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FACULTY OF ELECTRONICS, TELECOMMUNICATIOS AND INFORMATION TECHNOLOGY

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PH.D. THESIS

ROUTING MANAGEMENT IN THE FUTURE INTERNET

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1. Introduction

The centralized management found in today's network architectures will not be applicable for the future Internet, requiring new approaches in terms of management tools. Hence, new approaches are needed in terms of management tools and architectures. New trends focus on autonomous, scalable and intelligent networks, not requiring manual interventions of network administrators. The goal is to increase the automation, the flexibility and the manageability of future IP networks.

The main purpose of routing management is to administrate the routing functionalities so as to maximize network availability, ensuring the quality requirements of current and future connections. This is achieved through monitoring the available resources in the network and adaptively adjusting the parameters and the metrics of the routing protocols, depending on traffic conditions.

Some of the issues to be resolved by the management in the future Internet, in terms of routing operations are, among others: detection of anomalies and failures by computing periodical statistical indicators; dynamic congestion control; load balancing; intelligent traffic management by choosing between different routing approaches, etc.

2. Contributions to Routing Management in the Future Internet

1) State of the Art of Management Techniques for the Future Internet

This contribution contains an extensive study of management techniques for the future of Internet. The limitations of current management technologies are identified, together with future perspectives in the field of network administration. Different management techniques are analyzed and described, based on evolutionary strategies (PBNM – Policy-Based Network Management, ASA – Autonomic Service Architecture and FOCALE – Foundation Observation Comparison Action Learn Reason) or clean-slate approaches (ANA – Autonomic Network Architecture, AutoI – Autonomic Internet, Self-Net and INM – In-Network Management). The observations based on the state of the art of management techniques are utilized in the design phase of an autonomous routing management system which is aware of network status and can act independently in order to improve the routing process.

Publications: [Bar10a]

2) Proposed Methodologies for Congestion Detection

In this contribution two methodologies are proposed allowing the detection of congestion on the links of an IP network. The first method is based on the quality of video streams sent over RTP (Real-time Transport Protocol). This involves the evaluation of the following VQ (Video Quality)

metrics: the number of lost packets, the success rate of the transmission, the magnitude of loss events, the discontinuity counter (the frequency of loss events) and the jitter. The novelty of this approach relies in monitoring the VQ metrics on each router of the network, not just at the destination node. In this way, the measuring instrument can be used for controlling the rerouting of affected streams. The second method performs congestion detections on the basis of monitoring the Available Transfer Rate (ATR) on the network links and computing the following statistical indicators: SMA (Simple Moving Average) and SD (Standard Deviation). The first method proposed was implemented in C++ under Linux. The application is called `RTPsniffer` and consists of multiple threads (main, packet capture, VQ metrics and stop). Assuming that the flows were identified previously, at the reception of each new packet the computed VQ metrics are saved into the output file. The second method was not implemented as an independent application, but included as a software module into the system presented in Contribution 3.

Publications: [Bar09], [Bar10b], [Bar11b]

3) Design and Implementation of a Routing Management System

Based on the assessment of the current state of management for the future Internet (Contribution 1), considering especially issues regarding the routing strategy, an autonomous system is proposed that enables routing management based on network status awareness. Two types of management entities are proposed and implemented: *1)* Local Management Entity (LME) dealing with the local aspects of routing administration and *2)* Domain Management Entity (DME) responsible for problems requiring a global view of the network. The main goal is to include the monitoring process as an intrinsic part of the network architecture. The system is designed based on the idea of separating the network status monitoring and updating from the routing process itself. In order to monitor the state of the network and detect congested links, the tools designed in the second contribution are utilized. These provide information about the available transfer rate and the delay on the connections between neighboring nodes. The RTP packet drops are also measured. The management entities LME and DME were implemented in C++ under Linux, using the Qt framework and MySQL databases. Communication is done through XML (eXtensible Markup Language) messages, while the format of these messages is defined with the help of XSD (XML Schema Definition).

Publications: [Bar10b], [Bar11b], [Boa10a]

4) Congestion Management by Activating Network Coding

A possible application of the routing management system in the future Internet can be the control of congestion through Network Coding (NC) techniques. Since Network Coding requires a consistent amount of additional operations (involving both computational resources and link resources), it should be activated only if strictly necessary, i.e. if no other options are available for improving the quality of services in the network. The decision regarding the activation/deactivation of the network coding scheme is taken by the routing management system (especially DME) based on the given network conditions. The experimental results obtained with a preliminary practical implementation show that the activation of Network Coding improves the overall performance of the transmissions. For example, in the studied scenarios the rate of packet losses was reduced from 18%…21% without NC to 0.5%…3% when activating NC. A major drawback of NC is that it fails to fully eliminate packet losses because it cannot resolve the congestion, it can only limit its negative effects. Because of this disadvantage NC is not an optimal solution, despite delivering a better

Quality of Service (QoS) than a traditional routing protocol. Network Coding has been tested in a wired Ethernet network, but the true value of the technique can be seen when using wireless links.

Publications: [Cor11], [Pol09], [Rus10a]

5) Congestion Management through QoS-Aware Routing

Another application of the proposed routing management system is represented by a QoS-aware routing strategy. The metrics (based on which the routes are chosen) are modified dynamically, depending on the link resources available in the network. This routing strategy allows for congestion management through situation awareness which involves rerouting the transmissions under unfavorable traffic conditions, i.e. avoiding overloaded paths. The solution is tested in a real network topology and compared with OSPF (Open Shortest Path First) routing protocol. The main disadvantage of OSPF is that it is unable to properly detect the appearance of congestion in the network. Management proposed inhere involves using information about the current state of the network in order to adaptively adjust the routing mechanisms. The experimental results show that through the detection of critical traffic developments (available transfer rate below a threshold, too high latency) it is possible to reduce packet losses and delay. Thereby, the Quality of Experience (QoE) perceived by the end user can be improved significantly. At the same time, the proposed routing strategy eliminates the shortcoming of the OSPF protocol in terms of verifying connectivity between nodes. The routing management approach presented in this contribution cannot entirely avoid the appearance of congestion, but is able to control it and to eliminate it after it is detected. This reduces its negative impact on network transmissions, although no QoS assurance method is applied.

Publications: [Bar11b], [Boa10a], [Boa10b], [Rus10b], [Rus10c]

6) Implementation and Evaluation of Traffic Prediction Techniques

A set of data rates monitored in the network is given in order to forecast future values. Different types of prediction methods are implemented and compared: linear prediction techniques based on statistical models and nonlinear methods based on Neural Networks (NN). For the latter, the performance is assessed according to the method chosen for network training. Four different types of training paradigms are compared, three of them can be found in the literature (STL – Single-Task Learning, STL with multiresolution decomposition and MTL – Multi-Task Learning) and one is proposed by the author (MTL with multiresolution decomposition). The experimental results show that linear techniques are not suitable for network traffic prediction because they cannot adapt to the dynamic variation and the non-linear character of the data set. Among the analyzed methods, the best prediction accuracy was obtained with NN-based predictors applying multiresolution decomposition and single-step iterative prediction. A slightly poorer precision was obtained by the multi-task learning approach which presents the advantage of having a reduced computational complexity. The promising results regarding the performance of forecasting motivate us to practically implement a Neural Network-based predictor with MTL training paradigm (see Contribution 7). By integrating the prediction into a routing management system, it would be possible to improve the network performance based on adaptive management decisions.

Publications: [Bar11a], [Bar11c]

7) Improving Routing Management through Neural Networks-based Prediction

Through the ability of predicting the evolution of the available transfer rate, additional intelligence is integrated into management entities. This enables network performance optimization through autonomous adaptations, taking into account anticipated traffic conditions. In this contribution, the main objective of integrating forecasting capabilities into the management system is to improve the overall quality of video streams transmitted through congested networks. In addition, it aims to shorten the period in which the video image freezes due to high packet losses. A Neural Network predictor based on the Multi-Task Learning paradigm is implemented in C++ and integrated into the multipath routing management system. This predictive system controls the routing decisions of the Situation Aware Multipath (SAMP) routing algorithm based on the predicted ATR values. The solution is tested in real-time in a practical testbed and its performance is compared with that of the ECMP (Equal-Cost Multi-Path) routing protocol and SAMP without prediction. The experimental results show that the approach based on prediction results in a more efficient use of network links and it also reduces the number of lost packets. In the test scenario involving the SAMP routing algorithm, the rate of lost packets was reduced (e.g. from 1.78% without prediction to 0.54% with prediction), while in the case of ECMP packet losses were much higher (e.g. 30.96% of the total traffic). Improvements are due to the more rapid identification of congestion and taking measures in order to eliminate it.

Publications: [Bar11a], [Bar11d], [Boa11a], [Boa11b]

3. Final Remarks

The figure below presents the structure of the thesis.

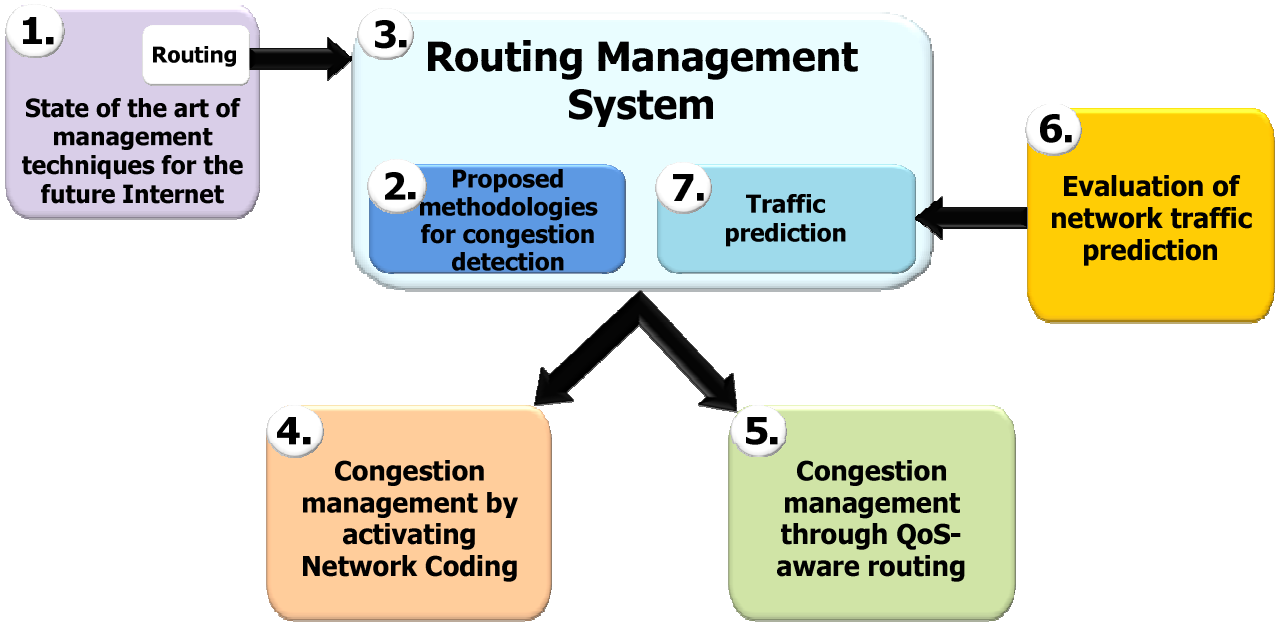

Figure 1. The structure of the contributions of this thesis

The core of the thesis is represented by the routing management system (Contribution 3) which was designed based on the current state of management techniques for the Future Internet (Contribution 1). This routing management system contains a module that allows congestion detection on the links of the administered network (Contribution 2). Two main areas of applications were identified for the proposed management system: congestion management by activating the Network Coding technique (Contribution 4) and congestion management through QoS-aware routing (Contribution 5). After evaluating by simulation different linear and nonlinear prediction techniques (Contribution 6), a method for predicting the Available Transfer Rate using neural networks was implemented and integrated into the proposed system (Contribution 7). This demonstrates in a multipath routing scenario that it is possible to improve the performance of the network using the forecasting module.

4. Awards

- **Second Special Prize** at the *6th Symposium for Students in Electronics and Telecommunications – SSET 2010*, organized by the Faculty of Electronics, Telecommunications and Information Technology, Technical University of Cluj-Napoca with the paper "Preliminary Implementation of a Situation Aware Multipath Routing Algorithm" (authors: G. Boanea, M. Barabas, A. B. Rus), Cluj-Napoca, Romania, May 27, 2010.

- The paper "Routing Management Based on Statistical Cross-Layer QoS Information Regarding Link Status" presented at the *11th International Conference on Knowledge in Telecommunication Technologies and Optics – KTTO 2011* has been selected for publishing in a special issue of the Przeglad Elektrotechniczny (*Electrical Review*) (ISSN 0033-2097), indexed Thomson ISI Web of Science.

5. List of Personal Publications

Books

[Cor11] L. M. Correia, H. Abramowicz, M. Johnsson, K. Wünstel (editors); V. Dobrota, Zs. Polgar, A. B. Rus, **M. Barabas**, G. Boanea (included in the list of contributors) et al., "CLQ-Based Testbed used for Generic Path", Chapter 12 "Prototype Implementations", pp. 271–276, *Architecture and Design for the Future Internet. 4WARD Project.* Series: Signals and Communication Technology. 1st Edition, Springer Science + Business Media, ISBN 978-90-481-9345-5, 2011.

Papers

[Bar09] **M. Barabas**, G. Boanea, K. Steenhaut, V. Dobrota, "Evaluating the Performances of the CastGate Tunnel Server over TCP and UDP Links in Multi-Client Configuration", *ACTA TECHNICA NAPOCENSIS Electronics and Telecommunications*, ISSN 1221-6542, Volume 50, Number 4, pp. 32–37. Technical University of Cluj-Napoca, Romania, 2009.

[Bar11b] **M. Barabas**, G. Boanea, A. B. Rus, V. Dobrota, "Routing Management Based on Statistical Cross-Layer QoS Information Regarding Link Status", *KTTO 2011 – 11th International Conference on Knowledge in Telecommunication Technologies and Optics*, ISBN 978-80-248-2399-7, pp. 8–13. Szczyrk, Poland, June 22–24, 2011.

[Bar11c] **M. Barabas**, G. Boanea, A. B. Rus, V. Dobrota, J. Domingo-Pascual, "Evaluation of Network Traffic Prediction Based on Neural Networks with Multi-task Learning and Multiresolution Decomposition", *ICCP 2011 – 7th IEEE International Conference on Intelligent Computer Communication and Processing*, ISBN 978-1-4577-1478-8, pp. 95–102. Cluj-Napoca, Romania, August 25–27, 2011.

[Bar11d] **M. Barabas**, G. Boanea, V. Dobrota, "Multipath Routing Management using Neural Networks-based Traffic Prediction", *EMERGING 2011 – The Third International Conference on Emerging Network Intelligence*, ISBN 978-1-61208-174-8. Lisbon, Portugal, November 20–25, 2011. (accepted)

[Boa10a] G. Boanea, **M. Barabas**, A. B. Rus, V. Dobrota, "Design Principles and Practical Implementation of a Situation Aware Multipath Routing Algorithm", *SoftCOM 2010 – 18th IEEE International Conference on Software, Telecommunications and Computer Networks*, ISBN 978-1-4244-8663-2, pp. 321–325. Split–Bol, Croatia, September 23–25, 2010.

[Boa10b] G. Boanea, **M. Barabas**, A. B. Rus, V. Dobrota, "Preliminary Implementation of a Situation Aware Multipath Routing Algorithm", *Novice Insights in Electronics, Communications and Information Technology*, ISSN 1842-6085, Issue 9, pp. 58–63. Technical University of Cluj-Napoca, Romania, 2010.

[Boa11a] G. Boanea, **M. Barabas**, A. B. Rus, V. Dobrota, J. Domingo-Pascual, "Performance Evaluation of a Situation Aware Multipath Routing Solution", *10th RoEduNet International Conference "Networking in Education and Research"*, ISSN 2247-5443, pp. 51–56. Iasi, Romania, June 23–25, 2011.

[Boa11b] G. Boanea, **M. Barabas**, V. Dobrota, "An Overview of Today's Multipath Routing", ACTA *TECHNICA NAPOCENSIS Electronics and Telecommunications*, ISSN 1221-6542, Volume 52, Number 3. Technical University of Cluj-Napoca, Romania, 2011. (submitted)

[Pol09] Zs. Polgar, Zs. Kiss, A. B. Rus, G. Boanea, **M. Barabas**, V. Dobrota, "Preliminary Implementation of Point-to-Multi-Point Multicast Transmission Based on Cross-Layer QoS and Network Coding", *SoftCOM 2009 – 17th International Conference on Software, Telecommunications and Computer Networks*, ISBN 978-1-4244-4973-6, pp. 131-135. Split–Hvar–Korkula, Croatia, September 24–26, 2009.

[Rus10a] A. B. Rus, **M. Barabas**, G. Boanea, Zs. Kiss, Zs. Polgar, V. Dobrota, "Cross-Layer QoS and Its Application in Congestion Control", *LANMAN 2010 – 17th IEEE Workshop on Local and Metropolitan Area Networks*, ISSN 1944-0367, Print ISBN 978-1-4244-6067-0, pp. 1–6. Long Branch, USA, May 5–7, 2010.

[Rus10b] A. B. Rus, V. Dobrota, A. Vedinas, G. Boanea, **M. Barabas**, "Modified Dijkstra's Algorithm with Cross-Layer QoS", *ACTA TECHNICA NAPOCENSIS Electronics and Telecommunications*, ISSN 1221-6542, Volume 51, Number 3, pp. 75–80. Technical University of Cluj-Napoca, Romania, 2010.

[Rus10c] A. B. Rus, **M. Barabas**, G. Boanea, V. Dobrota, "Implementation of QoS-Aware Virtual Routers", *ISETC 2010 – 9th International Symposium on Electronics and Telecommunications*, ISBN 978-1-4244-8457-7, pp. 161–164. Timisoara, Romania, November 11–12, 2010.

Doctoral Research Reports

[Bar10a] **M. Barabas**, "State of the Art of Routing Management" (Stadiul actual al managementului rutării), Doctoral Research Report 1. *Technical University of Cluj-Napoca*, Romania, March 2010.

[Bar10b] **M. Barabas**, "Evaluating the Performance of Routing Management" (Evaluarea performanţelor managementului rutării), Doctoral Research Report 2. *Technical University of Cluj-Napoca*, Romania, July 2010.

[Bar11a] **M. Barabas**, "Adaptive Routing Management" (Managementul adaptiv al rutării), Doctoral Research Report 3. *Technical University of Cluj-Napoca*, Romania, March 2011.

6. Projects

- POSDRU/6/1.5/S/5 ID 7676 – *„Project of Doctoral Studies Development in Advanced Technologies – PRODOC"*, 2008–2011

- FP7-ICT-2007-1 No. 216041 *"4WARD – Architecture and Design for the Future Internet"*, 2008–2010