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FACULTY OF ELECTRONICS, TELECOMMUNICATIOS AND INFORMATION TECHNOLOGY

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PH.D. THESIS

ENHANCEMENT OF MULTIPATH ROUTING IN THE FUTURE INTERNET

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1 Introduction

The Internet is a global communications network with a large user community. With the increasing number of Internet users, in order to satisfy their needs, more and more applications appear on the market, thereby the network must adapt to the new requirements. However, the protocols used in the current Internet did not have a significant evolution. From the services point of view the current network is based on a simple architecture. The intelligence is pushed at the edge of the network. One of the major problems is the „ossification" of the Internet in terms of services quality and architectural capacity. The Network Layer can transmit the packets from one point to another but cannot guaranty the delivery. Some of the missing aspects are: *1)* self-management functionalities; *2)* facilities for the addition of new functionality; *3)* support for a high-level integration between services and networks; *4)* Quality of Service features; *5)* facilities for security management, improved robustness and reliability and 6*)* flexible routing. The concept of Future Internet (FI) comprises a series of ideas and technologies that aim to change the existing approach of the current Internet. The goal is to cover the deficiencies by adapting the actual structure or by adopting a new clean-slate design.

The routing process is one of the major components in a communications system, the reliability and efficiency of the transmissions depend on the performance of the routing. This is the process that ensures the delivery of the packets in a network from the source to the destination. The design of a new routing solution is a challenge because it must have a distributed nature. Also it needs to be able to adapt to changes that may occur in the network topology or traffic conditions. The legacy routing solutions do not take into consideration the real state of the network and as a consequence, these methods cannot deal with all the challenges that arise, such as congestion, increased delay or low throughput. The result is a pronounced degradation of the transmission quality. Thus, a new approach is needed to ensure the requirements of new applications, high efficiency and robustness.

Multipath routing algorithms are the alternative to conventional routing. These solutions offer a more flexible and diverse routing technique that can be used for maximizing network resources utilization. In this case, the forwarding process takes advantage of alternative paths that exist between a source and a destination node. Depending on the application's communication needs, a corresponding path will be allocated. For example, VoIP (Voice over IP) and video conferencing traffic can use a low-delay path, while FTP (File Transfer Protocol) traffic uses a path with high throughput. The main advantages brought by a multipath routing solution are: 1) increased global throughput; 2) improved end-to-end reliability; 3) congestion avoidance; 4) customized routing in accordance with application performance requirements; 5) load balancing and 6) quality of services assurance. However, these advantages come with a cost: control plane, data plane and computational overheads.

Several applications (such as voice over IP, video conferencing, online games and high-definition video) have increased demands on throughput and robustness. Even short disruption, caused for example by routing convergence, can lead to unacceptable degradation of the delivered quality. The classical QoS approach based on resource reservation is not suitable anymore. A more efficient way to assure the quality of services is through intelligent multipath routing.

2 Contribution to multipath routing techniques in the Future Internet

1. Evaluation and Classification of Multipath Routing Techniques

This contribution presents an overview of the multipath routing aspects. To highlight the problems of today's routing, in the first part of this chapter the weaknesses of traditional routing were identified. Some of these are: no load balancing option, inefficient resource utilization, low convergence time and limited QoS support. Multipath routing is one of the alternatives to the single path schemes. Depending on the implementation mode of the main building blocks of a multipath routing solution, the methods were classified based on several criteria: 1) multiple paths computation algorithm (first k-shortest paths or disjoint paths); 2) load balancing split methods (packet, flow or flowlet granularity); 3) multipath forwarding mode (centralized or distributed); 4) update approaches (multiple routing configurations, proactive methods or tunneling). In the last part of this chapter a review of some concrete solutions from the literature was conducted. The presented methods have been divided into several categories such as: 1) solutions based on modified versions of Dijkstra's algorithm; 2) solutions based on link parameters prediction; 3) solutions based on QoS; 4) distributed and centralized solutions and 5) solutions based on biological models.

Publications: [Boa09], [Pol 09], [Boa11c], [Cor11]

2. Modified Version of the DFS Algorithm to Determine Multiple Paths in a Graph

One of the main components of any routing solution is represented by the network routes determination algorithm. For this process the network topology is transposed as a graph. Two basic search algorithms were analyzed: BFS (Breadth First Search) and DFS (Depth First Search). Because the main purpose of these methods is to find a single path between a source and a destination node, the multipath routing solution use a combination or a modified version of these algorithms. Some examples are: DT (Dijkstra Transversal), Dijkstra + DFS, BFS + DFS and other variations of Dijkstra's algorithm. The proposed path calculation algorithm is a modified version of the depth-first search algorithm. The method takes full advantage of the diversity of the existing paths without taking into account the independence of the routes. The basic idea is to start from the destination node and to explore along each branch until the source node is found, before backtracking. The visited nodes are marked in order to guaranty loop-less paths between two nodes. The DFS algorithm was chosen because it provides a fast determination of the first path from which the searching process of the entire set starts. A modified version of the algorithm was also proposed used to determine a reduced multiple routes set. In this case the paths with different gateways are preferred to the detriment of minimum cost paths.

Publications: [Boa10a], [Boa10b], [Boa11c], [Rus10b]

3. Design of a new Multipath Routing Algorithm SAMP (Situation Aware Multipath)

The main idea is based on a new approach where the management functions are separated from the actual routing, making the network status information reusable. Thereby, the routing

algorithm can focus on path determination and updating the routing tables. This approach was chosen because although it was considered that the routing solutions are able to handle routing and management functions, this is not done effectively. The routing protocols cannot handle all the problems of a network, one of them being represented by the congestion situation. Starting from this idea a new Situation Aware Multipath Routing Algorithm (SAMP) was designed. Three entities compose the routing system: SAMP, the management application and the CLQ (Cross Layer QoS) module. SAMP is dependent on the statistical (or predicted) network connections information (available transfer rate and latency) provided by the management application. The parameters measurements are performed by the CLQ module. The main features of SAMP are: load balancing (simultaneous transmission on multiple paths) and congestion avoidance (fast re-routing so that the problem areas are avoided). Some of the design criteria were: 1) to be a distributed multipath routing solution, 2) the packet transmission should be made simultaneously on several routes, 3) to ensure transparency for the end-user, 4) the routing process should be based on real network conditions and 5) the solution should be able to react in case of congestion or failure. The main characteristics of SAMP, established in the design process, are: simultaneous transmission on multiple routes, flow granularity traffic split and packet forwarding according to the real state of the network.

Publications: [Boa10a], [Boa10b], [Boa11c], [Rus10a], [Rus10c], [Bar11a], [Bar09]

4. Implementation of the Multipath Routing Algorithm SAMP

The routing algorithm designed in the previous contribution was implemented in C++ under Linux. SAMP is a dynamic multipath routing approach where the routes change depend on the state of the network, i.e. the path selection is influenced by the real-time conditions on the physical links. The necessary routing information (topology and parameters of links) are provided by the management application through several text files. SAMP does not change the packets that cross a node, thus no supplementary overhead is introduced at the data level. The traffic is processed only at the Linux kernel level. The VRF (Virtual Routing Forwarding) concept was used to divide the traffic between a source-destination pair on multiple paths. Each interface of a router will have a corresponding routing table with one entry represented by the default route to the direct connected node of that link. For actually forwarding the packets, the routing algorithm manipulates the routing tables using standard Linux capabilities. SAMP was tested in a real network that consists of a source node, a destination and six routers running on Linux-based machines. The routing system was composed of: SAMP + modified DFS, the management application [Bar11a], [Bar11c] and CLQ module [Rus11]. The performance evaluation was determined with respect to four video quality metrics: the number of lost packets, the magnitude of loss, discontinuity counter and success ratio. The results were compared with those obtained in the same condition by the OSPF protocol and two variants of the ECMP protocol. Two test scenarios were performed. In the first case the routing process is based on statistical information regarding the network links and in the second case the forwarding is based on traffic prediction and a packet loss indicator. In both scenarios only SAMP takes into account the real state of the network and avoids the congested areas. In terms of packets lost percentage the following results were obtained: the first scenario, 1% SAMP, 46% OSPF and 15% ECMP-like, the second scenario: 0.5% SAMP, 50% OSPF and 30% ECMP. The percentage of packets loss, in case of SAMP, is lower in the second scenario because the system reacts more quickly to congestion.

Publications: [Boa10a], [Boa10b], [Bar11a], [Bar11b], [Bar11c]

5. Design and Implementation of a Flow Identification Module in OPNET Simulator

Flow identification is a nesesary process for a multipath routing solution that divides the traffic at flow granularity. To accomplish this task a new module was implemented in OPNET modeler. Some of the simulator's facilities are: 1) fidelity to the real environment, 2) it is an object-oriented environment, 3) it provides multiple result analysis methods and 4) it offers a large variety of already implemented components. The new flow identification module, designed in ProtoC (an OPNET specific language), detects the network streams based on the triplet: destination IP address, source IP address and destination port. The main responsibility of the module is to maintain a valid list of the active flows in the network. Thereby, the tasks of this entity are: 1) identify a new flow; 2) for each flow update the time of the last incoming packet; 3) delete the inactive flows. The collected stream information is delivered to the multipath routing module. To integrate de new module in the basic structure of a router the *mac* module was modified. The comunication between the two entities is ensoured through packet streams. To evaluate the performance of the new module, multiple video streams were send in the network. The obtained results demonstrate the correlation between the global transmission rate and and the number of identified flows.

Publications: [Boa11a], [Boa11b]

6. Implementation and Performance Evaluation of a SAMP Module in OPNET Simulator

One of the main stages of the development of a new routing method is the simulation phase. This is a reliable and low cost solution that has some advantages such as: performance evaluation, parameter adjustment and a large test variety (different scenarios and network topologies). To demonstrate the scalability of the proposed multipath routing algorithm, SAMP, a new module was implemented in OPNET modeler. The role of this module is to provide situation aware multipath routing capabilities to the routers in the network. The integration of the new module was achieved by modifying the behavior of the *ip* module, which is a component of the basic structure of an OPNET router. For each data packet, based on the information received from the flow identification module, the new SAMP module will activate a certain routing table. The performance evaluation was performed in terms of network link resources utilization percentage, evolution of the global transfer rate and delay. The results were compared with those obtained by: OSPF, ECMP and EIGRP protocols. A significant improvement brought by SAMP was been observed. The proposed solution provides a resource utilization almost three times greater than OSPF (38% with respect to 13%), and compared to the multipath scheme ECMP, it procures more than 50% improvement. SAMP is also the only tested solution that takes into account the state of the links and therefore reacts to network congestion by avoiding the problem areas. Thus, in case of SAMP, the transfer rate is affected only for a short period of time while the other tested methods can provide less than a quarter of the necessary throughput.

Publications: [Boa11a], [Boa11b]

3 Final remarks

The current thesis presents a new situation aware multipath routing algorithm, SAMP, component part of a routing system. A new approach is proposed where the management

functions are separated from the actual routing, making the network status information reusable. The work started in the first phase with an overview of the existing multipath routing solutions. In the second phase a path calculation algorithm was proposed. The method is a modified version of the depth-first search algorithm that takes full advantage of the diversity of the existing paths without taking into account the independence of the routes. In the next step a situation aware multipath routing was designed. The implementation and performance of the new solution were accomplished in the last phase, both in a real environment and in a simulator.

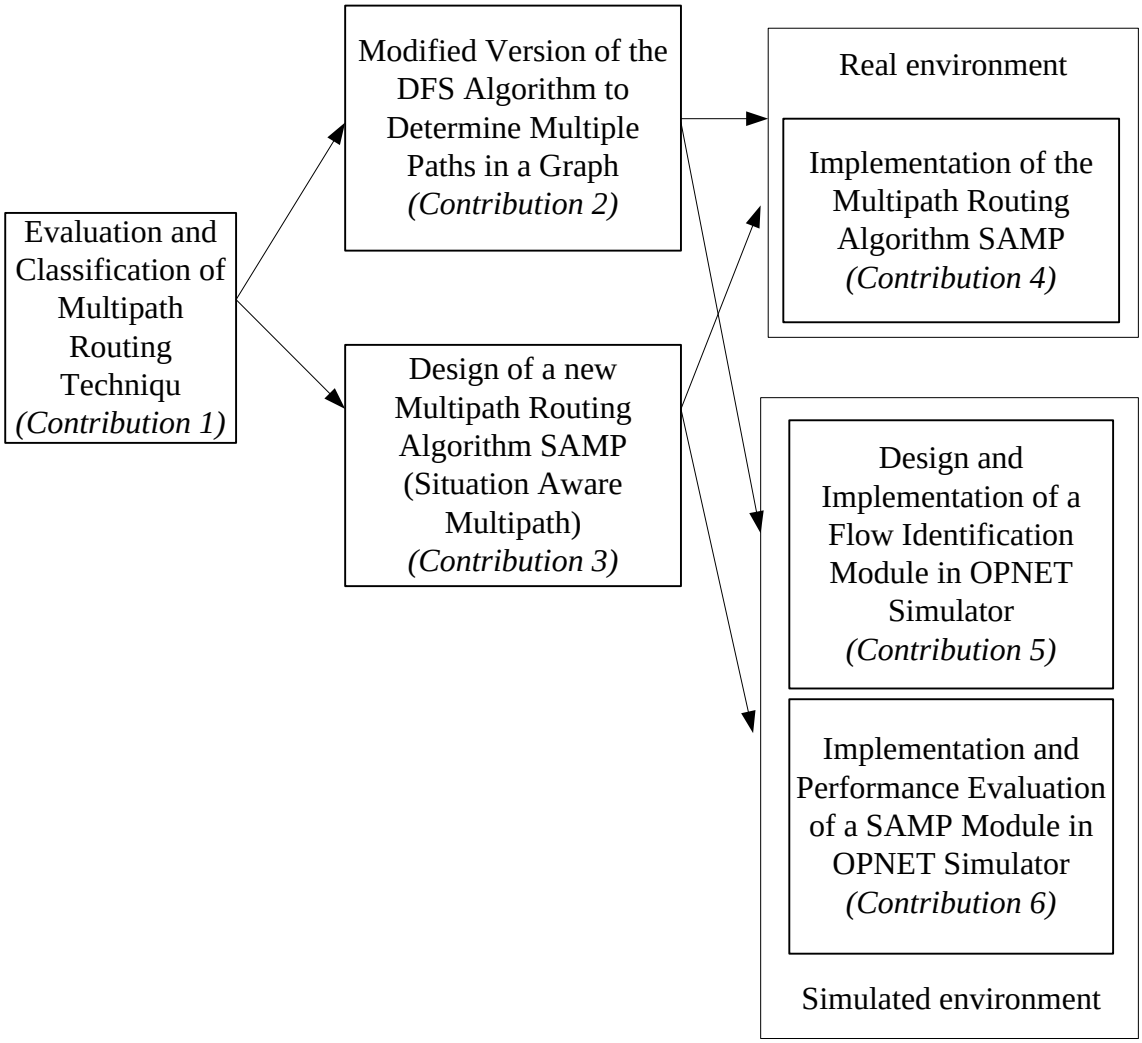

Figure 3-1: Structure of the contributions

4 Awards

- **Special Prize** at the "Students Scientific Communication Session in Electronics and Telecommunications", organized by the Faculty of Electronics, Telecommunications and Information Technology, Technical University of Cluj-Napoca, Romania, May 2010.

5 List of Personal Publications

Books

[Cor11] L. M. Correia, H. Abramowicz, M. Johnsson & K. Wünstel (editors), V. Dobrota, **G. Boanea** (inclusă în lista de autori) s.a., ”Chapter 12 - Prototypes”, *Architecture and Design for the Future Internet*, 4WARD Project, Series: Signals and Communication Technology, 1st Edition., 2011, XXIX, Springer, ISBN: 978-90-481-9345-5

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[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, Vol.50, No.4, 2009

[Bar11a] M. Barabas, **G. Boanea**, A. B. Rus, V.Dobrota, „*Routing Management Based on Statistical Cross-Layer QoS Information Regarding Link Status*,“ 11th International Conference on Knowledge in Telecommunication Technologies and Optics KTTO 2011, pp. 12–17, ISBN 978-80-248-2399-7, Szczyrk, Poloand, June 2011

[Bar11b] 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*,” IEEE International Conference on Intelligent Computer Communication and Processing ICCP 2011, Cluj-Napoca, Romania, August 2011

[Bar11c] M. Barabas, **G. Boanea**, V. Dobrota, „ *Multipath Routing Management using Neural Networks-based Traffic Prediction*,” The Third International Conference on Emerging Network Intelligence,Lisbon, Portugal, November 2011 (accepted)

[Boa10b] **G. Boanea**, M. Barabas, A. B. Rus, V. Dobrota, „*Design Principles and Practical Implementation of a Situation Aware Multipath Routing Algorithm*,” 17th Int.Conf. on Software, Telecommunications & Computer Networks IEEE SOFTCOM 2010, Split-Bol (Island of Brac), Croatia, Print ISBN: 978-1-4244-8663-2, INSPEC Accession Number: 11637618, pp.321-325, September 2010

[Boa11b] **G. Boanea**, M. Barabas, A. B. Rus, V. Dobrota, J. Domingo-Pascual, „*Performance Evaluation of a Situation Aware Multipath Routing Solution*,” RoEduNet IEEE International Conference “Networking in Education and Research”, pp. 51–56, ISSN 2247-5443. Iaşi, Romania, June 2011

[Boa11c] **G. Boanea**, M. Barabas, V. Dobrota, „*An Overview of Today’s Multipath Routing*,” *ACTA TECHNICA NAPOCENSIS*, Electronics and Telecommunications, ISSN 1221-6542, Vol.52, No.3, 2011 (submitted)

[Pol09] Z. Polgar, Z. 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*," 17th Int.Conf. on Software, Telecommunications & Computer Networks *IEEE SOFTCOM 2009*, Split-Hvar, Croatia, Print ISBN: 978-1-4244-4973-6, INSPEC Accession Number: 10951348, pp.131-135, September 2009

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[Rus10c] A. B. Rus, M. Barabas, **G. Boanea**, V. Dobrota, „*Implementation of QoS-Aware Virtual Routers*," International Symposium on Electronics and Telecommunications, ISETC 2010, Timisoara, Romania, ISBN: 978-1-4244-8460-7, pp. 161-164, November 2010

Doctoral Research Reports

[Boa09] **G. Boanea** „*Stadiul actual al rutării virtuale multicale*" Doctoral Research Report 1, Technical University of Cluj-Napoca, December 2009

[Boa10a] **G. Boanea** „*Evaluarea performanțelor ruțării virtuale multicale*" Doctoral Research Report 2, Technical University of Cluj-Napoca, July 2010

[Boa11a] **G. Boanea** „*Optimizarea rutării virtuale multicale*" Doctoral Research Report 3, Technical University of Cluj-Napoca, March 2011

6 Research Projects

- FP7-ICT-2007-1 No. 216041 „4WARD – Architecture and Design for the Future Internet", 2008-2010
- POSDRU/6/1.5/S/5 ID 7676 „PRODOC - Project of Doctoral Studies Development in Advanced Technologies", 2008-2011