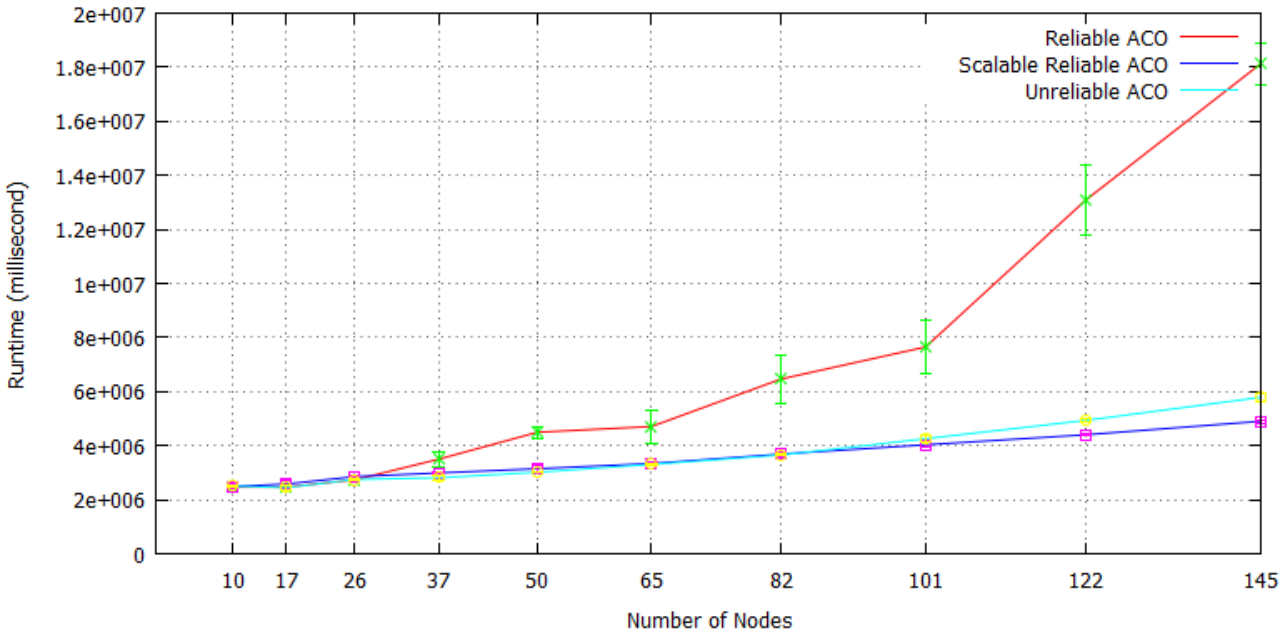


Figure 10: Week Scalability of Reliable SD Erlang ACO, Reliable and Unreliable Distributed Erlang ACO

3.3 Instant Messenger (Server)

Overview. An Instant Messenger (IM) is used to exchange messages between clients. The implemented IM has a client-server architecture where logged-in clients communicate with each other through a server. A client may have multiple open chat sessions but every session supports communication of only two clients, i.e. the benchmark does not support group chats at the moment. To log-in or initiate a conversation a `client` first contacts a `router` which in turn allocates a server process either to monitor a logged-in client (`client_monitor` process) or to perform message passing (`chat_session` process). The benchmark has two types of databases (ETS tables): `client_db` database keeps information about logged-in clients, and `chat_session_db` database keeps information about ongoing conversations. The `client_monitor` processes are only used to trap closed chat sessions and delete their entries from the `chat_session_db` database. The scalability is defined by the number of messages the system can handle and the time it takes to deliver the messages.

We have implemented only distributed Erlang version of the IM. The non-distributed Erlang version is for consistency only, and the SD Erlang version is in the early refactoring stage. The source code can be found in the following directories of the RELEASE project github repository:

- Distributed Erlang: `https://github.com/release-project/RELEASE/tree/master/Research/Benchmarks/Chat/D-IM`

Non-distributed Erlang version. In the non-distributed Erlang implementation all processes are located on a single node (Figure 11). The `client` processes exchange messages with each other through a `chat_session` process. To log-in a client process sends a message to the `router` process. The router process spawns a `client_monitor` process that monitors the client and keeps corresponding information about it in the `client_db` ETS table. To start a conversation a client again sends a request to the router process that spawns a `chat_session` process. The `chat_session` process passes information between the two chatting clients and keeps corresponding information about the session in the `chat_session_db` ETS table. In the benchmark no client interface is implemented instead we use a set of traffic generators.

Non2D. Changes required to turn the non-distributed Erlang IM into a distributed Erlang IM are as follows (Figure 12).

1. *Different types of processes on different nodes.* The `client` processes are started on hidden client nodes. We do that because the aim of the benchmark is to analyse the performance of the server part; therefore, client nodes share neither namespace nor connections of the servers. A `router` process also has a dedicated node. In fact there may be a multiple number of `router` processes

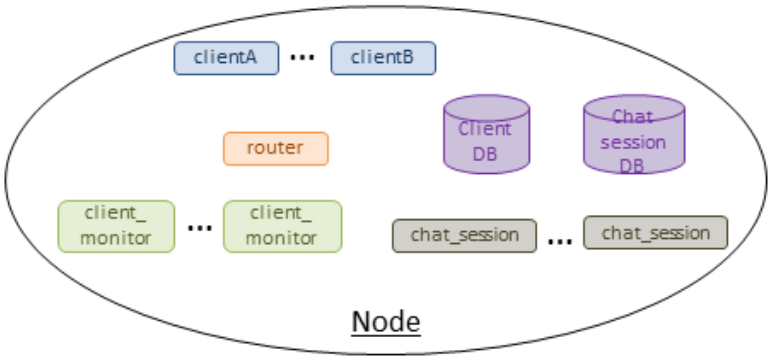


Figure 11: IM in Erlang

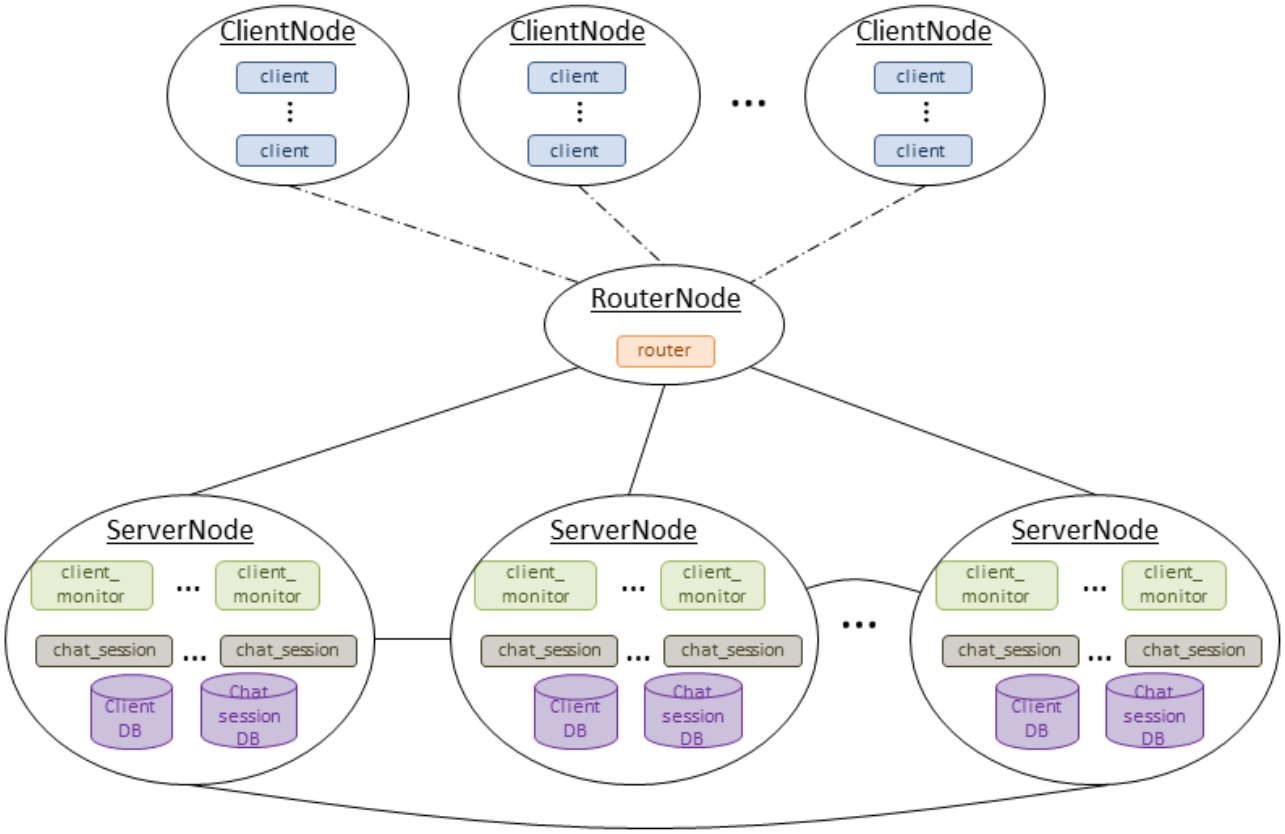


Figure 12: IM in Distributed Erlang

to avoid a single process bottleneck. The `client_monitor` and `chat_session` processes are spawned to server nodes. The nodes on which `chat_session` and `client_monitor` processes are spawned are picked on the basis of the hash values of the corresponding `client` processes. The `chat_session_db` and `client_db` processes also reside on the server nodes.

2. *Distributed Hash Tables (DHTs).* We distribute `chat_session_db` and `client_db` databases between server nodes.

Types of nodes and processes. The distributed Erlang implementation of the IM has the same types of processes as the non-distributed Erlang implementation. However, the former implementation has three types of nodes: client, router, and server. Client nodes keep client processes; the router node keeps router processes; the server nodes keep client_monitor processes, chat_session processes, and `chat_session_db` and `client_db` distributed databases.

Summary. To refactor the Erlang implementation of the IM into a distributed Erlang one the following modifications are required: (1) introduction of different types of nodes, i.e. client, router, server; (2) spawning processes to remote nodes, i.e. replacing `spawn(Module, Fun, Args)` by `spawn(Node, Module, Fun, Args)`. The target node is defined by the hash values of the corresponding client processes; (3) distribution of the `chat_session_db` and `client_db` databases between server nodes.

D2SD. Changes required to turn the distributed Erlang IM into an SD Erlang IM (Figure 13).

1. *Partitioning server nodes.* The IM server nodes are uniform, i.e. allocation of `client_monitor` and `chat_session` processes depends on the hash value of the corresponding `client` processes, therefore, the way server nodes are partitioned does not matter.

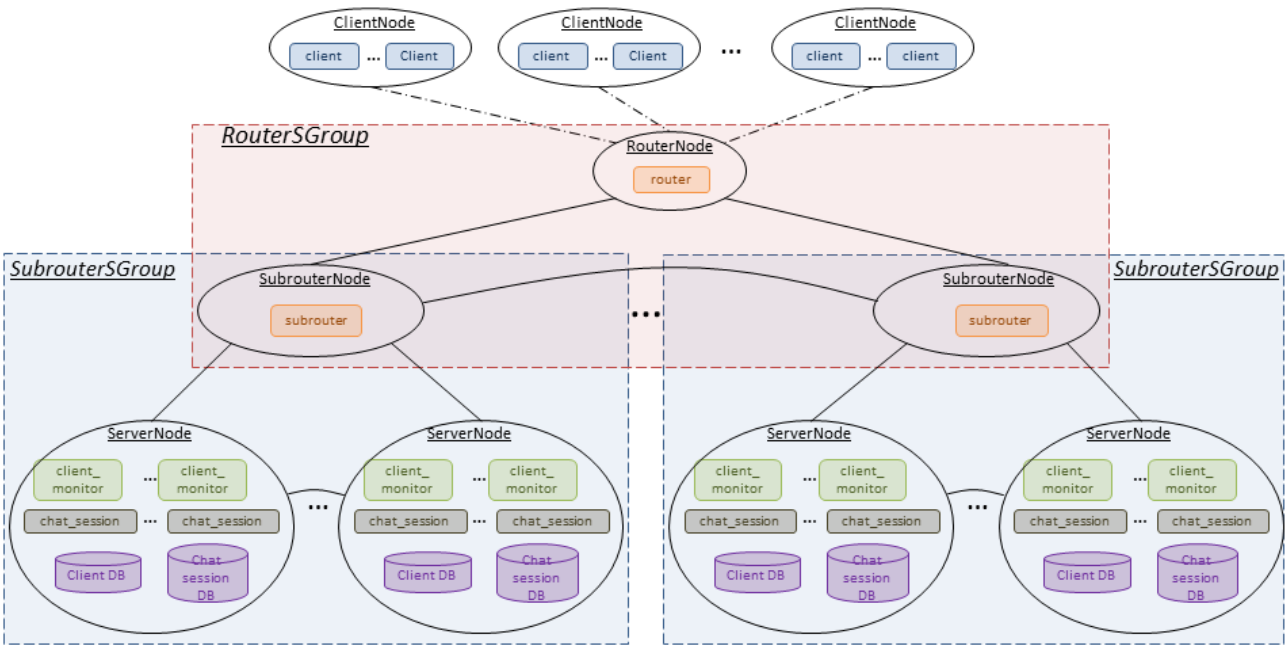


Figure 13: IM in SD Erlang

2. *Creating s_groups.* We add a subrouter node to every partition of server nodes, and create two types of s_groups: a router s_group, and subrouter s_groups. The router s_group consists of the router node and all subrouter nodes; and every subrouter s_group consists of a subrouter node and a set of server nodes.

3. *Introducing a subrouter level.* When a `router` process receives a message from a `client` process it takes a hash value of the client name as in the case of distributed Erlang, but this time the value defines the target `subrouter` process to which the `router` process forwards the message. When the `subrouter` process receives the message, it takes the hash again. This time the value defines the target server node in the subrouter s_group. After that the `subrouter` process spawns a corresponding process to that server node.

Types of nodes and processes. Router nodes only have `router` processes, and now the `router` processes have less responsibilities, i.e. they only forward `client` messages to corresponding `subrouter` processes. Subrouter nodes have `subrouter` processes. The rest of the nodes and processes are the same as in the distributed Erlang version.

Summary. To refactor a distributed Erlang IM into an SD Erlang one we do the following: (1) partition server nodes, (2) add subrouter nodes, (3) create router and subrouter s_groups, and 4) shift some functionality of the router nodes and processes to the subrouter nodes and processes.

3.4 Sim-Diasca (Multicomponent)

Overview. Sim-Diasca (SIMulation of DIscrete systems of All SCAles) is a distributed engine for large scale discrete simulations implemented in Erlang. The engine is developed at EDF R&D and is released under the LGPL license [EDF10]. Sim-Diasca is able to handle millions of relatively complex interacting model instances. To date the maximum number of Erlang nodes used to run the distributed Erlang version of Sim-Diasca is 32 on 256 cores.

Sim-Diasca is a very large and complex system; therefore, in this document we only cover components related to the scalability of the simulation engine. One of the main components that impact

scalability of Sim-Diasca are *Time Manager* processes that ensure uniform simulation time across the simulation, and are used to schedule simulation engine processes. The Time Managers are organised in a hierarchical manner, and are independent of the number of cores. There is one Root Time Manager and a number of Time Managers. The Root Time Manager spawns Time Managers that in turn supervise performance trackers.

In the non-distributed Erlang version of Sim-Diasca all processes run on a single node.

Non2D. To support distribution in Sim-Diasca EDF introduced a number of modifications and new elements in the simulation engine (Figure 14).

1. *Time Managers.* Every host has one Root Time Manager and a number of Time Managers. One of the Root Time Managers is also a Cluster Time Manager. Here, the Cluster Time Manager spawns Root Time Managers, and the Root Time Managers spawn Time Managers. Apart from the performance tracker the Time Managers supervise distributed data-exchanging services.

2. *Load Balancer.* Another element closely related to the Time Managers is a Load Balancer which is used to create actors on remote nodes. A Load Balancer process is spawned by the corresponding Root Time Manager, and there is only one Load Balancer process per node. On a remote node actors can be create in the following two modes: static mode by using round-robin or hint strategies, *or* dynamic mode by using load information of the nodes. A Load Balancer creates actors using the following synchronous functions:

   - `create_initial_actor/2,3` – no specific placement
   - `create_initial_placed_actor/3,4` – a process placement is based on a hint
   - `create_initial_actors/1,2` – a creation of a large number of actors with or without placement hints

3. *Instance Tracker.* To trace components of the simulation a distributed trace system called Traces is used. The system has six built-in trace channels: debug, trace, info, warning, error, fatal.

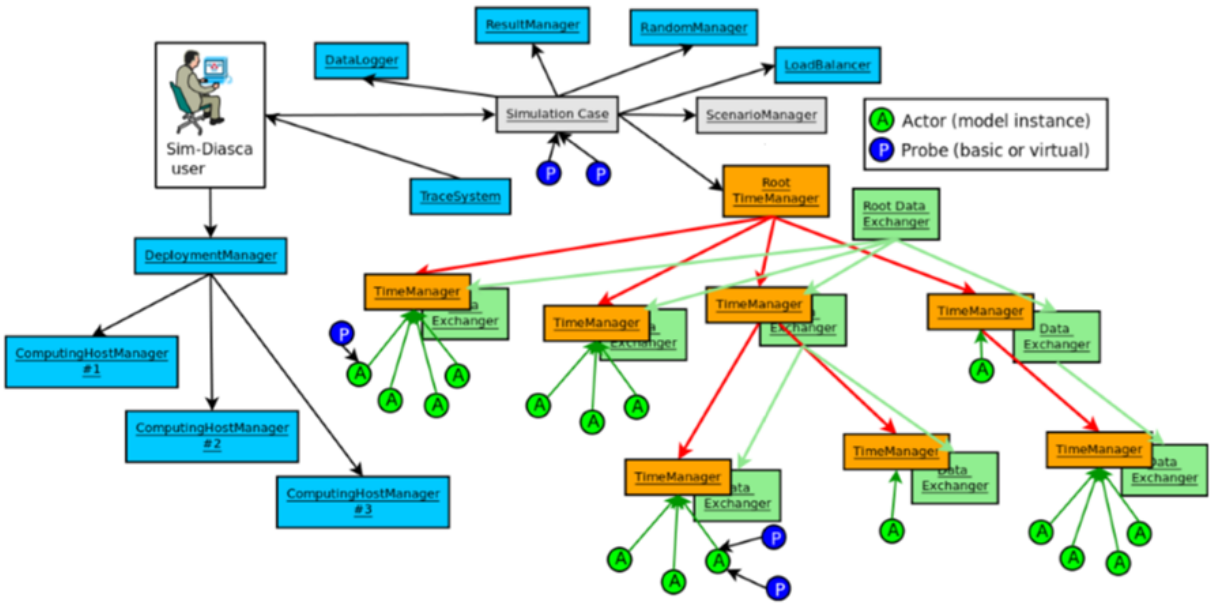


Figure 14: Sim-Diasca in Distributed Erlang [EDF10]

4. *Data Exchanger* is a distributed simulation service that is used to share data between actors locally. It is distributed in terms of any actor from a particular node can access data from its Data Exchanger with a negligibly low latency.

Types of nodes and processes. There are two types of nodes: a user node and computing nodes. The user node initiates the simulation and then collects statistics and results of the simulation. The computing nodes perform the actual simulation. Apart from the user host that may contain two nodes – the user node and a computing node – every host contains only one node (a computing node). All nodes are interconnected and are known in advance, i.e. the participating hosts are listed in `sim-diasca-host-candidates.txt`.

Summary. In the distributed Erlang version two types of nodes were introduced: a client node and computing nodes. To synchronise simulation time across nodes an additional level of hierarchy for Time Managers was introduced. An introducing of load management and hint mechanisms enabled to distribute load between nodes. To spawn a process the target node is defined either by a hint (to place frequently communicating processes close to each other) or by load balancing (the processes are spawned to the least loaded nodes).

D2SD. SD Erlang Sim-Diasca can be implemented on the basis of locality, i.e. the nodes are grouped in s_groups depending on the communication distance. The core elements of the structure will be *Time Managers*, i.e. we propose to add additional levels in the hierarchy of the Time Managers to ensure uniform simulation time in the whole system without necessity to synchronise all nodes in one go all the time (Figure 15). Currently SD Erlang Sim-Diasca is in a design stage due to resolving its other scalability issues by the RELEASE consortium.

Figure 15: Sim-Diasca in SD Erlang (WP5)

3.5 Summary

The refactoring of non-distributed Erlang applications into distributed Erlang ones, and then distributed Erlang applications into SD Erlang ones is very much application specific. However, we can identify some common patters.

Refactoring a non-distributed Erlang application into a distributed Erlang one.

1. Spawning processes to remote nodes, i.e. replacing `spawn(Module, Fun, Args)` by `spawn(Node, Module, Fun, Args)` and defining the target nodes.
2. Introducing distributed databases, e.g. the DHT in SD Orbit.
3. Tuning the performance, i.e. deciding on the right number of different types of nodes and processes.

Refactoring a distributed Erlang application into an SD Erlang one:

1. Grouping nodes in s_groups. Depending on the application we may need the following: (a) define the structure of s_groups (e.g. hierarchical, ring, star), (b) decide which nodes it is better to group, (c) add gateway processes and a corresponding functionality to enable remote nodes to communicate with each other without establishing a direct connection, (d) introduce submaster nodes and processes and shift on them some functionality from the master nodes and processes to offload the later.
2. Tuning the performance by determining the size of s_groups and the number of gateway processes.

We further discuss SD Erlang scalability principles and application methodology in Section 4.1.3.

4 Distributed Erlang Scalability Principles & Application Methodology

In this section we focus on distributed Erlang scalability issues that is we do not cover single node scalability issues. The later can be found elsewhere, e.g. deliverables of WP2 and [CV14, Arm13, CT09]. We start with all-to-all connections (Section 4.1), then discuss global namespace (Section 4.2), and finish with a discussion on single process bottleneck issues (Section 4.3).

4.1 Replacing All-to-all Connections

4.1.1 Issues with All-to-all Connections.

In many distributed Erlang systems nodes are normal and the flag of transitive connectivity is set; so, all nodes in the system are interconnected. Thus the total number of connections is $n(n-1)/2$, and every node supports $(n-1)$ connections. Every connection requires a separate TCP/IP port. When nodes are connected they monitor each other by sending heartbeat messages. In small systems maintaining, a fully connected network is not an issue; however, when either traffic or the number of nodes grows a fully connected network requires significant resources and becomes a burden to maintain. For example, in a heavily loaded game server a fully connected network of 16 nodes becomes an issue, less loaded applications may display difficulty in maintaining a fully connected network at approximately 70-200 nodes [GCTM13].

4.1.2 Ad Hoc Approaches

There are a number of approaches that Erlang developers use to overcome the issue of a fully connected network in distributed Erlang.

One game company disables transitive connectivity flag and manually connects normal nodes according to some topology. In this case, the nodes have normal node properties but do not share connections, and the whole application is built around preventing nodes from establishing new connections. In March 2014 the company was dealing with up to 16 Erlang nodes.

Another game company Spil Games [Spi14] uses hidden nodes and a predefined configuration. The configuration contains a set of nodes the current node is allowed to connect to. The mechanism is suitable for systems with well defined types of nodes similar to a web server where particular types of nodes are responsible for particular parts of a web-page. Additionally, nodes do not require a common namespace, i.e. if needed this mechanism should be implemented separately. The mechanism reportedly scales up to a thousand Erlang nodes.

Another approach is using OTP global_groups by partitioning a set of nodes into global_groups. Each group has its own namespace. Nodes within the global_group have transitive connections, and non-transitive connections with nodes outside of the global_group. The drawback is that the approach is limited to the cases when the network can be partitioned.

4.1.3 RELEASE Approach: s_groups

In the RELEASE project we have introduced s_groups which are *similar* to global_groups in that each s_group has its own namespace, and transitive connections are only with nodes of the same s_group. The *difference* with global_groups is in that a node can belong to an unlimited number of s_groups which enables to form different types of topologies. To create a new s_group the `s_group:new_s_group(SGroupName, [Node])` function is used. We can also add nodes to an s_group using `s_group:add_nodes(SGroupName, [Node])` function, remove nodes from an s_group using `s_group:remove_nodes(SGroupName, [Node])` function, and delete an s_group using `s_group:delete_s_group(SGroupName)` function. Details of SD Erlang implementation and its functions are covered in the following RELEASE project deliverables: D3.2: Scalable SD Erlang Computation Model [REL13a] and D3.3: Scalable SD Erlang Reliability Model [REL13b].

When s_groups are arranged in a hierarchical manner one can find similarities between Erlang nodes that belong to a number of s_groups (let us call them gateway nodes) and *super-peers*, i.e. nodes that act simultaneously as a server and a peer [BYGM03]. However, in SD Erlang whether a gateway node has a super-peer functionality depends on the application and is not imposed by s_groups.

The reason we have introduced s_groups was to reduce the number of connections a node maintains but at the same time provide nodes an opportunity to keep distributed Erlang connections, i.e. when a node joins an s_group it is automatically connected to all nodes in that s_group. Another aim was to reduce the common namespace which in distributed Erlang and in SD Erlang is closely connected to transitive connectivity. We discuss impact of shared namespace in Section 4.2.

In the exemplars we discuss in Section 3 the sets of nodes are arranged in a hierarchical manner in SD Erlang. A natural question would be "Why not introduce hierarchical s_groups with a built-in routing instead of overlapping s_groups where routing should be implemented individually depending on an application". The reason is that by introducing SD Erlang we aimed to provide a tool that a developer can use to reduce the number of connections but keep Erlang distribution properties and functionality between some groups of nodes, rather than introducing a scheme that developers would have to fit their application in.

How to structure nodes to scale? To scale a set of Erlang nodes the nodes can be structured, for example, in a hierarchical manner. In this case if we have a master node it should be at the root of the

system, and the worker nodes are leaves. S_groups can also be arranged in, for example, a ring or star manner.

Which nodes to group? To identify the most suitable nodes to group in s_groups Percept2 [REL14c] and devo [REL14b] tools that WP5 is developing can be used. Percept2 can show how the communication between nodes works, and devo will be able to show how nodes have affinity with each other. The discussion on devo tool and examples on how to use it is planed to be discussed in the upcoming deliverable D5.4: Interactive SD Erlang Debugger.

How to determine the size of s_groups? The size of an s_group depends on the intensity of the inter- and intra-s_group communication, and global operations. The larger these parameters the smaller the number of nodes in the s_group. To analyse intra- and inter-s_group communications the devo tool can be used. Further discussion on tools and examples on automating generic parts of the refactoring process is provided in deliverable D5.3: Systematic Testing and Debugging Tools [REL14a].

In the exemplars from Section 3 we observed patterns in grouping nodes, i.e. partitioning, hierarchical grouping, and hierarchical grouping with redundancy. To automate and simplify the mechanism of grouping nodes we propose `s_group:grouping/1` function that takes a list of nodes together with some additional parameters, creates s_groups, and returns a result. Below we discuss the details of each type of grouping.

4.1.4 Functions to Group Nodes

Partitioning. The function requires a list of nodes and the number of s_groups, and it returns a list of s_groups where each s_group contains approximately an equal number of nodes. For example, we provide the following input data in the function from Listing 1: `NodeDistribution=[6,6,6,5]`, `[Nodes] = [N1,N2,...,N23]`, assume that nodes are initially disconnected, and get the following result `[{G1,[N1,..,N6]}, {G2,[N7,...,N12]}, {G3,[N13,...,N18]}, {G4,[N19,...,N23]}]` (Figure 16).

Listing 1: Partitioning a Set of Nodes

```
-spec grouping({partition, [Node], NodeDistribution}) -> [{SGroupName, [Node]}]
                                                        | {error, Reason}
      Node :: node(),
      NodeDistribution :: [integer()],
      SGroupName :: group_name(),
      Reason :: term().
```

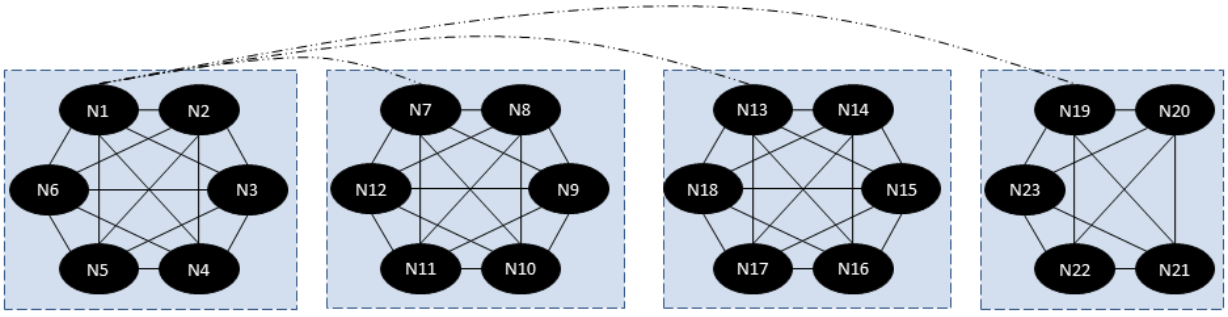


Figure 16: Partitioning

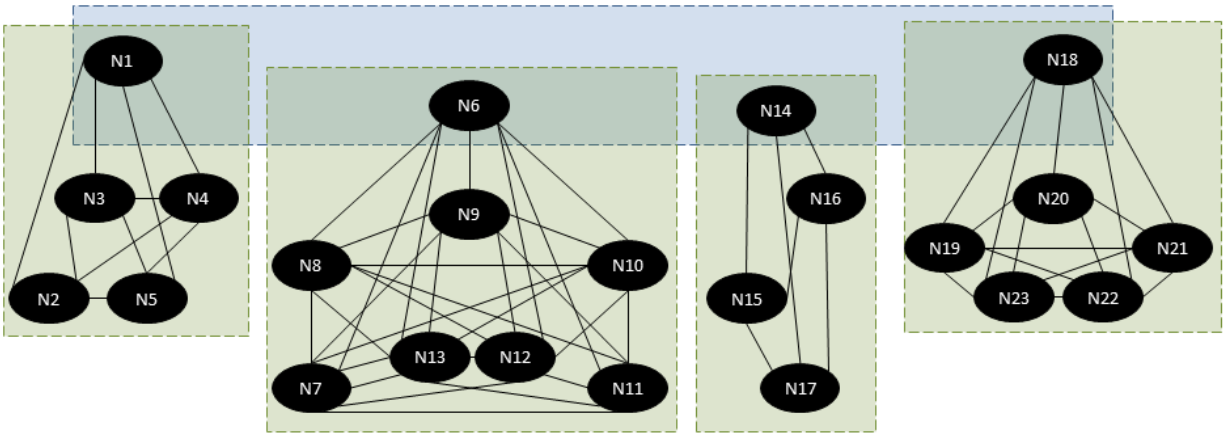


Figure 17: Hierarchical: no root level + 2 levels

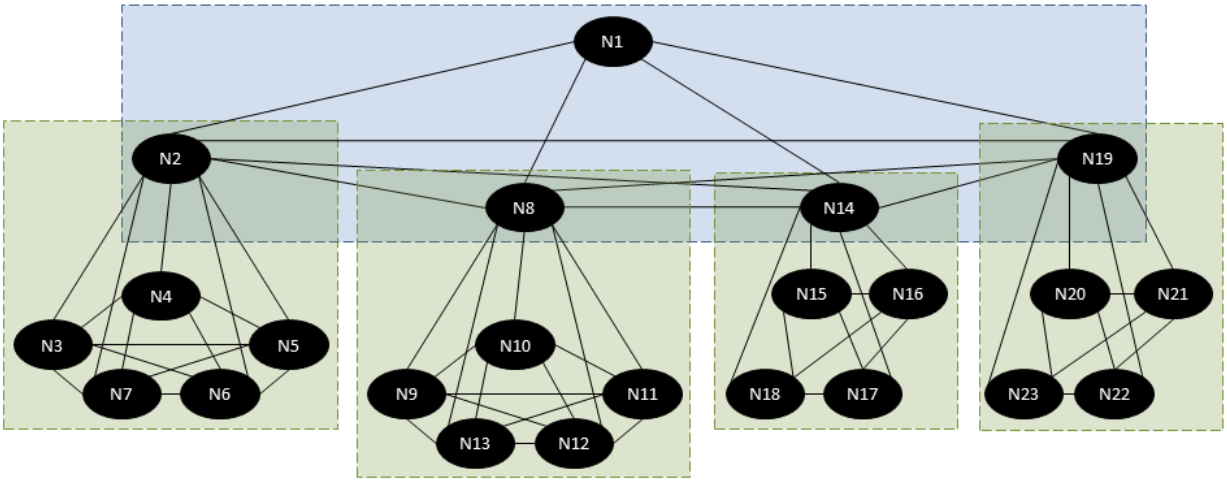


Figure 18: Hierarchical: a root level of one node + 2 levels

Hierarchical grouping. The function requires a list of nodes and the node distribution on each level (Listing 2). Depending on the values of `NodeDistribution` parameter the hierarchical grouping may have a number or none of root nodes, and a different number of levels.

Listing 2: Hierarchical Structure with a Single Root Node

```
-spec grouping({hierarchical, [Nodes], NodeDistribution}) -> [{SGroupName, [Node]}]
                                                           | {error, Reason}

      Node :: node(),
      NodeDistribution :: [term()],
      SGroupName :: group_name(),
      Reason :: term().
```

For example, we have 23 disconnected nodes and we want to group them in a number of ways, e.g.

- No root level + 2 levels (Figure 17). In this case `NodeDistribution=[0,[4],[4,7,3,5]]`.

- 3 levels with a root node (Figure 18). In this case `NodeDistribution=[1,[4],[5,5,4,4]]`.
- 4 levels with two root nodes (Figure 19). In this case `NodeDistribution=[2,[3],[2,2,2],[2,3,2,2,2,1]]`.

Hierarchical structure with redundancy. This function enables to group nodes in such a way that s_groups have multiple gateway nodes, i.e. the nodes that belong to multiple s_groups. For example, to group 23 disconnected nodes in a way as presented in Figure 20 the parameter `NodeDistribution`

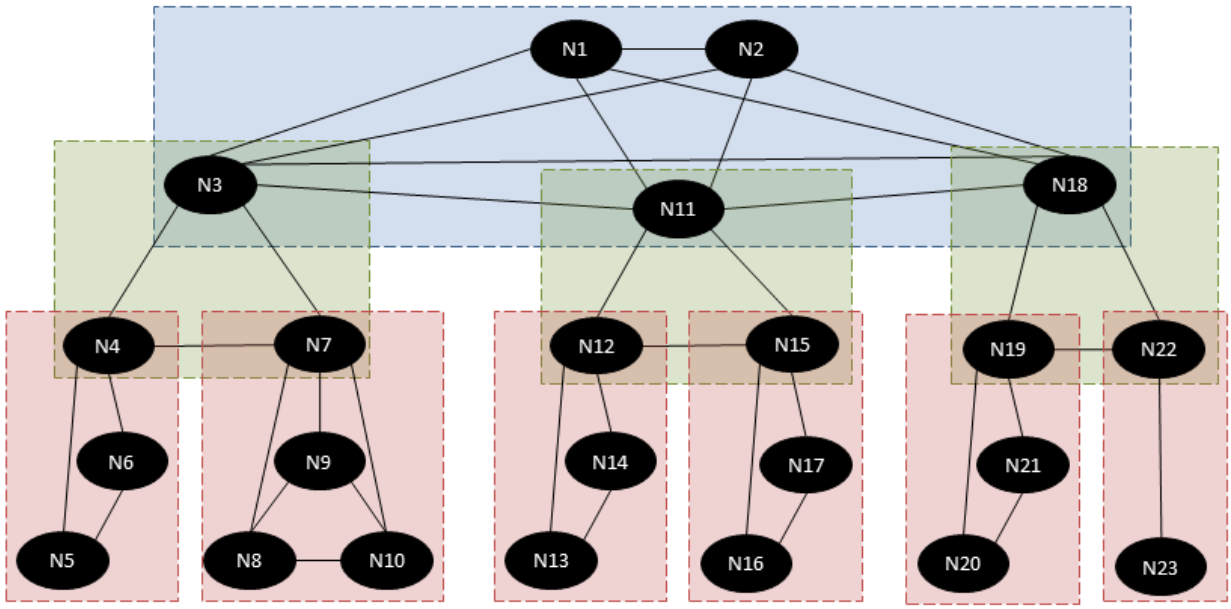


Figure 19: Hierarchical: a root level of 2 nodes + 3 levels

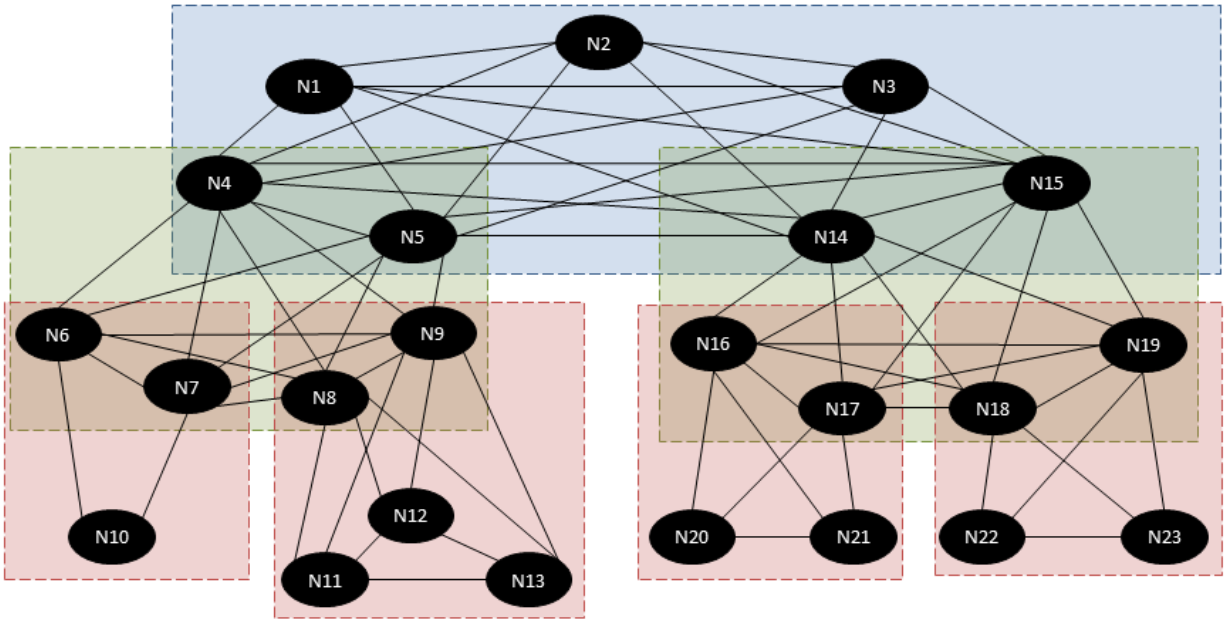


Figure 20: Hierarchical with Redundancy

from Listing 3 should be as follows `NodeDistribution=[3,[4],[2,4,2,4],[2,1,2,3,2,2,2,2]]]`.

Listing 3: Hierarchical Structure with Redundancy

```
-spec grouping({hierarchical_redundancy, [Nodes], NodeDistribution}) ->
                                                    [{SGroupName, [Node]}] | {error, Reason}
      Node :: node(),
      NodeDistribution :: [term()],
      SGroupName :: group_name(),
      Reason :: term().
```

4.2 Replacing Global Namespace

Global namespace in distributed Erlang and SD Erlang is about ability to reach a process using its name rather than a pid. This was introduced mostly for reliability purposes, i.e. if a process fails and then is restarted its pid changes but the process can be still accessed using the same name. In distributed Erlang and SD Erlang the global name registration is closely connected to transitive connections, i.e. nodes that transitively share connections also share a name space. In distributed Erlang all connected normal nodes have a common namespace, and in SD Erlang nodes that belong to a particular s_group share the namespace of that s_group.

In distributed Erlang when a name is registered globally its name and pid are replicated on all connected normal nodes. When the pid terminates it is automatically unregistered from all nodes. The name is either registered on all connected normal nodes or on none. In SD Erlang we use the same principle but now we have introduced additional parameter – SGroupName – that defines in which s_group the name should be registered. The name then is replicated on all nodes that belong to that s_group. To register a name in an s_group the node should belong to that s_group. Other than that

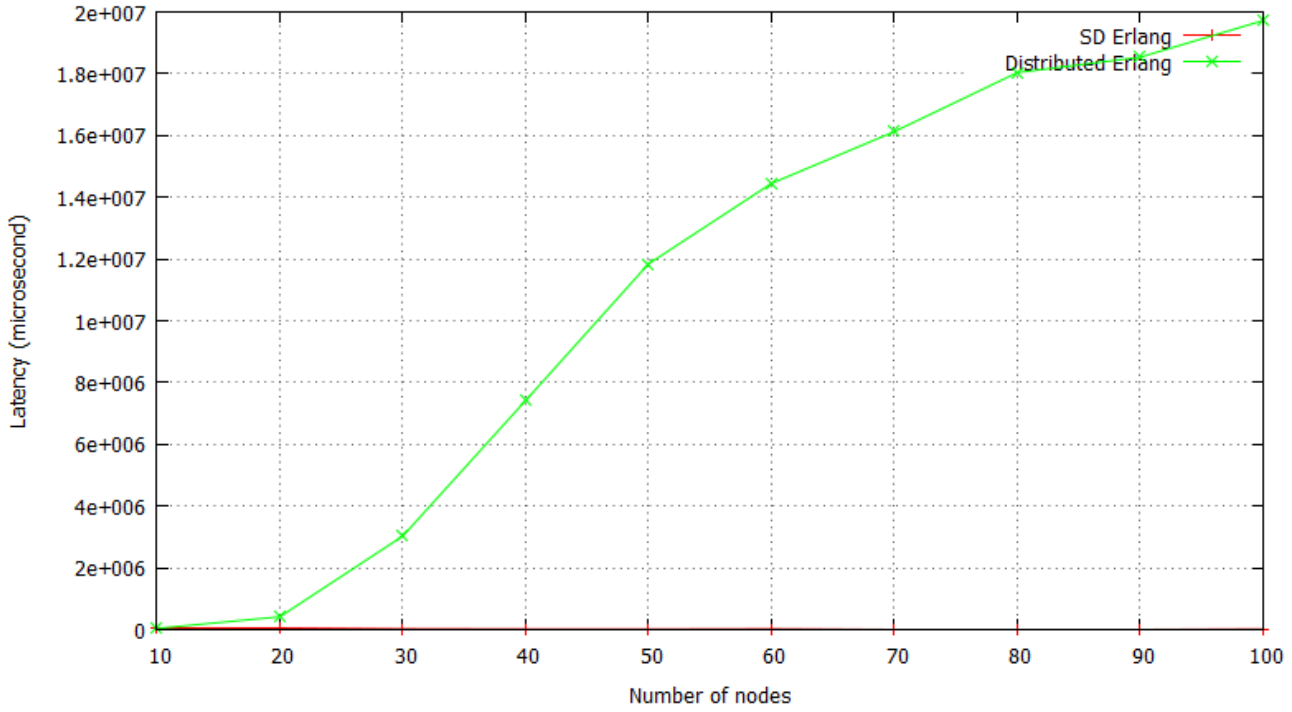


Figure 21: Latency of Global Operations in Distributed Erlang

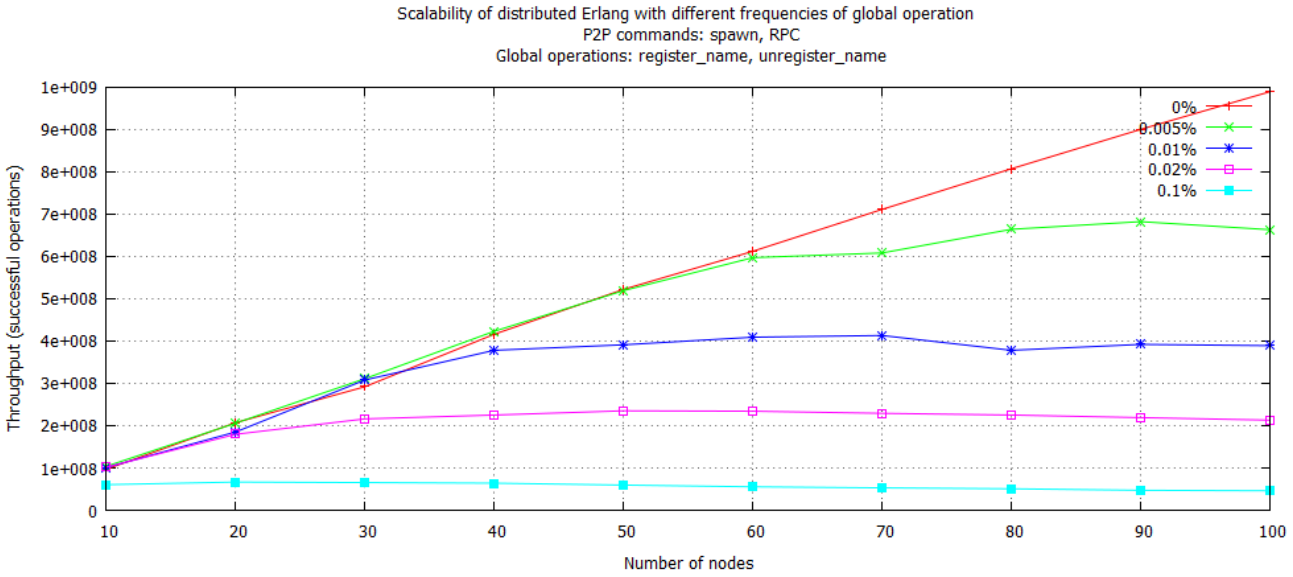


Figure 22: Impact of Global Operations on Scalability

the mechanism of registering and unregistering global names is the same as in distributed Erlang.

The reason we have reduced the common namespace to s_groups in SD Erlang rather than keeping it global is due to the fact that global registration in distributed Erlang is very expensive in terms of time it takes to replicate data on all nodes. For example, to register a name on 20 nodes in Distributed Erlang takes 0.8s, whereas to register a name on 50 nodes takes 12s (Figure 21). These measurements were done using DEbench benchmarking tool [REL13a]. In Figure 22 we show throughput depending on the number of nodes for different percentage of global operations. As we see even as small as 0.05% of global operations has a significant impact on the throughput. Therefore, we do not want to register many names, but rather only those that many processes from remote nodes may frequently communicate with. We also do not expect registered processes to be restarted continuously as this will require constant name re-registration and will slow down the system significantly.

Of course, the above approach is only one possibility way of implementing a global namespace. For example, Joe Armstrong suggested an idea to have global names in distributed Erlang but replace the type of routing by using a Kademlia or Tapestry-like approach, i.e. when registering a name it is registered on the nodes which hash values have minimal distances to the hash value of the process' name. The mechanism will not require name replication on all nodes but only on the small number of nodes. However, it will require a new routing mechanism to locate the nodes on which the name is registered.

4.3 Eliminating Single Process Bottleneck

A single process bottleneck is a well known problem in parallel and distributed systems. In Erlang context it occurs when a process is not able to process messages in its mailbox in a timely manner. The most widely used technique to tackle the single process bottleneck is to introduce identical processes that share the incoming messages.

The potential points of single process bottlenecks in SD Erlang are gateway processes on submaster nodes. The purpose of gateway processes is to route messages from a node of one s_group to a node of another s_group without creating a direct connection between the nodes. Therefore, a submaster node should have a sufficient number of gateway processes to serve all inter-s_group communication. In the

Orbit example to eliminate a single process bottleneck we have introduced multiple gateway processes per a gateway node. Thus, when a process wants to send a message to a process in another s_group, it picks a gateway process randomly. The process of identifying a single process bottleneck in Orbit example using Percert2 tool [REL14c] developed by the Kent team is demonstrated in [TL13].

5 Reliability Principles

SD Erlang has the same philosophy as distributed Erlang that is "let it crash", and the same reliability model based on the supervision. We use such standard distributed Erlang mechanisms as introducing redundancy and replicas, placing replicas on different nodes and hosts, organising the system in accordance with a supervision tree, implementing mechanisms of restarting failed processes and nodes. The following additional SD Erlang reliability features are due to introducing s_groups.

1. *Failure of a gateway process or node.* This may cause a system partition, because currently routing between s_groups is performed by router processes. Therefore, to ensure that the system continues a normal execution such standard reliability mechanism as redundancy can be used. For example, we can use two gateway nodes instead of one, and in case of a failure of one of the nodes the other node can temporarily overtake the load while the first node is in the process of recovery.

2. *Remote supervision.* At the moment it is impossible to spawn (or monitor) a process from one node to another without establishing a direct connection between the two. However, we can again use routing via gateway nodes and introduce remote supervision. For example, we want to spawn a process from $ServerNodeA$ in $SubrouterSGroup1$ on $ServerNodeD$ in $SubrouterSGroup2$ (Figure 23). In this case we can send a message from $ServerNodeA$ to $Subrouter4$, i.e. $ServerNodeA \rightarrow Subrouter1 \rightarrow Subrouter4$, and then $Subrouter4$ spawns a process on $ServerNodeD$. When the process fails, $Subrouter4$ traps it and sends a message to $ServerNodeA$, i.e. $Subrouter4 \rightarrow Subrouter1 \rightarrow ServerNodeA$.

Currently, the routing mechanisms are implemented specifically for the applications but we may consider to include a general or common case in the Erlang/OTP. Below we discuss SD Erlang reliability principles using IM benchmark. The benchmark helps to demonstrate our findings in a particular example, and is a typical Erlang application.

IM Reliability. The IM benchmark has the following components (Section 3.3, Figure 13).

- Client nodes and client processes
- Router nodes and router processes
- Subrouter nodes and subrouter processes
- Server nodes, client_monitor processes, chat_session processes, client_monitor_db, and chat_session_db
- Router s_group and subrouter s_groups

An example of a reliable version of IM implemented in SD Erlang is presented in Figure 23. From the SD Erlang point of view a failure of the following IM components is of the most interest.

- *Subrouter process.* There should be a supervisor process on the subrouter node (e.g. `subrouter_sup`) that can quickly identify the failure and restart the process, and while the process is restarted other subrouter processes can redistribute the load.

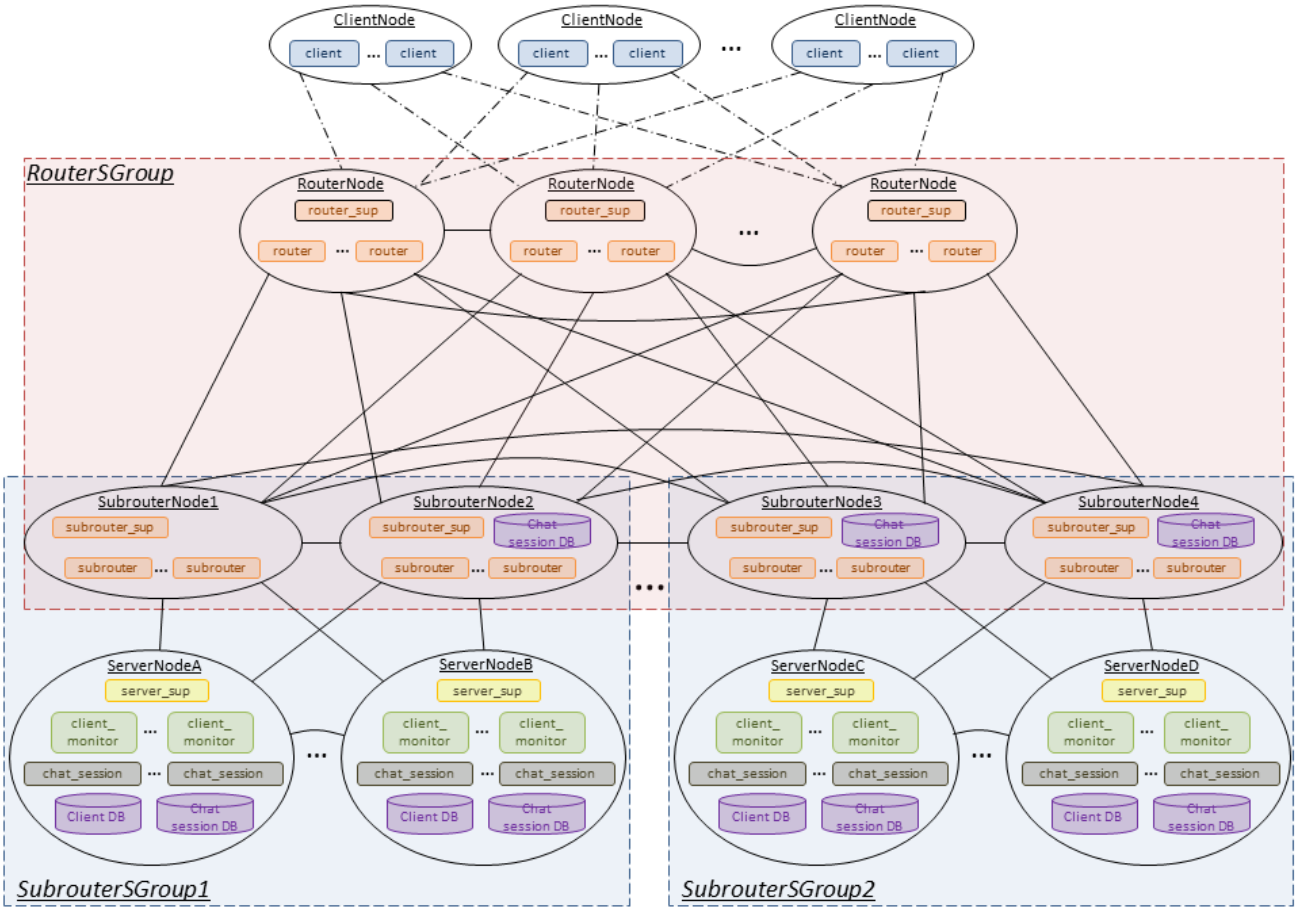


Figure 23: Reliability in SD Erlang IM

- *Subrouter node.* The `subrouter_sup` process from a remote node should be able to restart the node together with its `subrouter_sup` process, and then the `subrouter_sup` process will restart the remaining processes on the node. In the meantime the remaining subrouter nodes can distribute the load. A subrouter node can be monitored from another subrouter node located either in the same or in a remote subrouter s_group.
- *Subrouter s_group.* A `router_sup` processes should be able to restart subrouter nodes together with their `subrouter_sup` processes which in turn will restart the remaining components in the s_group. The effected clients will need to restart their session which in the meantime will be served by remaining server nodes. The `client_monitor_db` and the `chat_session_db` should be replicated on nodes from remote s_group.

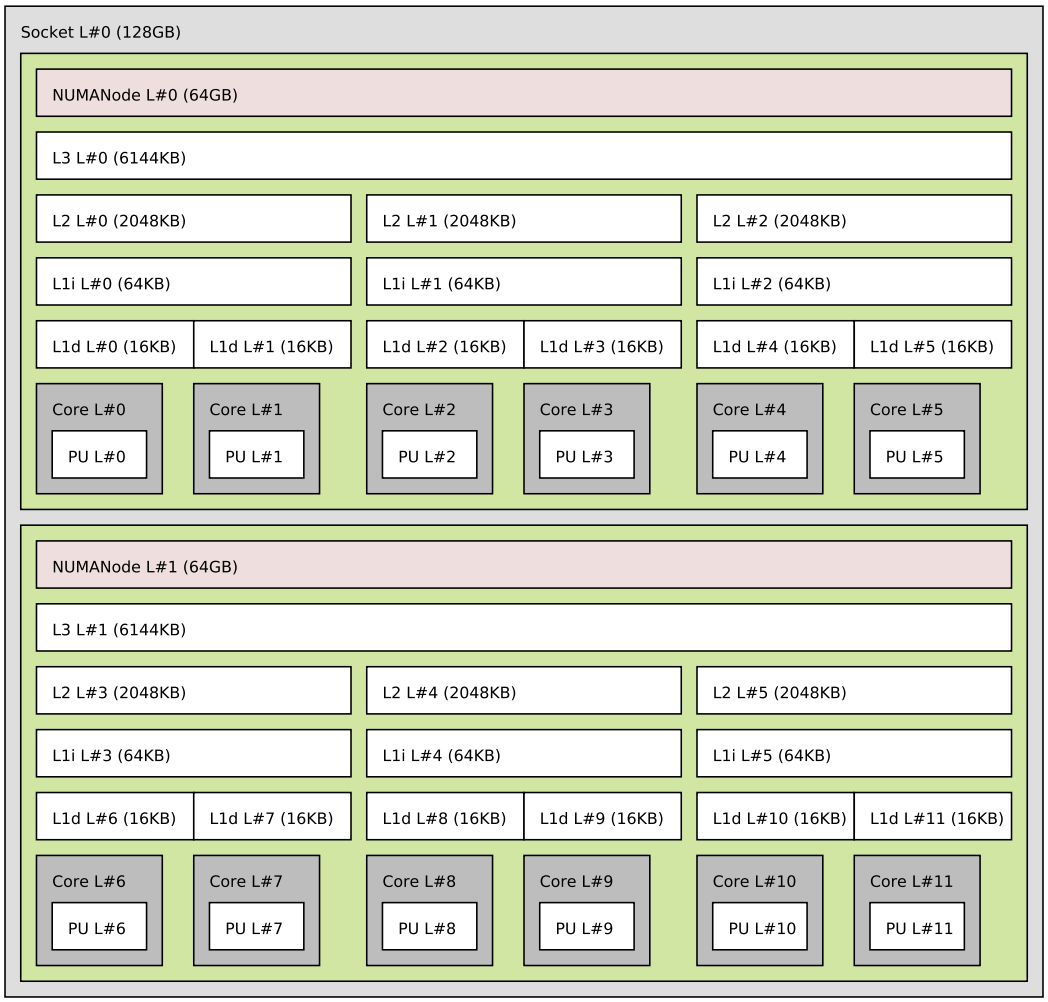
6 Performance Portability

One of our aims of the RELEASE project and WP3 in particular is to enable the construction of distributed Erlang applications which are not only scalable, but also *portable* in terms of performance. By this we mean that it should be possible to deploy applications on different systems and achieve good performance with minimal (ideally zero) need for the programmer to tailor the application for the particular system that the application is running on. For example, some process in a distributed application may need to be executed on a machine which has a large amount of RAM, or which

has a particular library installed, or which can communicate at high speed with the spawning node. Instead of hard-coding the names of suitable nodes into the program, we want to enable applications to find suitable nodes *automatically* at execution time. This would simplify both deployment and code maintenance. We use the term *semi-explicit placement* to describe this process. Instead of specifying a node by its name, a programmer can request (at runtime) a node or list of nodes which conform to given restrictions.

Our earlier deliverables already include some groundwork for the implementation of performance portability via semi-explicit placement. In deliverables D3.1: Scalable Reliable SD Erlang Design [REL12, §6] and D3.2: Scalable SD Erlang Computation Model [REL13a, §4], we introduced the `choose_node/1` function which allows a user to select a node to spawn a process on. The specification of `choose_node/1` allows the user to restrict nodes according to s_group names, and also according to *attributes* which nodes may possess.

One of the properties we are interested in is *communication distance*. The idea here is that if two processes are expected to exchange a large number of messages, then they should be placed on nodes which can communicate quickly: for example, two nodes running on the same NUMA region of an SMP machine, or two nodes running on machines which are connected by a high-speed network. Conversely, if a process is expected to perform a lengthy computation with no communication except for when it



(Four sockets like this)

Figure 24: Structure of SMP Machine

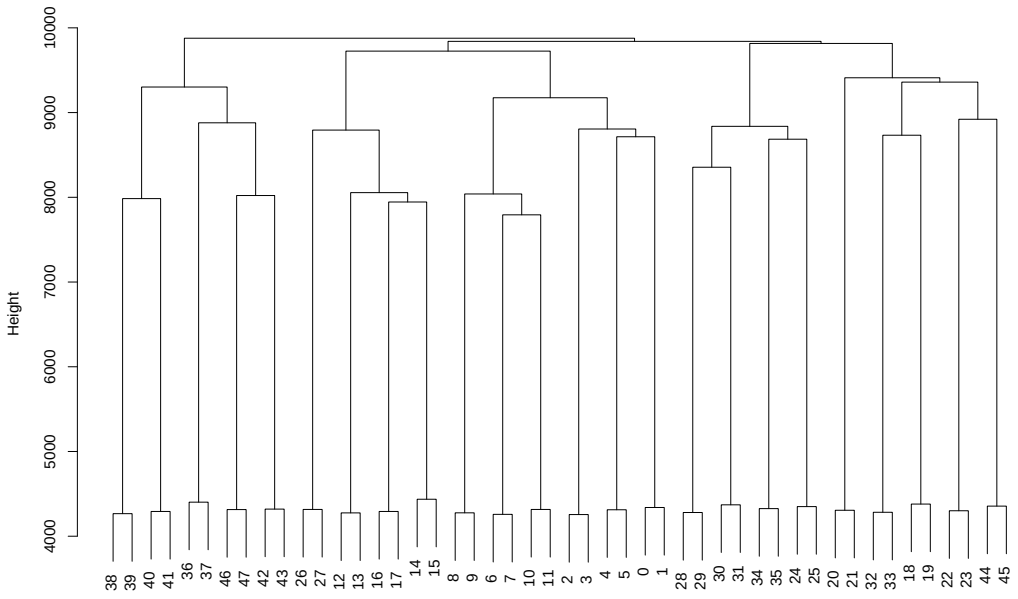


Figure 25: Communication-time Dendrogram for SMP Machine

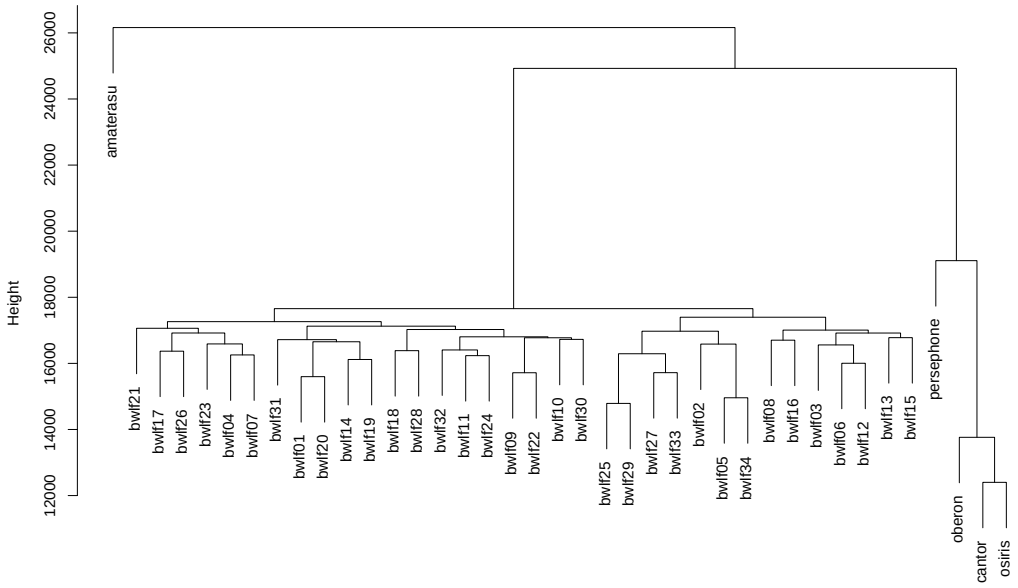


Figure 26: Communication-time Dendrogram for Network

returns its result, we may be happy to place it on a node with a high communication latency.

The key idea here, originating in [MST13], is to construct a tree whose leaves are our computational nodes, and where subtrees correspond to various levels in a communication hierarchy, such as large-scale clusters, local Ethernet networks, cores within a multicore machine. The set of nodes is equipped with a distance function which makes it into a *metric space*, and this gives us a precise notion of communication distance between the nodes in a distributed Erlang system, where nodes which communicate quickly with one another are regarded as being close together whereas nodes which communicate more slowly are regarded as being further apart. We will describe this idea in detail in deliverable D3.5: SD Erlang Performance Portability Principles (due M40).

This is an idealised model, and it is not immediately clear whether it corresponds to reality. However, we have performed some experiments which suggest that the model is in fact accurate. We took a 48-core machine with a complex NUMA structure (see Figure 24, which shows one of four identical sockets (AMD Opteron 6348)) and ran pairs of Erlang VMs pinned to all possible combinations of cores. The VMs sent a large number of messages to each other, and we recorded the average time taken for messages to travel back and forth 100 times. We then used *agglomerative clustering* methods from statistics (see [KR90] or [HTF01, §14.3.12]) to produce the *dendrogram* shown in Figure 25, which shows how "far apart" the cores are in terms of communication latencies. It can be seen that the dendrogram captures the hierarchical NUMA structure of the system very accurately. This is somewhat surprising, because separate Erlang VMs on the same machine communicate via TCP/IP. It might have been expected that the overhead incurred by this would have hidden any effects of the memory hierarchy, but this is clearly not the case.

We performed a similar experiment to measure inter-machine communication time on a Glasgow University departmental network with a large number of machines: the results are shown in Figure 26. Again, we see that there are subnetworks with speedy internal communication but slower external communication; in particular, a Beowulf cluster connected to the larger network stands out very clearly.

The point of these results is that the actual communication times between cores of an SMP machine, or between machines in a network, conform closely to the tree which we obtain just by looking at the physical structure of the machine or network. Since such trees are the basis of our metric-space methods, this suggests that we can use these methods with high confidence that they describe relationships between actual communication times, without having to perform lengthy timing analyses.

7 Implications and Future Work

In this deliverable we address methodology and patterns for scalability of SD Erlang applications. To identify patterns we have considered four benchmarks of different types, and provided a description of their refactoring first from non-distributed Erlang to distributed Erlang, and then to SD Erlang (Section 3). We outlined the main steps of the refactoring process and found that D2SD like Non2D refactoring is application specific but we can observe some generic rules. These are grouping nodes, shifting some functionality from master/router nodes to submaster/subrouter nodes, and tuning the performance. We have also discussed how to determine the size of s_groups and how to decide which nodes to group. These can be done by using Persept2 and devo tools developed by the Kent team. In this deliverable we do not repeat information provided in WP5 deliverables and demos, but rather give citations to the corresponding sources.

In terms of methodology we discuss issues with all-to-all connections and ways of arranging nodes using s_group, reducing the size of common namespace, and things to look out, such as single process bottlenecks on gateway nodes (Section 4). In terms of patterns we have observed a few of those and implemented them in the benchmarks. The first pattern is grouping (Section 4.1.4). From the observed benchmarks it emerges that hierarchical grouping is the most popular one. Therefore, we propose `s_group:grouping/1` function to simplify the process of node grouping. Another pattern – routing

via gateways – is related to remote node monitoring and node communication without establishing a direct connection between the nodes (Section 5). We have also discussed reliability principles of SD Erlang which has the same reliability philosophy and mechanisms to support it as distributed Erlang. Additional features, such as remote supervision and reliability of gateway processes and nodes are due to introducing s_groups.

D3.5. For deliverable D3.5: SD Erlang Performance Portability Principles (due M40), we plan to complete the implementation of the `choose_node/1` function by adding support for attributes of machines and networks. We will consider simple static attributes such as the number of cores or the size of the memory on a node, together with dynamic attributes such as computational or communication load. The implementation will require us to devise methods for a machine to discover its own attributes (this is easy for static attributes, which can simply be stored in a configuration file, but more complicated when attributes can vary over time), and also to propagate attribute information between nodes so that a node which is looking for somewhere to spawn a process has enough information to enable it to make a reasonable decision.

We already have a preliminary implementation of the tree-based distance calculations discussed in Section 6, and this will also be integrated with the `choose_node/1` function. We will also have to show that our implementation gives us something worthwhile, and we plan to do this by taking a number of applications and modifying them to use s_groups and semi-explicit placement, and then comparing the behaviour of the new version with the original one on several different systems. We hope that we will be able to achieve portable performance without incurring excessive overhead due to our extensions to the Erlang system.

Other Topologies. To date we have scaled Erlang applications using only s_groups organised in a hierarchical tree structure. Our plan is to try other topologies as well. For example, in the current SD Erlang ACO version, each colony carries out a number of local iterations then sends its current best solution to a submaster node which chooses the best s_group solution and broadcasts it back to all its colonies. Periodically, submaster nodes send their solutions to the master node that chooses globally best solution which then is broadcasted back to the submaster nodes and to the colonies. Instead, we could arrange s_groups in a circle and at the end of each cycle of s_group iterations, get them to send their solutions to the s_group on their right, for example. At the very end, when we need to return the best solution from all of the colonies: we can either do this by returning it to a specified node, or we can propagate solutions round the ring, choosing the best solution at every stage.

Change Log

Version	Date	Comments
0.1	21/08/2014	First Version Submitted to Internal Reviewers
0.2	23/09/2014	Revised version based on comments from K. Sagonas submitted to the Commission Services
1.0	23/09/2014	Final version submitted to the Commission Services

A Notes on Ant Colony Optimisation in Erlang

A.1 The Single Machine Total Weighted Tardiness Problem

We are going to look at the Single Machine Total Weighted Tardiness Problem (SMTWTP), which appears to have originated in [McN59]. In the SMTWTP, we are given an ordered sequence of *jobs*

$$J_1, \ldots, J_N \tag{1}$$

which are to be executed in order on a single machine without pausing between jobs. Each job J_j has

- A *processing time* (or *duration*) p_j
- A *weight* w_j
- A *deadline* (or *due date*) d_j.

We define the *tardiness* of J_j to be

$$T(j) = max\{0, C_j - d_j\},$$

where $C_j = \sum_{i=0}^{j} p_j$ is the completion time of job j (so $T(j)$ will be zero if job j completes before its deadline). The *total weighted tardiness* of the sequence $J_1, \ldots, J_N$ is

$$T = w_1 T_1 + \cdots + w_N T_N. \tag{2}$$

Our goal is to arrange the sequence of jobs in such a way as to minimise the total weighted tardiness: essentially, we get penalised when jobs are finished late, and we want to do the jobs in an order which minimises the penalty. This problem is known to be NP-hard [DL90, LRKB77, Law77]. Typically, interesting problems are ones in which it is not possible to schedule all jobs within their deadlines.

A.1.1 Example data for the SMTWTP.

Many papers dealing with the SMTWTP make use of the ORLIB datasets originating in [PVW91].[2]. There are 125 instances each for problems of size 40, 50 and 100; for sizes 40 and 50 the best solutions are known, whereas for size 100 solutions which are conjectured to be the best ones are given. We are fairly certain that these solutions must have been shown to be optimal by now, but we have not found an explicit reference for this yet.

These instances are perhaps rather easy for current machines and techniques, and new instances are described in [Gei10a][3]; there are 25 "hard" instances of size 100, and 25 instances of size 1000. The new instances were generated using the technique described in [PVW91] (and also in [MM00, Gei10a], which may be easier to access). This technique is fairly simple, so we have produced an Erlang implementation which can generate instances of arbitrary size for use in scaling experiments.

[2]These datasets can be downloaded from `http://people.brunel.ac.uk/~mastjjb/jeb/orlib/wtinfo.html`.

[3]These datasets can be downloaded from `http://logistik.hsu-hh.de/SMTWTP`. The download also contains solutions generated by Geiger [Gei10b] which he says have been shown to be optimal by Shunji Tanaka, of Department of Electrical Engineering at Kyoto University: see `http://turbine.kuee.kyoto-u.ac.jp/sim`tanaka/SiPS/.

A.2 Ant Colony Optimisation

A.2.1 Overview

Ant Colony Optimisation (ACO) is a "metaheuristic" which has proved to be successful in a number of difficult combinatorial optimisation problems, including the Travelling Salesman, Vehicle Routing, and Quadratic Assignment problems. A detailed description of the method and its applications can be found in the book [DS04][4]; a more recent overview can be found in [DS10]. There is a vast amount of research on this subject: an online bibliography at `http://www.hant.li.univ-tours.fr/artantbib/artantbib.php` currently has 1089 entries.

The ACO method is inspired by the behaviour of real ant colonies. Ants leave their colonies and go foraging for food. The paths followed by ants are initially random, but when an ant finds some food it will return to its home, laying down a trail of chemicals called *pheromones* which are attractive to other ants. Other ants will then tend to follow the path to the food source. There will still be random fluctuations in the paths followed by individual ants, and some of these may be shorter than the original path. Pheromones evaporate over time, which means that longer paths will become less attractive while shorter ones become more attractive. This behaviour means that ants can very quickly converge upon an efficient path to the food source.

This phenomenon has inspired the ACO methodology for difficult optimisation problems. The basic idea is that a (typically very large) search space is explored by a number of artificial ants, each of which makes a number of random choices to construct its own solution. The ants may also make use of heuristic information tailored to the specific problem. Individual solutions are compared, and information is saved in a structure called the *pheromone matrix* which records which records the relative benefits of the various choices which were made. This information is then used to guide a new generation of ants which construct new and hopefully better solutions. After each iteration, successful choices are used to reinforce the pheromone matrix, whereas pheromones corresponding to poorer choices are allowed to evaporate. The process finishes when some termination criterion is met: for example, when a specified number of iterations have been carried out, or when the best solution has failed to improve over some number of iterations.

Detailed information about the biological and computational aspects of the ACO paradigm can be found in Dorigo and Stützle's book [DS04]. We will outline the specifics of the method in the case of the SMTWTP in the next subsection. Note, though, that ACO is not regarded as the best technique for the SMTWTP problem. Various papers (see [BSD00, Gei09], for example) suggest that the Iterated Dynasearch method of [CPvdV02] is superior; see also [GDCT04] and [BW06].

A.2.2 Application to the SMTWTP.

A number of strategies have been proposed for applying the ACO method to the Single Machine Total Weighted Tardiness Problem. Our initial implementation is based on [BBHS99b],[dBSD00], and [MM00], which give sequential ACO algorithms for solving the SMTWTP.

We have a collection of N jobs which have to be scheduled in some order. The pheromone matrix is a $N \times N$ array τ of floats, with τ_{ij} representing the desirability of placing job j in the ith position of a schedule.

The algorithm involves several constants:

- $q_0 \in [0, 1]$ determines the amount of randomness in the ants' choices.
- $\alpha, \beta \in \mathbb{R}$ determine the relative influence of the pheromone matrix τ and heuristic information η (see below).

[4] This can be downloaded from the internet.

- $\rho \in [0, 1]$ determines the pheromone evaporation rate.

The algorithm performs a loop in which a number of ants each construct new solutions based on the contents of the pheromone matrix, and also on heuristic information given by a matrix η (different or each ant); however, the entries η_{ij} are only used once each, and are calculated as the ants are constructing their solutions: it is never necessary to have the entire matrix η in memory.

Ant behaviour. In detail, each ant constructs a new solution iteratively, starting with an empty schedule and adding new jobs one at a time. Suppose we are at the stage where we are adding a new job at position i in the schedule. The ant chooses a new job in one of two ways:

- With probability q_0, the ant deterministically schedules the job j which maximises $\tau_{ij}^{\alpha}\eta_{ij}^{\beta}$. Various choices of heuristic information η have been proposed; here, we have used the *Modified Due Date* (MDD) [BBHS99b] given by
$$\eta_{ij} = 1/max\{T + p_j, d_j\}$$
where T is the total processing time used by the current (partially–constructed) schedule. This rule favours jobs whose deadline is close to the current time, or whose deadline may already have passed. Other heuristics commonly used for the SMTWTP are *Earliest Due Date* (EDD) [Emm69] and *Apparent Urgency* (AU) [MRV84].

- With probability $1 - q_0$, a job j is chosen randomly from the set U of currently-unscheduled jobs. The choice of j is determined by the probability distribution given by
$$P(j) = \frac{\tau_{ij}^{\alpha}\eta_{ij}^{\beta}}{\sum_{k \in U} \tau_{ik}^{\alpha}\eta_{ik}^{\beta}}$$

In the sequential version of the algorithm, an ant can perform a *local pheromone update* every time it adds a new job to its schedule. This involves weakening the pheromone information for the job it has just scheduled, thus encouraging other ants to explore different parts of the solution space. In our concurrent implementation, several ants are working simultaneously, and we have omitted the local update stage since it would involve multiple concurrent write accesses to the pheromone matrix, leading to a bottleneck.

Global Pheromone Update. At the start of the algorithm, the elements of the pheromone matrix are all set to the value
$$\tau_0 = \frac{1}{AT_0},$$
where M is the number of ants (as usual), and T_0 is the total weighted tardiness of the schedule obtained by ordering the jobs in order of increasing deadline (this is called the *Earliest Due Date* schedule).

After each ant has finished, their solutions are examined to select the best one (based on lowest total tardiness: see Equation A.1). The pheromone matrix is then updated in two stages:

- The entire matrix τ is multiplied by $1 - \rho$ in order to evaporate pheromones for unproductive paths.

- The path leading to the best solution S is reinforced. For every pair (i, j) with job j at position i in S, we replace τ_{ij} by
$$\tau_{ij} + \rho/T,$$
where T is the total weighted tardiness of the current best solution.

There are many alternative strategies in the literature. For example, all ants may be allowed to contribute to the pheromone update (possibly weighted according to the quality of their solution); different evaporation strategies may be used; a different reinforcement factor may be used; the entries of τ may be constrained to lie within some specified maximum and minimum values τ_{min} and τ_{max}. See [DS04] (especially §3.3.3) for details and references.

Parallelisation. To a large extent the ACO algorithm is naturally parallel: we have a number of ants constructing solutions to a problem independently, and if we have multiple processors available then is would seem sensible to have ants acting in parallel on separate processors rather than constructing solutions one after the other. There is some literature on this (see [BKS97, MM98, MM99, RL02, RV09] for example), but perhaps not as much as we would have expected.

Local Search. The basic ACO algorithm generally gets close to a local minimum, but may not find it precisely. The quality of solutions can be improved by performing a *local search* [CPvW98, dBSD01] just before the global update stage. This involves looking at solutions in some neighbourhood of the current best solution, and moving to the one which improves the solution most. This process is repeated until no improvement is found. Various neighbourhood structures have been considered: for example, one may consider schedules which differ by a single interchange of jobs, or one where a single job is removed and inserted at a different position. Currently, our Erlang implementation includes an option for a naive version of local search (techniques such as dynamic programming can be used to improve the efficiency of the search considerably, but we have not yet implemented this). However, we have turned this off for the experiments reported below because a considerable amount of computation is required and number of iterations is unpredictable: this leads to variations in execution time which obscure the influence of the factors which we are really interested in, such as the number of parallel ants.

A.3 Implementation in Erlang (Single Machine)

Our initial implementation runs on a single Erlang node, preferably running on an SMP machine. We represent the pheromone matrix as an ETS (or DETS) table which stores each row of the matrix as an N-tuple of real numbers. This is accessible to all processes running in the Erlang VM.

The program takes three arguments. The first argument is the name of a file containing input data for the SMTWTP problem: this consists of an integer N and 3 sets of N integers, representing the processing times, the weights, and the deadlines for each job. The second argument is the number M of ants which should be used, and the third argument is the number K of iterations of the main "loop" of the program (ie, the number of generations of ants).

After reading its inputs, the program creates and initialises the table representing the pheromone matrix, then spawns M ant processes. The program then enters a loop in which the following happens:

- The ants construct new solutions (as described above) in parallel.
- When an ant finishes creating its solution, it sends a message containing the solution and its total tardiness to a supervisor process.
- The supervisor compares the incoming messages against the current best solution.
- After all M results have been received, the supervisor uses the new best solution to update the pheromone matrix.
- A new iteration is then started: again, each ant constructs a new solution.
- After K iterations, the program terminates and outputs its best solution.

A.3.1 Difficulties with Erlang

Two factors make Erlang somewhat unsuitable for implementation of the ACO application.

Firstly, a considerable amount of integer and floating-point calculation (including exponentiation) is performed. There will be some overhead in performing this in the Erlang VM, rather than directly in C, for example.

More seriously, it is necessary to allocate large amounts of heap space during the calculation. As mentioned above, it is necessary to calculate some heuristic information, conceptually stored in a matrix η. In fact, we store this information in a list of pairs $\{j, \eta_{ij}\}$ where j is the (integer) identifier of a job, and η_{ij} is the heuristic information indicating the desirability of scheduling job j at the current position i in the schedule. We only require information for unscheduled jobs j, but η_{ij} depends on the jobs which have already been scheduled. This means that we must construct a new list every time an ant schedules a new job, and thus during the construction of a single schedule each ant must allocate $N + (N-1) + \ldots + 2 = (N^2 + N - 2)/2$ list cells (each containing a pair $\{j, \eta_{ij}\}$); when we get to the last job, there is only one choice, so we do not have to allocate a list of length 1). For $N = 1000$, this is 500,499 heap cells which have to be allocated every time an ant constructs a solution (and remember that we have multiple ants, each constructing a new solution for every iteration of the main loop of the ACO algorithm). In contrast, in C we could use a single array of length N in conjunction with an array saying which jobs are currently unscheduled, and reuse these every time we add a job to the schedule. This would be a massive saving in heap allocation, and it may well be worth using Erlang's native interface to implement a simple library of mutable arrays with `get` and `set` functions.

Addendum. We tried to implement mutable arrays using NIFS, but actually it slowed the whole thing down by about another 50%. We are guessing that the problem here is that it is possible to get floats out of Erlang objects and into C arrays, but there is quite a lot of overhead because you have to unbox an Erlang heap object to get a C double when you write an element of the array, and then when you read an element you have to re-box it into an Erlang object again (and this of course requires some new memory to be allocated in the heap).

One could try to overcome this by storing pointers to boxed objects in the array, but we think that would not work because as far as we can see there is no way to tell the Erlang garbage collector that you are keeping a pointer to something that it owns, and then there is a danger that your pointer would become invalid because the garbage collector might delete or move the object you are pointing to. In short, we think that was a dead-end: they really do not want you making mutable data structures.

A.3.2 Behaviour

The execution time of the program is linear in K and quadratic in N, due to the allocation issues discussed above, and also due to the fact that since the entire $N \times N$ matrix τ has to be traversed by each ant and later rewritten in the global update stage.

It is more difficult to see how the execution time is influenced by M (the number of ants), and we carried out extensive experiments on a number of different machines to examine this. We used two different versions of the program, one with the pheromone matrix stored in an ETS table and the other using a DETS table. ETS (Erlang Term Storage) tables are kept in memory and disappear when the VM shuts down; tables are visible to all processes running in the same VM, but are not visible to other VMs (even ones running on the same host). DETS tables as stored on disk and are persistent, but have the advantage that they can be accessed by nodes running on different machines if the machines happen to share a disk (over NFS, say). The code for the two versions was largely identical, with only minor changes required for the two types of table.

Detailed information is given later in Section B, but the basic result is that for the ETS version the execution time appears to vary linearly with the number of ants. One might expect that the execution

time would be roughly constant when the number of ants is less than the number of CPUs, and then would increase linearly. Oddly, this does not appear to happen: in most cases the trend is entirely linear, with no visible change when the number of ants exceeds the number of processors.

For the DETS version, execution times were also more or less linear, but execution times were many times slower (by a factor of 6 to 20, depending on the machines involved and the size of the input). We initially tried this with the DETS table stored on an NFS filesystem, but then later tried it with the table stored in the `/scratch` partition on the local disk: this way generally slightly faster (but never more than 2%), so it would appear that using DETS tables is not a good way for the ACO application to share data. Persistence is also something of a nuisance because if a program happens to crash or is terminated early, you are left with a disk copy of the DETS table which must be removed manually.

A.4 Distributed ACO techniques

Our main interest is in distributed applications, so we have also implemented a distributed version of the ACO program. A plausible strategy is to have separate colonies operating on separate machines, either completely independently or with some communication.

Some research has been done on systems involving multiple ant colonies in the context of the Travelling Salesman Problem (see [KYSO00, MRS02], for example). Here, several ant colonies construct solutions independently but occasionally exchange information. This has at least two advantages:

- Colonies which have got stuck at a local minimum have a chance to escape, or are just ignored.
- It appears that strategies which may be efficient for solving some ACO instances may not be so efficient for others. Using a multi-colony approach, different colonies can use different heuristics and different values of the parameters α, β, ρ, and q_0 mentioned above.

This is encouraging, because it suggests that there may be real benefits to be obtained by using a distributed approach. One might consider sharing entire pheromone matrices between colonies (which would be expensive, due to high communication due to the large size of the matrices), but it seems that it is better to share only *the best solution*: for example, [MRS02][§4] says

> *The results of Krüger, Middendorf, and Merkle (1998) for the Traveling Salesperson problem indicate that it is better to exchange only the best solutions found so far than to exchange whole pheromone matrices and add the received matrices, multiplied by some small factor, to the local pheromone matrix.*

This makes sense, because instead of restarting each colony from an identical point after every synchronisation, it allows colonies to influence each other while retaining some individuality. This reduces the amount of data transfer significantly: instead of having to transmit N^2 floats, we only have to transfer N integers.

A number of different strategies have been proposed for exchanging information: for example, propagating the global best solution to every colony, or arranging the colonies in a ring where each colony shares its best solution with its successor. The relative merits of several strategies are considered in [MRS02].

A.4.1 Implementation strategy

The fact that pheromone matrices do not have to be shared in their entirety is encouraging. The experiments described in Section B below show that ETS tables are substantially better than DETS tables for storing pheromone information, and if individual colonies do not have to share too much information then each colony can keep its pheromone information in its own ETS table.

My initial approach has been to implement individual colonies using essentially the same code as the SMP version of the program described earlier. A number of Erlang VMs are started on different machines in a network (possibly with more than one VM per machine), and each of these will run a single colony. There is a single master node which starts the colonies and distributes information (like the input data and parameter settings) to them; each colony runs a specified number of ants for a specified number of generations, and then reports its best solution back to the master. The master chooses the best solution from among the colonies and then broadcasts it to all of the colonies, which use it to update their pheromone matrices and then start another round of iterations. This entire process is repeated some number of times, after which the master shuts down the colonies (but leaves their VMs running) and reports the best result. The current implementation is quite simplistic, only using basic features of Distributed Erlang; all communication is done via PIDs (not global names) and there is no attempt at fault-tolerance.

Initial experiments give good results, with optimal solutions being found for almost all of the 40-job instances from ORLIB in a few seconds (for high-quality results, we can use an optional (and inefficiently implemented) local search strategy which increases solution time by 50% or so for the small problems we've looked at so far). It'll be more challenging to test the program on larger examples.

Currently, each colony uses the same parameter settings, but the code allows this to be easily changed at the point where the master initialises the colonies; we hope to experiment with this shortly. It would also be interesting (especially from the point of view of SD Erlang) to experiment with other communication topologies.

Fault tolerance How fault-tolerant do we wish to be? In some situations it is probably not too important if a single colony fails, since the others will just be able to carry on independently. This depends strongly on the information-exchange strategy though. For example, in the ring-shaped topology mentioned above, the failure of a single colony would be disastrous, since it would break the communication process completely. On the other hand, the initial strategy which we have adopted (communicating a single global best solution between multiple colonies) has a dedicated process which collects solutions from the colonies and then distributes the best solution to all the colonies. Failure of this supervising process would be problematic since the colonies would then need to come to a consensus on who should take over the supervision.

Another issue which might become interesting in a distributed multi-colony setting is that there may be some heterogeneity in the systems. If one machine is five times as fast as the others, will it spend 80% of its time idle while it waits for the others to catch up? Perhaps the answer to this would be to run multiple colonies on separate Erlang nodes on the fast machine, or to get it to perform a larger number of iterations of its main loop. This kind of information might be something which we could discover using SD-Erlang's *attributes*.

A.5 Measuring Scalability

One issue which we have not mentioned yet is the question of how we measure scalability. Standard measures of scalability consider speedups obtained from running an algorithm on multiple cores or machines, but this may not be appropriate for the ACO application. In contrast to problems which can be divided into sub-problems which can be solved separately, we do not necessarily run any *faster* by making our application distributed, but we may improve the *quality* of our solution since multiple colonies can construct solutions independently, and there is more chance of finding a good solution with more colonies.

We could of course make an entirely sequential version of our application, where each colony runs its first ant, then its second, and so on, for a number of generations; we would also run the colonies in sequence, comparing results once every colony has finished, and then starting a new iteration. Suppose

we have the following:

- C colonies
- K_1 iterations of the main loop in the master process (each involving one activation of the colonies)
- K_2 generations of ants for each activation of the colony
- A ants per colony

Then if the time taken for a single ant to construct a solution is T_0, the total time required for a completely sequential execution of the system will be of the order of

$$CK_1K_2AT_0.$$

If we take fairly conservative figures for these, say $C = 40, A = 20, K_1 = 100, , K_2 = 50$, then we'd expect the purely sequential version to take roughly 4,000,000 times longer than a distributed version. This may be rather too large to measure. It might be more realistic to measure the overhead incurred by running multiple colonies in a distributed system in comparison with a single colony running on a single machine.

A completely different way to measure improvement might be in terms of solution quality, and this seems to be something that is done in some papers on Ant Colony Optimisation. For example, optimal solutions are known for the ORLIB instances mentioned above, and one measure of quality that is been used is to apply an ACO algorithm several times to each instance and then report the number of exact solutions found and the average deviation from the optimal cost: see [dBSD00, MM00] for example.

Yet another technique which has been used (see [MM00]) is to measure the average time taken for the ACO algorithm to converge on the known optimal solution is found, but we are not sure exactly how one would go about this. The behaviour of the SMP version of the program suggests that in many cases the algorithm will converge on a local minimum and stay there. Other runs with the same input may find the global best solution, but the stochastic nature of the ACO algorithm makes it hard to predict if this will happen, or if an execution which appears to have got stuck might in fact escape to a better solution if given sufficient time.

Perhaps a reasonable way to proceed would be to look at both of the first two methods. We could look at small runs of the SMP version and use this to predict how long a full run would take, and then compare that time with the time taken for the distributed version to perform a complete run. In tandem with this, we could use metrics of solution quality to show that distribution gives good solutions in reasonable time.

B ACO Performance

B.1 Performance of SMP version of ACO application

We ran the ACO application on a number of different machines, with inputs of size 50 (small) and 500 (relatively large). Each run involved 50 generations of ants. We varied the number of ants between 1 and 100 (or less in some cases when execution times were very large), and with 10 runs for each number of ants. Times were obtained using Erlang's `timer:tc` function to time the execution of the main algorithm, ignoring start-up time including reading files and setting up initial data structures.

The machines used were at Heriot-Watt University. We used the machines `bwlf01`, ..., `bwlf34` (connected in a Beowulf cluster), `cantor`, and (later) `jove`. The characteristics of these machines are as follows:

- `bwlf01`–`bwlf15`: 8 Intel Xeon E5504 processors (2GHz), 12 GB of RAM.

- bwlf16–bwlf32: 8 Intel Xeon E5506 processors (2.13GHz), 12 GB of RAM.
- bwlf33: 8 Intel Xeon E5450 processors (3GHz), 16 GB of RAM.
- bwlf34: 8 Intel Xeon E5450 processors (3GHz), 12 GB of RAM.
- cantor: 48 AMD Opteron 6348 processors (1.4 GHz), 512 GB of RAM.
- jove: 24 Intel Xeon X5650 processors (2.67 GHz), 22GB of RAM.

B.2 Experiments: ETS

Figures 27 and 28 show the mean execution times for inputs of sizes 50 and 500 respectively, on bwlf15, bwlf22, bwlf33, and cantor. We see that time varies more on less linearly with the number of ants. There is some anomaly with respect to processor speeds: for the bwlf machines, the processing time decreases with increasing processor speed, but the cantor machine, which is only half as fast as bwlf33 performs considerably faster. Note though that cantor has 6 times as many processors and 32 times as much memory.

It might be expected that when the number of ants is less than or equal to the number of processors, the execution time would be constant, and that it would increase linearly for larger numbers of ants. This doesn't quite seem to be the case.

Figure 29 shows the minimum execution times (from 10 runs) for up to 20 ants on the bwlf machines: the vertical red line lies between 8 and 9 ants, 8 being the number of processors on these machines. We see a definite discontinuity after 2 processors, but the situation isn't very clear-cut beyond that.

Figure 30 shows the corresponding plots for inputs of size 500. We see a definite discontinuity after 7 ants for this larger input size; the effect is much more pronounced than for size 50.

In Figure 31 we show minimum execution times on the 48-core machine cantor for the number of ants less than 60. The vertical red lines occur after 12, 24, 36, and 48 processors. There's a definite change after 12 processors (and cantor has four 12-core sockets), and times become irregular for between 36 and 48 ants, but that's about all we can say. I'm not sure what to make of these pictures: they may just show the peculiarities of the Erlang VM's SMP scheduling strategy.

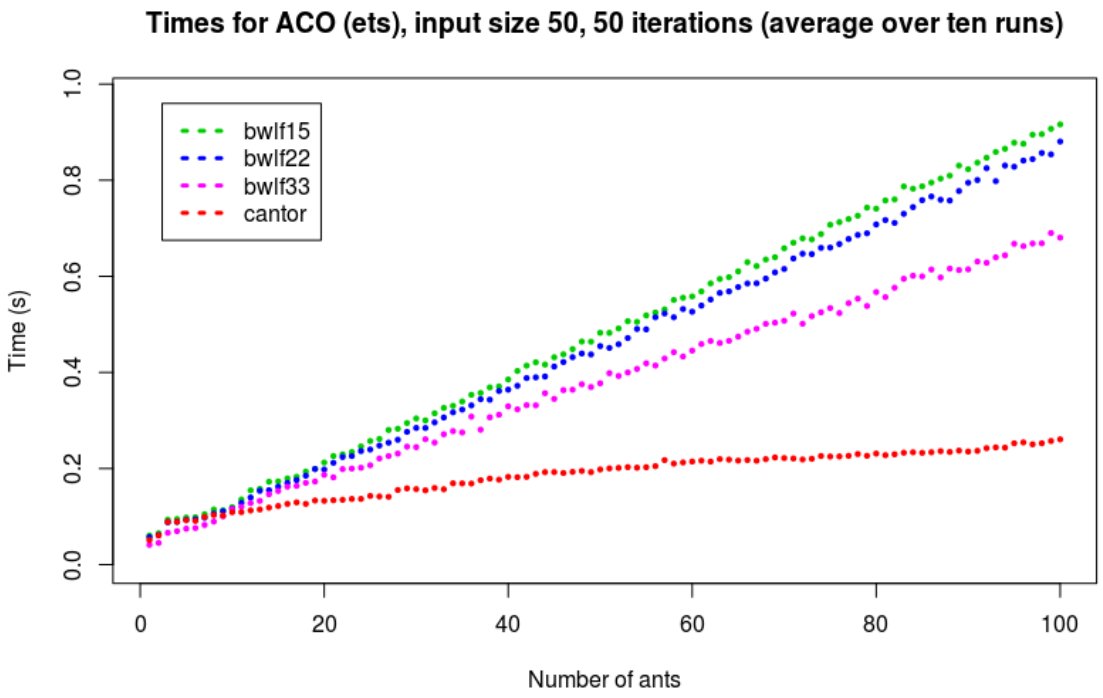


Figure 27: Execution times for ETS version, input size 50

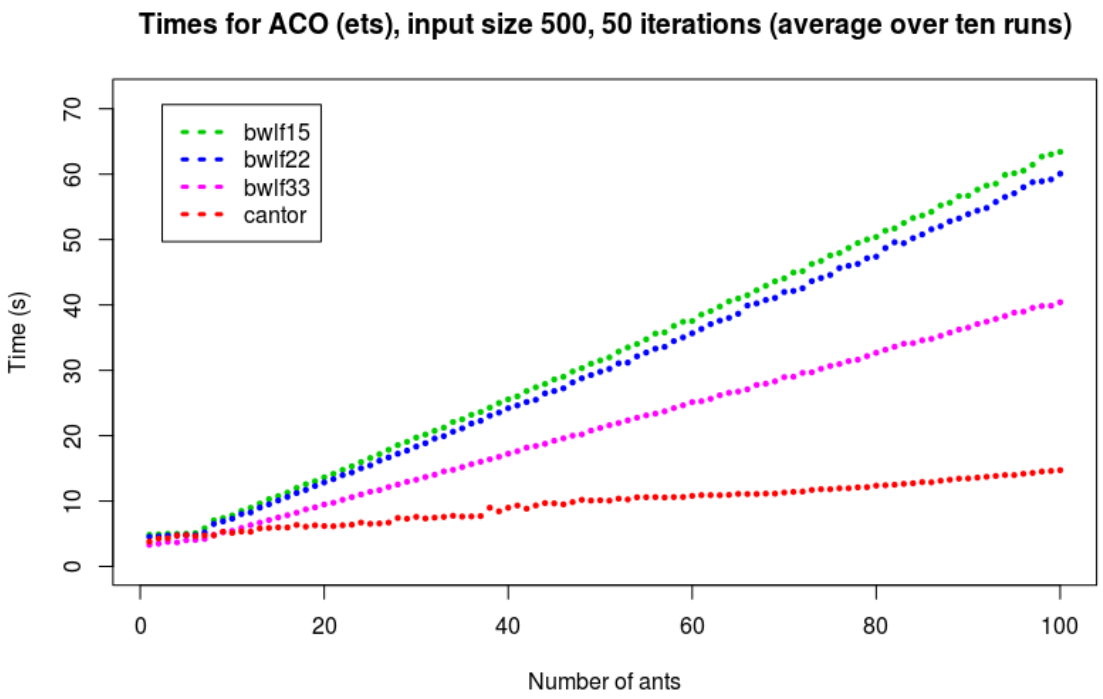


Figure 28: Execution times for ETS version, input size 500

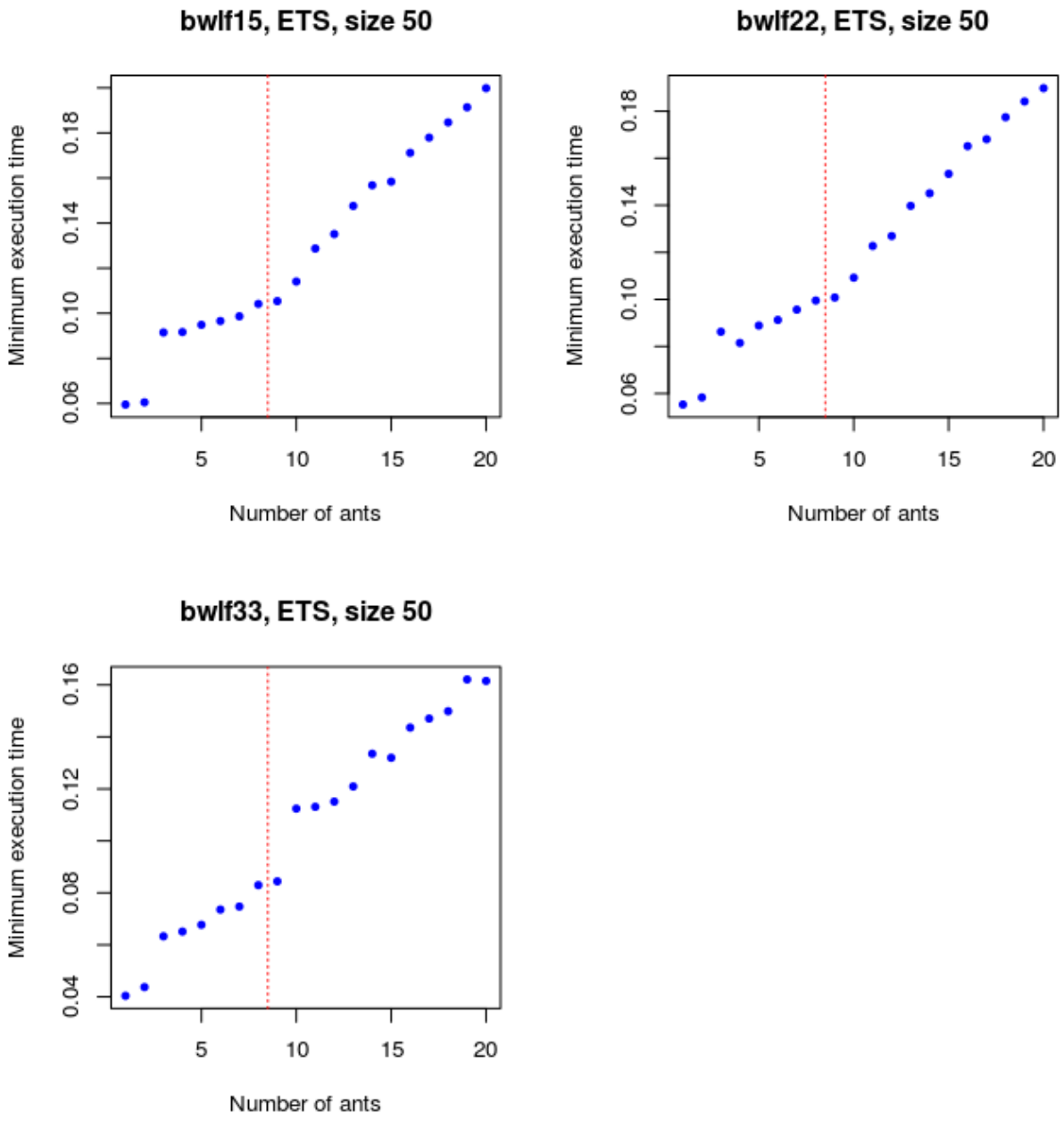


Figure 29: Execution times for ETS version, input size 50

B.3 Experiments: DETS

We repeated the earlier experiments with the DETS version of the program, except that for inputs of size 500, the experiments were taking a very long time so we stopped after 60 ants. Figures 32 and 33 show runtimes on combined plots. We see that runtimes are much longer (graphs of relative slowdown follow later), and that there's less variation between machines than in the ETS case. Presumably this is because disk access is taking up a lot of time. Also, there's no noticeable difference when the number of ants is less than the number of cores.

In Figures 34–40 we show graphs including mean, maximum, and minimum times for each exper-

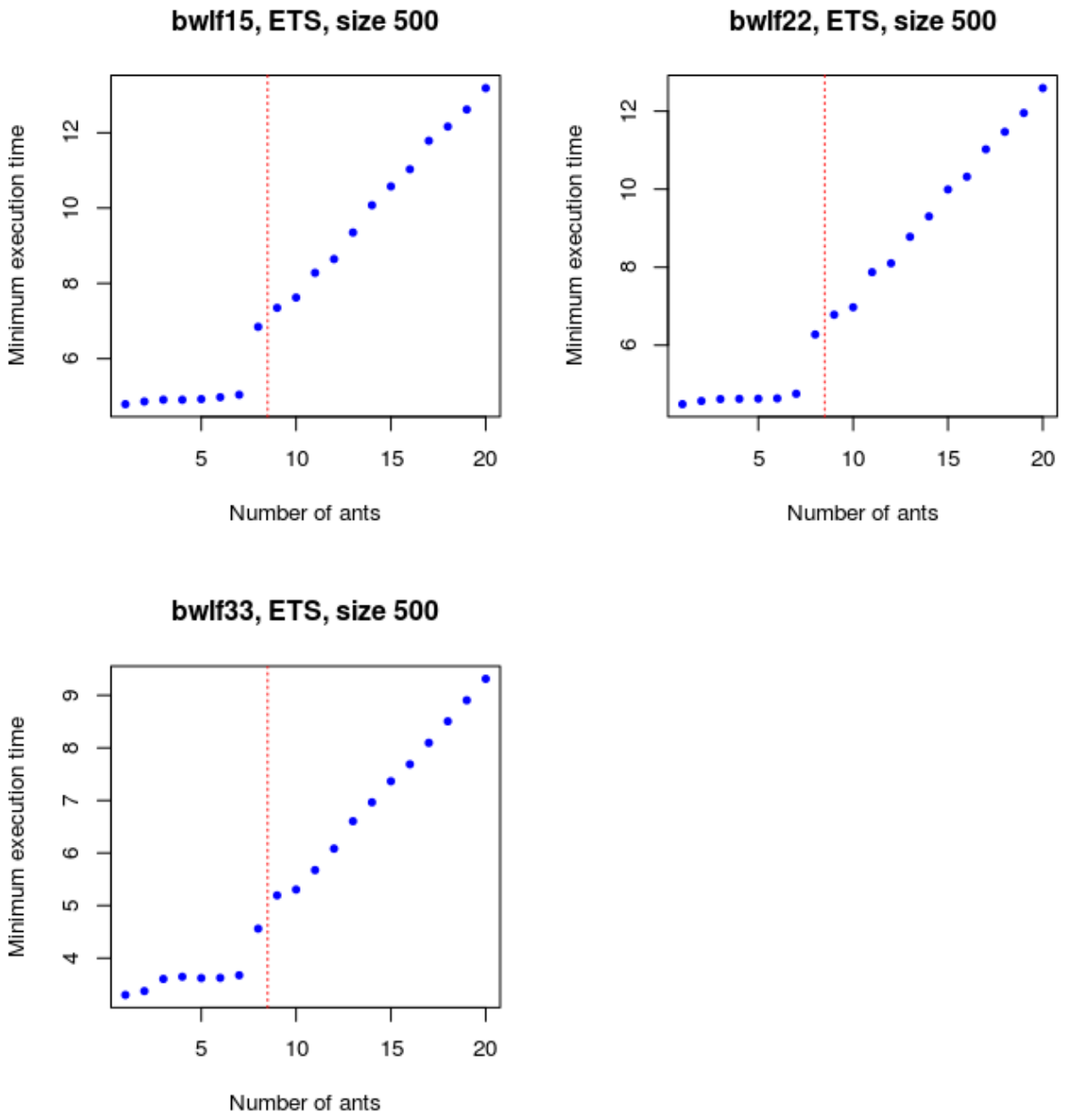


Figure 30: Execution times for ETS version, input size 500

iment. The `cantor` machine was in use, so we were unable to get any data for input size 500 for it. Note also that `bwlf15`, which we used in our earlier experiments, was in use, so we used `bwlf12` instead. The characteristics of the two machines are the same, so this shouldn't matter too much.

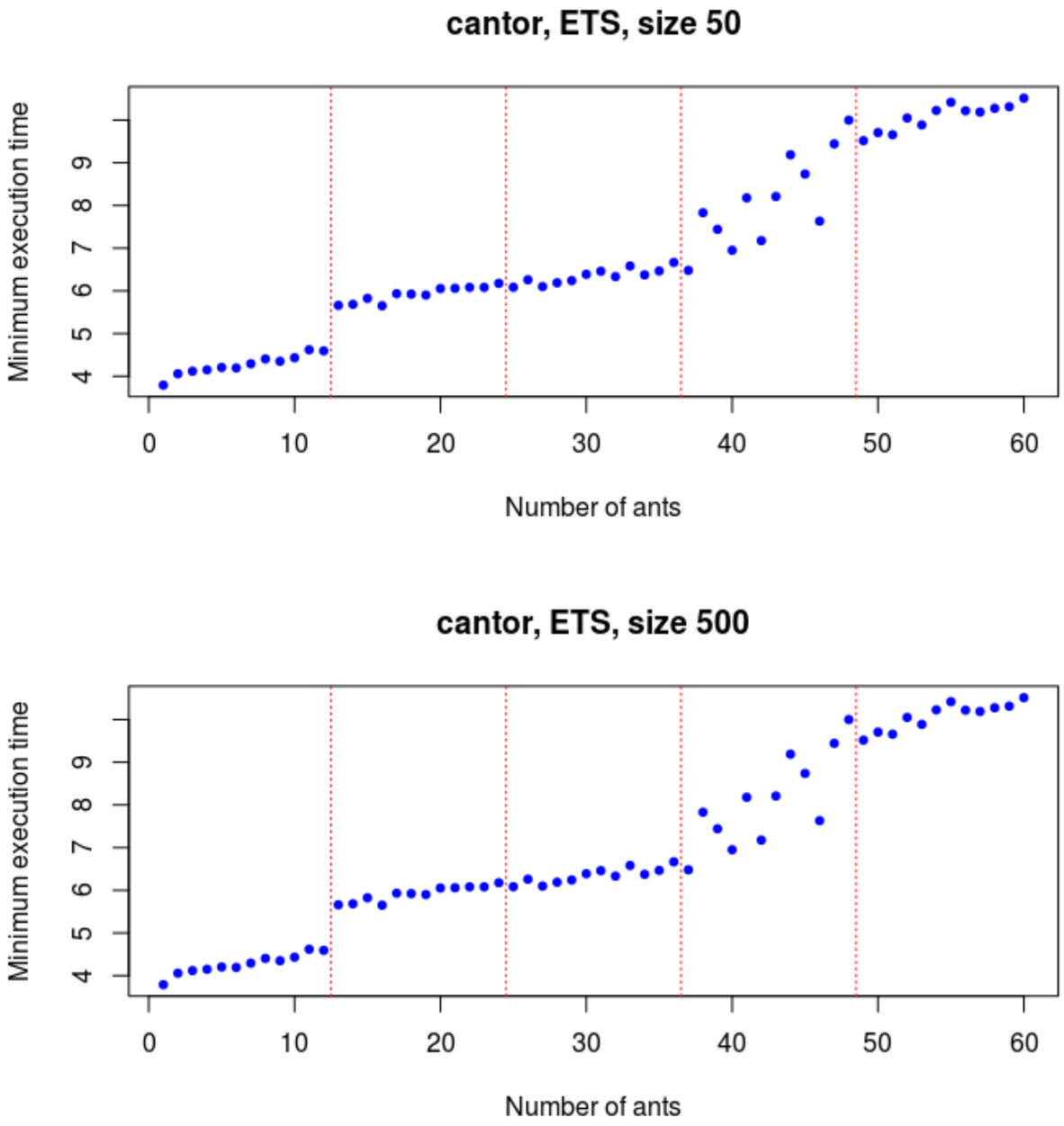


Figure 31: Execution times for ETS version on cantor

B.4 Comparing ETS and DETS

We have seen that the DETS version of the program is much slower than the ETS version. Figures 41 and 42 compare the two versions in detail. For each machine, we look at the ratio of (mean) execution time between the DETS version and the ETS version. For size 50, we see that on the `bwlf` machines the DETS version takes 10–12 times longer than the ETS version for small numbers of ants, but that the ratio decreases to about 6 or 8 for larger numbers. For `cantor`, the situation is reversed. The ratio increases from about 10 to over 20 as we increase the number of ants.

For input size 500, we only have data for the `bwlf` machines for the DETS version (and only up to

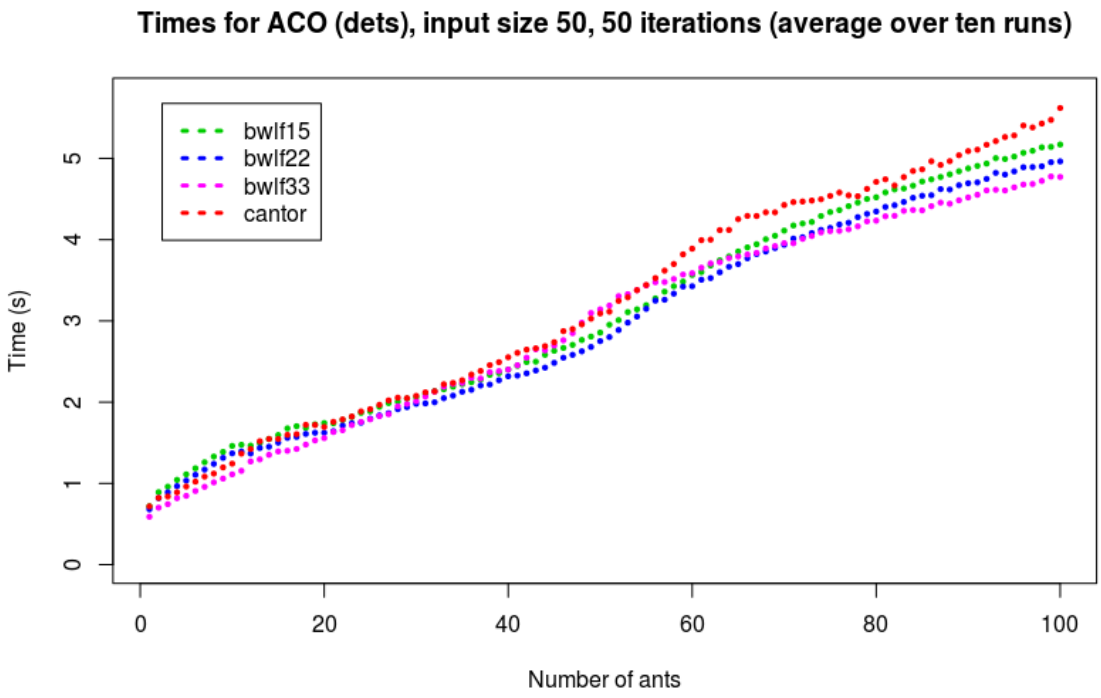


Figure 32

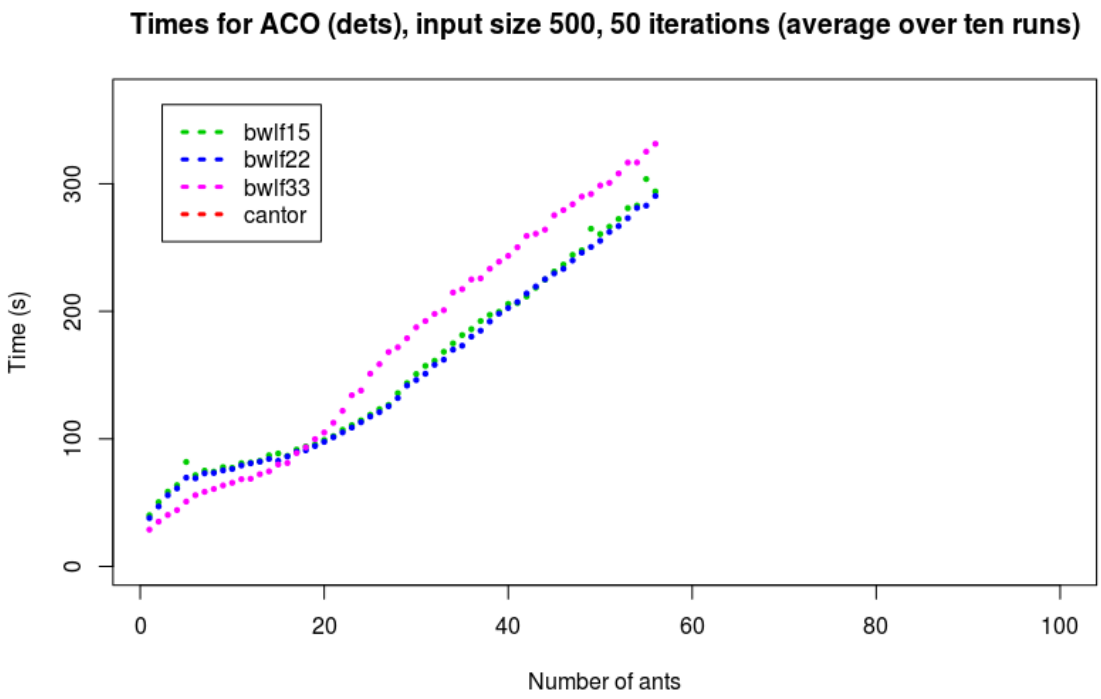


Figure 33

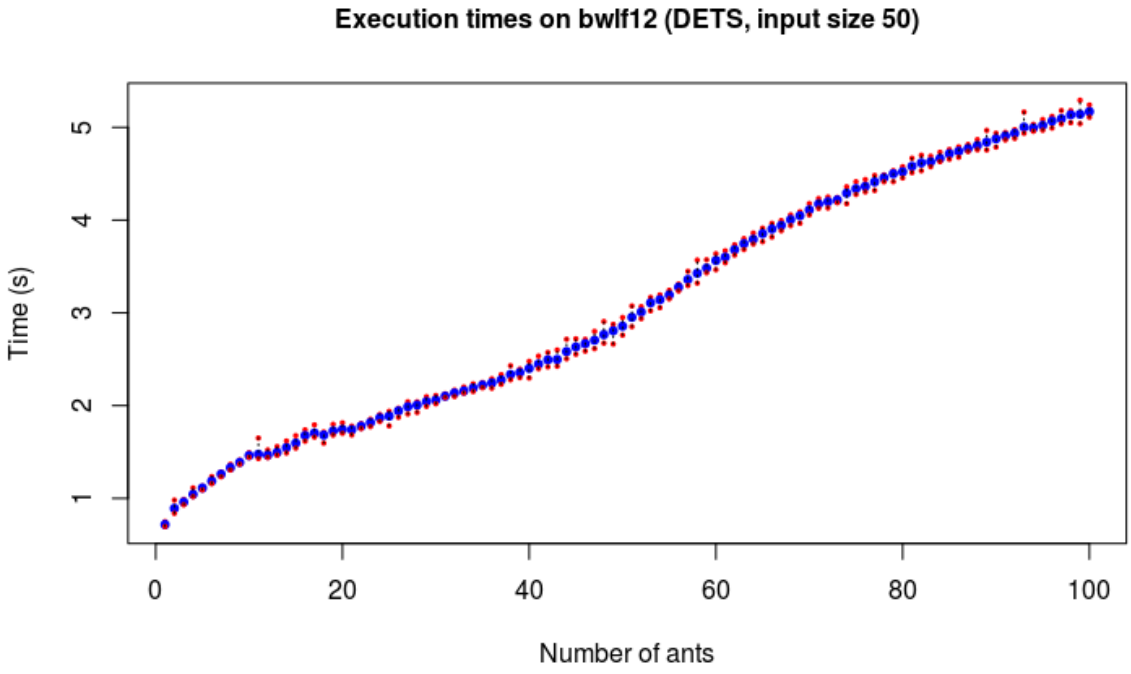


Figure 34

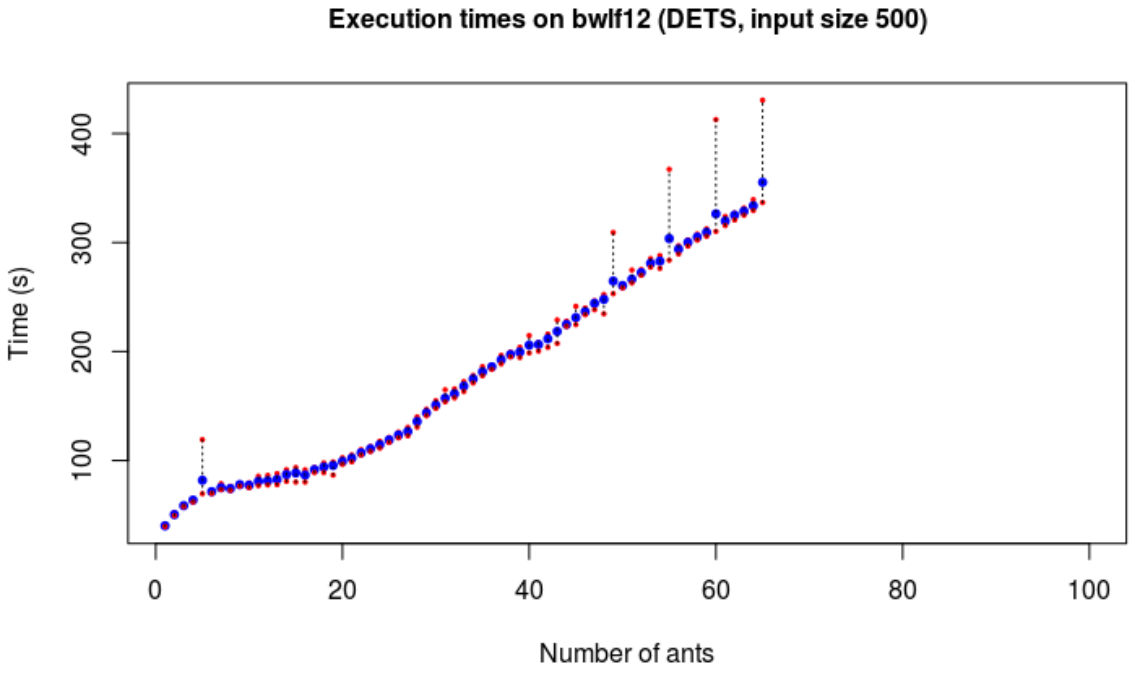


Figure 35

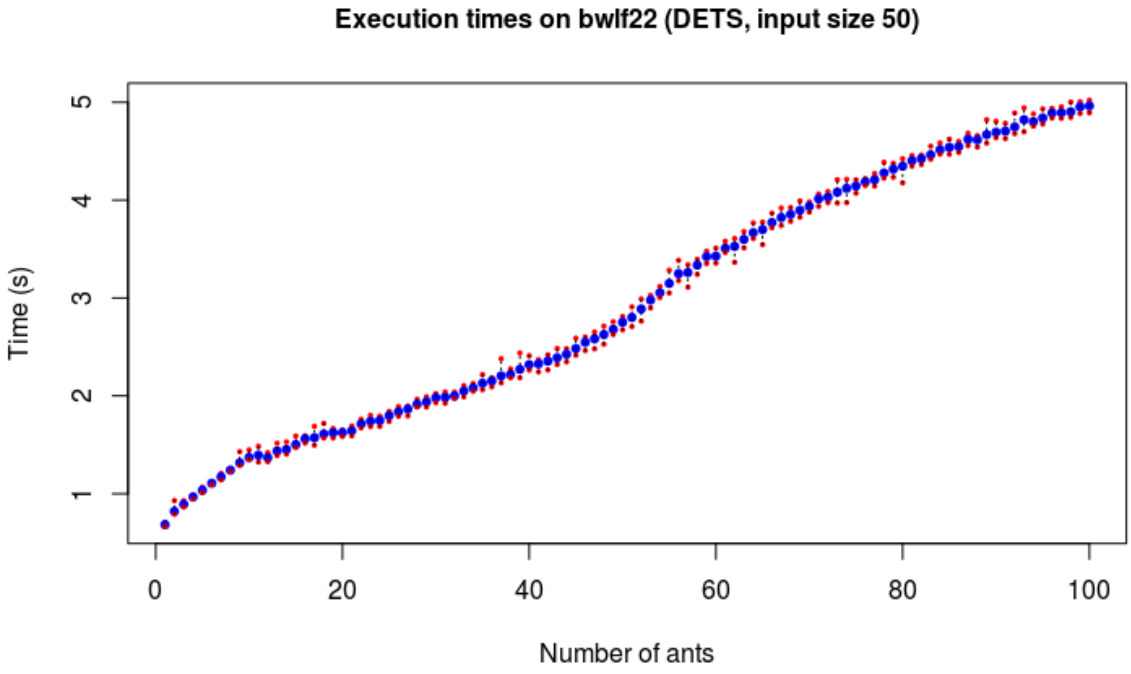


Figure 36

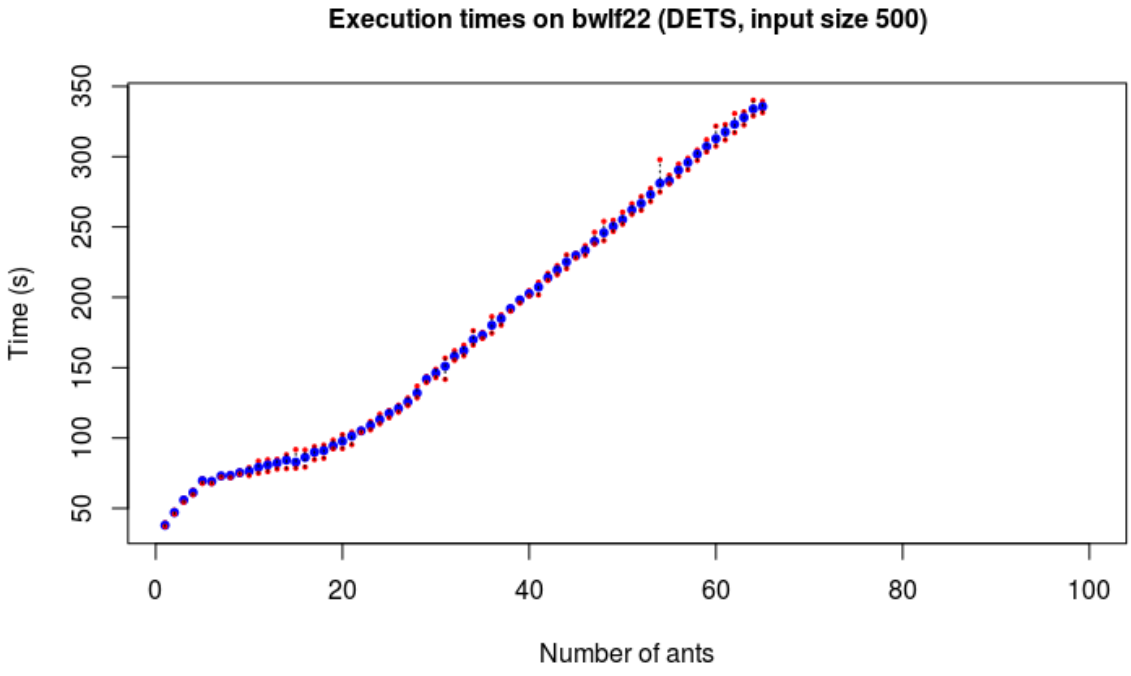


Figure 37

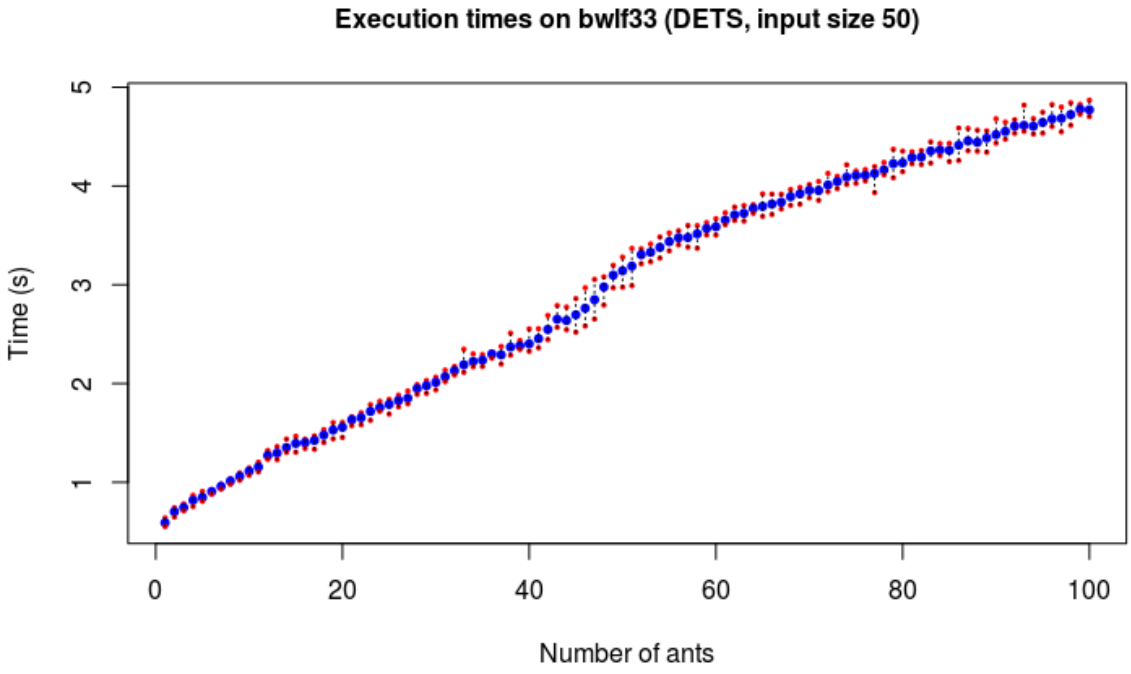


Figure 38

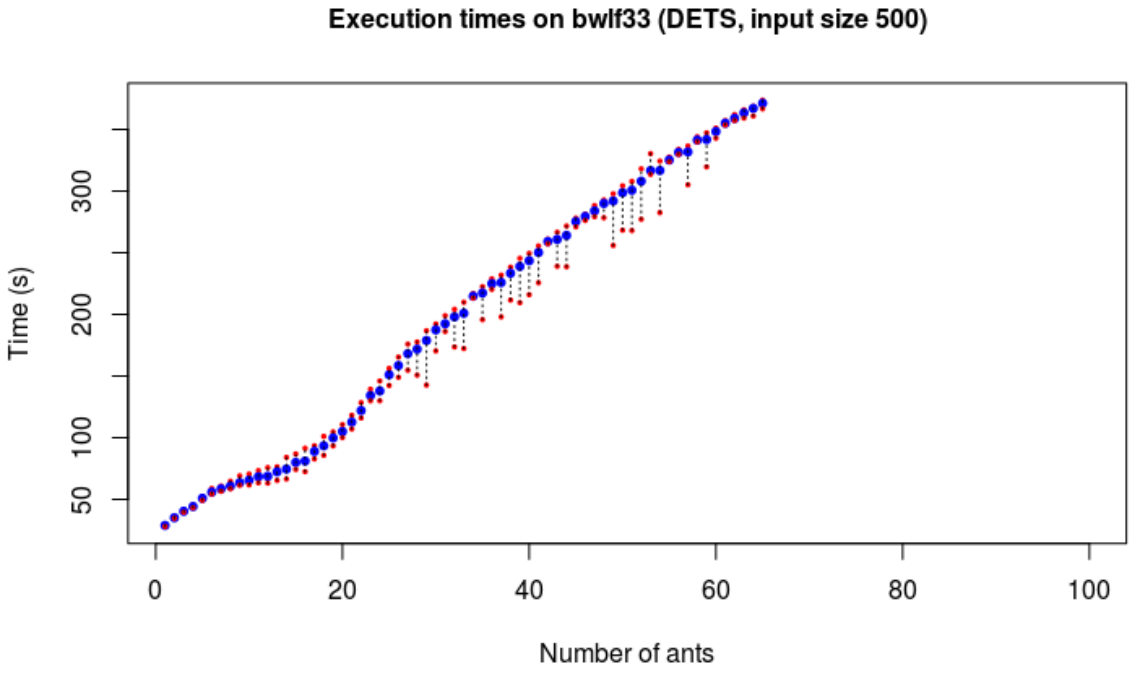


Figure 39

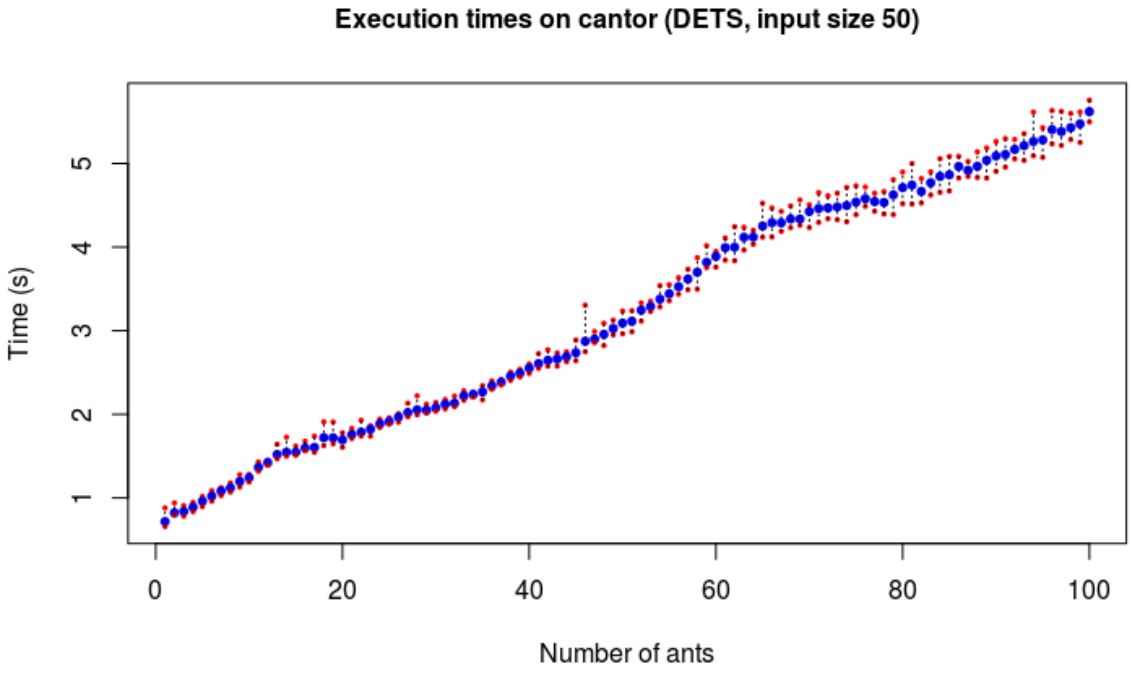


Figure 40

60 ants). For `bwlf12/15` and `bwlf22`, the situation is not unlike that for input size 50 (but with an eightfold time increase for large numbers of ants instead of a sixfold one). For `bwlf33`, it's completely different: the ratio drops and then bounces back to about 14 for large numbers of ants. Again, I've no idea why this is.

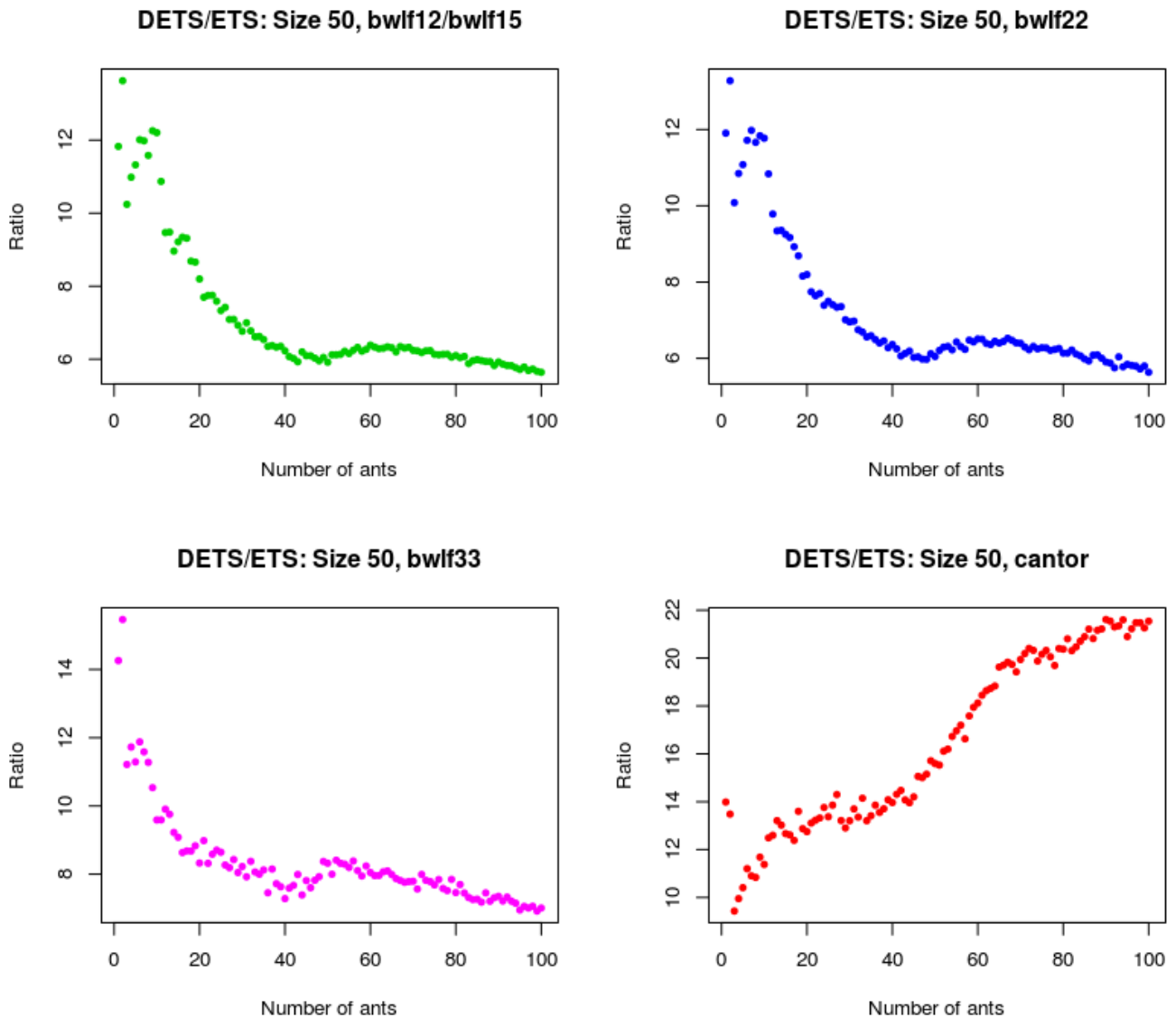


Figure 41

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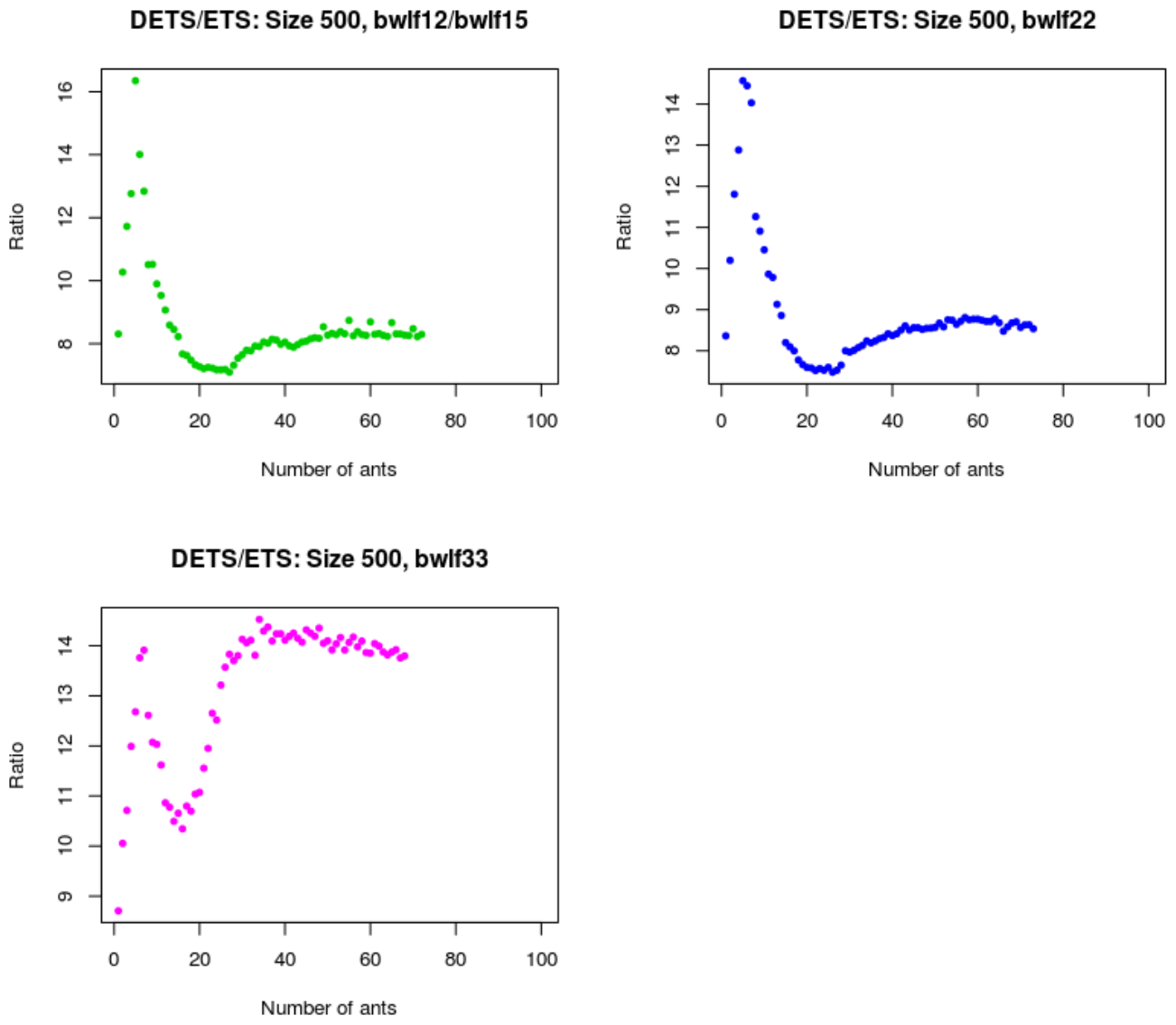

Figure 42

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