

# The Cross Entropy Ant System for Network Path Management

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Finding paths between nodes is a basic enabling functionality in a communication network. At first glance, this may seem to be a trivial task. However, finding a path when no global information is available, is a challenge. Furthermore, paths should ensure an overall good utilisation of network resources, providing low delays and losses as well as the needed capacity between nodes. Paths should be altered as the network load and topology are changed, and paths should rapidly be recovered when network elements fail. The path management function has throughout the history of communication networks been designed to meet the prime requirement of the service provided by the network within what was technologically feasible. The future network will provide a multitude of services with, to some degree, conflicting requirements. At the same time inherent robustness and autonomy of network operation are of increasing importance. This invites new approaches relative to those used in the traditional communication network and the Internet. One such approach is to use swarm intelligence, where mobile agents explore, map and manage the network in a manner similar to the way insects, e.g. ants and bees, deal with their environment.



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With the above in mind, we have developed a distributed, robust and adaptive swarm intelligence system for dealing with path management in communication networks. The system is called the Cross Entropy Ant System (CEAS), and is based on increasing the probability of finding a (near) optimal solution by an increasingly focused random search. As a background for the system, this paper gives a brief discussion on path finding challenges and trade-offs. Following up is a description of CEAS where its robustness and adaptivity are demonstrated on a variety of case studies using different management strategies, like: shared backup path protection (SBPP), p-cycles, resource search under QoS constraints and adaptive paths with stochastic routing. This paper also includes a description of a running implementation of CEAS based on small home routers. The implementation demonstrates and visualises the inner workings of the method.



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## 1 Introduction

Being able to transfer addressed information between sources and destinations is the prime function of a communication network. Hence, how to find paths for the data flow between source and destinations through the network is one of the most salient issues and important functions in network architecture and operation. In this paper, the function is denoted *path finding*, irrespective of whether physically or virtually circuit switched paths (or circuits) are found, or stable routes for connectionless forwarding are obtained.

diverse schemes, see for instance [1]. In the early Internet, the prime objective was to have a routing scheme which was inherently robust and would find a path between source and destination irrespective of the current topology. This scheme has evolved to a range of routing protocols, see for instance [2]. The ability to deal with failures of network elements has always been an important issue, with schemes ranging from 1+1 protection of the physical circuits to elaborate end-to-end restoration schemes, as described in for instance [3,4].

Throughout history, the path finding applied is a trade-off between requirements of the network service and available technology. The early POTS<sup>1)</sup> networks had a hierarchical routing scheme, which gradually evolved into a more non-hierarchical and adap-

A common characteristic of the state of art schemes, is that they apply some degree of preplanning, e.g. allocation of link weights to links in OSPF<sup>2)</sup> and IS-IS<sup>3)</sup>, introduction of operator policies in BGP<sup>4)</sup>, planning of (G)MPLS<sup>5)</sup> shared protection paths. For a

1) Plain Old Telephony Service

2) The Open Shortest Path First (OSPF) protocol is a hierarchical for routing in an Internet domain, using a link-state in the individual areas that make up the hierarchy. A computation based on Dijkstra's algorithm is used to calculate the shortest path tree inside each area. See IETF RFC 2328.

3) IS-IS is like OSPF a protocol for routing in an Internet domain, based on Dijkstra's algorithm, standardised as ISO10589. See IETF RFC 1195.

4) The Border Gateway Protocol (BGP) is the routing protocol between the domains (Autonomous Systems – AS) of the Internet. It is a path vector protocol and makes routing decisions based on path, network policies and/or rule-sets. See IETF RFC 4271.

































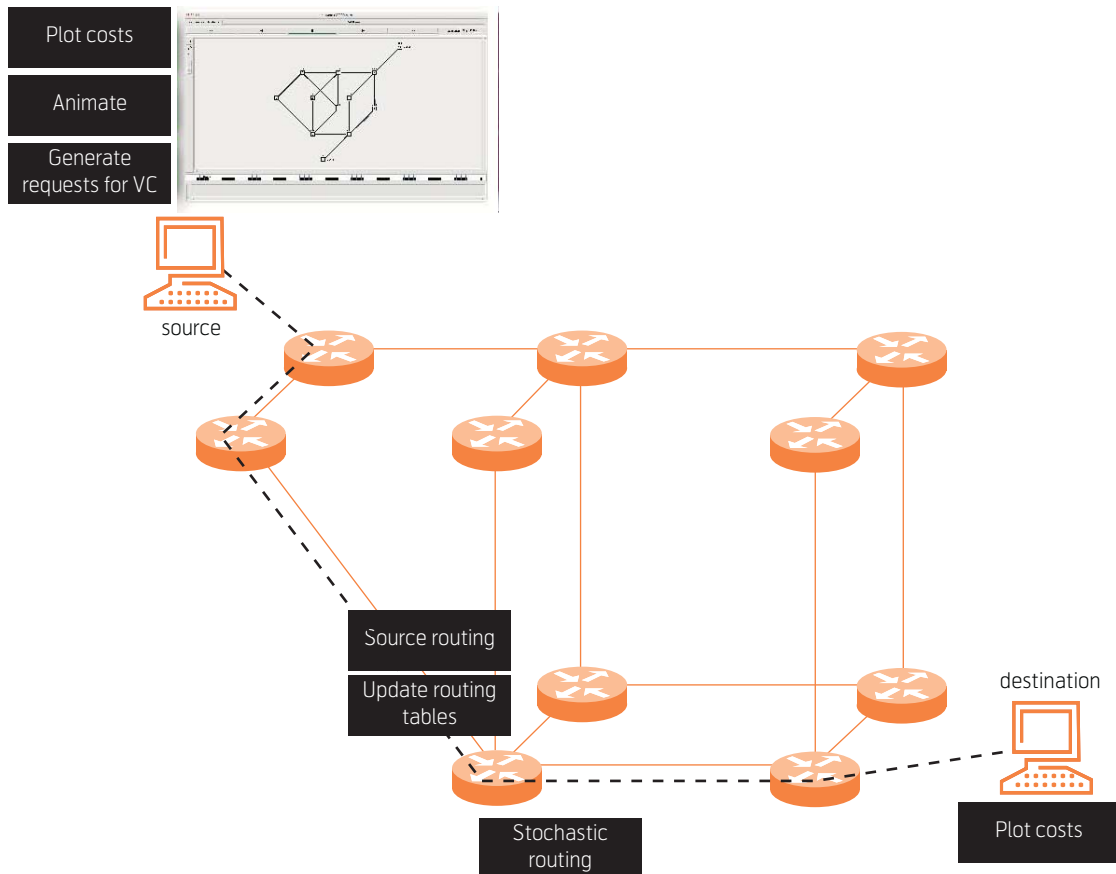


Figure 14 AntPing implementation

For the first version of this prototype the initial demo network topology is fixed and both sender and receiver processes are executed on external machines. In [62] the functionality of AntPing is extended to enable a self-configuring topology and to provide receiver processes in Click on every router. The latter implies that adding several destinations is possible without adding extra equipment.

**Visualisation & interaction.** The purpose of the demonstrator is to illustrate the inner workings of a swarm based method and to provide an interactive technical installation. The ant algorithm is animated live by use of Network Animator (*nam* [63]) showing how ants are moving and being dropped in the network, and how the topology is changing with link and node failures and restorations. The animation also shows ants that do not find the destination but are dropped because the Time-To-Live (TTL) is expired. Changes in cost values as a function over time of each virtual path are plotted live by use of *gnuplot* [64], both the cost of the current best path, and the cost of the last path found.

It is up to the users/audience to introduce network dynamics. They may unplug and re-plug cables between the nodes and/or the power supply to the nodes. Due to the extensions introduced in [62] new

interfaces or links can also be added and several virtual connections can be established and monitored.

## 6 Closing Comments

Considering that finding paths between nodes is the basic and fundamental enabling functionality in a communication network, and that service handling in the future networks puts a wider range of requirements; an extension of the state-of-art in path management functionality is mandatory. Rather than pursuing “ad-hoc” improvements of current schemes or resorting to centralized management, we have addressed the problem by developing and applying the Cross Entropy Ant System (CEAS). This inherently robust, truly distributed and dynamically self-optimizing approach represents an important alternative paradigm for path management. The fact that CEAS has been applied to and is coping well with different relevant network management challenges, is a promising indication of its future.

There are, however, challenges ahead. We are confident that CEAS will operate in topologies typical for intradomain networks. Dealing with dynamic path management in the interdomain, as well as more comprehensive resource management tasks, requires additional functionality and improved insight into the



Figure 15 Setup from the lab (LinkSys WRT54GS (v4.0) routers)

rate of convergence and scalability issues. We intend to look further into these issues. With respect to the results presented in this paper, we will continue to look into how further improvements can be made to the system and merge our experience both with the simulated versions and the prototype implementations into an efficient design and implementation.

## References

- 1 Ash, G R. *Dynamic Routing in Telecommunications Networks*. McGraw-Hill Professional, First ed., November 1, 1997. (ISBN 0-07-006414-8)
- 2 Huitema, C. *Routing in the Internet*. Prentice Hall PTR, 2 ed., November 1999.
- 3 Grover, W D. *Mesh-based Survivable Transport Networks : Options and Strategies for Optical, MPLS, SONET and ATM Networking*. Prentice Hall PTR, 2003.
- 4 Vasseur, J-P, Pickavet, M, Demeester, P. *Network Recovery : Protection and Restoration of Optical, SONET-SDH, IP, and MPLS*. The Morgan Kaufmann Series in Networking, Morgan Kaufmann, 2004.
- 5 Krunz, M, Matta, I (Eds.). Quality of service routing – Special issue. *IEEE Communications Magazine*, 40, Jun 2002.
- 6 Cholda, P, Mykkeltveit, A, Helvik, B, Wittner, O, Jajszczyk, A. A survey of resilience differentiation frameworks in communication networks. *Communications Surveys and Tutorials*, 9 (4), 2007.
- 7 Rubinstein, R Y. The Cross-Entropy Method for Combinatorial and Continuous Optimization. *Methodology and Computing in Applied Probability*, 127–190, 1999.
- 8 Ball, M O. *Handbooks in Operation Research and Management Science, Network Models*, 7. North Holland, 1995.
- 9 Pioro, M, Medhi, D. *Routing, Flow and Capacity Design in Communication and Computer Networks*. Morgan Kaufmann Publishers, March 2004. (ISBN 0125571895)
- 10 Kirkpatrick, S, Gelatt, C D, Vecchi, M P. Optimization by Simulated Annealing. *Science*, 220, 671–680, 1983.
- 11 Glover, F, Laguna, M. *Tabu Search*. Kluwer Academic, 1997.
- 12 Goldberg, D. *Genetic Algorithms in Search, Optimization and Machine Learning*. Addison Wesley, 1998.
- 13 ITU. *Types and characteristics of SDH network protection architectures*. Geneva, 1998. ITU-T G.841 (10/98).
- 14 ITU. *ATM protection switching*. Geneva, 1999. ITU-T I.630 (02/99).
- 15 Shen, G, Grover, W D. Survey and performance comparison of dynamic provisioning methods for optical shared backup path protection. *2nd International Conference on Broadband Networks*, 2005, 2, 1310–1319, 2005.
- 16 Jozsa, B G, Orincsay, D, Kern, A. Surviving multiple network failures using shared backup path protection. *Proceedings, Eighth IEEE International Symposium on Computers and Communication (ISCC 2003)*, 2, 1333–1340, 2003.
- 17 Zhou, L, Held, M, Sennhauser, U. Connection availability analysis of shared backup path-pro-

- tected mesh networks. *Journal of Lightwave Technology*, 25, 1111–1119, 2007.
- 18 Mello, D A A, Pelegrini, J U, Ribeiro, R P, Schupke, D A, Waldman, H. Dynamic provisioning of shared-backup path protected connections with guaranteed availability requirements. *2nd International Conference on Broadband Networks 2005*, 2, 1320–1327, 2005.
  - 19 Rai, S, Mukherjee, B, Deshpande, O. Ip resilience within an autonomous system: current approaches, challenges, and future directions. *IEEE Communications Magazine*, 43, 142–149, 2005.
  - 20 Nelakuditi, S, Lee, S, Yu, Y, Zhang, Z-L, Chuah, C-N. Fast local rerouting for handling transient link failures. *IEEE/ACM Transactions on Networking*, 15, 359–372, 2007.
  - 21 Menth, M, Martin, R, Hartmann, M, Spoerlein, U. *Efficiency of routing and resilience mechanisms*. Currently under submission, May 2007.
  - 22 Schoonderwoerd, R, Holland, O, Bruten, J, Rothkrantz, L. Ant-based Load Balancing in Telecommunications Networks. *Adaptive Behavior*, 5 (2), 169–207, 1997.
  - 23 Di Caro, G, Dorigo, M. AntNet: Distributed Stigmergetic Control for Communications Networks. *Journal of Artificial Intelligence Research*, 9, 317–365, 1998.
  - 24 Wittner, O, Helvik, B E. Distributed soft policy enforcement by swarm intelligence; application to load sharing and protection. *Annals of Telecommunications*, 59, 10–24, 2004.
  - 25 Wittner, O. *Emergent Behavior Based Implements for Distributed Network Management*. Trondheim, Norwegian University of Science and Technology (NTNU), Department of Telematics, November 2003. (PhD thesis)
  - 26 Wedde, H F et al. Beeadhoc: an energy efficient routing algorithm for mobile ad hoc networks inspired by bee behavior. In: *Proceedings of the 2005 conference on Genetic and evolutionary computation (GECCO '05)*, New York, 2005, 153–160, ACM Press.
  - 27 Di Caro, G, Gambardella, L M. AntHocNet: An Adaptive Nature-Inspired Algorithm for Routing in Mobile Ad Hoc Networks. *European Transactions on Telecommunications (ETT) – Special Issue on Self Organization in Mobile Networking*, 16 (5), 443–455, 2005.
  - 28 Ducatelle, F, Gambardella, L M. Survivable routing in ip-over-wdm networks: An efficient and scalable local search algorithm. *Optical Switching and Networking*, 2 (2), 86–99, 2005.
  - 29 Steels, L. Towards a theory of emergent functionality. In: Meyer, J-A, Wilson, S (eds.) *From Animals to Animats: Proceedings of the First International Conference on Simulation of Adaptive Behavior, SAB'90, Complex Adaptive Systems*, 451–461. Cambridge, MA, The MIT Press, 1990.
  - 30 Damper, R I. Editorial for the special issue on 'emergent properties of complex systems': Emergence and levels of abstraction. *International Journal of Systems Science*, 31 (7), 811–818, 2000.
  - 31 Engelbrecht, A P. *Fundamentals of computational swarm intelligence*. Wiley, 2005. (ISBN 13 978-0-470-09191-3)
  - 32 Dorigo, M, Maniezzo, V, Colomi, A. The Ant System: Optimization by a colony of cooperating agents. *IEEE Transactions on Systems, Man, and Cybernetics Part B: Cybernetics*, 26 (1), 29–41, 1996.
  - 33 Heidelberger, P. Fast simulation of rare events in queueing and reliability models. *ACM Transactions on modelling and Computer Simulation*, 5, 43–85, 1995.
  - 34 De Boer, P-T, Kroese, D P, Mannor, S, Rubinstein, R Y. A tutorial on the cross-entropy method. *Annals of Operations Research*, 134, 19–67, 2005.
  - 35 Helvik, B E, Wittner, O. Using the Cross Entropy Method to Guide/Govern Mobile Agent's Path Finding in Networks. In: *Proceedings of 3rd International Workshop on Mobile Agents for Telecommunication Applications*, August 14–16, 2001, Springer Verlag.
  - 36 Heegaard, P E, Wittner, O, Nicola, V F, Helvik, B E. Distributed asynchronous algorithm for cross-entropy-based combinatorial optimization. In: *Rare Event Simulation and Combinatorial Optimization (RESIM/COP 2004)*, Budapest, Hungary, September 7–8, 2004.
  - 37 Stutzle, T, Hoos, H. MAX-MIN Ant System. *Journal of Future Generation Computer Systems*, 16, 889–914, 2000.

- 38 Kjeldsen, V. *Cooration through pheromone sharing in swarm routing*. Norwegian University of Science and Technology, 2007. (Master thesis)
- 39 Heegaard, P E, Wittner, O. Restoration performance vs. overhead in a swarm intelligence path management system. In: Dorigo, M, Gambardella, L M (eds.) *Proceedings of the Fifth International Workshop on Ant Colony Optimization and Swarm Intelligence (ANTS2006)*, LNCS, Brussels, Belgium, September 4–7, 2006, Springer.
- 40 Heegaard, P E, Wittner, O J. Self-tuned refresh rate in a swarm intelligence path management system. In: *Proceedings of the EuroNGI International Workshop on Self-Organizing Systems (IWSOS 2006)*, LNCS, University of Passau, Germany, September 18–20, 2006, Springer.
- 41 Heegaard, P E, Wittner, O, Helvik, B E. Self-managed virtual path management in dynamic networks. In: Babaoglu, O et al. (eds.) *Self-\* Properties in Complex Information Systems. Lecture Notes in Computer Science*, LNCS 3460, 417–432, Springer, 2005. (ISSN 0302-9743)
- 42 Shannon, C E. A mathematical theory of communication. *Bell System Technical Journal*, 27, 379–423, 623–656, July, October 1948.
- 43 Wittner, O, Helvik, B E. *Simulating mobile agent based network management using network simulator*. Poster in Fourth International Symposium on Mobile Agent System (ASA/MA 2000), September 2000.
- 44 Wittner, O, Heegaard, P E, Helvik, B E. Scalable distributed discovery of resource paths in telecommunication networks using cooperative ant-like agents. In: *Proceedings of Congress on Evolutionary Computation, CEC2003*, Canberra, Australia, IEEE, December 2003.
- 45 Kjeldsen, V, Wittner, O J, Heegaard, P E. Distributed and Scalable Path Management by a System of Cooperating Ants. In: *Proceedings of the International Conference on Communications in Computing (CIC 2008)*, Las Vegas, USA, July 14–17, 2008.
- 46 Kirkerud, B. *Object-oriented programming with SIMULA*. Addison Wesley, 1989.
- 47 Birtwistle, G. *Demos – a system for discrete event modelling on simula*. 1997.
- 48 Wittner, O, Helvik, B E. Cross Entropy Guided Ant-like Agents Finding Dependable Primary/ Backup Path Patterns in Networks. In: *Proceedings of Congress on Evolutionary Computation (CEC2002)*, Honolulu, Hawaii, IEEE, May 12–17, 2002.
- 49 Garey, M R, Johnson, D S. *Computers and Intractability: A Guide to the Theory of NP-Completeness*. Freeman, 1979.
- 50 Stamatelakis, D, Grover, W. Rapid Span or Node Restoration in IP Networks using Virtual Protection Cycles. In: *Proceedings of 3rd Canadian Conference on Broadband Research (CCBR'99)*, Ottawa, 7 November 1999.
- 51 Wittner, O, Helvik, B E, Nicola, V F. Internet failure protection using hamiltonian pycles found by ant-like agents. *Journal of Network and System Management, Special issue on Self-Managing Systems and Networks*, 2005.
- 52 Heegaard, P E, Wittner, O, Helvik, B E. Self-managed virtual path management in dynamic networks. *Lecture Notes in Computer Science, Hot Topics*, 3460, 417–432, 2005.
- 53 Heegaard, P. *Performance monitoring of routing stability in dynamic networks*. Section 5 in Deliverable 05: Models for basic services in AHN, P2P and Grid networks in IST-FET Project BISON, December 2003. (IST-2001-38923)
- 54 Heegaard, P, Fuglem, I. *Demonstrator 1: Ant-based monitoring on software ip routers*. Tech. Rep., BISON, 2006. (IST-2001-38923)
- 55 Hesby, N, Heegaard, P E, Wittner, O. Robust connections in ip networks using primary and backup paths. In: *Proceedings of the 17th Nordic Teletraffic Seminar*, Fornebu, Norway, 25–27 August 2004.
- 56 Kohler, E et al. The click modular router. *ACM Transactions on Computer Systems*, 18, 263–297, 2000.
- 57 Struve, D. *Kaariboga mobile agents*. September 2003. <http://www.projectory.de/kaariboga/>, visited October 2003.
- 58 Mykkeltveit, A, Heegaard, P, Wittner, O. Realization of a distributed route management system on software routers. In: *Proceedings of Norsk Informatikkonferanse*, Stavanger, Norway, 29 Nov – 1 Dec 2004.

- 59 Mykkeltveit, A. *Realization of a distributed route management system by mobile agents*. Tech. Rep., Dept. of Telematics, NTNU, 2003.
- 60 Sanfilippo, S. *hping*. <http://wiki.hping.org/> [online] – last checked 2007-09-05.
- 61 *Openwrt*. <http://wiki.openwrt.org> [online] – last checked 2007-09-05.
- 62 Kristiansen, T A. *Self-configured demonstrator of the Cross Entropy Ant System*. Norwegian University of Science and Technology, 2007. (Master thesis)
- 63 *Nam: Network animator*. <http://www.isi.edu/nsnam/nam/> [online] – last checked 2007-09-05.
- 64 *Gnuplot*. <http://www.gnuplot.info/> [online] – last checked 2007-09-05.

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