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Intelligent layer 2 switching by CE-ants

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Problem Description

The objective of this project assignment is to investigate if the CE-ant path finding system developed at the department may be applicable as an alternative ethernet layer 2 switching protocol. Standard protocols in todays ethernet switches must be studied as well as the CE-ant system foundations. Pros and con of the approaches should be investigated.

My objective is compare “Ethernet Layer 2 switching” and “Layer 2 Switching by CE-ants”. To do this, I will study both systems and I will compare them qualitative (theoretical issues) and quantitative (I will try to simulate both systems in order to view their behavior in several situations).

After compare two systems, I will evaluate the possibility to use CE-ants method as a substitute of Ethernet Layer two switching, to discover if the advantages of CE-ants method are significant and disadvantages are insignificant to the Layer 2 Switching typical use.

Assignment given: 12. September 2006
Supervisor: Bjarne Emil Helvik, ITEM

Dedication

Als meus pares, Alfons i Montse,

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Abstract

Living in Information Society, we always want to improve the networks to get more reliability, more bit rate, less “ping”. CE ant Layer 2 systems appear in order to change the concept of usual centralized networks, where the control is centralized and paths are decided before to start the transmission (with the consequent impossibility of balance the load).

Layer 2 networks provide fast forwarding of packets from one link to another, without checking IP direction and avoiding to use some error corrections (like in Layer 3 networks), so they do not spend time in too much things, this is the reason because we use Layer 2 networks.

The main aim for this work has been to study CE ant systems in Layer 2 networks and ameliorate the behaviours that can be improved by simulations of previous theoretical study. After 4 proposals studied, two of them have been discarded and other two have been confirmed as improvements. These improvements let us to use two different cost functions (for different environments of the network) in order to decide the optimal path.

Keywords: *Layer 2 network, swarm intelligence, CE ants, network management strategies, NS-2, Path cost function, backtracking, load balancing.*

Acronyms

IP	Internet Protocol
MAC	Media Access Control
OSI	Open Systems Interconnection
CSMA/CD	Carrier Sense Multiple Access Collision Detect
CE	Cross Entropy
NS-2	Network Simulator 2
CAM	Content-Addressable Memory
STP	Spanning Tree Protocol
RSTP	Rapid Spanning Tree Protocol
LAN	Local Area Network
BPDU	Bridge Protocol Data Units.
VLAN	Virtual Local Area Network
SI	Swarm intelligence
BGP	Border Gateway Protocol
OSPF	Open Shortest Path First
p.d.f.	Probability Density Function
RTT	Round Trip Time
TPB	Two Pheromone type Behaviour

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1. Introduction

Nowadays, there are millions of computers in the world. The computer's "boom" was in 90's, when public computer networks started to be accessible to most of the people. Networks are bigger and bigger every day since they started and they have needed devices (hardware and software) to help the transmission. In order to do this work more easily, some models have been created, like OSI model, where networks are divided into 7 operation layers (5 basics). Each layer has specific characteristics and introduces more complexity (errors control, retransmissions,...) to the network, but at the same time, each upper layer introduces delays and processing times depending on the complexity used.

Figure 1. OSI stack model

Switching is a layer 2 operation in the OSI stack and its decisions are based in destination MAC addresses. The main objective of layer 2 switching was to split networks with too much end-terminal devices in different "collision domains". Hubs broadcast packets through all their ports without any control, they are "repeaters" and it can cause a lot of collisions in networks with more than one end-terminal due to ethernet uses CSMA/CD (Carrier Sense Multiple Access Collision Detect). The systems that use CSMA/CD are characterized because their terminals transmit the data when they have to and, if there is a collision, data is transmitted again later. In order to improve the behaviour of ethernet, Switches operates like Hubs (Hubs does not solve the problem), but they only retransmit the packets toward the port which is connected to destination end-terminal or to another

network device that belongs to the path towards destination (Switch operation is explained in *section 2*).

Several techniques have been developed in order to find network paths from source to destination, but most of them have centralized control and they are not adaptive. Applying swarm intelligence to find paths in the network we improve these issues and add possibility of multipath to the network, something that is very advantageous for networks with redundant paths.

In this thesis we have studied the layer 2 switching by CE ants, which means to study the use of swarm intelligence in layer 2 networks. The objectives are to study CE ant systems, to propose improvements to make better its implementation in real networks, to compare different proposals, to decide which are the best options and to check the proposals in typical layer two networks. Some basic issues of functioning of the network, like cost function, how to balance the load, where to take decisions and others from CE ants networks, organization of pheromones and where to store the path in order to do backtracking after calculate the value of the pheromone are studied.

In order to find reliable results, the methodology followed has been divided in three parts. The first one is a theoretical study proposing solutions to the problems and comparing which advantages and disadvantages can each option have. For us to know if the proposals work in critical situations in networks, the second part has been to do simulations and comparing the different proposals with the results of simulations (they are done with NS-2 simulator, modifications over extension by Otto Wittner, what has spend most time in the making of this thesis), some typical layer 2 networks has been studied in this part of the work. Finally, the conclusions come from a mix between both methods (theoretical study and simulation study), reflecting upon the results and deciding which is the best solution.

2. Switching

In the introduction the basis of the Layer 2 (and basis of switching) has been explained, and in this section it is illustrated how the switches (switch devices), whose behaviour belong to Layer 2 in the OSI stack, work in order to view the behaviour of network units. Therefore, switching is the name of the behaviour of the networks with switches (or bridges).

A Switch is a device that can connect different types of packet switched network segments (Ethernet, Token Ring, Fibre Channel or others) together to form heterogeneous network operating at OSI layer 2. They are devices that have MAC addresses for each port and are connected to other devices with MAC addresses, which with these, the switches decide where to send the packets (frames).

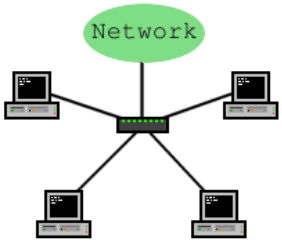


Figure 2. Switch connected to a network and end terminals

Switch operation:

As frame (layer 2 packet) comes into the switch, the incoming port is identified, and port ID is stored in the switch's MAC addresses table with the originating MAC address. This table often uses a content-addressable memory, so it is sometimes called the “CAM table”. Then, the switch transmits selectively the frame through specific ports decided by comparing the frame's destination MAC address and previous entries in the MAC addresses table. If destination MAC address is unknown (it is not in MAC addresses table), the switch transmits the frame out of all ports of the

connected interfaces except incoming port. If the destination MAC address is known, the frame is forwarded only to the port related with this destination MAC address in the MAC addresses table. If the destination MAC address is the same that incoming port, the frame is filtered out and not forwarded.

Forwarding methods:

There are four forwarding methods that switches can use:

- Cut through: The switch only reads up to the frame's MAC address before starting to forward. There is no error checking in this method.
- Store and forward: the switch buffers and, typically, performs a checksum on each frame before forwarding it.
- Fragment free: The switch check first 64 bytes of the frame, where addressing information is stored. There is no data error checking.
- Adaptive switching: Automatically switching between the other three forwarding methods.

3. Spanning Tree Protocol (STP)

This thesis talks about special ways to find paths, hence we introduce knowledge about actual standardized way to find them. The Spanning Tree Protocol (STP) is a method to define different paths on a network in order to improve some of its issues. It is defined by IEEE in 802.1d-1998 Standard (nowadays, the standard working is 802.1d-2004, where STP was suppressed and Rapid STP, RSTP, was included, but both follow the same basis, although there are several proposals in the "network investigation world" to find optimal paths.)

The Spanning Tree Protocol (STP) disables, with its algorithm, redundant paths in a network to avoid loops, and enables them when a fault, such as a broken link or node, in the network means that loops are needed to keep traffic flowing.

LANs and switches can be connected in an arbitrary topology resulting in more than one path between two switches. If there are loops in the network, frames transmitted onto the network would circulate around the loop indefinitely, decreasing the performance of the LAN. On the other hand, multiple paths through the network provide the opportunity for redundancy and backup in network faults. The Spanning Tree is created through the exchange of Bridge Protocol Data Units (BPDUs) between the switches in the LAN when they start up, or when a change in the configuration of the network is detected.

There are many algorithms to "construct" Spanning Trees, they differ in optimization, speed and load for the construction and special advantages, but all of them ensures that the LAN contains no loops and that all nodes (or LANs if the spanning tree is been constructed for an extended LAN) are connected by:

- Detecting the presence of loops and automatically computing a logical loop-free portion of the topology, called Spanning Tree.
- Automatically recovering from a switch failure that would split LAN by reconfiguring the spanning tree to use redundant paths, if available.

One example of network with different Spanning Trees established is a “grid topology” network, such in *Figure 3*, where there are four spanning trees, each one without loops. If one link goes down and breaks the used spanning tree, it can continue the transmission through other spanning trees without this link (it is not always possible to find spanning trees to cover all the possibilities of broken links). Usually, each Spanning Tree is assigned to a VLAN to know where the packets have to be sent in each node.

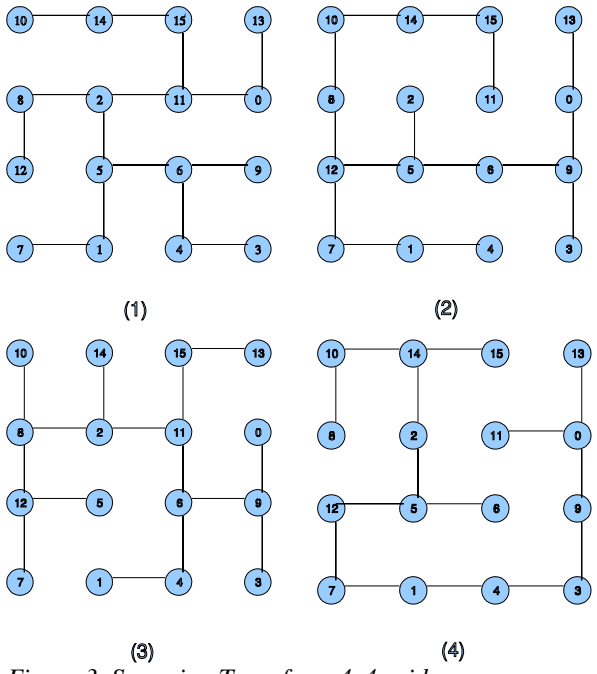


Figure 3. Spanning Trees for a 4x4 grid

Spanning Tree has the following properties:

- A single switch forms a unique root (node where the spanning tree construction starts, 0 in last *Figure 3*) to the tree.

- Each switch or LAN in the tree, except the root switch, has a unique parent, known as the designated switch.
- Each port connecting a switch to a LAN has an associated cost. The root path cost is the sum of the costs for each segment between the switch and the root switch.

The algorithms uses the following process to establish the spanning tree:

1. A unique root switch is elected by the switches in LAN
2. A designated switch is elected for each LAN in the extended LAN by the switches in the LAN.
3. The logical spanning tree is computed with an algorithm and redundant paths are removed.

The maintenance of spanning trees is done by replacing a failed path with a redundant backup path, detecting and removing loops by declaring ports as redundant and removing them from the logical spanning tree, and maintaining timers that control the ageing of the forwarding database entries.

Spanning Tree Protocol has some advantages and disadvantages, and what we look for with CE ant systems is how to improve the finding path system and take advantage from disadvantages of STP. We want a system that find paths without loops and automatically recovers from failures, which are the advantages of STP, and solve the disadvantages of it, that are to have load dependence, adaptability to the network changes and support for multipath switching.

4. Swarm intelligence

Swarm intelligence (SI) is an artificial intelligence technique based around the study of collective behaviour in decentralized, self-organized systems. Swarm intelligence is a metaphor to solve distributed problems like animals in nature. Swarm is a group of autonomous animals that are distributed, but each one is involved in group work without centralized control. Each individual can communicate with the group through any signal (i.e. pheromones to decide the path to get the food in ants colonies). In our model, each individual animal will be an agent that will have this behaviour.

The main characteristics of swarm intelligence systems are:

- **Autonomy**, human supervision is not needed.
- **Adaptability**, system changes are detected and the agents can decide new paths in case of environment changes. The simile in networks would be adding or disconnecting nodes or failures in the network links.
- **Fast propagation** of changes through the system.
- **Scalability**, the population can be increased or reduced.
- There is **no central control**, so most of the failures in the system can be solved by itself.
- The agents **work in parallel**, and this means that there are a lot of searching path “threads” at the same time.

5. Layer 2 switching model by CE ants

This section is based on a mix of two papers with references *[2]* and *[3]*, written by *Bjarne E. Helvik, Otto Wittner and Poul Heegaard*.

5.1. Finding the shortest path

The main issue of all routing systems for networks is to transmit the data between a given source and destination by the optimal path (optimal path may mean different things depending on the design of the network; the path is optimal in terms of cost, and cost can be defined such Q2S, delay, free bandwidth, transmission time...) Some examples are BGP and OSPF in Internet.

Swarm intelligence systems based on ants finding food behaviour are able to find a solution close to the optimal path between a source and destination. *Figure 4* shows how an ant colony changes the path (reroute) when an obstacle appears. Number 1 in this figure shows the system "running", where ants are travelling through the shortest path, and if an obstacle appears, ants cannot follow the pheromones (2 in figure) and explore new paths, in this case two different options, both sides of the obstacle (number 3) that have the same probability that the ants go through them. Due to the fact that the upper path is shorter, ants walking on it will leave more and stronger pheromones and the next ants will follow the path with more pheromones (number 4). Number 5

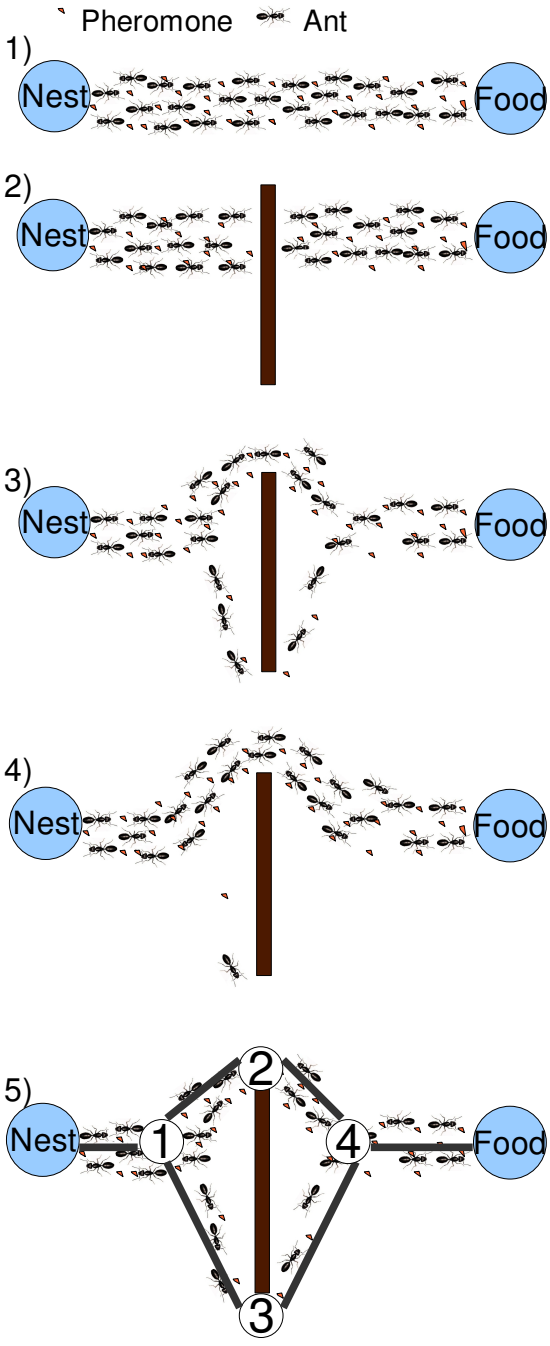


Figure 4. Ant colony behaviour when an obstacle is found

is an extra picture where there is a simile between the ants system described and a network with 2 possible paths to reach the destination (*Nest* is like the source and *Food* is the destination). Going through one path or the other depends on the pheromones, which define a probability matrix P_t^{sd}

("s"->source, "d"->destination and "t"->instant of time), for example $P_t^{14} = \begin{matrix} ij \\ 1 \\ 2 \\ 3 \\ 4 \end{matrix} \begin{matrix} 1 & 2 & 3 & 4 \end{matrix} \begin{bmatrix} 0 & 0.7 & 0.3 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

where "0.7" and "0.3" is the probability that the agents (packets behaving like ants) will go through this path to reach the destination.

Basic characteristics of this system operation are:

- Lots of ants are moving from the nest to the food at the same time and asynchronously.
- These ants have an indirect communication between them with chemical trails of messages in the ground that all ants can smell (pheromones, these trails are values stored in nodes in data networks).
- A stochastic process can be used to model the behaviour of an ant walking in the network. With information about neighbouring and distribution of pheromones, an ant generates a probability distribution. A draw from the distribution produces a directional vector that controls the ant's forwarding movement.
- The search is iterative, the ants move along the same path one time and another and the pheromones are continuously updated.

5.2. Cross Entropy Ants (CE ants)

CE ant systems are swarm intelligence systems inspired in ant's behaviour finding food. The principal idea is to have a lot of simply like-ant mobile agents searching for paths in the network all the time. When an agent finds a path, it starts to do backtracking and leaving marks (pheromones)

like trails left by real ants as it has been expressed before. Due to the quality of the path found, the pheromones will have more or less strength. Pheromones are stored in network nodes, actually, nodes hold distributions of pheromones pointing toward their neighbour nodes. When a new agent, searching destination, arrives to the node, it selects the next node to visit stochastically based on the pheromone distribution seen in the visited node. Using such ant trail marking, together with the evaporation of the pheromone, the overall process converges quickly toward having the majority of the agents following a single trail that tends to be a nearly optimal path. The behaviour of Cross Entropy ants is, in addition to a copy of the behaviour of real ants, founded in Rubinstein's stochastic optimization method.

The path management strategy implemented depends on how the quality of the path is determined, that is how to calculate the cost (cost is the lack of quality). Traffic streams between pairs of nodes in the network are indexed by *m.* A path for this stream found by the *t*'th agent is denoted π_t^m. A link connecting two adjacent nodes *i*, *j* has a link cost L_{ij}. The link cost may depend on the traffic stream to be carried and when the cost is observed. If this is the case the cost observed by the *t*'th ant is denoted $L_{t,ij}^m$. The cost function, L, of a path is the sum of the link costs, i.e.

$$L(\pi_t^m) = \sum_{ij \in \pi_t^m} L_{t,ij}^m \qquad \textit{Eq. 1}$$

5.3. Management strategies

Management strategy should be reflected in the path cost function of each individual ant to determine the cost due to wanted behaviour. Two of most important strategies are presented:

- **Primary/Backup:**

  The objective of this strategy is to provide guarantees for maintenance of the service in a single link failure. This is done finding pairs of disjoint paths, primary and backup. For this reason, ants searching primary paths should detest ants searching backup paths. The capacity of the

primary paths will be used in fault free operation, and ants finding primary paths should detest each other because using a common link could cause overload. On backup paths, the capacity will be allocated and shared with other backup paths. Backup paths having primary paths with common links should avoid using common links in the backup path in order to avoid overload in backup common link if there is a failure in primary common link. All these requests must be reflected in path cost function, giving high penalties to the paths that do not fulfil them.

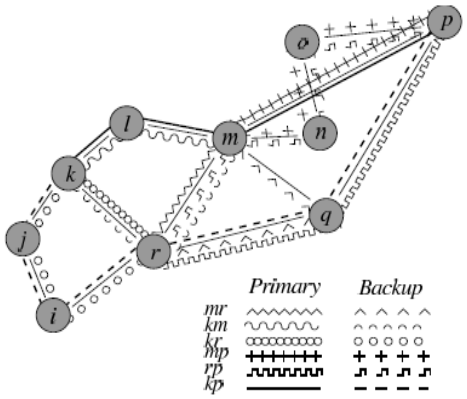


Figure 5. A primary/backup pattern for 6 duplex connection in the Norwegian university backbone IP network

In *Figure 5,* 6 connections between nodes using primary backup management strategy are shown.

- **Adaptive path:**

  This strategy has been designed in order to achieve fast restoration and adaptivity for link failures and changes in traffic loads. For this reason, the cost function has to depend on the carried traffic like transfer times, delays or free capacity of each link. This strategy permits to have several possible paths to transmit when the path that is being used fails. It can take more time than primary/backup strategy, but it finds the best path in the moment of failure. Another advantage of this strategy is that it favours load balancing. All the studies in this thesis are based on this strategy, which is updating the paths and pheromones in the network all the time.

5.4. The cross entropy method

The Cross Entropy method is used to find the optimal solution to discrete combinatorial problems that are solved based on a Kullback-Leibler cross entropy, importance sampling, Markov chain and the Boltzmann distribution. Next, the method is outlined.

This method, presented by Rubinstein, is based on a random search for an optimal path, even though there is a very low probability for a path to be optimal (there are a big number of possible paths in a network, this number increases with the size of the network). Hence, the probability of observing the optimal path is increased by applying importance-sampling-like technique. In our context, this approach may be regarded as a centralised search for a single best path in a network. In this section, the cross entropy (CE) method is summarized with the above "ant terminology" with the modification that t is now interpreted as a batch of N ants rather than a single ant (it is shown in step 2 of the iteration steps in next paragraph).

The total allocation of pheromones in a network is represented by probability matrix P_t where an element $P_{t,ij}$ reflects the normalized intensity of pheromones pointing from node i toward node j. An ant's stochastic search for a simple path resembles a Markov Chain selection process based on P_t. By importance sampling in multiple iterations Rubinstein alters the transition matrix (P_t -->P_{t+1}) and increases, as mentioned, certain probabilities such that agents eventually find nearly optimal paths with high probabilities. Cross entropy is applied to ensure efficient alternation of the matrix. To speed up the process even more, a performance function weights the path qualities such that high quality paths have greater influence on the alternation of the matrix, (in step 2). Rubinstein's CE algorithm has 4 steps. The indexes m and r are omitted since a single path and single kind of agent are considered:

1. At the first iteration $t = 0$, select a start transition matrix $P_{t=0}$ (for example, uniformly distributed)

2. Generate N paths from P_t. Calculate the minimum parameter γ_t, denoted temperature, to fulfil average path performance constraints, i.e.

$$\min \gamma_t \text{ s.t. } h(P_t, \gamma_t) = \frac{1}{N} \sum_{k=1}^{N} H(\pi_k, \gamma_t) > \rho \qquad \textit{Eq. 2}$$

A performance function of current routing probabilities, $h(P_t, \gamma_t)$ has been introduced which is based on the Boltzmann function:

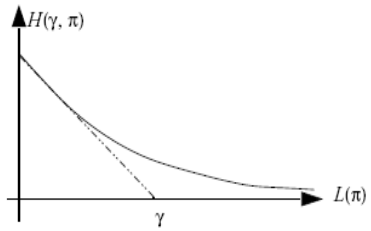


Figure 6. Illustration of Boltzmann function

where $H(\pi_k, \gamma_t) = \exp(-L\frac{(\pi_k)}{\gamma_t})$ is the performance function returning the quality of path π_k. $L(\pi_k)$ is the cost of path used and ρ has to be $10^{-6} \leq \rho \leq 10^{-2}$ (ρ is the search focus parameter). The minimum solution for γ_t implies a certain reinforcement (dependent on ρ) of high quality paths and produces a minimum average $h(P_t, \gamma_t) > \rho$ over all path qualities in the current batch of N paths.

It is shown in *Figure 6* that as the temperature decreases, an increasing weight is put on the smaller path costs.

3. Having γ_t calculated from step 2 and $H(\pi_k, \gamma_t)$ for $k = 1,2..., N$, in this step it will be generate a new transmission matrix P_{t+1} which maximises the "closeness" (minimizes the cost) to the optimal matrix, by solving

$$\max_{P_{t+1}} \frac{1}{N} \sum_{k=1}^{N} H(\pi_k, \gamma_t) \sum_{ij \in \pi_k} \ln P_{t+1,ij} \qquad \textit{Eq. 3}$$

where $P_{t+1,ij}$ is the transition probability from node i to j at iteration $t+1$.
The solution of *Eq 3* is shown in reference *[19]* to be:

$$P_{t+1,ij} = \frac{\sum_{k=1}^{N} I(\{i,j\} \in \pi_k) H(\pi_k, \gamma_t)}{\sum_{l=1}^{N} I(\{i\} \in \pi_l) H(\pi_l, \gamma_t)} \qquad \textit{Eq. 4}$$

where $I(X)=1 \; if \; X=true$ and $I(X)=0 \; if \; X=false$. *Eq 4* become a minimised cross entropy between P_t and P_{t+1}, and ensures an optimal shift in probabilities with respect to γ_t and the performance function.

4. Steps 2 and 3 have to be repeated until $H(\hat{\pi}, \gamma) \approx H(\hat{\pi}, \gamma_{t+1})$ where $\hat{\pi}$ is the best path found.

5.5. Distributed cross entropy method

What today is known as *CE ants* is a distributed and asynchronous version of Rubinstein's CE algorithm, developed in reference *[20]*. By a few approximations, *Eq 4* and *Eq 2* may be replaced by autoregressive counterparts based on

$$P_{t+1,ij} = \frac{\sum_{k=1}^{t} I(\{i,j\} \in \pi_k) \beta^{t-k} H(\pi_k, \gamma_t)}{\sum_{l=1}^{t} I(\{i\} \in \pi_l) \beta^{t-l} H(\pi_l, \gamma_t)} \qquad \textit{Eq. 5}$$

and

$$min \, \gamma_t \, s.t. \, h_t'(\gamma_t) > \rho \qquad \textit{Eq. 6}$$

where

$$h_t'(\gamma_t) = h_{t-1}'(\gamma_t)\beta + (1-\beta) H(\pi_t, \gamma_t) = \frac{1-\beta}{1-\beta^t} \sum_{k=1}^{t} \beta^{t-k} H(\pi_k, \gamma_t) \qquad \textit{Eq. 7}$$

and where $\beta \in \langle 0,1 \rangle$ (typically close to 1) controls the history of paths remembered by the system (i.e. replaces N in step 2). All development of the auto-regression is shown in reference *[20]*. Step 2 and 3 in the algorithm can now be performed immediately after a single new path π_t is found (*t*

again represents the *t*'th ant), and a new probability matrix P_{t+1} can be generated. Hence CE ants may be understood as an algorithm where search ants evaluate a path found (and calculate γ_t by *Eq 6*) right after they reach their destination node, and then immediately return to their source node backtracking along the path. During backtracking, pheromones are placed by updating the relevant probabilities in the transition matrix, i.e. applying $H(\pi_t, \gamma_t)$ through *Eq 5*.

The autoregressive schemas applied in CE ant system are compact, this means that the system becomes both computationally efficient, requires limited amounts of memory and is simple to implement.

5.6. Elite CE ants

The concept of elitism in CE ant systems is introduced in reference *[18]*. The new system, called *elite CE ants*, performs significantly better in terms of the number on path traversals required to converge toward a near optimal path. The kind of distribution an ant makes depends on the cost of the path it has traversed relative to the cost of the paths found by other ants. All ants contribute in updating the temperature γ_t as in *Eq 6*. However, a limited set of ants, denoted the elite set, updates a different temperature γ_t^*. Only ants belonging to the elite set backtrack their paths and update pheromones applying $H(\pi_k, \gamma_t^*)$ in *Eq 5*, and hence, reducing the total number of backtracking traversals and pheromone updates.

The criterion for determining if an ant is in the elite set is based on the fact that the best solutions in CE ants method relates to ρ through $e^{-L(\pi_t)/\gamma_t} > \rho$, as is shown in step 2 of "The cross entropy method" section. The elite set criteria is a rearrangement of this relationship. An ant is considered an elite ant if the cost of the path found by the ant satisfies

$$L(\pi_t) < -\gamma_t \ln \rho \qquad \textit{Eq. 8}$$

where γ_t is the temperature updated by all ants. Hence, when removing parts of the search space which enables elite ants to find their paths, for example by a link failure in the best path found, the

temperature γ_t will increase and allow ants with higher path costs to perform pheromone updates. Hence dynamic network conditions are handled. Note also that elite criteria does not introduce any additional parameters. It is self-tuning.

5.7. Implementation in simulator

An extension of NS-2 (*Network Simulator*) for CE ant system has been developed by Otto Wittner in Telematics department of NTNU university. It has been used for simulations about all theoretic proposals and studies previously done. Everything that will be explained next, is about swarm extension without the modifications made to simulate the variants defined in this thesis (they will be explained later and code can be found in *Appendix*), so basic knowledge about NS-2 simulator are supposed.

The extension of the simulator is programmed in C++, this language is an object oriented programming language, this means that there are many classes and that the code is divided in them. However, in *Swarm* extension there is one main class called *swarmrtm* where the biggest part of the behaviour of the system is defined, how an agent moves in the system and what it does in each node. Next, the actions in the simulations for an agent will be described, which is very similar to explain how a CE ants system works.

It is important to know beforehand that three types of packets (agents/ants) are defined. *Datapacket* ants are the packets that carry the data that has to be transmitted from source node to destination node. These agents follow the pheromone system in order to go towards destination through the optimal path, but they do not modify the gamma of the transmission and do not backtrack (they do not update the pheromones). *Normal* ants are the agents that have the behaviour explained in previous sections. They are little packets that look for optimal paths using CE method. They modify the gamma when they are at destination and, if they are elite ants, they modify elite gamma and update pheromones in path nodes when they do the backtracking. Finally, *Explorer* ants travel in the network with random (uniform p.d.f) decisions in each node when it has to decide the next. Like

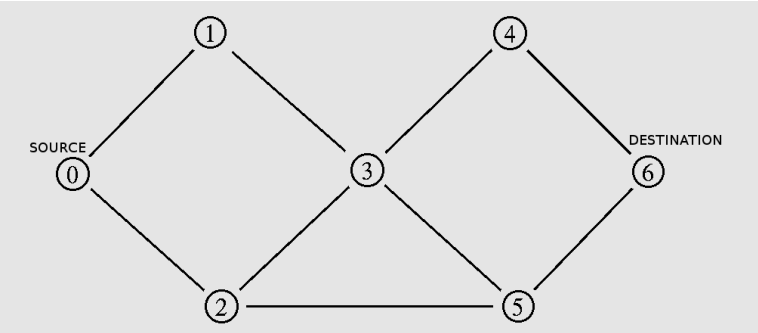
Normal ants, *Explorer* ants modify the gamma and they can belong to the elite set. Usually, they find worst paths than *Normal* and *Datapacket* ants, but their use is to observe the network constantly and if, for example, a new path is added and it is better than the path used by *Normal* and *Datapacket* ants, *Explorer* ants will find it (more or less quickly depending on the size of the network and the rate of *Explorer* ants; as bigger the network and as lower the rate, less probabilities for a single agent to find that path). When a simulation starts, during the initialization time (set in TCL script) all the agents have *Explorer* ants behaviour in order to check all possible paths to decide which is the optimal one, if this is not done there is a high chance to forget several paths to check, and maybe they are better (in terms of cost) and unused. Usually, the rate of this packets is much lower than *Normal* ants.

When an agent arrives to a node, it checks if the node is a destination node. If the agent (not *Explorer* ant, *Explorer* ants decide their path randomly) is not at destination, it reads which is the neighbourhood and, for unvisited neighbours, the agent looks at the pheromone vector (where the pheromone value for each neighbour is stored to reach the destination). If there is no unvisited neighbours, then the simulator allows to revisit any network (or go home node if home node is neighbour). With this, the simulator covers all the cases (if there is no pheromones, the decision is probabilistic with uniform p.d.f.) and an agent can decide which is the next link to go. Two other things done in each node are to store the node id in the packet, in order to remember the path, and to calculate the cost of the following link storing it in a field in the agent packet. In the destination node, agents are differentiated between *Datapacket* ants and other ants. *Datapacket* ants are eliminated (transport of data following pheromones has already been simulated) and *Normal* and *Explorer* ants prepare the backtracking, which means to modify the gamma, to check if the ant is elite ant or not, and to modify the elite gamma. The ants that do not belong to the elite set are deleted after modifying the gamma (the behaviour has already been simulated). Elite ants are going to do the backtracking. Backtracking is to “re-walk” the path from the source to destination but in reverse direction and updating the pheromone levels for all the nodes where the ant goes and deleting the node id of the nodes already visited from the agent packet. When the ant returns to the home node, the packet is deleted (the behaviour has already been simulated).
This is an overview of how the simulator works. Remember that, in *Appendix*, the modifications to simulate specific behaviours of this thesis are explained and the code is shown.

6. Proposals and studies

CE ant systems have been developed theoretically and mathematically and have been simulated in different systems. What is presented in this section are 4 discussions about proposals of changes to improve the CE ant systems when they are implemented in a real Layer 2 network and 1 study about how load balancing works in the system. All these ideas are discussed theoretically first and simulated later in order to evaluate if it is an improvement or simply a way to discard.

In order to check how the proposals works, a network has been designed with simplicity in order to be able to easily predict what will happen. This asymmetrical network has few, but sufficient, paths to make possible its study. These requests are collected in the next network.



network 1. Sample little network that permits the easiness of know when, where and how the things happen

6.1. Path Cost Function

One of most important things when a network (or its behaviour) is designed is posing the question "Which is the best path from source to destination?" or, what is the same, how to decide which path is better than others. Sometimes it is decided by the number of hops that is used from source to destination (very easy to find), and other times a metric is defined for each link and the system tries to minimize the sum of these metrics to get to the destination. All the imaginable options that evaluate the quality of a path are possible. All these things are called "Path cost" and they have to be proportional to the lack of quality of the path. In CE ant system (Adaptive path management strategy) having a traffic depending path cost is important to achieve load balancing and distribution for the paths of the network. Some traffic depending path costs are time of transmission (more traffic implies more time), queue length (more traffic implies larger queues), free capacity (more traffic implies less free capacity)...

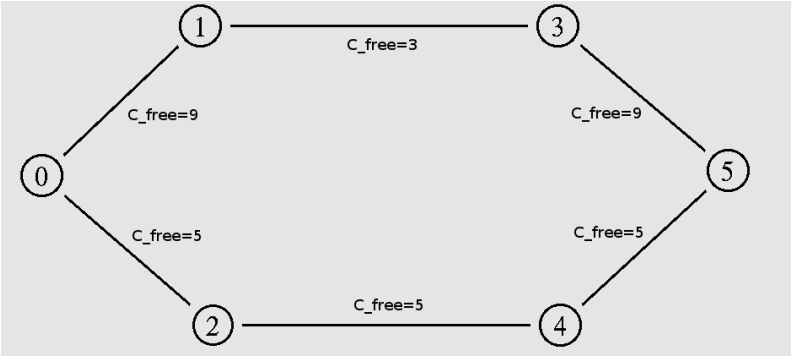
Two path costs have been studied in this thesis to evaluate the quality of a path found by ants. The first one is "Free capacity" (actually, the inverse of free capacity) and the other is "Time of transmission".

Free capacity path cost seems like the most logical way to differentiate paths when the system is deciding, because if it works well, all the paths tend to have the same free capacity and it depends directly from the traffic. Another thing that seems as an advantage when we use this way is the simplicity of the formula to find the path of the link:

$$\frac{1}{C_{free}} = \frac{1}{C_T - C_{used}} \qquad \textit{Eq. 9}$$

where C_{free} is free capacity, C_T is total capacity of the link (or bandwidth) and C_{used} is the used capacity of the link (traffic). It is shown in *Eq.9* that doing the inverse of C_{free} we have a value proportional to lack of quality that can be used as path cost. But studying this formula two problems appear that are difficult to solve. One problem comes when offered traffic is larger than total capacity of the link, then CE ant system could not evaluate the paths. It is difficult that this occurs,

but if it happens, the system could crash, because gamma is not prepared to control that. The other problem is that free capacity of a path should be calculated finding bottle necks and this, as well as difficult to implement, is useless in ant system, where it is essential that the cost of the path is the sum of cost of each hop. The next picture shows this problem, where bottle neck of path 1 (nodes 0-1-3-5) is 3 and its cost is lower than the cost of path 2 (nodes 0-2-4-5), as is shown in *Eq. 10* and *Eq. 11*, whose bottle neck is 5.



network 2. Network to show the problem of bottle necks using CE ant system

$$L(\pi_{0-1-3-5}) = \sum \frac{1}{C_{free}} = \frac{1}{9} + \frac{1}{3} + \frac{1}{9} = 0{,}56 \qquad \textit{Eq. 10}$$

$$L(\pi_{0-2-4-5}) = \sum \frac{1}{C_{free}} = \frac{1}{5} + \frac{1}{5} + \frac{1}{5} = 0{,}6 \qquad \textit{Eq. 11}$$

Time of transmission path cost is the other option studied in this thesis. It is related with the traffic too, because depending on the traffic on a link, the time of transmission will be higher or lower. The biggest advantage of this path cost, as well as it is traffic depending, is that the cost is additive, so it fulfils the requests of CE ant system path cost.

The development to get the formula used to find path cost is:

$$T_W = \left(\frac{\rho}{1-\rho}\right) T_S \qquad \textit{Eq. 12}$$

$$T_{TX}=T_W+T_S+T_D=(\frac{\rho}{1-\rho})T_S+T_S+T_D=(\frac{1}{1-\rho})T_S+T_D \quad \textit{Eq. 13}$$

where T_{TX} is the transmission time, T_W the waiting time, $T_S=L/C$ the service time and $\rho=\lambda/\mu$ the utilization of the link (the same ratio than traffic that goes through the link over traffic that link is capable to send), so $(\rho/1-\rho)$ the queue length (in number of packets). The final formula is:

$$T_{TX}=(\frac{1}{1-\rho})\frac{L}{C}+T_D \quad \textit{Eq. 14}$$

where L is size of packets and C is the capacity of the link (bandwidth). This is the "prediction" way to find transmission time, so $(\rho/1-\rho)$ is not the real queue that there is in a link, it is just a prediction when we know the traffic of the system. Hence, if we know that all the links have queues, we could use:

$$T_{TX}=\frac{Queue\ length+L}{C}+T_D \quad \textit{Eq. 15}$$

It is useful for higher utilization in the links in the *next sections*, so in lower utilizations there is a lot of time without queues in the links and a lot of paths would have the same cost value when, really, the transmission time is different.

Studying paths cost functions theoretically we view that transmission time cost function with *Eq. 14* is the best option to use it in CE ant systems. In the following sections "Two pheromone type behaviour" and "Two measure behaviour" we try to mix advantages from more than one cost function.

simulations:

A simulation of the *network 1* with constant bit rate traffic has been made using links with bandwidth of 155 Mbps and 0,2 ms of delay. This way, we can know which has to be the behaviour

in each moment. At second 90 of simulation, link between nodes 2 and 5 goes down and it goes up at second 150.

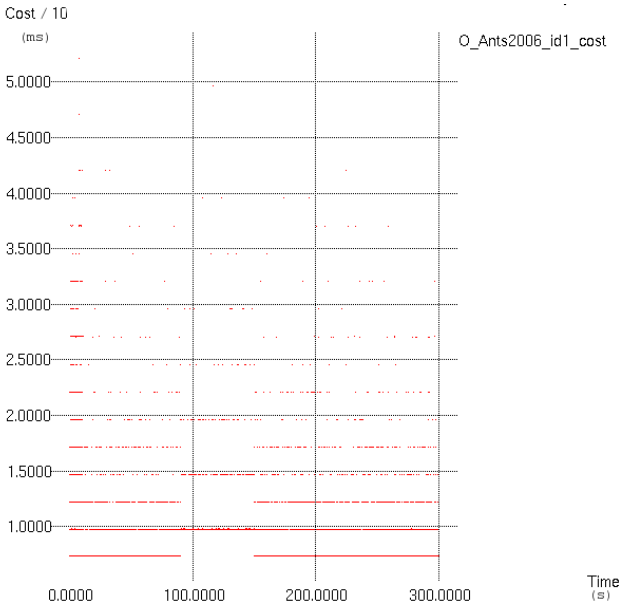


Figure 7. Transmission time cost graph from a simulation in network 1

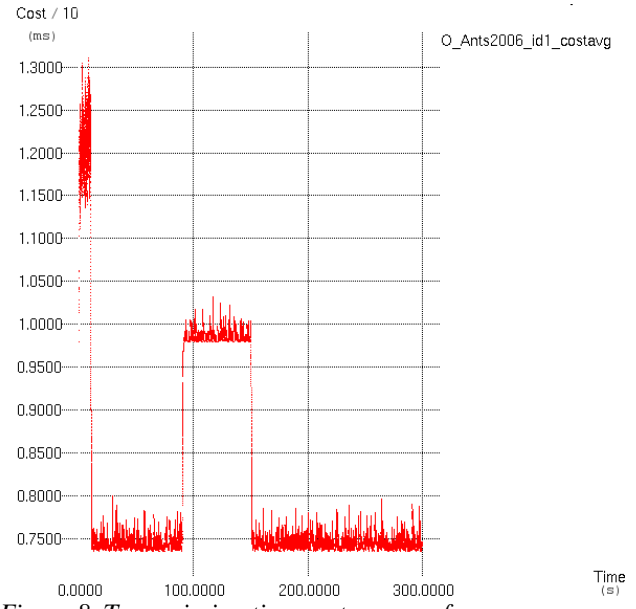


Figure 8. Transmission time cost average from a simulation in network 1

As *Figure 7* shows, the cost of agents (each point represents one agent) is concentrated around some lines of cost, these lines are the cost of different possible paths. Most agents are concentrated in lower cost paths (path decided as better is 0-2-5-6), as it is logical due to the fact that the CE ant system behaviour always searches the optimal path. Most of the agents in higher cost paths are *Explorer* ants that do not follow pheromones. It is easy to view that between seconds 90 and 150 (while the link between nodes 2 and 5 is down) there is no points in some lines because these lines are cost lines of paths including a link that is down and ants have to change their path to another which is up (in this case there are more than one path with the lower cost, they are 0-1-3-4-6, 0-1-3-5-6, 0-2-3-5-6 and other paths of 4 links). The path decided is 0-2-3-5-6 because the utilization is very low and the load does not have to be distributed between more than one path and this path decided is the most similar to the path chosen for transmission before the link has gone down. The most important thing is that ants tend to go through the lowest cost path, and it can be seen in Average cost graph (*Figure 8*) which happens while the link is down and the system changes the path.

Next simulation is the same network than before, but more than one transmission is done and the distribution of load that gives the use of transmission time as a cost function can be studied. Cost graphs are very similar to the ones studied in the single transmission case, and load distribution can be seen in *table 1*, where the first column is all transmissions made (indicating source and destination), first row is the links between 2 nodes and marks *X* are links where the ants of this transmission go through (tx4 is distributed in two paths, 3-4-6 and 3-5-6, this is the reason of 1/2X, because is half of load).

Table 1

	N0-N1	***N0-N2***	***N1-N3***	***N2-N3***	***N2-N5***	***N3-N5***	***N3-N4***	***N5-N6***
tx1(0-6)		X			X			X
tx2(1-2)			X	X				
tx3(2-4)				X			X	
tx4(3-6)						*1/2X*	*1/2X*	*1/2X*
tx5(0-5)		X			X			

After this study we have seen that Transmission time cost function fulfils all the requests to be decided as a cost function of CE ant systems. As well as what we studied (it distributes the load, it converges and it is very stable), transmission time cost function influences directly to q2s of the system, which means that the system always searches for the best path using a cost perceived for the users.

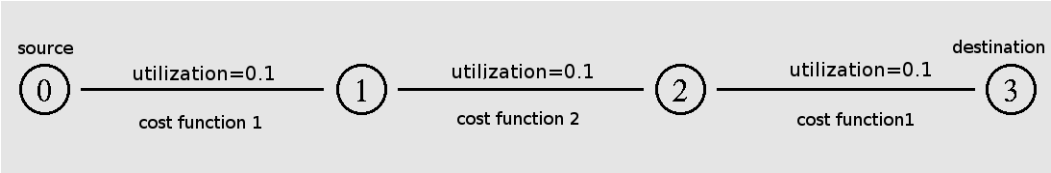
6.2. Two Pheromone Type Behaviour and Two Measure Behaviour

Most cost functions for paths have limits that, when are exceeded, produce wrong cost values or make the function useless. We can find some examples in cost functions studied in PATH COST section (section 6.1), where Free capacity cost function does not work in the case that the link receives more traffic than it can transmit with its bandwidth (it is very rare, but it is possible in specific moments), or functions for transmission time where, in the case that we use predicted queues, the system fails in the same case that free capacity and it is far from reality (and not at real time, it is an average) as higher is the utilization. In transmission time cost function using real queues, when traffic is close to 0 or very low, it is difficult to differentiate paths using queue lengths, because most times there are no queues.

In order to solve the problem described, two ideas of modifications for CE ant systems have been developed, and they are “two pheromone type behaviour” and “two measure behaviour”. Both have the same idea, to combine two cost functions in one system, but different ways, with different complexity, different advantages and different disadvantages. Next, they are explained.

6.2.1. Two measure behaviour

Two measure behaviour is a behaviour designed for CE ant systems that combines different cost functions for each link depending on a condition. In our study case, the condition is the utilization of the link and different cost functions are the two functions defined in *Cost path section* for transmission time (*Eq. 14* and *Eq. 15*). In each node the utilization of the next link is checked, and if it is higher than a threshold, then it uses the second cost function (using real queues in the function). If the utilization is lower than threshold, the cost function used is the first one (expected queues in a link). *Network 3* shows how this proposal works.



network 3. Path of transmission where cost function 2 is used in link between nodes 1 and 2

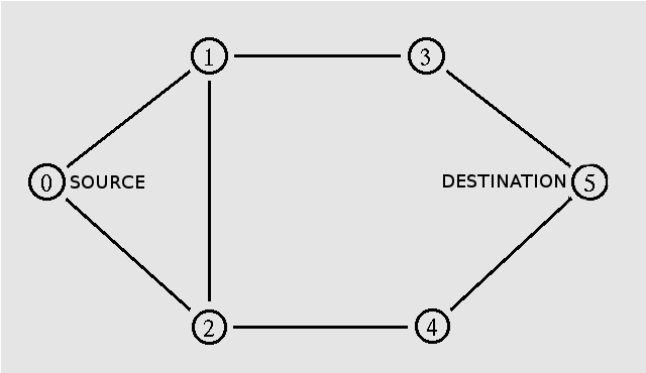
Supposing that utilization threshold is 0.5, the path cost from source to destination when an ant arrives at destination is:

$$L(\pi_1) = L_{link1}(\rho = 0{,}1) + L_{link2}(queue\ depending) + L_{link3}(\rho = 0{,}1) \qquad \textit{Eq. 16}$$

It seems like a good option, but the problem of this way is that both cost functions should be continuous and they have to be comparable (between them) to avoid problems with gamma.

Simulations:

In order to simulate a network where the ants must chose links with high utilization, a new network has been designed. In this network (*network 4*), the traffic has to go through link between node 1 and 3 or through link between nodes 2 and 4. We can generate extra traffic in these links to force occupation higher than threshold.



network 4. Network created to force utilization higher than threshold in all the possible paths (just from node 1 to node 3 and from node 2 to node 4)

The simulation is running during 70 seconds and, from second 20 to second 40, there are transmissions from 1 to 3 and from 2 to 4 sending more traffic than a half of the link's capacity. The result of the simulation is the following:

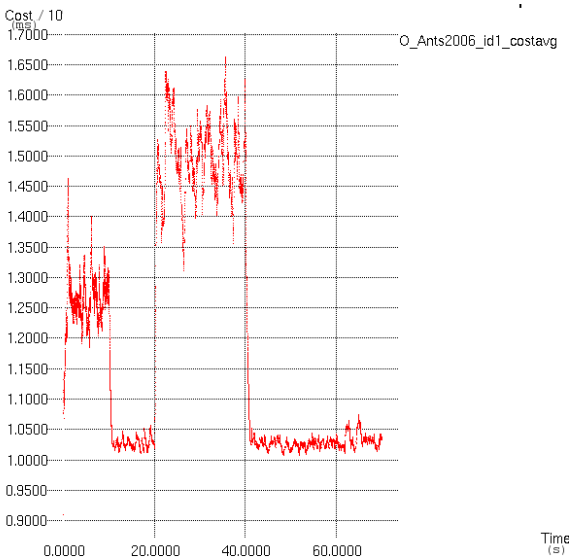


Figure 9. Cost graph for network 3 with "Two measure behaviour"

It is easy to see in *Figure 9* that between seconds 20 and 40, the cost is different, higher than rest of the time. This is because there is a lot of traffic during these 20 seconds. The problem shown in the graphic is the big range of cost during this time, which means that when we use real queue cost function (*Eq. 15*) there is no average between samples and queues are very variable in two different time instants. In order to check if this two measure method is useful or just something similar to

evaluating the network always with the same equation, some parts of a file *output.log* with utilization and both costs are shown:

```
Time 15.0
utilization=0.361826
Cost with cost function 1 is 314113.474917, with cost function 2 would be 314707.253977
utilization=0.361826
Cost with cost function 1 is 314113.474917, with cost function 2 would be 313393.751655
utilization=0.393735
Cost with cost function 1 is 317848.371576, with cost function 2 would be 330260.632111
utilization=0.405696
Cost with cost function 1 is 1020505.979350, with cost function 2 would be 743029.643085
utilization=0.387419
Cost with cost function 1 is 340893.873114, with cost function 2 would be 339024.936995
utilization=0.374209
Cost with cost function 1 is 315517.729668, with cost function 2 would be 308345.087034
utilization=0.387419
Cost with cost function 1 is 340893.873114, with cost function 2 would be 337225.001838
```

Figure 10. Part from log of difference cost functions in second 15 of simulation, it means when there is no too much traffic

```
Time 30.0
utilization=0.727864
Cost with cost function 1 would be 1940780.411623, with cost function 2 is 864156.752592
utilization=0.746855
Cost with cost function 1 would be 422047.008876, with cost function 2 is 501704.074797
utilization=0.845026
Cost with cost function 1 would be 535371.220865, with cost function 2 is 653618.940628
utilization=0.719926
Cost with cost function 1 would be 456935.987791, with cost function 2 is 454095.691026
utilization=0.773253
Cost with cost function 1 would be 442874.357372, with cost function 2 is 573455.431458
utilization=0.664942
Cost with cost function 1 would be 378311.376450, with cost function 2 is 356703.466896
utilization=0.818208
Cost with cost function 1 would be 492262.941639, with cost function 2 is 635359.853974
utilization=0.773253
Cost with cost function 1 would be 507214.948719, with cost function 2 is 615250.696314
utilization=0.733930
Cost with cost function 1 would be 468187.858812, with cost function 2 is 446542.218168
utilization=0.759512
Cost with cost function 1 would be 2164187.436801, with cost function 2 is 907739.795243
utilization=0.784590
Cost with cost function 1 would be 453386.142581, with cost function 2 is 644622.304295
```

Figure 11. Part from log of difference cost functions in second 30 of simulation, it means when there is too much traffic in links {1-3} and {2-4}

This text extracts from *output.log* file lets us to see that in second 15 of the simulation, when the utilization is around 0.38, results from both functions of cost are similar and the cost function used is what uses predicted queues. In second 30, when there are more transmissions and the utilization is around 0.75, results from the second cost function are very variables and, most times, different to results from cost function 1. For this reason, it is better to use this second function in this case even if the system is a little unstable (such in *Figure 9*).

6.2.2. Two Pheromone type behaviour

Two pheromone types behaviour is another proposal in the direction to solve the same problem that two measure behaviour, the problem about the limit of some cost functions and the possibility to use two different cost functions depending on any parameter. In our case, we have studied both functions of transmission time cost and the threshold to change the cost function used. The idea of this behaviour is to have two types of pheromones (it means two pheromone vectors for each node, two gammas, ..., all duplicated). Usually, just one pheromone type that uses first cost function is used, but if the threshold (utilization in our case) is exceeded in all possible paths (there is no paths from source to destination without a link with more occupation than threshold) the system will change and start to use the other pheromone type, that uses second cost function to calculate the cost. Theoretically, initialization time where ants search for all the paths is not needed because both pheromone type agents look for paths with little traffic. It is related with the capacity of links and the best cost for one pheromone type agents should be the same than for other agents. Instead of "Two measure behaviour", in this case, to have similar values from both cost functions is not necessary because each type of pheromones has its gamma. Next, how the system works is explained:

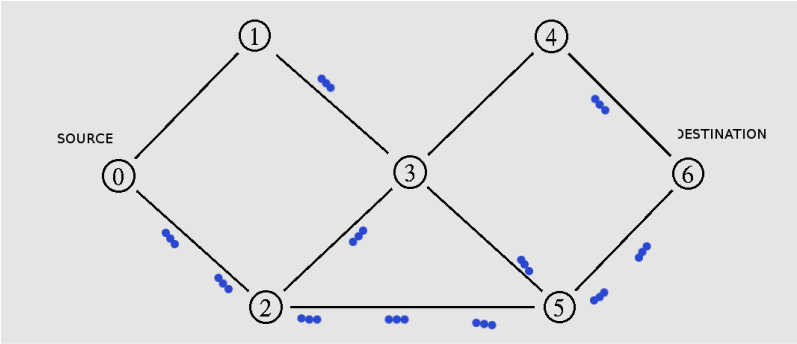


Figure 12. Agents following {0-2-5-6} path, moreover explorer ants in other paths

Agents using first pheromone type look for the paths with less transmission time. Due to CE ant system adaptivity, agents are going through links with less cost (or shortest paths). When they go through a link with utilization higher than threshold, a flag is set to one in agent packet to mark source node after backtracking. If most of agents that go back to the source have the flag set on one,

the system starts to transmit agents using the second pheromone type. One way to control agents with flag in the source (used in simulator) is to make an average of this bit while agents are arriving (the size average window can be decided with β in *Eq. 17*) and set a threshold where the used type of pheromone is changed. The result of make an average is:

$$Average = \beta \cdot Average + (1-\beta) \cdot agent\ flag \qquad \textit{Eq. 17}$$

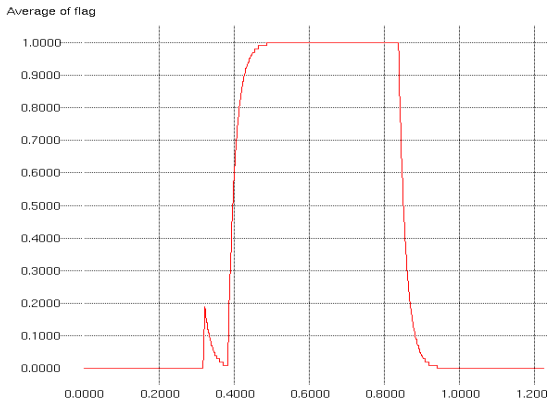


Figure 13. Graphical representation of Eq. 17 seting flag to 1 in intervals {0.31,0.32} and {0.38,0.64}

where there are few ants arriving with flag set to one around 0.3 of x axis and all ones between 0.38 and 0.64. This graph has been generated with parameter $\beta = 0.95$ and it is shown that if we set a threshold, i.e. at 0.9, the graph takes more time going from 0 to threshold (when system changes from first to second pheromone type) than going from 1 to threshold (when system changes from second to first pheromone type). This is the behaviour that we want, because the system changes from first to second pheromone type when a lot of ants find paths with links with utilization higher than threshold and when, using second pheromone type, any path with all links with utilization lower than threshold is found, the system changes quickly to main pheromone type (first cost function).

Simulations:

To simulate two pheromone types behaviour, we need to create the situation where the change is

made, hence, we have used the *network 4*, where it is easy to create that all paths have at least one link with more than threshold utilization (the same traffic than Two measure behaviour section (6.2.1), created between seconds 20 and 40). When we set the threshold of occupation to 0.5 and threshold of the average for the flag to 0.9, we get the next graphs:

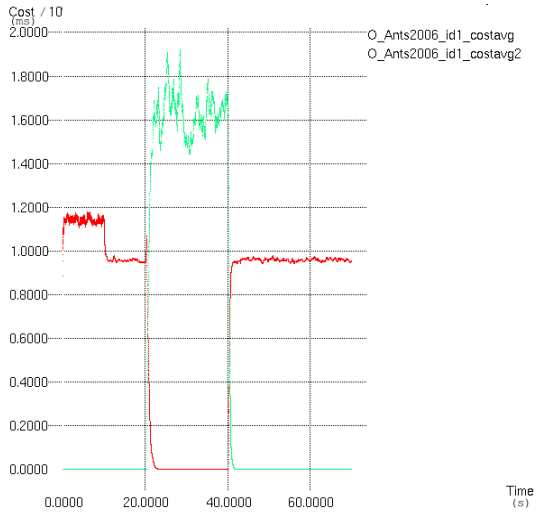


Figure 14. Cost average for a system with Two pheromone type behaviour

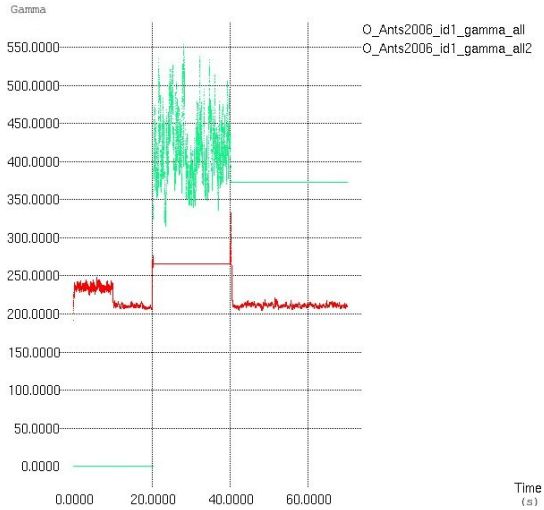


Figure 15. Gamma (elite ants + normal ants) for a system with Two pheromone type behaviour

where red lines are the cost and gamma for the agents that follow first pheromone type and green lines are the cost and gamma for agents that follow second pheromone type. The first problem observed in both pictures is the adaptivity time taken by the system to go from one pheromone type to the other one and the unexpected peaks that appear in this moment (change of pheromone types). Gammas are totally different from each other, something that, as explained before, permits the system to have cost functions that have different magnitude order. Otherwise, the same problem that appeared in the "Two measure behaviour" about big range occurs when we use the formula with real queues (*Eq. 15*). This problem is easy to solve doing an average (with a small window) of queues, but doing this average some information is lost and the system stops being updated with real time information of the network, so we have to be careful with this average and the window that we use.

Looking in simulation output files, we have checked that the load is distributed through paths 0-2-4-5 and 0-1-3-5, assigning less load to the second one, that is the path that has the link whose bandwidth is 4 Mbps (1 Mbps less than other links in the network).

In *Figure 16* and *Figure 17* (zooms from *Figure 14*), we can see the transitions of cost from the first pheromone type to the second one and from the second to the first, respectively. What is important is the pheromone type that has to be used from the given moment, which means that for the transition between the first and the second pheromone we will study the cost of second pheromone type and for transition between second and first pheromone type we will study the cost of first pheromone type. The most important thing to study is the time that it takes to change the method. First transition time is around 2 seconds, while second transition time is around 1 second. These times are acceptable compared with the time without using "Two pheromone type behaviour" (*Figure 18* and *Figure 19*) where time for first transition is around 1.5 seconds and 1 second for second transition. However, this transition time could be reduced generating some *Explorer* ants of the pheromone that does not work.

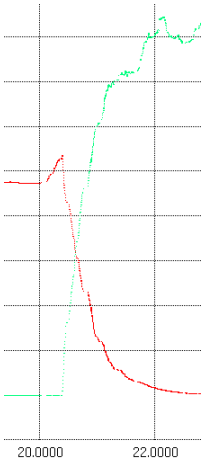


Figure 16 Moment when system changes from first to second pheromone type

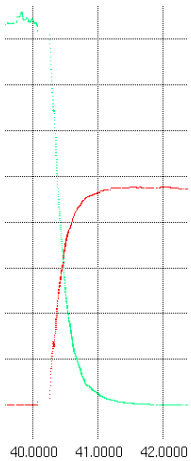


Figure 17. Moment when system changes from first to second pheromone type

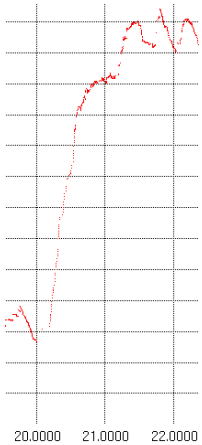


Figure 18. Moment when system starts to be overloaded

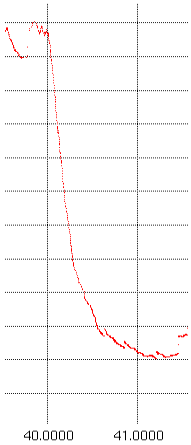


Figure 19. Moment when system leaves to be overloaded

Shown that transition times are not a problem, we can state that "Two pheromone type behaviour" is a good solution for problems about limited cost functions and a good improvement for networks in which it is useful to use two cost functions according to the conditions.

Both solutions for the problem defined (Two measure behaviour and Two pheromone type behaviour) are good to solve it. The advantage and usefulness of Two pheromone type behaviour is that it permits to use cost functions with, as well as different magnitude order, different units (bps, s, etc) and its biggest disadvantage is that it requires more complexity from the network (a lot of parameters have to be duplicated). This proposal is useful for networks with high traffic through them, which happens few times because networks are usually designed to manage more than enough load, in these cases, using this system is a waste memory and resources from switches.

A variant of two pheromone behaviour is to use it to get different proprieties depending on transmissions, i.e., it is possible to set one pheromone type to follow paths with less transmission time and other pheromone type to follow paths with less dropped packets (for this, some explorer ants from the pheromone type that is not working should be generated). With this distinction a safe path for important packets and fast path for normal packets could be found. Another example is to decide on how some agents should follow cost paths that minimize RTT (Round Trip Time) and other agents should follow cost paths that minimize transference time for big amounts of data. Just like in these last two examples, a lot of other uses differentiating two path types are possible.

6.3. Remembering Forwarding Path

Always, when an agent goes through the network, the system has to store the path, in order to backtrack after the agent finds the destination, and calculate, from cost value obtained along the path, the pheromones that it will leave in each path node.

One option is to store agent (ant) IDs, agent sources and ingoing ports in tables of each node where the agent goes through. Agent IDs and agent sources are stored because it is the only possibility to identify each agent from each node transmitting in CE ant system, and ingoing ports (or previous nodes) are stored to know where the agent comes from and where it must go after the actual node during backtracking. Because agents can be dropped or lost and not all the agents do backtracking (just elite ants), these tables should delete entries for agents that have been more time in the memory using a timer, thing that is a problem if the network is very large, because then the entries have to be in the memory a lot of time. The biggest advantage when using this method is that packets do not have to be modified with any field indicating path. On the other hand, if there are a lot of transmissions, the tables are bigger and bigger and every time that a packet gets back to the node it should check this table.

The other option is storing the path followed in ant packet. Each time that an agent arrives to a node, an identifier for recognition of the path in the backtracking is stored in the packet. This identifier can be a node ID (size magnitude like MAC addresses, 6 bytes), that stores the path in the agent packet. By this way it is possible to avoid revisit nodes for each agent and other restrictions that help agents to find the destination faster. The identifier can also be the ingoing port to the node (Port IDs), using this identifier, during the backtracking, the node merely has to observe in the packet which was the ingoing port during forwarding phase and sends the packet toward this port. Using ingoing port as identifier we lose some advantages like avoiding revisit nodes, but the size of packets is much lower than using node IDs since most switches have 40 ports as maximum (in simulations take 256 as maximum to use the worst case, 1 byte needed to store the port ID).

Simulations:

In this section of simulations we simulate both behaviours that store the identifier in the packet in order to compare them and discover if the advantages and disadvantages of both can be compared. *Network 1* is chosen, with several transmissions between its nodes and a link, between nodes 2 and 5, failure at second 20, that is recovered at second 40. In *Figure 20* we can study the cost of transmission from node 0 to node 6.

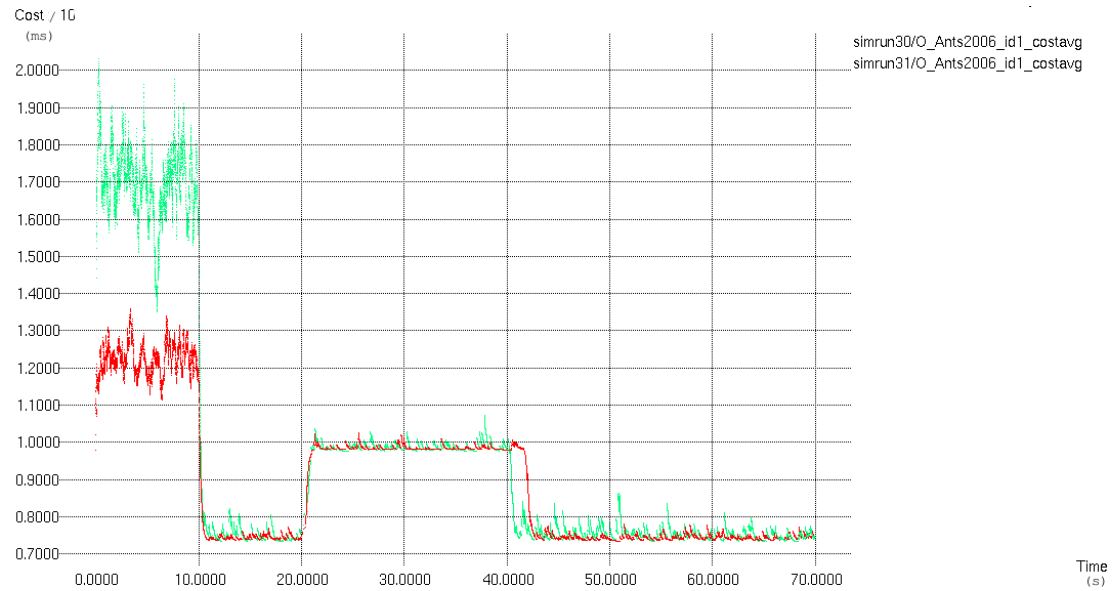


Figure 20. Cost average of both systems, "Store Port IDs" and "Store node IDs"

where green line is the simulation with port ID as a identifier and red line is the simulation with node ID as a identifier. The first objective to develop the method storing port IDs in the packet instead of storing node IDs was to reduce the traffic of the network because size of packets are lower, in the simulation we can see that what happen is the contrary because the paths for the storing port IDs method are longer and add more traffic than what they save with their lower size.

But something unexpected appears in *Figure 20*, the system storing ports in the packet converges more quickly than the other when we add a link (around 2.5 seconds) and this is always good. We have simulated the system in other networks with different traffic and, usually, Store ports IDs method converges slower than Store node IDs behaviour in more than 85% of cases studied. So, in

Figure 20, this happens because a small network is used and this specific traffic generated "lucky" conditions that produce this "illogical" result.

In order to view different environments to compare this identifier, in *Figure 21*, we have run a simulation of a network with 217 nodes and more than 20 transmissions,

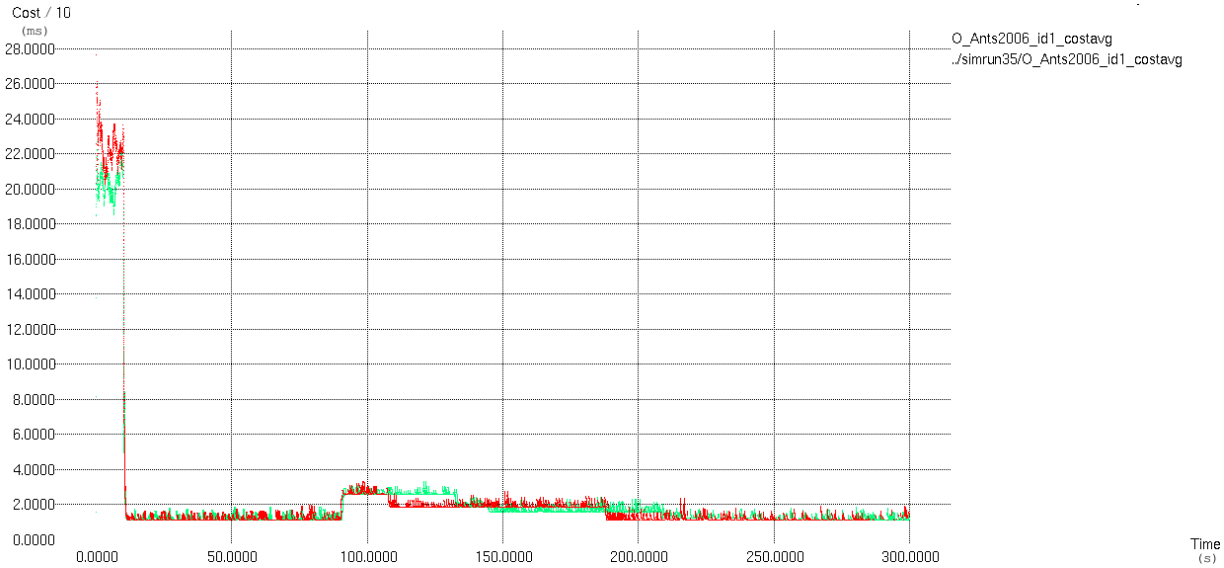


Figure 21. Cost average for a transmission in a meshed network of 217 nodes and more than 20 transmissions

where there are a lot of changes (links up and down) between seconds 90 and 180, red line is the system storing node IDs and green line is the system storing port IDs. During some intervals of time, cost of green line (storing port IDs) is lower than the cost of the red one (storing node IDs), which means that the traffic is lower (low traffic produces less transmission times), but the difference between them is insignificant and it does not compensate the big delay that storing port IDs introduces in convergence to optimal path (between 15 and 20 seconds depending the case).

All the cases studied confirm that storing ports in the identifier is not a good option to implement in a network because it is bad for large networks as well as little networks.

6.4. Generating agents

No papers and thesis, this one included, talk about basic and simple things that can affect the system greatly, such as where to generate agent packets. In order to simulate most characteristics, we use nodes that generate agent packets and we forget about the possibility that they can be generated in End Stations (also conversion from cost value to pheromone value and all things told in the thesis that was made in source and destination nodes could be made in End Stations). There are differences, advantages and disadvantages summarized in next table:

End Stations	**Advantages** - We can better distribute the traffic if we use CE ant systems only to find the path (i.e. primary backup). - One station can be connected to more than one switch and decide which path is better. - Switches need less intelligence.
	Disadvantages - Generates a lot of agent packets (many End Stations are connected to each node usually, so there are more End Stations than nodes in the network). - End stations need to work with more intelligence (usually there are more End-stations than switches). - It is useless if we have each End-Station connected to one switch because we lose the advantages.
Network Switches	**Advantages** - It reduces the agent packets traffic through the network. - It increments the scalability of the network permitting to add End stations and reuse pheromones that have already been put in the system. - A End-Station can be added without the need to generate agent traffic. - It is easier to simplify the network topology.
	Disadvantages -It is a problem to connect one End-Station to more than one switch. In this situation there would be two different gammas and the system would not know which is the best path from source to destination.

After this Advantages/disadvantages discussion, it is logical to say that using CE ant system between nodes provides more and better performance in most cases (all cases except when an End Station is connected to two nodes like in *Figure 23*, which is very rare in a network).

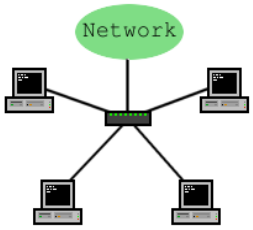


Figure 22. Each End Station connected to one switch

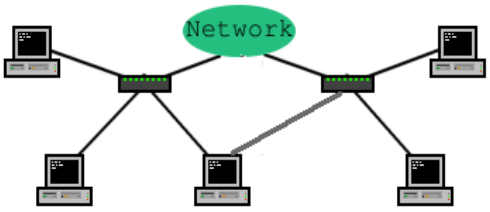


Figure 23. Network with an End Station connected to 2 switches

6.5. Load Balancing

This section is not a proposal or discussion, like last sections, about the system. Instead, this section is a study of a propriety that can be achieved with CE ant systems (Adaptive management), load balancing. In other sections (i.e. Path cost section, 6.1) it has been shown that load is distributed in the network in order to have minimal cost value for all paths. The system is a feedback system, so it changes depending on previous states:

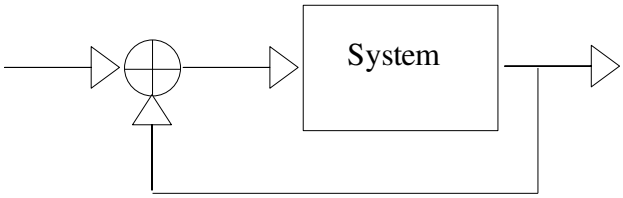


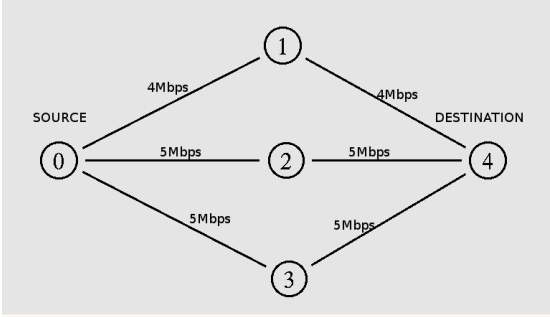
Figure 24. Scheme for a feedback system

Feedback systems (like *Figure 24*) change their behaviour depending on their entries and the state of the system just before these entries. This is the behaviour of CE ant systems, when information is entered to the system (cost value), it gives an output updating pheromones in the network, output that is also used to do that new entrance packets (ant packets) arrives to destination through optimal path.

Load balancing has always been an objective because it minimizes (since network is designed for more traffic than maximum transmitted) the probability of overload and tries that all paths have the same cost, or minimum difference between cost of the paths.

As we defined in section Switching by CE ants (section 5) we got for each node, a probability matrix to decide the next node. Remember P_t^{sd} and *Figure 4*. With this matrix, the system decides which ratio of traffic is sent to each node. If two possible paths of the network have the same cost, the probability matrix will show 0.5 and 0.5 in the positions of these links. If one of them is better than the other, the system will modify the probabilities until similar proportion between them and costs is achieved.

An easy case to view that load is distributed is in *network 5*:



network 5. Netwrok designed to check the load balancing of CE ant systems

In order to check how the load is distributed we have counted the number of ants that have gone through each path during 1 second of simulation (not during initialization time and avoiding explorer ants) and the results has been these:

	Path 0 14	***Path 0 2 4***	***Path 0 3 4***
Number of ants per path	397	2525	2600
Proportion	0,07	0,46	0,47

Where paths containing nodes 2 and 3 have similar number of agents (they have the same bandwidth) and path through node 1 has a little number of ants through it (the bandwidth is lower). Due to the fact that the utilization in paths {0,2,4} and {0,3,4} is very low, path {0,1,4} is not needed, or just for specific cases.

And the Probability matrix would be:

$$P_t^{04} = \begin{array}{c} ij \\ 0 \\ 1 \\ 2 \\ 3 \\ 4 \end{array} \begin{array}{c} \begin{array}{ccccc} 0 & 1 & 2 & 3 & 4 \end{array} \\ \begin{bmatrix} 0 & 0.07 & 0.46 & 0.47 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \end{array}$$

7. CE ant systems in typical Layer 2 networks

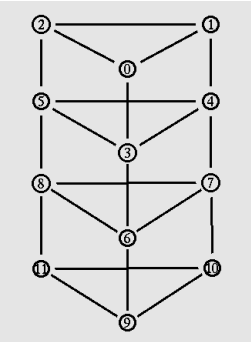
In *section 6* we have studied different proposals in networks designed specially to view how they work and check if they are useful in critical situations. In this section we will study typical Layer 2 networks, like an office building and TV factory. It is difficult to study very big networks, so, in some cases, they have been simplified.

Trondheim's wireless network was a candidate to be studied in this section. We got the topology but it was a tree topology, so there is just one path from source to destination and CE ant system is useless. The network was designed a few months ago and it is planned to add redundant paths in the next months, but the redundant paths added produce a very simple network, similar to cases studied in proposals and studies section (section 6), so its study has been discarded.

7.1. Office Building

An office building is a place where it is typical to use Layer 2 networks for the internal network and one router (gateway, Layer 3) to put the traffic to internet.

We consider a building of 4 floors (to make the study easier), where 60 people work in each one, and 3 stairways (network wires go through upstairs holes). In each floor there are three layer 2 switches that are connected between them and have 20 computers connected per switch. *Network 6* is which has this topology.



network 6. Office building (4 floors, 3 switches per floor)

Next table is the distribution of load through the network. All traffic is CE ant traffic searching for best path. Each row is a transmission from source to destination (S-D) and each column is a link (i.e. L01 is the link from node 0 to node 1). Because of the few transmissions and not the same traffic in all nodes, the total traffic for each links is not the same, but the system tends to be as equitable as possible when it gives out the paths.

		L01	L02	L12	L03	L25	L14	L34	L35	L45	L36	L47	L58	L67	L68	L78	L69	L710	L811	L910	L911	L1011
ID	S-D																					
1	0-11				X						X						X				X	
2	7-5									0.76X		0.76X	0.24X			0.24X						
3	2-4			X			X															
4	1-10						X					X						X				
5	7-9																	X		X		
6	3-8								X				X									
7	5-9												X						X		X	
8	2-9					X			0.87X		0.87X		0.13X				0.87X		0.13X		0.13X	
9	4-11											X				X			X			
10	6-1	0.27X			0.27X		0.73X	0.73X			X											
	Total	*0.27X*	*0*	*X*	*1.27X*	*X*	*2.73X*	*0.73X*	*1.87X*	*0.76X*	*2.87X*	*2.76X*	*2.37X*	*0*	*0*	*1.24X*	*1.87X*	*2X*	*2.13X*	*X*	*2.13X*	*0*

After seeing that the system distributes the load between paths, we will compare the cost function (graph that shows us more information) of system with only one pheromone type and system with two pheromone types.

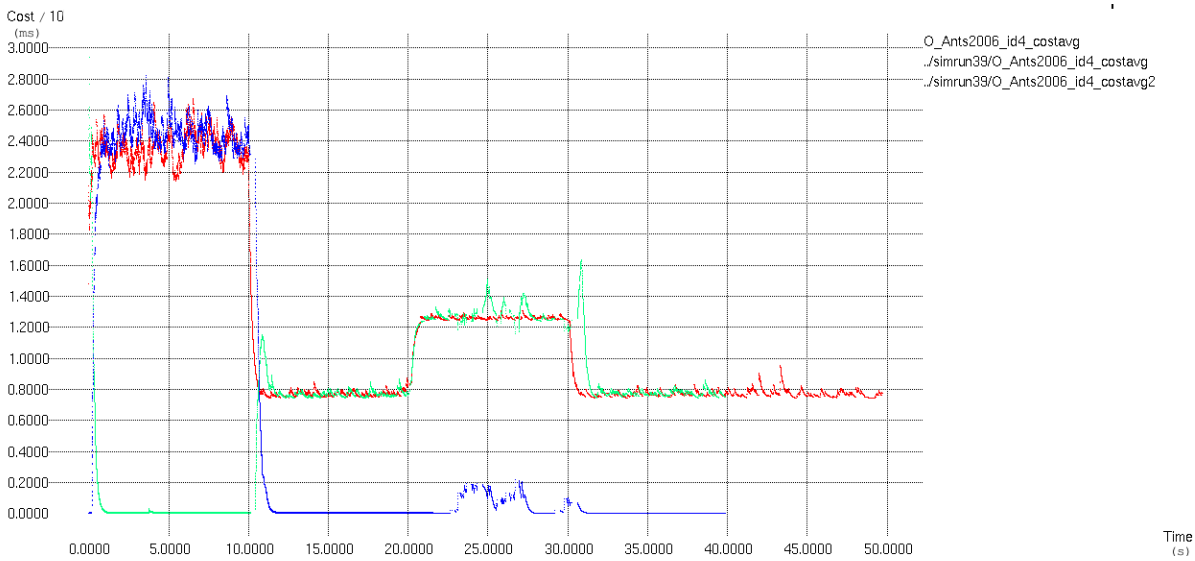


Figure 25. Cost average graph comparing systems with One pheromone type and Two pheromone type in Office building network

where red line is the cost of system with "One pheromone type", green and blue line are first and second pheromone from the system with two pheromone type respectively. We have used the transmission with ID4 to generate these graphs, because it goes through two of most used links (as can be seen in distribution load table) and the two pheromone type behaviour is easier to see. The system of two pheromones behaviour is made with the requirement that it runs if all possible paths cross the threshold for change from first to second pheromone type, so in the graph we can observe that during initialization time (first 10 seconds), where all agents are *Explorer* ants and there is a lot of traffic in the network, second pheromone type is used to mark the path. Also, when there are changes in the network and all agents are looking for paths, second pheromone type agents enter in action and help first pheromone type ants to find the path and then they disappear. *Figure 25* shows that the convergence in Two pheromone type behaviour is slower than in One pheromone type behaviour. This comes from bad stability of gamma in transition instants in TPB, thing that should be studied in the future, using some *Explorer* ants (or *Normal* ants) for first pheromone while second one is working and the opposite way (*Explorer* or *Normal* ants for second pheromone while first one is working) could be a good option to solve that. Next, we present *Figure 26*, a graph where the gammas for both systems (TPB system has two gammas) can be seen with the same colours per graph than *Figure 25*.

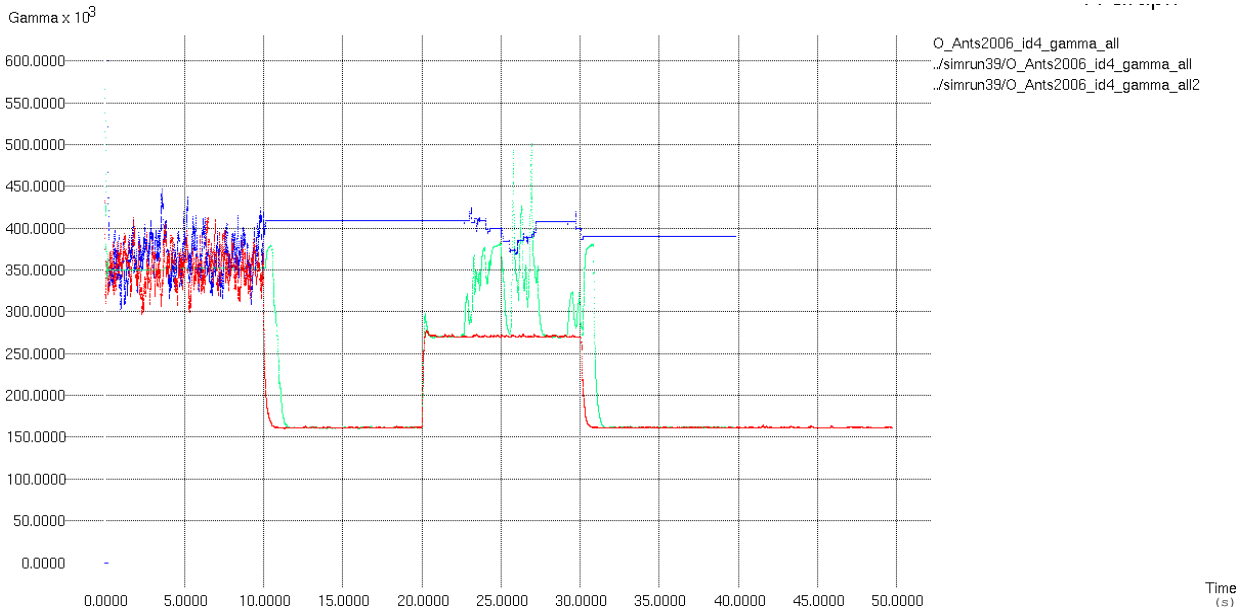


Figure 26. Gamma graph comparing systems with One pheromone type and Two pheromone type in Office building network

Just after changes in the network, there is (in TPB) alternation of pheromone used, this makes that gammas are unstable. As we said before, this should be solved with some agents (few ants, just to maintain the pheromones) continuously searching for the best path for one pheromone type while the system with the other pheromone type is working. This would eliminate the problems with stability in the moments when the network changes and should achieve an earlier convergence of the network.

7.2. T.V. factory

Another typical place where Layer 2 networks are used is factories. Simplifying, they usually have 4 or 5 departments: Human resources, Engineering, Design, Production lines and Warehouse. We have put our attention in a TV factory whose topology is known for us:

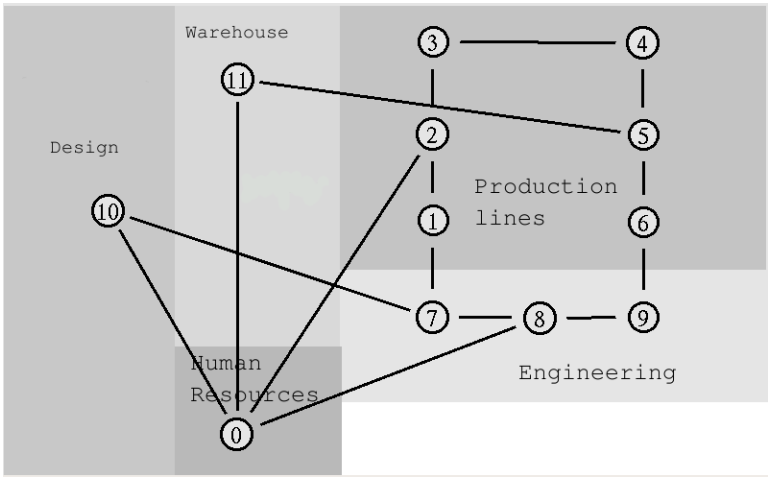
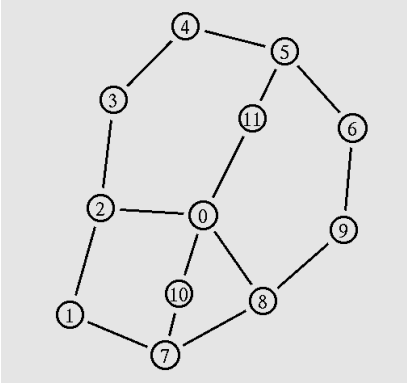


Figure 27. Network topology for a known TV factory



network 7. Re-layout of topology of TV factory

Figure 27 and *network 7* are the same network, one distributed in different parts of the factory, the other one, simplified to make its study easy. Every department has to communicate with Human Resources to update information about workers, so there will be some traffic in that direction. But most traffic will be from and to engineering, with all production lines and with design.

To view how the load is distributed we will generate the same table than for Office building case:

		L02	L08	L010	L011	L115	L107	L12	L23	L34	L45	L56	L69	L89	L78	L71
ID	S-D															
1	0-8		X													
2	0-11				X											
3	0-10			X												
4	0-2	X														
5	7-8														X	
6	7-9													X	X	
7	8-9													X		
8	1-7															X
9	2-7							X								X
10	3-7							X	X							X
11	4-9										X	X	X			
12	5-9											X	X			
13	6-9												X			
14	10-7						X									
15	11-5					X										
16	11-2	X			X											
	Total	*2X*	*X*	*X*	*2X*	*X*	*X*	*2X*	*X*	*0*	*X*	*2X*	*3X*	*2X*	*2X*	*3X*

In the table it is shown that no transmissions are distributed between more than two paths (unlike in Office building network), this is because network links make the network high percent meshed and there is always one short path and very large alternative paths in most cases, so the short path

should have a very high utilization for the system to use the alternative paths.

In order to view what happened to the network in eventual link failure cases we have simulate that the link between nodes 6 and 9 goes down from second 20 to second 35. We want to check the convergence of transmissions that goes through this link (id11, id12 and id13):

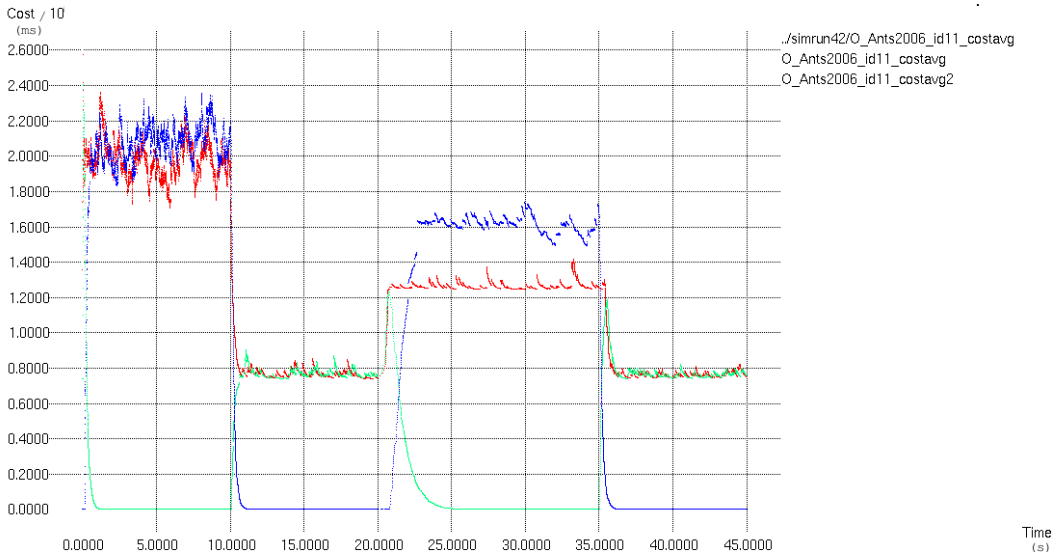


Figure 28. Cost average graph comparing systems with One pheromone type and Two pheromone type in TV factory network

where, like in previous graphs, in *Figure 28*, red line is the cost (cost average) of the system with one type of pheromones and green and blue lines are the cost average of first and second pheromone type in the system with two types. The graph is made with agents going from node 4 to 9, so the shortest path before link goes down is {4,5,6,9} and when the link is down, shorter paths have at least 4 nodes between node 4 and node 9. That does not mean that the shorter paths are better than longer paths, we are using transmission time, but it gives us an idea of the difficulty to find the new path when the shortest is down and we are using two pheromone types (it could be solved by the same way told before, including some ants while one pheromone type is not used). For this reason, when the link goes down the TPB system converges slower than one pheromone type system and convergence is similar in both systems when the link is recovered.

8. Conclusions

All possible conclusions to be found from the work of this thesis have been discussed in the subsections of Proposals and Studies (*section 6*). Hence, conclusions is a summary of all discussions previously done.

After learning about CE ant systems behaviour, we have proposed 5 ideas to be studied. They are:

- Use of transmission time path cost.
- Use of Two measure behaviour.
- Use of Two pheromone type behaviour.
- Store Port IDs in packets instead of Store node IDs.
- Agent generation in End Stations instead of in Network nodes.

Some of these proposals have been discarded after theoretical study, like where to generate the agents, we have seen that it introduces disadvantages in face of just one advantage for a very special case. And other proposals have been discarded after simulations, like in the case of Store port IDs, which produces the opposite effect desired, and Two measure behaviour, that introduces some improvements to the system, but worse improvements than Two pheromone type behaviour.

Both transmission time cost and Two pheromone type behaviour have obtained good results in all our theoretical and simulation tests.

Transmission time cost function fulfils all the requests needed for a CE ant system path cost function. As well as what we studied (it distributes the load, it converges and it is very stable), transmission time cost function influence directly to q2s of the system, which means that the system always searches for the best path using a cost value perceived for the system users.

Two pheromone type behaviour is also an improvement to the system when we need to use different cost functions for different environments. In our case, this method improves the system using two different cost functions depending on the utilization of the links of the path. This behaviour achieves that for very high utilizations of links we can use a reliable and on-time function and for very low utilizations, we can use an approximate cost value more useful for our system. The only problem of TPB systems is the transition moments between the use of two types of pheromones, where, during little time, there is instability that produces transition times larger than expected.

In the future, the way to improve the TPB should be studied, specifically the problem of transition times. Our first ideas have been given in this thesis, like generating some ants (*Explorer* or *Normal*) following and updating the pheromone that is not working in the system. Another solution could be to generate an amount of *Explorer* ants when a change in the system is detected. Or maybe other better solutions could be found, but that is the way to follow.

This thesis gives some basic principles and demonstrate that a lot of ideas can be proposed and studied in the future of CE ant systems, where some of them will be improvements and others just demonstrations to discard ways of study, but without them, the systems would not be improved.

In the following years, more practical things have to be studied and decided, such as how to design devices, how to distribute the packets, and other important aspects of the network performance

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Appendix

As we told in section where CE ant system extension for NS-2 designed by Otto Wittner, the programming language is C++ and the code written in C++ is divided by classes. Next, we present the code of modified files marking which are the modifications made. These files will be supplied in a CD attached to the thesis. We strongly recommend to study the code from source files, due to printed is more difficult to understand.

The files that we have modified are (paths from “ns-2.30”):

- ~/queue/queue.cc
- ~/queue/queue.h
- ~/link/delay.cc
- ~/link/delay.h
- ~/swarm/common/swarm-rtmodule.cc
- ~/swarm/common/swarm-rtmodule.h
- ~/swarm/O_Ants2006/O_Ants2006_trace.cc
- ~/swarm/O_Ants2006/O_Ants2006_trace.h
- ~/swarm/O_Ants2006/O_Ants2006_swarmrtm.cc
- ~/swarm/O_Ants2006/O_Ants2006_swarmrtm.h

where O_Ants2006 system is a variant of Ants2006 system designed before.

Firstly, we have generate some functions to get the information that we want, next the traffic function (it has to return the traffic of the link) and bandwidth function, it has to return the bandwidth of the link.

– ~/link/delay.cc:

```
void LinkDelay::recv(Packet* p, Handler* h)
{
	//(Oriol):
	#define BETA 0.95
	double txt = txtime(p);
	Scheduler& s = Scheduler::instance();
	double c_time=s.clock();//(Oriol)
	txt_=txt;

	if (c_time!=0)
	{
		if(c_time > finish_packet_time())
		{
			traffic_= traffic_*BETA + (1 - BETA)*(size_anterior_/ (c_time -
					finish_packet_time()) );
			//printf("traffic_=%lf, size anterior_=%lf, time=%lf\n", traffic_,
					size_anterior_, c_time-finish_packet_time());
		}else{
			traffic_= traffic_;

		}
	}
	else {
		traffic_=0;
		size_anterior_=0;
	}
	size_anterior_=8*hdr_cmn::access(p)->size();
	finish_packet_time_=c_time;//(Oriol)
	if (dynamic_) {
		Event* e = (Event*)p;
		e->time_= txt + delay_;
		itq_->enque(p); // for convinience, use a queue to store packets in transit
		s.schedule(this, p, txt + delay_);
	} else if (avoidReordering_) {
		// code from Andrei Gurtov, to prevent reordering on
		//   bandwidth or delay changes
		double now_ = Scheduler::instance().clock();
		if (txt + delay_ < latest_time_ - now_ && latest_time_ > 0) {
			latest_time_+=txt;
			s.schedule(target_, p, latest_time_ - now_ );
		} else {
			latest_time_ = now_ + txt + delay_;
			s.schedule(target_, p, txt + delay_);
		}

	} else {
		s.schedule(target_, p, txt + delay_);
	}
	s.schedule(h, &intr_, txt);
}
```

where variable traffic_ stores the traffic that the system want to send through the link. The function that returns it is defined in:

– ~/link/delay.cc:

```
class LinkDelay : public Connector {
 public:
       LinkDelay();
       void recv(Packet* p, Handler*);
       void send(Packet* p, Handler*);
       void handle(Event* e);
       double delay() { return delay_; }
       inline double txtime(Packet* p) {
              return (8. * hdr_cmn::access(p)->size() / bandwidth_);
       }
       double bandwidth() const { return bandwidth_; }                    //(Oriol)
       double traffic() const { return traffic_; }                        //(Oriol)
       double finish_packet_time() { return finish_packet_time_; }        //(Oriol)
       double gettxt(){ return txt_; }                                    //(Oriol)
       void pktintran(int src, int group);
 protected:
       int command(int argc, const char*const* argv);
       void reset();
       double bandwidth_;  /* bandwidth of underlying link (bits/sec) */
       double delay_;             /* line latency */
       double traffic_;                 //(Oriol)
       double txt_;                     //(Oriol)
       double finish_packet_time_;      //(Oriol)
       double size_anterior_;           //(Oriol)
       Event intr_;
       int dynamic_;       /* indicates whether or not link is ~ */
       double latest_time_;       /* latest scheduled packet time, for use
                           *  with avoidReordering_ */
       PacketQueue* itq_;
       int total_[4];
       int avoidReordering_;      /* indicates whether or not to avoid
                           *  reordering when link bandwidth or delay
                           *  changes */
};
```

Other function needed is the queue function, that returns the value of the queue of the link:

– ~/queue/queue.c:

```
void Queue::recv(Packet* p, Handler*)
{
	//(Oriol):
	#define BETA 0.6

	double now = Scheduler::instance().clock();
	bits_avg_=bits_avg_*BETA + (1-BETA)*8*byteLength(); //(Oriol)
	//printf("queue=%lf\n", bits_avg_);                 //(Oriol)
	enque(p);
	if (!blocked_) {
		/*
		 * We're not blocked.  Get a packet and send it on.
		 * We perform an extra check because the queue
		 * might drop the packet even if it was
		 * previously empty!  (e.g., RED can do this.)
		 */
		p = deque();
		if (p != 0) {
			utilUpdate(last_change_, now, blocked_);
			last_change_ = now;
			blocked_ = 1;
			target_->recv(p, &qh_);
		}
	}
}
```

And file queue.h where is defined the function that returns bits_avg_ value:

– ~/queue/queue.h:

```
class Queue : public Connector {
public:
       virtual void enque(Packet*) = 0;
       virtual Packet* deque() = 0;
       virtual void recv(Packet*, Handler*);
       virtual void updateStats(int queuesize);
       void resume();

       int blocked() const { return (blocked_ == 1); }
       void unblock() { blocked_ = 0; }
       void block() { blocked_ = 1; }
       int limit() { return qlim_; }
       double bitsLengthAvg() { return bits_avg_; } //(Oriol)
       int length() { return pq_->length(); } /* number of pkts currently in
                                       * underlying packet queue */
       int byteLength() { return pq_->byteLength(); }       /* number of bytes *
                                       * currently in packet queue */
       /* mean utilization, decaying based on util_weight */
       virtual double utilization (void);

       /* max utilization over recent time period.
          Returns the maximum of recent measurements stored in util_buf_*/
       double peak_utilization(void);
       virtual ~Queue();
protected:
       Queue();
       void reset();
       int qlim_;          /* maximum allowed pkts in queue */
       double bits_avg_;         //(Oriol)
       int blocked_;       /* blocked now? */
       int unblock_on_resume_;   /* unblock q on idle? */
       QueueHandler qh_;
       PacketQueue *pq_;   /* pointer to actual packet queue
                            * (maintained by the individual disciplines
                            * like DropTail and RED). */
       double true_ave_;   /* true long-term average queue size */
       double total_time_; /* total time average queue size compute for */


       void utilUpdate(double int_begin, double int_end, int link_state);
       double last_change_;  /* time at which state changed/utilization measured */
       double old_util_;     /* current utilization */
       double util_weight_;  /* decay factor for measuring the link utilization */
       double util_check_intv_; /* interval for reseting the current
                                utilization measurements (seconds) */
       double period_begin_;     /* time of starting the current utilization
                                measurement */
       double cur_util_;   /* utilization during current time period */
       int buf_slot_;            /* Currently active utilization buffer */
       double *util_buf_;    /* Buffer for recent utilization measurements */
       int util_records_;  /* Number of recent utilization measurements
                              stored in memory. One slot in buffer holds
                              period of util_check_intv_ seconds. */
       // measuring #drops

};
```

In order to use these functions depending on the node where we are (node running the program) and node to visit (queue and traffic are for the link between to nodes), we have to modify the files with the name swarm-rtmodule:

– ~/swarm/common/swarm-rtmodule.cc:

```
//(Oriol):
double Neighbour::bandwidth()
{
	if (linkelements_.find("DelayLink") != linkelements_.end() )
	{
		return (((LinkDelay*)linkelements_["DelayLink"])->bandwidth() );
	}

	return 0;
}

//(Oriol)
double Neighbour::traffic()
{
	if (linkelements_.find("DelayLink") != linkelements_.end() )
	{
		return (((LinkDelay*)linkelements_["DelayLink"])->traffic() );
	}

	return 0;
}

//(Oriol)
double Neighbour::ultimtemps()
{
	if (linkelements_.find("DelayLink") != linkelements_.end() )
	{
		return (((LinkDelay*)linkelements_["DelayLink"])->finish_packet_time() );
	}

	return 0;
}

//(Oriol)
double Neighbour::retard()
{
	if (linkelements_.find("DelayLink") != linkelements_.end() )
	{
		return (((LinkDelay*)linkelements_["DelayLink"])->delay() );
	}

	return 0;
}

//(Oriol)
double Neighbour::bitsQueueDrT()
{
	if (linkelements_.find("Queue") != linkelements_.end() )
	{
		return (((Queue*)linkelements_["Queue"])->bitsLengthAvg() );
	}
```

```
        return 0;
}
```

And the file ".h" to define what has been programmed in ".cc" file:

– ~/swarm/common/swarm-rtmodule.h:

```
class Neighbour {
       // Handles info related to a link connecting a neighbour node
public:
       Neighbour(nsaddr_t, NsObject *);
       ~Neighbour();

       // Return true if neighbour is one hop away.
       bool oneHopAway() { return (! linkelements_.empty() ); };
       nsaddr_t addr() { return addr_; };
       NsObject* entry() { return entry_; };

       double traffic();               //(Oriol)
       double retard();                //(Oriol)
       double ultimtemps();            //(Oriol)
       double bitsQueueDrT();          //(Oriol)
       double bandwidth(); // Return the Bandwidth of the link (Oriol)
       bool linkdown();    // Return true if link to neighbour is down or does not exist

       // Return link properties
       //  double getBandwidth();
       //int getQueuelength();
       //double getProbagationdelay();
       //double getSecuritylevel();

protected:

       static const char* known_linkelementclass_[];    // Lookup table with recognised
                                                           link element classes

       nsaddr_t addr_;                   // Address of this neighbour
       NsObject* entry_;                 // Entry point for this neighbour

       //     list<lelement> linkelements_;      // Sequence of link elements leading to
                                                     neighbour
       map<const char*, Connector*, ltstr> linkelements_;     // Sequence of link
                                                              elements leading to neighbour

};
```

The most important file, where the biggest part of the behaviour has been designated, is O_Ants2006_swarmrtm.cc. We show next the file preceded of ".h" file in order to do easier the understanding.

– ~/swarm/O_Ants2006/O_Ants2006_swarmrtm.h:

```
#ifndef ns_O_Ants2006_swarmrtm_h
#define ns_O_Ants2006_swarmrtm_h

#include <list>
#include <set>
#include "delay.h"
#include "swarm-rtmodule.h"
#include "O_Ants2006_trace.h"
#include "CEants.h"

#define SERVICE_TIME  0.001       // Simulated swarm agent processing time

// Ant behaviour types
#define O_Ants2006_normal 0
#define O_Ants2006_explorer 1
#define O_Ants2006_datapacket 2

class O_Ants2006_data : public AppData {
       // Packet data holding state of swarm agent
public:
       O_Ants2006_data(int behaviour, int pheroid, int max_ttl,
                            double beta, double rho, double D, double alfa, double
                                 current_rate) : AppData(SWARM_DATA) {
              // Init.
              state_ = SWS_IDLE;
              behaviour_ = behaviour;
              pheroid_ = pheroid;
              max_ttl_ = max_ttl;

              alfa_ = alfa;
              current_rate_ = current_rate;

              tabulist_ = new list<pair<nsaddr_t, NsObject*> >();

              birthtime_ = 0;

              gamma_ = 0;
              gamma2_ = 0;              //(Oriol)
              beta_ = beta;
              rho_ = rho;
              D_ = D;
              L_path_ = 0;
              L_path2_ = 0;             //(Oriol)
       }

       O_Ants2006_data(O_Ants2006_data& d) : AppData(d) {
              // Make this a copy of "d"
              state_ = d.state_;
              behaviour_ = d.behaviour_;
              pheroid_ = d.pheroid_;
              max_ttl_ = d.max_ttl_;
```

```
            alfa_ = d.alfa_;
            current_rate_ = d.current_rate_;

            tabulist_ = new list<pair<nsaddr_t, NsObject*> >(d.tabulist());
            //tabulist_ = new list<pair<nsaddr_t, NsObject*> >();

            birthtime_ = d.birthtime_;

            gamma_ = d.gamma_;
            gamma2_ = d.gamma2_;      //(Oriol)
            beta_ = d.beta_;
            rho_ = d.rho_;
            D_ = d.D_;
            L_path_ = d.L_path_;
            L_path2_= d.L_path2_;     //(Oriol)
      }

      virtual ~O_Ants2006_data() {
            delete tabulist_;
            //delete tabuentrylist_;
      }

      // Access methods
      inline int& state() {return state_; };
      inline int& behaviour() {return behaviour_;};
      inline int& pheroid() {return pheroid_; };
      inline int& max_ttl() {return max_ttl_; };
      inline int& go_second() {return go_second_; };                          //(Oriol)
      inline int& go_first() {return go_first_; };                            //(Oriol)
      inline int& from1st() {return from1st_; };                              //(Oriol)
      inline list<pair<nsaddr_t, NsObject*> >& tabulist() {return *tabulist_; };
      //     inline list<NsObject*>& tabuentrylist() {return *tabuentrylist_; };
      //inline NsObject*& last_node() {return last_node_;};
      inline float& birthtime() {return birthtime_; };
      inline double& gamma() {return gamma_;};
      inline double& gamma2() {return gamma2_;};                              //(Oriol)
      inline double& beta() {return beta_;};
      inline double& rho() {return rho_;};
      inline double& D() {return D_;};
      inline double& L_path() {return L_path_;};
      inline double& L_path2() { return L_path2_;};                           //(Oriol)
      inline double& alfa() {return alfa_;};
      inline double& current_rate() {return current_rate_;};

      virtual int size() const { return 1; //sizeof(state_) +
//                                       sizeof(pheroid_) +
      //                                       tabulist_->size() * sizeof(nsaddr_t); }
}

      virtual AppData* copy() { return new O_Ants2006_data(*this); }

protected:
      // Swarm agent state info
      int state_;                 // State of agent
      int behaviour_;             // Behaviour type
      int pheroid_;               // Swarm agent species id
      int max_ttl_;               // Initial value for ttl field
      int go_second_;             // (Oriol) Flag that says if continue with first or
                                        second pheromone (0 and 1)
      int go_first_;              // (Oriol)
      int from1st_;               // (Oriol)

      double alfa_;                // Weight for geometric rate averaging
      double current_rate_;        // Agent generation rate when this agent was created
```

```
        list<pair<nsaddr_t, NsObject*> >* tabulist_;         // List of already visited
                                                                nodes
        //     list<NsObject*>* tabuentrylist_;   // List of entries towards already
                                                        visited nodes
        //NsObject* last_node_;                          // Pointer to entry of last node

        float birthtime_;            // Time of "birth"

        double gamma_;               // "Temperature"
        double gamma2_;              // "Temperature" (Oriol)
        double beta_;                // "Evaporation factor"
        double rho_;                 // Search focus
        double D_;                   // Applied for rho reduction
        double L_path_;              // Path cost
        double L_path2_;                  // Path cost 2 (Oriol)
};


class O_Ants2006_SwarmRtM : public SwarmRtModule  {
        // Swarm system routing module
        // implementing O_Ants2006_ii_impl_rate ant
public:
        O_Ants2006_SwarmRtM();

        virtual const char* module_name() const { return "O_Ants2006"; }
        virtual void expire(Event *);                           // Timeout handler
        virtual int command(int argc, char const *const *argv);

        float get_cost();                       //(Oriol) Return cost recoded by current
                                                        swarm agent
        float get_cost2();                   // (Oriol)Return cost recoded by current swarm
                                                        agent
        float get_gamma();                   // Return gamma (temperature) recoded by
                                                        current swarm agent (elite)
        float get_gamma2();                  // (Oriol) Return gamma (temperature) recoded
                                                        by current swarm agent (elite) 2
        float get_gamma_all();               // Return gamma (temperature) for all agents
        float get_gamma_all2();              // (Oriol) Return gamma (temperature) for all
                                                        agents 2
        list<pair<nsaddr_t,NsObject*> >& get_path();        // Return path traversed by
                                                                current swarm agent
        float get_delay();                   // Return delay experienced by current swarm
                                                        agent
        float get_elitelimit();              // Return limit for elite set membership
        float get_elitelimit2();             // (Oriol) Return limit for elite set
                                                        membership 2
        float get_rho();                     // Return rho applied

        inline double& ind_queues() {return ind_queues_;};  //(Oriol)
        int get_pheroid();                     // Return pheromone id
        int get_behaviour();                   // Return behaviour flag (0 = normal, 1 =
                                                        explorer)
        map<nsaddr_t, double>&  get_phero();  // Return map of pheromone values for
                                                        current agent
        map<nsaddr_t, double>&  get_phero2(); //(Oriol) Return map of pheromone values for
                                                        current agent
        double get_backtrack_rate();           // Return estimated rate of backtracking
                                                        agents

protected:
        void recalc_gamma(GammaAutoreg&, double, double, double);  // Calculate new
                                                                temperature (gamma)
        void rho_reduction(double);            // Adjust rho if no new best path has been
```

```
                                        found by the last D agents

O_Ants2006_data* swarmagent_;           // Pointer to current visiting swarm agent
                                            data structure


double ultim_temps_;
float cost_actual_;                                 //(Oriol) Actual cost
float cost_actual2_;                                //(Oriol) Actual cost2
PheroTable pherotable_;                 // Table of pheromones towards neighbour
                                            nodes
PheroTable pherotable2_;                // (Oriol) Table of pheromones towards
                                            neighbour nodes
double ind_queues_;                     //(Oriol) flag to know if agent has to be
                                            sent with go_second set on.
bool trace_phero_;                      // Flag for enabling trace of pheromone
                                                value
bool trace_phero2_;                     // (Oriol) Flag for enabling trace of
                                            pheromone value
set<int> trace_pheros_   ;              // Set of phero ids to be traced
set<int> trace_pheros2_   ;             // (Oriol) Set of phero ids to be traced
map<nsaddr_t,double> phero_list_;       // Map of neighbour-node-address and
                                            pherolevels
map<nsaddr_t,double> phero_list2_;      // (Oriol) Map of neighbour-node-address
                                            and pherolevels

// (Maps below are indexed by pheroid)
map<int,GammaAutoreg> gammaautoreg_;          // Temperature autoregression
                                                  parameters
map<int,GammaAutoreg> gammaautoreg_elite_;    // Temperature autoregression
                                                  parameters for elite
                                                  O_Ants2006_ii_impl_rates
map<int,double> best_cost_;                   // Best cost found so far
map<int,double> period_since_new_best_;       // Time period since a new best
                                                  cost was found
map<int,double> rho_reduction_factor_;        // Factor applied to tighten rho
map<int,GammaAutoreg> gammaautoreg2_;          // (Oriol) Temperature
                                                  autoregression parameters
map<int,GammaAutoreg> gammaautoreg_elite2_;    // (Oriol) Temperature
                                                  autoregression parameters for
                                                  elite O_Ants2006_ii_impl_rates
map<int,double> best_cost2_;                   // (Oriol) Best cost found so far
map<int,double> period_since_new_best2_;       // (Oriol) Time period since a new
                                                  best cost was found


double backtrack_rate_estimate_;                  // Estimate of rate of
                                                        backtracking ants
double last_backtrack_time_;              // Arrival time of latest backtracking
                                              ant
list<double> backtrack_interarrival_time_samples_;  // Window of interarrival time
                                                        samples
double backtrack_interarrival_sum_;               // Sum of samples in window

double forward_rate_estimate_;            // Etimates of rate of incoming forward
                                              ants
double last_forward_time_;                // Arrival time of latest forward ant
Packet* last_forward_agentpacket_;        // Copy of last forward agent packet
list<double> forward_interarrival_time_samples_;  // Window of interarrival time
                                                        samples
double forward_interarrival_sum_;                // Sum of samples in window

bool local_boost_;                        // Flag indicating if local
                                              boosting/generation of agents should
                                              happend on link failures
```

```
        int min_replica_;                          // Minimum no of forward ant copies
                                                       generated as the result of a local
                                                       boost
        map<Neighbour*, bool> last_neighbourhood_;       // State of connections to
                                                            neighbour nodes the last time
                                                            a packet/agent arrived
        void local_boost(NsObject*);                      // Execute local boost
        map<int,double> current_normal_rate_;          // Current rate reported for normal
                                                            agents
        map<int,double> current_explorer_rate_;        // Current rate reported for
                                                            explorer agents


};

#endif
```

In next file is easy to differentiate the programming for different behaviours because they have “if()” sentences with the flag that activate each behaviour:

– ~/swarm/O_Ants2006/O_Ants2006_swarmrtm.cc:

```
#include <stdio.h>

#include "O_Ants2006_swarmrtm.h"
#include "delay.h"
#include <vector>
#include <algorithm>
#include <values.h>

#define T_INFINITY_APPROX 3000
#define STORE_PORTS_BEHAVIOR 0 //(Oriol) Decide the behavior of the agents,
                                  1=>comportament de ports :: 0=>comportament de ids
#define TWO_MEASURE_BEHAVIOR 0 //(Oriol) IMPORTANT:if TWO_PHERO_BEHAVIOR IS ENABLED,
                                  THIS MUST BE DISABLED
#define TWO_PHERO_BEHAVIOR 0   //(Oriol) Decide the behavior of the system, 1=>two
                                  pheros per link  ::0=>one phero per link
#define BETA_QUEUES 0.95     //(Oriol) Decide how many paths with queue have to be found
                                  to change pheromone
#define LIMIT_PHEROS 0.95    //(Oriol) Decide when to change from one pheromone to the
                                  other one
#define MAX_UTILIZATION 0.5         //(Oriol) Decide when the second pheromone (or
                                       measure)  is used (utilization + queue length).
                                       NOTE: always < 0.999999


O_Ants2006_SwarmRtM::O_Ants2006_SwarmRtM() : SwarmRtModule()
{

       // Set swarm type
       myswarmtype_ = SWT_O_Ants2006;

       trace_phero_ = false;
       trace_pheros_.clear();
       if(TWO_PHERO_BEHAVIOR==1){
       trace_phero2_ = false;
       trace_pheros2_.clear();}

       backtrack_rate_estimate_ = 0;
       cost_actual_=0;
       cost_actual2_=0;
       last_backtrack_time_ = 0;
       forward_rate_estimate_ = 0;
       last_forward_time_ = 0;
       last_forward_agentpacket_ = NULL;
       forward_interarrival_sum_ = 0;
       backtrack_interarrival_sum_ = 0;
       local_boost_ = false;
       min_replica_ = 0;
       ind_queues_=0;
       ultim_temps_=0;
}


void O_Ants2006_SwarmRtM::expire(Event* e)
```

```
  // Timeout handler
  // ... continue to implement swarm agent behaviour
{

      // Prepare access to swarm agent state in packet (p_ is current packet)
      swarmagent_ = (O_Ants2006_data*)p_->userdata();

      // Access headers
      hdr_cmn* ch = hdr_cmn::access(p_);
      hdr_ip* ip = hdr_ip::access(p_);

      // I m p l e m e n t   s w a r m   a g e n t   b e h a v i o u r

      // Short behaviour description:
      // - Visits new nodes until destination node or a dead end is reached, i.e. all
            neighbours have been visited.
      // - Destination can be any node including the source node. If dest = source, a
            TSP route is searched for.
      // - If dead end and a neigbour is destination node, goes to destination. Hence
            given a fully meshed network, it finds an Hamiltonian path.
      // - If dead end and destination is not neighbour, select next node uniformly
            among neigbours. i.e. revisit.
      // - Only elite O_Ants2006 update pheromones, however the temperature for all ants
            regulates the elite set

      switch (swarmagent_->state()) {
      case SWS_IDLE:
            // Agent is at home node ready to start forward seach
            swarmagent_->state() = SWS_FORWARDSEARCH;
            swarmagent_->birthtime() = now();
            swarmagent_->go_second() = 0;    //(Oriol)
            swarmagent_->go_first() = 0;     //(Oriol)
            swarmagent_->from1st() = 0;      //(Oriol)
            swarmagent_->L_path()=0;
            swarmagent_->L_path2()=0;

            if(TWO_PHERO_BEHAVIOR==1)
            {
                  if(ind_queues_ <= LIMIT_PHEROS)
                  {
                        swarmagent_->from1st()=0;
                  }else{
                        swarmagent_->from1st()=1;
                  }

            }


            if (swarmagent_->behaviour() == O_Ants2006_datapacket) {
                  // Agent is a datapacket ant
                  // Log trace info
                  if (trace_)
                        trace_->sample(this, O_Ants2006_DATAPACKETCOUNT );
            } else {
                  // Log trace info
                  if (trace_)
                        trace_->sample(this, O_Ants2006_FORWARDCOUNT);
            }

            // Set color in nam
            ip->flowid() = 0;

      case SWS_FORWARDSEARCH:
```

```
// Store copy of packet. To be used during local boost.
if( swarmagent_->behaviour() == O_Ants2006_normal && local_boost_) {
	if (last_forward_agentpacket_)
		Packet::free(last_forward_agentpacket_);
	last_forward_agentpacket_ = p_->copy();
}
// Update rate estimate of forward ants (normal + explorer)
if (swarmagent_->behaviour() == O_Ants2006_normal || swarmagent_-
>behaviour() == O_Ants2006_explorer) {
	double interarrival_time = now() - last_forward_time_;
	forward_interarrival_time_samples_.push_back(interarrival_time);
	double old_sample = 0;
	if (forward_interarrival_time_samples_.size() >= swarmagent_-
	>alfa() ) {
		old_sample = forward_interarrival_time_samples_.front();
		forward_interarrival_time_samples_.pop_front();
	}
	forward_interarrival_sum_ += interarrival_time - old_sample;
	forward_rate_estimate_ = ( forward_interarrival_sum_ > 0 ?
		forward_interarrival_time_samples_.size() /
			forward_interarrival_sum_ : 0);
	//forward_rate_estimate_ = forward_rate_estimate_ * swarmagent_-
		>alfa() + (1.0 - swarmagent_->alfa()) / (now() -
			last_forward_time_);

	//			if (node_address() == 4 )
	//printf("%e rate %e (%e, %e)\n", now(), forward_rate_estimate_,
		swarmagent_->alfa(), last_forward_time_);

	last_forward_time_ = now();
}



if (node_address() != ip->daddr() || swarmagent_->tabulist().empty()) {
	// Not yet at destination...


	// Build list of neighbour nodes not already visited.
	vector<pair<NsObject*, double> > new_neighbours;
	vector<pair<Neighbour*, double> > neigh_new_neighbours; //(Oriol)
	Neighbour* neigh_homenode_entry; //(Oriol)
	int j;			//(Oriol)for the store port IDs simulation
	double pherolevel_sum = 0;
	double pherolevel_sum2 = 0; //(Oriol) SUM of pheromones2
	bool homenode_is_neighbour = false;
	NsObject* homenode_entry = NULL;
	for (list<Neighbour*>::iterator i = neighbourhood_.begin();  i !=
		neighbourhood_.end(); i++) {

		// Check for changes in neighbourhood
		if (last_neighbourhood_.find(*i) != last_neighbourhood_.end()
		&& last_neighbourhood_[*i] != (! (*i)->linkdown()) ) {
			// Change in link state for old neighbour.
			if (local_boost_)
				// Execute local boosting
				local_boost((*i)->entry());
		}
		// Remember neighbour and link state
		last_neighbourhood_[*i] = (! (*i)->linkdown());

		// Check if link to neighbour is up/down
		if ( (*i)->linkdown() )
			// Skip neighbour
```

```
        continue;

// Check if neighbour has been visited
bool neighbour_visited = false;
//(Oriol) Initial behavior, storing IDs in the agent
if(STORE_PORTS_BEHAVIOR==0)
{
        for (list<pair<nsaddr_t, NsObject*> >::iterator j =
        swarmagent_->tabulist().begin();
                j != swarmagent_->tabulist().end(); j++) {
               if ( (*i)->addr()  ==  j->first ) {
                      neighbour_visited = true;
                   break;
               }
        }
}
if(STORE_PORTS_BEHAVIOR==1)//behavior storing Ports in agent
{
        for (list<pair<nsaddr_t, NsObject*> >::iterator j =
        swarmagent_->tabulist().begin();
                j != swarmagent_->tabulist().end(); j++) {
                list<pair<nsaddr_t, NsObject*> >::iterator
                prova=j;
                      prova++;
               if ( ((*i)->addr()  ==  j->first) &&
               ((prova)==swarmagent_->tabulist().end())) {
                      neighbour_visited = true;
                   break;
               }
        }


}

if (! neighbour_visited) {
        // Unvisited (new) neighbour found

        if (TWO_PHERO_BEHAVIOR==0) //(Oriol) use of 1 pheromone
                                          behaviour
        {
               // Find pheromone level (if any) towards neigbour
               PheroTableKey pk((*i)->entry(), swarmagent_-
               >pheroid());
               PheroTable::iterator p = pherotable_.find(pk);
               pherolevel_sum += (p != pherotable_.end() ? (p-
               >second).pherolevel() : 0);

               // Store link entry towards neigbour and
                      accumulated phero level towards neigbour
               new_neighbours.push_back(pair<NsObject*,
               double>((*i)->entry(), pherolevel_sum));
               neigh_new_neighbours.push_back(pair<Neighbour*,
               double>(*i, 0));//
        }

        if (TWO_PHERO_BEHAVIOR==1)//use of 2 pheromones
                                    behavior
        {
               // Find pheromone level (if any) towards neigbour
               if(swarmagent_->from1st()==0)//flag that means
                                          which behavior have a
                                          particular agent, 0=>
                                          first pheromone :: 1=>
                                          second pheromone
```

```
                        {

                                PheroTableKey pk((*i)->entry(),
                                swarmagent_->pheroid());
                                PheroTable::iterator p =
                                pherotable_.find(pk);
                                pherolevel_sum += (p != pherotable_.end() ?
                                (p->second).pherolevel() : 0);

                                // Store link entry towards neigbour and
                                accumulated phero level towards neigbour
                                new_neighbours.push_back(pair<NsObject*,
                                double>((*i)->entry(), pherolevel_sum));

                        neigh_new_neighbours.push_back(pair<Neighbour*,
                        double>(*i, 0));//(Oriol)

                        }else{

                                PheroTableKey pk((*i)->entry(),
                                swarmagent_->pheroid());
                                PheroTable::iterator p =
                                pherotable2_.find(pk);
                                pherolevel_sum2 += (p != pherotable2_.end()
                                ? (p->second).pherolevel() : 0);

                                // Store link entry towards neigbour and
                                accumulated phero level towards neigbour
                                new_neighbours.push_back(pair<NsObject*,
                                double>((*i)->entry(), pherolevel_sum2));
                        neigh_new_neighbours.push_back(pair<Neighbour*,
                                double>(*i, 0));//(Oriol)
                        }
                }



        }
        // Check if home node is neighbour
        if ( ! homenode_is_neighbour && (*i)->addr() == ip->daddr()) {
                homenode_is_neighbour = true;
                homenode_entry = (*i)->entry();
                neigh_homenode_entry = *i;//(Oriol)
        }
}

// for the agents always can revisit all nodes in store ports
behavior
if (STORE_PORTS_BEHAVIOR==0)
{
        if (new_neighbours.empty()) {
                // All neighbours have been visited
                if(homenode_is_neighbour) {
                        // Return to homenode
                        new_neighbours.push_back(pair<NsObject*,
                        double>(homenode_entry, 1));
                        neigh_new_neighbours.push_back(pair<Neighbour*,
                        double>(neigh_homenode_entry, 0));
                        pherolevel_sum = 1;
                        if (TWO_PHERO_BEHAVIOR==1) pherolevel_sum2=1;
                } else {
                        // Allow revisit to any neighbour
                        for (list<Neighbour*>::iterator i =
                        neighbourhood_.begin(); i !=
```

```
                        neighbourhood_.end(); i++) {
                              new_neighbours.push_back(pair<NsObject*,
                              double>((*i)->entry(), 0));
                        neigh_new_neighbours.push_back(pair<Neighbour*,
                        double>(*i, 0));//(Oriol)
                        }
                  }
            }
      }
      if (STORE_PORTS_BEHAVIOR==1)//(Oriol)
      {
            if (new_neighbours.empty()) {
                  for (list<Neighbour*>::iterator i =
                  neighbourhood_.begin(); i != neighbourhood_.end(); i++)
                  {
                        new_neighbours.push_back(pair<NsObject*,
                        double>((*i)->entry(), 0));
                        neigh_new_neighbours.push_back(pair<Neighbour*,
                        double>(*i, 0));//(Oriol)
                  }
            }
      }

      // Select which neighbour to visit next by applying pheromone
            distribution
      NsObject* nextnode = NULL;
      Neighbour* neigh_nextnode = NULL; //to save the next node in
                                        neighbour format
      if (TWO_PHERO_BEHAVIOR==0)
      {
            if (pherolevel_sum == 0 || swarmagent_->behaviour() ==
            O_Ants2006_explorer )
            {
                  // No pheromones found or explorer behaviour set. Make a
                        uniform distribution.
                  long n = randomgen_.rand_int(1, new_neighbours.size());
                  nextnode = new_neighbours[n-1].first;
                  neigh_nextnode= neigh_new_neighbours[n-
                  1].first;//(Oriol)
            } else {
                  // Apply "roulett wheel" method base on pheromone
                        distribution to select next node
                  double u = randomgen_.uniform_double();
                  j=0;//(Oriol)
                  for (vector<pair<NsObject*, double> >::iterator i =
                  new_neighbours.begin(); i != new_neighbours.end(); i++)
                  {
                        //printf("<%e %d>, ", i->second,
                        ((entry2neighbour_.find(i->first))->second)-
                        >addr());

                        if ( u <= (i->second / pherolevel_sum)) {
                              // Select node to be next
                              nextnode = i->first;
                              neigh_nextnode=
                              neigh_new_neighbours[j].first;

                              break;
                        }
                        j++;
                  }
            }
      }else{
            if ((pherolevel_sum == 0 && swarmagent_->from1st()==0) ||
```

```
	(pherolevel_sum2 == 0 && swarmagent_->from1st()==1) ||
	swarmagent_->behaviour() == O_Ants2006_explorer ) {
		// No pheromones found or explorer behaviour set. Make a
			uniform distribution.
		long n = randomgen_.rand_int(1, new_neighbours.size());
		nextnode = new_neighbours[n-1].first;
		neigh_nextnode= neigh_new_neighbours[n-
		1].first;//(Oriol)
	} else {
		// Apply "roulett wheel" method base on pheromone
			distribution to select next node
		double u = randomgen_.uniform_double();
		j=0;
		for (vector<pair<NsObject*, double> >::iterator i =
		new_neighbours.begin(); i != new_neighbours.end(); i++)
		{
			//printf("<%e %d>, ", i->second,
			((entry2neighbour_.find(i->first))->second)-
			>addr());
			if(swarmagent_->from1st()==0)
			{
				if ( u <= (i->second / pherolevel_sum)) {
					// Select node to be next
					nextnode = i->first;
		neigh_nextnode=neigh_new_neighbours[j].first;
					break;
				}
			}else{
				if ( u <= (i->second / pherolevel_sum2)) {
					// Select node to be next
					nextnode = i->first;
					neigh_nextnode=
					neigh_new_neighbours[j].first;
					break;
				}
			}
			j++;

		}
		//printf("\n");
	}
}

//Update packetsize
//ch->size() = swarmagent_->size() + sizeof(hdr_cmn) +
	sizeof(hdr_swarm);
//ch->size() *= 10; // Scale up a little to make packet visible in
	nam
//ch->size() = 1;
if(swarmagent_->behaviour()!=O_Ants2006_datapacket)
{
	if (STORE_PORTS_BEHAVIOR==0) ch->size() = ch->size() + 8*6;
		//(Oriol) Each node stored is 6 bytes MAC adress
	else ch->size() = ch->size() + 8; // (Oriol) Maximum switches
		supposed of 256 ports
}else{
	ch->size()=1520;
}
// Record current visit and entry to next node

swarmagent_->tabulist().push_back(pair<nsaddr_t,
NsObject*>(node_address(), nextnode));

if (trace_phero_ && (trace_pheros_.empty() or
```

```
trace_pheros_.find(swarmagent_->pheroid()) != trace_pheros_.end() ) )
       // Sample pheromone values
       trace_->sample(this, O_Ants2006_PHEROMONES );

//(Oriol) Touch to trace second pheromone (this and all the features)


if (TWO_PHERO_BEHAVIOR==1) //(Oriol)
{
       if (trace_phero2_ && (trace_pheros2_.empty() or
       trace_pheros2_.find(swarmagent_->pheroid()) !=
       trace_pheros2_.end() ) )
              // Sample pheromone values
              trace_->sample(this, O_Ants2006_PHEROMONES2 );
}


       //Here, the cost function has to be defined (Oriol)


       //(Oriol) cost functions of Tdelay
       double utilization;

       utilization= neigh_nextnode->traffic() / neigh_nextnode-
       >bandwidth();
       printf("utilization=%lf \n", utilization);
       if(((swarmagent_->from1st()==0) && TWO_PHERO_BEHAVIOR==1) ||
       TWO_PHERO_BEHAVIOR==0)
       {
              if(TWO_MEASURE_BEHAVIOR==0)
              {

                     swarmagent_->L_path() = swarmagent_->L_path() +
                     100000000*1000*((ch->size()/neigh_nextnode-
                     >bandwidth())*(1/(1-utilization)) +
                     neigh_nextnode->retard());
                     if (swarmagent_->L_path() ==0) swarmagent_-
                     >L_path()=0.000001;
                     if (utilization > MAX_UTILIZATION &&
                     TWO_PHERO_BEHAVIOR==1)
                     {
                            swarmagent_->go_second()=1;
                            swarmagent_->go_first()=1;
                     }

              }else{
                     if(utilization<MAX_UTILIZATION)
                     {
                            //This cost is the transfer time exactly,
                                   but using a mean of utilization
                            swarmagent_->L_path() = swarmagent_-
                            >L_path() + 100000000*1000*((ch-
                            >size()/neigh_nextnode->bandwidth())*(1/(1-
                            utilization)) + neigh_nextnode->retard());

                            if (swarmagent_->L_path() ==0) swarmagent_-
                            >L_path()=0.000001;
                            printf("Cost with cost function 1 is %lf,
                            with cost function 2 would be %lf\n",
                            100000000*1000*((ch->size()/neigh_nextnode-
                            >bandwidth())*(1/(1-utilization)) +
                            neigh_nextnode->retard()),
                            100000000*1000*((ch->size()+neigh_nextnode-
                            >bitsQueueDrT())/neigh_nextnode-
```

```
                                        >bandwidth() + neigh_nextnode->retard()));
                                }else{
                                        //This is the real transfer time for a link
                                        printf("Cost with cost function 1 would be
                                        %lf, with cost function 2 is %lf\n",
                                        100000000*1000*((ch->size()/neigh_nextnode-
                                        >bandwidth())*(1/(1-utilization)) +
                                        neigh_nextnode->retard()),
                                        100000000*1000*((ch->size()+neigh_nextnode-
                                        >bitsQueueDrT())/neigh_nextnode-
                                        >bandwidth() + neigh_nextnode->retard()));
                                        //printf("llarg cua=%lf\n",neigh_nextnode-
                                        >bitsQueueDrT());
                                        swarmagent_->L_path()=swarmagent_->L_path()
                                        + 100000000*1000*((ch->size() +
                                        neigh_nextnode-
                                        >bitsQueueDrT())/neigh_nextnode-
                                        >bandwidth() + neigh_nextnode->retard());
                                        if (swarmagent_->L_path() ==0) swarmagent_-
                                        >L_path()=0.000001;
                                }
                        }
                }else{


                        swarmagent_->L_path2() = swarmagent_->L_path2() +
                        100000000*1000*((ch->size() + neigh_nextnode-
                        >bitsQueueDrT())/neigh_nextnode->bandwidth() +
                        neigh_nextnode->retard());
                        if (swarmagent_->L_path2() ==0) swarmagent_-
                        >L_path2()=0.000001;
                        if(utilization > MAX_UTILIZATION)
                        {
                                swarmagent_->go_first()=1;
                                swarmagent_->go_second()=1;
                        }
                }



        // Move to next node (i.e. send agent state to next node)
        nextnode->recv(p_,h_);
        // Trigger local boost if appropriate
        //local_boost();

        break;


} else {
        // Agent is at destination, prepare for backtracking

        // Record current visit
        swarmagent_->tabulist().push_back(pair<nsaddr_t,
        NsObject*>(node_address(), NULL));

        if (swarmagent_->behaviour() == O_Ants2006_datapacket) {
                // Agent is a datapacket ant, is simulation a data-packet
                // Log trace info
                if (trace_)
                {
                        trace_->sample(this, O_Ants2006_PATH |
                        O_Ants2006_DATAPACKETRECEIVED |
                        O_Ants2006_DATAPACKETCOST);
                        if(TWO_PHERO_BEHAVIOR==1) trace_->sample(this,
```

```
                O_Ants2006_DATAPACKETCOST2); //(Oriol)
        }
        // Terminate agent
        Packet::free(p_);
        break;
}

if (TWO_PHERO_BEHAVIOR==0)
{
        if (gammaautoreg_.find(swarmagent_->pheroid()) ==
        gammaautoreg_.end()) {
                // First agent with this pheroid. Init misc variables
                rho_reduction_factor_[swarmagent_->pheroid()] = 1;
                best_cost_[swarmagent_->pheroid()] = MAXDOUBLE;
                period_since_new_best_[swarmagent_->pheroid()] = 0;
        }
}else{
        if (swarmagent_->from1st()==0)
        {
                if (gammaautoreg_.find(swarmagent_->pheroid()) ==
                gammaautoreg_.end()) {
                        // First agent with this pheroid. Init misc
                        variables
                        rho_reduction_factor_[swarmagent_->pheroid()] =1;
                        best_cost_[swarmagent_->pheroid()] = MAXDOUBLE;
                        period_since_new_best_[swarmagent_->pheroid()]=0;

                }
        }else{
                if (gammaautoreg2_.find(swarmagent_->pheroid()) ==
                gammaautoreg2_.end()) {
                        // First agent with this pheroid. Init misc
                        variables
                        rho_reduction_factor_[swarmagent_->pheroid()] =1;
                        best_cost2_[swarmagent_->pheroid()] = MAXDOUBLE;
                        period_since_new_best2_[swarmagent_->pheroid()]
                        =0;
                }
        }
}


// Calculate cost
//double L_path = now() - swarmagent_->birthtime();
//(Oriol) Calculate cost due to swarmagent_->L_path() that has been
        recorded during all the path
double L_path;
if(TWO_PHERO_BEHAVIOR==0 || (TWO_PHERO_BEHAVIOR==1 && (swarmagent_-
>from1st()==0)))
{
        L_path=swarmagent_->L_path();
}else{
        L_path=swarmagent_->L_path2();
}

//if(now() > 268.0 && now() < 269.0 )
//    printf("%f L_path: %f Bh: %d\n", now(), L_path,  swarmagent_-
>behaviour());

// Perform rho-reduction DISABLED
//                  rho_reduction(L_path);

swarmagent_->rho() *= rho_reduction_factor_[swarmagent_->pheroid()];
```

```
// Calculate new temperature (gamma) for all agents //(Oriol)
if (TWO_PHERO_BEHAVIOR==0 || (TWO_PHERO_BEHAVIOR==1 && ( swarmagent_-
>from1st()==0))) recalc_gamma(gammaautoreg_[swarmagent_->pheroid()],
swarmagent_->L_path(), swarmagent_->beta(), swarmagent_->rho());

//(Oriol)
if (TWO_PHERO_BEHAVIOR==1 && swarmagent_->from1st()==1)
recalc_gamma(gammaautoreg2_[swarmagent_->pheroid()], swarmagent_-
>L_path2(), swarmagent_->beta(), swarmagent_->rho());

// Log trace info
if (trace_)
{

      if (TWO_PHERO_BEHAVIOR==0) trace_->sample(this,
      O_Ants2006_GAMMA_ALL | O_Ants2006_ELITELIMIT | O_Ants2006_PATH
      | O_Ants2006_COST_ALL | O_Ants2006_ARRIVEDCOUNT);
      if (TWO_PHERO_BEHAVIOR==1) trace_->sample(this,
      O_Ants2006_GAMMA_ALL | O_Ants2006_ELITELIMIT | O_Ants2006_PATH
      | O_Ants2006_COST_ALL | O_Ants2006_ARRIVEDCOUNT |
      O_Ants2006_GAMMA_ALL2 | O_Ants2006_COST_ALL2);

}

// Check if path found is in "elite set"(Oriol)
if(TWO_PHERO_BEHAVIOR==0 || TWO_PHERO_BEHAVIOR==1 && ( swarmagent_-
>from1st()==0))
{
      if (  swarmagent_->behaviour() == O_Ants2006_normal &&
              swarmagent_->L_path() >= (- log(swarmagent_->rho()) *
            gammaautoreg_[swarmagent_->pheroid()].gamma())) {
            // Path not in elite set
            // Terminate agent
            Packet::free(p_);
            break;
      }
}else{
      if (  swarmagent_->behaviour() == O_Ants2006_normal &&
            swarmagent_->L_path2() >= (- log(swarmagent_->rho()) *
            gammaautoreg2_[swarmagent_->pheroid()].gamma())) {
            // Path not in elite set
            // Terminate agent
            Packet::free(p_);
            break;
      }
}


// Calculate new temperatur (gamma) for elite agents (Oriol)
if (TWO_PHERO_BEHAVIOR==0 || (TWO_PHERO_BEHAVIOR==1 && (swarmagent_-
>from1st()==0)))
{
      recalc_gamma(gammaautoreg_elite_[swarmagent_->pheroid()],
      L_path, swarmagent_->beta(), swarmagent_->rho());
      // Store gamma and path cost as agent state
      swarmagent_->gamma() = gammaautoreg_elite_[swarmagent_-
      >pheroid()].gamma();
      //swarmagent_->L_path() = L_path;
      swarmagent_->gamma2() = gammaautoreg_elite2_[swarmagent_-
      >pheroid()].gamma();
}
if (TWO_PHERO_BEHAVIOR==1 && swarmagent_->from1st()==1)
{
      recalc_gamma(gammaautoreg_elite2_[swarmagent_->pheroid()],
```

```
                L_path, swarmagent_->beta(), swarmagent_->rho());
                // Store gamma and path cost as agent state
                swarmagent_->gamma() = gammaautoreg_elite_[swarmagent_-
                >pheroid()].gamma();
                swarmagent_->gamma2() = gammaautoreg_elite2_[swarmagent_-
                >pheroid()].gamma();
                //swarmagent_->L_path2() = L_path;
        }


        // Set color in nam
        ip->flowid() = 1;
        // Reset ttl
        ip->ttl() = swarmagent_->max_ttl();

        // Log trace info
        if (trace_)
        {
                if (TWO_PHERO_BEHAVIOR==0) trace_->sample(this,
                O_Ants2006_COST | O_Ants2006_GAMMA_ELITE |
                O_Ants2006_GAMMA_DIFF | O_Ants2006_GAMMA_REL | O_Ants2006_RHO
                | O_Ants2006_BACKTRACKCOUNT);

                if (TWO_PHERO_BEHAVIOR==1) trace_->sample(this,
                O_Ants2006_COST | O_Ants2006_GAMMA_ELITE |
                O_Ants2006_GAMMA_DIFF | O_Ants2006_GAMMA_REL | O_Ants2006_RHO
                | O_Ants2006_BACKTRACKCOUNT | O_Ants2006_COST2 |
                O_Ants2006_GAMMA_ELITE2 | O_Ants2006_GAMMA_DIFF2 |
                O_Ants2006_GAMMA_REL2);
        }
        //printf("Abans de passar backtracking a state");
        swarmagent_->state() = SWS_BACKTRACKING;
        // (... continous into next case ...)
    }

case SWS_BACKTRACKING: {

    // Get entry to previously visited node.
    NsObject* previous_node = swarmagent_->tabulist().back().second;

    //printf("DEBUG bt %f %ld %d<-", now(), (long)swarmagent_, node_address());
    //printf("Comenca el backtracking");
    if(previous_node) {

        //printf ("%d ", ((entry2neighbour_.find(swarmagent_-
                >tabulist().back().second))->second)->addr() );

        // Update pheromones (Oriol)
        double L_on_gamma;
        if (TWO_PHERO_BEHAVIOR==0 || (TWO_PHERO_BEHAVIOR==1 && (swarmagent_-
        >from1st()==0)))
        {
                if(swarmagent_->gamma()!=0) L_on_gamma = swarmagent_->L_path()
                / swarmagent_->gamma();
                else L_on_gamma = swarmagent_->L_path() / 0.000001;
        }else{
                if(swarmagent_->gamma2()!=0) L_on_gamma = swarmagent_-
                >L_path2() / swarmagent_->gamma2();
                else L_on_gamma = swarmagent_->L_path2() / 0.000001;
        }
        double H = exp( - L_on_gamma );
        for (list<Neighbour*>::iterator i = neighbourhood_.begin();  i !=
        neighbourhood_.end(); i++) {
```

```
    // Check if neighbour is node visited last time
    bool neigbour_is_last = ((*i)->entry() == previous_node);

    // Update pheromones (Oriol)
    PheroAutoreg& p = pherotable_[PheroTableKey((*i)->entry(),
    swarmagent_->pheroid())];
    if (TWO_PHERO_BEHAVIOR==0 || (TWO_PHERO_BEHAVIOR==1 &&
    (swarmagent_->from1st()==0)))
    {
           p = pherotable_[PheroTableKey((*i)->entry(),
           swarmagent_->pheroid())];
           p.pherolevel() = (neigbour_is_last? H : 0) +
                  p.A() +
                  ( p.C() * p.B() == 0 || swarmagent_->gamma() > (2
                  * p.C() / p.B()) ?
                   - p.B() / swarmagent_->gamma() + p.C() /
                   (swarmagent_->gamma() * swarmagent_->gamma()) :
                   - p.B() * p.B() / (4 * p.C() ) );
    }else{
           p = pherotable2_[PheroTableKey((*i)->entry(),
           swarmagent_->pheroid())];

                  p.pherolevel() = (neigbour_is_last? H : 0) +
                         p.A() +
                         ( p.C() * p.B() == 0 || swarmagent_-
                          >gamma2() > (2 * p.C() / p.B()) ?
                          - p.B() / swarmagent_->gamma2() + p.C() /
                           (swarmagent_->gamma2() * swarmagent_-
                               >gamma2()) :
                          - p.B() * p.B() / (4 * p.C() ) );

    }



    // Check for "underflow"
    if (p.pherolevel() < 0) {
           // Reset all phero parameters
           p.pherolevel() = 0;
           p.A() = 0;
           p.B() = 0;
           p.C() = 0;
    } else {
           // Update pheromone autoreg parameters
           p.A() = swarmagent_->beta() * (p.A() + (neigbour_is_last
           ? H*(1+L_on_gamma * (1+L_on_gamma/2)) : 0) );
           if (TWO_PHERO_BEHAVIOR==0 || (TWO_PHERO_BEHAVIOR==1 &&
           (swarmagent_->from1st()==0)))
           {
                  p.B() = swarmagent_->beta() * (p.B() +
                  (neigbour_is_last ? H*(swarmagent_->L_path() +
                  swarmagent_->L_path() * swarmagent_->L_path() /
                  swarmagent_->gamma() ) : 0) );
                  p.C() = swarmagent_->beta() * (p.C() +
                  (neigbour_is_last ? H*(swarmagent_->L_path() *
                  swarmagent_->L_path() / 2 ) : 0) );
           }else{
                  p.B() = swarmagent_->beta() * (p.B() +
                  (neigbour_is_last ? H*(swarmagent_->L_path2() +
                  swarmagent_->L_path2() *

swarmagent_->L_path2() / swarmagent_->gamma2() ) : 0) );
                  p.C() = swarmagent_->beta() * (p.C() +
```

```
                                (neigbour_is_last ? H*(swarmagent_->L_path2() *
                                 swarmagent_->L_path2() / 2 ) : 0) );
                        }

                }
        }
}

//          printf("\n");


// Update rate estimate of backtracking (elite) ants
double interarrival_time = now() - last_backtrack_time_;
backtrack_interarrival_time_samples_.push_back(interarrival_time);
double old_sample = 0;
if (backtrack_interarrival_time_samples_.size() >= swarmagent_->alfa() ) {
      old_sample = backtrack_interarrival_time_samples_.front();
      backtrack_interarrival_time_samples_.pop_front();
}
backtrack_interarrival_sum_ += interarrival_time - old_sample;
backtrack_rate_estimate_ = (backtrack_interarrival_sum_ > 0 ?
backtrack_interarrival_time_samples_.size() / backtrack_interarrival_sum_ :
0);
//backtrack_rate_estimate_ = backtrack_rate_estimate_ * swarmagent_->alfa()
+ (1.0 - swarmagent_->alfa()) / (now() - last_backtrack_time_);
last_backtrack_time_ = now();

// Remove current node from tabulist
swarmagent_->tabulist().pop_back();
if (swarmagent_->tabulist().empty()) {
      // Backtracking completed
      //(Oriol) This is to check if there are a lot of paths with queue
      if(TWO_PHERO_BEHAVIOR==1)
      {
            if (swarmagent_->go_first()==0) swarmagent_->go_second()=0;
                  //in order to change from queues to not queues
            if( swarmagent_->go_second()==1)
            {

                  ind_queues_=BETA_QUEUES*ind_queues_ + (1-BETA_QUEUES)*1;
            }else{
                  ind_queues_=BETA_QUEUES*ind_queues_;
            }
      }

      // Terminate agent
      Packet::free(p_);
      break;
}


// Move to next node
Neighbour* next_node = (addr2neighbour_.find( swarmagent_-
>tabulist().back().first ) )->second;
if (next_node )
      (next_node->entry())->recv(p_, h_);
else
      // Link between nodes in tabulist no longer exist
      Packet::free(p_);
break;
}
default:
      printf("O_Ants2006_SwarmRtM::runSwarmAgent: Invalide swarm agent state
            %d\n", swarmagent_->state());
```

```
		Packet::free(p_);
		break;
	}

	// Process next queued packet (if any)
	poll_queue();

}

void O_Ants2006_SwarmRtM::rho_reduction(double L_path)
	// Adjust rho if when convergence is considered too slow
{
	if(! swarmagent_)
		//Do nothing
		return;
	/*
	if (swarmagent_->behaviour() == O_Ants2006_normal &&
		gammaautoreg_.gamma() - gammaautoreg_elite_.gamma() > swarmagent_-
		>gammadiff_limit()) {
		// Difference between  gamma for all agents and elite agents is exceeding
			limit
	*/
	if (best_cost_[swarmagent_->pheroid()] > L_path) {
		// New best cost
		best_cost_[swarmagent_->pheroid()] = L_path;
		period_since_new_best_[swarmagent_->pheroid()] = 0;
	} else
		period_since_new_best_[swarmagent_->pheroid()] += 1;

	if (period_since_new_best_[swarmagent_->pheroid()] > swarmagent_->D() ) {
		// Adjust rho reduction factor
		rho_reduction_factor_[swarmagent_->pheroid()] *= 0.95;
		period_since_new_best_[swarmagent_->pheroid()] = 0;

		// printf("%f Adjusting rho for %d: %le\n ", now(), swarmagent_->pheroid(),
				rho_reduction_factor_[swarmagent_->pheroid()]); fflush(NULL);

	}

}

void O_Ants2006_SwarmRtM::recalc_gamma(GammaAutoreg& gammaauto, double L_path, double
					beta, double rho)
	// Calculate new temperatur (gamma) and update autoreg parameters for gamma
{
		if (gammaauto.A() == 0 &&
			gammaauto.B() == 0 &&
			gammaauto.gamma() == 0 &&
			gammaauto.t() == 0)
			// Init. gamma
			gammaauto.gamma() = - L_path / log(rho);

		double beta2t = 0;
		// A large t is approxed with t=infinity.
		if (gammaauto.t() < T_INFINITY_APPROX) {
			gammaauto.t() += 1;
			 beta2t = pow(beta, gammaauto.t());
		}
		double L_on_gamma;
		if(gammaauto.gamma()!=0) L_on_gamma = L_path / gammaauto.gamma();
		else  L_on_gamma = L_path / 0.000001;
		double H = exp( - L_on_gamma );

		double new_gamma =  (gammaauto.B() + L_path * H) /
```

```
                        (gammaauto.A() + H * (1+ L_on_gamma) - rho *
                         ((1 - beta2t)/(1 - beta)));

                // Check for "underflow"
                if (new_gamma > 0 )
                        gammaauto.gamma() = new_gamma;
                else
                        printf("O_Ants2006_SwarmRtM::recalc_gamma: Gamma less than 0
                                (%lf).\n", new_gamma);

                // Update autoreg parameters for gamma
                if(gammaauto.gamma()!=0) L_on_gamma = L_path / gammaauto.gamma();
                else L_on_gamma = L_path / 0.000001;
                H = exp( - L_on_gamma );

                gammaauto.A() = beta * (gammaauto.A() + H * (1 + L_on_gamma));
                gammaauto.B() = beta * (gammaauto.B() + L_path * H);

}



float O_Ants2006_SwarmRtM::get_cost()
        // Return cost recoded by current swarm agent
{
        return swarmagent_->L_path();

}

float O_Ants2006_SwarmRtM::get_cost2()
        // Return cost recoded by current swarm agent
{
        return swarmagent_->L_path2();
}

float O_Ants2006_SwarmRtM::get_gamma()
        // Return gamma (temperature) recoded by current swarm agent
        // This gamma is controlled by elite ants
{
        return swarmagent_->gamma();
}

float O_Ants2006_SwarmRtM::get_gamma2()
        // Return gamma (temperature) recoded by current swarm agent
        // This gamma is controlled by elite ants
{
        return swarmagent_->gamma2();
}

float O_Ants2006_SwarmRtM::get_gamma_all()
        // Return gamma (temperature) updated by all ants
{
        return gammaautoreg_[swarmagent_->pheroid()].gamma();
}

float O_Ants2006_SwarmRtM::get_gamma_all2()
        // Return gamma (temperature) updated by all ants
{
        return gammaautoreg2_[swarmagent_->pheroid()].gamma();
}

list<pair<nsaddr_t,NsObject*> >&  O_Ants2006_SwarmRtM::get_path()
```

```
	// Return path traversed by current swarm agent
{
	return swarmagent_->tabulist();
}

float O_Ants2006_SwarmRtM::get_delay()
	// Return delay experienced by current swarm agent
{
	return 0;
}

float O_Ants2006_SwarmRtM::get_elitelimit()
	// Return limit for being in elite set
{
	return (- log(swarmagent_->rho()) * gammaautoreg_[swarmagent_-
		>pheroid()].gamma());
}

float O_Ants2006_SwarmRtM::get_elitelimit2()
	// Return limit for being in elite set
{
	return (- log(swarmagent_->rho()) * gammaautoreg2_[swarmagent_-
>pheroid()].gamma());
}

float O_Ants2006_SwarmRtM::get_rho()
	// Return rho applied
{
	return swarmagent_->rho();
}

int O_Ants2006_SwarmRtM::get_pheroid()
	// Return pheromone id
{
	return swarmagent_->pheroid();
}

int O_Ants2006_SwarmRtM::get_behaviour()
// Return behaviour flag (0 = normal, 1 = explorer)
{
	return swarmagent_->behaviour();
}

map<nsaddr_t, double>&  O_Ants2006_SwarmRtM::get_phero()
	// Return current pheromone value for current agent
{
	phero_list_.clear();

	for (list<Neighbour*>::iterator i = neighbourhood_.begin(); i !=
		neighbourhood_.end(); i++) {
		// Find pheromone level (if any) for current agent towards neigbour
		PheroTableKey pk((*i)->entry(), swarmagent_->pheroid());
		PheroTable::iterator p = pherotable_.find(pk);
		phero_list_[((entry2neighbour_.find((*i)->entry()))->second)->addr()] =
			(p != pherotable_.end() ? (p->second).pherolevel() : 0);
	}

	return phero_list_;
}

map<nsaddr_t, double>&  O_Ants2006_SwarmRtM::get_phero2()  //(Oriol)
	// Return current pheromone value for current agent
{
	phero_list2_.clear();
```

```
	for (list<Neighbour*>::iterator i = neighbourhood_.begin(); i !=
	neighbourhood_.end(); i++) {
		// Find pheromone level (if any) for current agent towards neigbour
		PheroTableKey pk((*i)->entry(), swarmagent_->pheroid());
		PheroTable::iterator p = pherotable2_.find(pk);
		phero_list2_[((entry2neighbour_.find((*i)->entry()))->second)->addr()] = (p
		!= pherotable2_.end() ? (p->second).pherolevel() : 0);
	}

	return phero_list_;
}


double O_Ants2006_SwarmRtM::get_backtrack_rate()
		// Return estimated rate of backtracking agents
{
	return backtrack_rate_estimate_;
}

void O_Ants2006_SwarmRtM::local_boost(NsObject* failed_link_entry)
// Execute local boost if required, i.e. generate a set of additional forward agents
{
	// Prepare prob. dist. (pdf) based on "pheromones"
	vector<pair<NsObject*, double> > neighbours;
	double pherolevel_sum = 0;
	for (list<Neighbour*>::iterator i = neighbourhood_.begin(); i !=
	neighbourhood_.end(); i++) {

		// Check if link to neighbour is up/down
		if ( (*i)->linkdown() )
			// Skip neighbour
			continue;

		// Find pheromone level (if any) towards neigbour
		PheroTableKey pk((*i)->entry(), swarmagent_->pheroid());
		PheroTable::iterator p = pherotable_.find(pk);
		double phero_level=(p != pherotable_.end() ? (p->second).pherolevel() : 0);
		pherolevel_sum +=  phero_level;

		// Store link entry towards neigbour and accumulated phero level towards
			neigbour
		neighbours.push_back(pair<NsObject*, double>((*i)->entry(), phero_level));
	}

	// Get pheromone level on failed link too
	PheroTableKey pk(failed_link_entry, swarmagent_->pheroid());
	PheroTable::iterator p = pherotable_.find(pk);
	double phero_level_failed_link =  (p != pherotable_.end() ? (p-
	>second).pherolevel() : 0);

	// Calculate size of boost (equ. 9 in paper, and rate weighted by pheromonlevel on
		failed link)
	double current_rate =  ((O_Ants2006_data*)last_forward_agentpacket_->userdata())-
	>current_rate();
	double rate_weight = phero_level_failed_link / (pherolevel_sum +
	phero_level_failed_link);
	double boost_size = min_replica_ *
		( 1 + (neighbourhood_.size() - 1 ) * (forward_rate_estimate_ * rate_weight
		/ current_rate));

	printf("%f local boost at %d:\n\tForward rate estimate %f\n\tCurrent rate
		%f\n\tRate weight %f\n\tBoost size %f\n\tBoost distr.: ",
		   now(), node_address(), forward_rate_estimate_, current_rate,
```

```
                rate_weight, boost_size);

        for (vector<pair<NsObject*, double> >::iterator i = neighbours.begin(); i !=
        neighbours.end(); i++) {
                // Generate a boost of agents relative to pheromone level towards neighbour
                int num_agents = (int)( boost_size * (i->second / pherolevel_sum) );

                // Generate boosts of agents. Apply uniform distribution.
                //int num_agents = (int)(boost_size / neighbours.size() );

                num_agents = (num_agents > 0 ? num_agents : 1 );     // Round up

                printf("%d ->%d, ", num_agents, ((entry2neighbour_.find(i->first))-
                        >second)->addr());

                for (int j=0; j < num_agents; j++) {

                        // Prepare copy of last forward agent sent
                        Packet* p = last_forward_agentpacket_->copy();

                        // Send packet
                        (i->first)->recv(p,h_);

                }
        }
        printf("\n"); fflush(NULL);

}
```