COMPRESSION AND EXPANSION IN GRAPHS USING OVERLAYS

BILAL KHAN * AND KIRAN R. BHUTANI †

Abstract. In this paper, we describe how to construct physical computer network topologies which can support the establishment of overlays that reduce or increase the distances between nodes. Reducing pairwise distances (i.e., *compression*) implies that the overlay enjoys significantly lower inter-node latencies compared to the ambient physical network; such an overlay can be used to implement a "high-performance mode" for disaster situations in which network responsiveness is of critical importance. On the other hand, increasing pairwise distances (i.e., *expansion*) implies that the overlay exhibits significantly higher inter-node latencies compared to the ambient physical network; such an overlay can be used to implement a brief "dilated state" in networks that have been infected by a malicious worm, where slowing down the infection spread allows greater time for antidote generation. We show that it is possible to design physical networks which support overlays whose logical link bandwidth is *equal* to the physical link bandwidth while providing arbitrarily high compression or expansion. We also show that it is possible to "grow" such networks over time in a scalable way, that is to say, it is possible to retain the compression/expansion properties while augmenting the network with new nodes, by making relatively small adjustments to the physical and overlay network structure.

Key words. graphs embeddings, diameter, expansion, compression, overlays

1. Introduction. In the last few years we have witnessed a renewed interest in applications of peer-to-peer overlay networks. Within an overlay network, each logical link is implemented as a multi-hop connection over a path in an underlying physical network. The overlay's configuration and protocols ensure that data can travel along a logical link without undergoing expensive processing at intermediate physical nodes. Overlays thus enable network designers to superimpose alternate topologies (i.e., "virtual networks") whose properties diverge considerably from those of the ambient physical network. The malleability thus obtained is very valuable, since modifications to the physical network topology are both time consuming and expensive, while alterations to the overlay topology are, by comparison, implementable inexpensively and quickly. The mathematical theory of overlays has been developed and applied in many areas, including the simulation of one parallel architecture on another [4, 8, 10, 11], the design of active networks [7], the layout of virtual paths in circuit switched networks [1, 6, 9], scalable distributed content-addressable storage [13, 18], and construction of efficient multicast trees [3]. Today, the design and implementation of network overlays is made commonplace by readily available tools such as Xbone, 6Bone, and Dynabone [14, 17].

*DEPARTMENT OF MATHEMATICS AND COMPUTER SCIENCE, CITY UNIVERSITY OF NEW YORK AND JOHN JAY COLLEGE OF CRIMINAL JUSTICE, NEW YORK, NY 10019.

†DEPARTMENT OF MATHEMATICS, THE CATHOLIC UNIVERSITY OF AMERICA, WASHINGTON D.C. 20064.

Delaram Kahroabei and Amitabh Chaudhury for many spirited discussions about this problem during the early stages of our work.

REFERENCES

[1] S. Ahn, R. P. Tsang, S.-R. Tong, and D. H.-C. Du, Virtual path layout design on ATM networks, Proc of IEEE INFOCOM, Toronto, Ontario, Canada, 1994, pp. 192–200.

[2] D. G. Andersen, H. Balakrishnan, M. F. Kaashoek, and R. Morris, Resilient overlay networks, Proc of SOSP, Chateau Lake Louise, Banff, Canada, 2001, pp. 131–145.

[3] S. Banerjee, C. Kommareddy, K. Kar, B. Bhattacharjee, and S. Khuller, Construction of an efficient overlay multicast infrastructure for real-time applications, Proc of IEEE INFOCOM, San Franciso, CA, 2003, pp. 1521–1531.

[4] S. L. Bezrukov, B. Monien, W. Unger, and G. Wechsung, Embedding ladders and caterpillars into the hypercube, Discrete Applied Mathematics 83 (1998), 21–29.

[5] C. Chuah. A scalable framework for IP-network resource provisioning through aggregation and hierarchical control, Ph.D. thesis, University of California, Berkeley, 2001.

[6] T. Eilam, M. Flammini, and S. Zaks, A complete characterization of the path layout construction problem for ATM networks with given hop count and load, Proc of International Colloquium on Automata, Languages and Programming (ICALP), Bologna, Italy, 1997, pp. 527–537.

[7] V. Ferreria, A. Rudenko, K. Eustice, R. Guy, V. Ramakrishna, and P. Reiher, Panda: Middleware to provide the benefits of active networks to legacy applications, Proc of DARPA Active Networks Conference & Expo, Los Alamitos, CA, 2002. pp. 319.

[8] L. S. Heath, A. L. Rosenberg, and B. T. Smith, The physical mapping problem for parallel architectures, J ACM 35 (1988), 603–634.

[9] J. D. Kock and A. Krzesinski, Computing an optimal virtual path connection network by simulated annealing, Proc of the 1st Annual South African Telecommunications Network and Applications Conference (SATNAC), 1998, pp. 611–617.

[10] F. T. Leighton, Introduction to parallel algorithms and architectures: Arrays, trees & hypercubes, Morgan Kaufmann, San Francisco, CA, 1991.

[11] B. Monien and H. Sudborough, Embedding one interconnection network in another, Computational Graph Theory, Computing Supplement 7, Springer-Verlag, 1990, 257–282.

[12] J. Newsome and D. Song, Gem: Graph embedding for routing and data-centric storage in sensor networks without geographic information, Proc of 1st International Conference on Embedded Networked Sensor Systems, ACM Press, Los Angeles, CA, 2003, pp. 76–88.

[13] I. Stoica, R. Morris, D. Karger, F. Kaashoek, and H. Balakrishnan. Chord: A scalable peer-to-peer lookup service for Internet applications, Proc of ACM SIGCOMM Conference, San Diego, CA, 2001, pp. 149–160.

[14] J. Touch, Dynamic Internet overlay deployment and management using the X-Bone, Computer Networks 36 (2001), 117–135.

[15] S. Waharte, J. Xiao, and R. Boutaba, Overlay wireless sensor networks for application-adaptive scheduling in WLAN, Proc of HSNMC, Toulouse, France, 2004, pp. 676–684.

[16] J. Wang and A. Chien, Using overlay networks to resist denial-of-service attacks, Technical Report, CSE Department, University of California, San Diego, 2003.

[17] Y. Wang and J. Touch, Application deployment in virtual networks using the X-Bone, Proc of DARPA Active Networks Conference & Expo, Los Alamitos, CA, 2002, pp. 484–493.

[18] B. Y. Zhao, J. D. Kubiatowicz, and A. D. Joseph, Tapestry: An infrastructure for fault-tolerant wide-area location and routing, Technical Report UCB/CSD-01-1141, University of California, Berkeley, 2001.