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PHD THESIS

METHODS AND TECHNIQUES FOR INTEGRATION OF NETWORK CODING ALGORITHMS INTO COMMUNICATIONS

Abstract

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Contents of the thesis

Keywords

Architectures, network coding, communication networks, integration and optimization techniques.

Introduction and motivation

In the past two decades telecommunication networks became an important part of everyday life. The increasing number of users, the diversity of the devices connected to the network and the variety of the services became a problem of the Internet. The basic architecture of the Internet did not change in the past 30 years. Network Coding (NC) techniques, introduced by Ahlswede in 2000, represent a promising solution to security problems, routing, efficient resource usage and quality assurance.

The basic idea of Network Coding is that the network nodes can realize arithmetic operations on the received packets. It was proved that broadcast and multicast protocols have better performances using NC and unicast protocols have at least the same performances using NC as the protocols without NC. NC techniques have a large applicability in multicast data transmissions, peer-to-peer networks, sensor networks, wireless networks, security, network monitoring, distributed storage, etc. In the past decade many studies about NC were published, but the majority are pure theoretical, the studies regarding the practical integration of NC into real communication networks are relatively few.

The objectives of the thesis

The main objective of the thesis is the integration of network coding techniques into different types of communication networks. This integration implies a series of problems, yet unsolved completely. NC techniques require additional transmission and computational resources, so they have to be activated only in the moments when the data transmission are not possible without NC due to the conditions in the network. The performances of NC depend significantly on the network topology, the complexity of the coding solution increases with the size of the network. In many cases it is not necessary for every node in the network to realize coding operations and selecting only a subset of nodes for coding reduces significantly the computational complexity. In a communication network flows with different characteristics are transmitted and the NC coding/decoding algorithms have to be able of coding/decoding of these flows. The architectures of the current networks do not allow the direct integration of network coding, so it is necessary to define, identify and implement new architecture modules which facilitate the implementation of NC.

According to the problems described above, the objectives of the thesis are:

- the proposal of algorithms for identification of network topologies in which NC can be applied;
- the optimization of coding topologies for efficient usage of network resources;
- the optimization of network topologies for increasing the quality of transmissions;
- the proposal of solutions for flow control and synchronization in the scope of using NC;
- the proposal of a solution for using NC for congestion control;
- the definition of NC activation/deactivation algorithms and the necessary signaling messages;
- the definition of architecture elements which allow the integration of NC into communication networks.

Structure of the thesis

The first chapter represents the introduction of the thesis including the motivation, the definition of the main objectives and a synthesis of the contributions of the thesis.

The second chapter presents the state of the art in the field of the thesis. The first part describes the theoretical aspects of network coding techniques and their classification, and the second part presents the architecture proposals for the future Internet, presenting the most important research projects dealing with them.

In the third chapter the general problems related to the integration of NC into real communication networks are presented. In order to make this integration possible the coding network has to be identified, there has to be a strong interaction between the components of the network for dynamic activation/deactivation of the coding operations and the nodes capable of these operations have to be selected. In this chapter the basic architecture of a NC capable network was proposed, being identified

the most important management and processing modules, the architecture of NC capable nodes contains the identified modules was also proposed and the signaling protocol used for coding/decoding operations control was described. The methods and principles proposed in this chapter represent the basis of the integration solutions presented in the other chapters.

In the fourth chapter methods for the selection of the nodes involved in NC and of the topologies capable of NC are proposed. For this selection process optimization methods are used, which can be applied in any network independently from their type. The considered optimization methods can be included in two categories: deterministic methods and evolutionary methods. The discrete Lagrange multiplier, which represents the deterministic method, is used to achieve congestion control in a communication network while minimizing the resources needed for transmissions. The theoretical aspects of this method, the adaptation of it to the given problem and the experimental results are described. It was shown that the proposed solution has a high degree of scalability and it is efficient in what concerns the required additional resources. As an evolutionary method a genetic algorithm was presented, which is used for the selection of nodes which have to implement the coding operations. The complexity, scalability and processing time performances of the implemented genetic algorithm were evaluated for different parameters of the algorithm. The scope of this evaluation was to obtain a set of optimal parameters of the algorithm which can offer a good optimization solution for medium complexity network topologies.

The fifth chapter presents the integration of NC techniques into cooperative wireless communication networks. Two types of network codes are considered: XOR between the packets and the use of Reed-Solomon codes. The network model, the theoretical analysis of these codes are described and methods for cooperation cluster structuring are proposed. For the selection of the network topologies in which NC is implemented genetic algorithms are used. After optimization a cooperation cluster is obtained which requires less additional resources and assures better performances than the original cluster. The adaptation of the genetic algorithms to this problem is described, the objective functions are defined and the implementation of the simulators used is presented. The experimental results show that the proposed algorithm for the structuring and optimization of the cooperation cluster, in which NC based on XOR operation is used, using genetic algorithms is a flexible and efficient method when multiple requirements are imposed for the cooperative topologies. The proposed graph optimization algorithm tested on medium complexity graphs provided a significant decrease of the outage probability of the network and a smaller medium BLER value. The solution based on Reed-Solomon codes improves the quality of transmissions in wireless sensor networks having cluster tree topology. The results show that the decrease of the BLER value can be obtained, and that the genetic algorithms allow the selection of the nodes involved in NC operations such that the global performances are improved.

The sixth chapter describes the integration of NC techniques into real communication networks. The implementation of two types of codes is presented: codes based on XOR operation between the packets and codes based on RNC. The network coding techniques were implemented practically being evaluated on real testbeds whose configurations are also presented. The most important aspects of the integration are described: the signaling protocols defined, the structure of the packets, the application specific headers, the control and synchronization of the flows to ensure the correct decoding of the packets. The XOR-based techniques are used for video transmissions, the quality of transmission being evaluated according to objective and subjective criteria. The tests showed that, from the point of view of lost packets, the use of NC techniques increased the performances significantly. The mathematical framework proposed for using RNC in data dissemination applications is based on the theory of the RNC codes used for multicast transmissions. The construction of the coding matrices is proposed such that for each destination it is possible to select the data flows which it wants to decode in the conditions when the sum transfer rate of the source flows is higher than the capacity of the network. The developed method allows multiple unicast transmissions with a global rate approaching the capacity of the network between a source and destinations. The proposed solution was evaluated using a testbed which allows the physical adjustment of the transfer rate on some links. The measurements show significantly better performances than the transmissions without RNC.

The seventh chapter contains the description of network architectures proposed for the future Internet, which were identified by the author as being suitable for NC integration. Several architectures are presented, the most important being the one proposed in the FP7 4WARD research project. The main architecture elements which allow the integration of NC are identified. The architecture of the NC capable

generic path factory was proposed, a signaling sequence between the NC capable network components, the GPF and INM CLQ, was elaborated. A method for instantiation of multipoint-to-multipoint generic paths based on the inheritance property of the simple generic paths was proposed. The testbed was extended in order to evaluate the proposed concepts and methods and the interactions between them. The architectures of the mediation points participating in the NC coding/decoding process were also proposed and particularized for integration of NC into wireless networks. Solutions for integration of NC into other architectures proposed for the future Internet, FIND, service centric architecture, FARA, SILO and RBA, are also analyzed. Two concrete solutions of NC integration were proposed considering the SILO and RBA architectures.

Contributions of the thesis

Contribution 1: Identification of the problems and requirements related to the integration of network coding techniques into communication networks with proposals of practical solutions for NC capable network topology identification, for NC capable node architecture and for a signaling protocol for dynamic coding operation activation/deactivation. The contributions are included in chapter 3 and some of the presented aspects were published in the articles [Pol09] and [Kis11].

Contribution 2: The development of the method for identification and optimization of network topologies using the discrete Lagrange multiplier and its application for the implementation of a congestion control solution based on Network Coding. This contribution refers to the elaboration of the mathematical model adapted to the requirements of the simple topologies, which are instantiated around the bottleneck link and capable of NC, identification and optimization problem, the generalization of the solution considering different types of topologies, the implementation of simulators used for verifying the defined mathematical model and the evaluation of the optimization algorithms and validation of the mathematical model for different cases.

Contribution 3: Optimization, from the point of view of costs, of the network topologies in which NC is implemented using genetic algorithms for the identification of the nodes which have to perform coding operations. The contribution refers to the implementation of a simulator for verifying the performances of the genetic algorithms and the definition of the optimal parameters of the genetic algorithm which offer a good solution of the optimization problem in the case of medium complexity topologies. Contributions 2 and 3 were described in chapter 4, and the results formed the basis of the publications [Kis10], [Kis11a] and [Kis12a].

Contribution 4: The development of a solution for genetic algorithm based optimization of centralized wireless networks which implement NC techniques in the scope of improving the performances of the transmissions. The contribution includes the adaptation of the genetic algorithms to the problems of wireless networks, the implementation of simulators for validation of the optimization methods and evaluation of the genetic algorithms used through simulations. This contribution is presented in chapter 6. The research activity in this direction conducted to the elaboration of articles [Pol12], [Kis12d] and [Bot10].

Contribution 5: Integration of XOR operation based network coding techniques into a real communication network. In this scope the dynamic coding/decoding methods were developed, the signaling protocol used for dynamic NC operation activation/deactivation was realized, flow synchronization methods at the coder and decoder were implemented, the software modules integrated into a real network were implemented and the solution was practically tested.

Contribution 6: The development of the RNC coding solution for multiple unicast transmissions in directed networks and the evaluation in a real communication network. This contribution includes the elaboration of the mathematical basis of the RNC codes used for multiple unicast transmissions, the definition of the trafic model of the test flows, elbaoration of the practical coding/decoding and flow synchronization methods, software implementation of these coding techniques and testing of the RNC solution. Contribution 5 and 6 are described in chapter 6 and formed the basis of the publication [Kis12c].

Contribution 7: Integration of network coding techniques into different architectures proposed for the future Internet. In this scope an integration model into the architecture concepts proposed by the FP7 4WARD research project was defined, other architectures proposed for the future Internet which allow the integration of NC techniques were identified and concrete integration solutions were proposed. This contribution is presented in chapter 7 and the results were published in the articles [Kis11b], [Kis12b], [Rus10] and [Cor11].

List of publications

Research reports

[KisR1] **Z. Kiss**, "Stadiul actual în dezvoltarea metodelor de integrare a tehnicilor de codare de rețea în rețele de comunicații", Universitatea Tehnică din Cluj-Napoca, ianuarie 2011.

[KisR2] **Z. Kiss**, "Soluții propuse pentru integrarea tehnicilor de codare de rețea în rețele de comunicații", Universitatea Tehnică din Cluj-Napoca, iulie 2011.

[KisR3] **Z. Kiss**, "Evaluarea soluțiilor propuse pentru integrarea tehnicilor de codare de rețea în rețele de comunicații", Universitatea Tehnică din Cluj-Napoca, ianuarie 2012.

International conferences

[Kis12c] **Z. Kiss**, Z. Polgar, "Random Network Coding Based Solution for Resource Efficient Data Dissemination", *8th International Conference on Intelligent Computer Communication and Processing*, Cluj-Napoca, Romania, August 30 - September 1 2012.

[Kis12d] **Z. Kiss**, Z. Polgar, M. Stef, V. Bota, "Network Coding Solution for Improving Transmission Reliability in Wireless Sensor Networks Employed in Industrial Monitoring", *35th International Conference on Telecommunications and Signal Processing*, Prague, Czech Republic, 3-4 July 2012.

[Kis11a] **Z. Kiss**, Z. Polgar, M. Giurgiu, V. Dobrota, "Resource Efficient Network Coding Based Congestion Control for Streaming Applications", *34th International Conference on Telecommunications and Signal Processing*, Budapest, Hungary, 18-20 August 2011.

[Kis11b] **Z. Kiss**, Z. Polgar, A. B. Rus, V. Dobrota, "Integration of Coding and Cooperation Techniques into Communication Networks: An Architecture Framework", *10th RoEduNet International Conference*, Iași, Romania, 23-25 June 2011.

[Bot10] A. Botos, Z. Polgar, **Z. Kiss**, "FECTCP for High Packet Error Rate Wireless Channels", *8th International Conference on Communications* , Bucharest, Romania, 10-12 June 2010.

[Rus10] A. B. Rus, M. Barabas, G. Boanea, **Z. Kiss**, Z. Polgar, V. Dobrota, "Cross-Layer QoS and Its Application in Congestion Control", *17th IEEE Workshop on Local and Metropolitan Area Networks*, Long Branch, New Jersey, USA, 5-7 May 2010.

[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 International Conference on Software, Telecommunications & Computer Networks*, Split-Hvar-Korcula, Croatia, 24-26 September 2009.

Journals

[Kis12a] **Z. Kiss**, Z. Polgar, M. Giurgiu, V. Dobrota, "Network Coding Based Resource Efficient Congestion Control for Video Streaming", *Telecommunication Systems*, ISSN: 1572-9451 (Online), ISSN: 1018-4864 (Print), Springer.

[Pol12] Z. Polgar, **Z. Kiss**, M. Stef, A. Hosu, V. Bota, "Improving Link Reliability through Network Coding in Cooperative Cellular Networks", *Radioengineering*, ISSN: 1210-2512, Vol. 21., No. 2., pp. 673-682, Brno, Czech Republic, June 2012.

[Kis12b] **Z. Kiss**, Z. Polgar, G. Medan, M. Giurgiu, "Integration of Network Coding Techniques in Future Internet Architectures", *Acta Technica Napocensis, Electronics and Telecommunications*, ISSN: 1221-6542, Vol. 53., No. 1., pp. 31-36, Cluj-Napoca, Romania, March 2012.

[Kis11] **Z. Kiss**, Z. Polgar, C. Vinti, M. Varga, A.B. Rus, V. Dobrota, "Network Coding-based Congestion Control at Network Layer: Protocol Design and Evaluation", *International Journal of Computer Networks & Communications*, ISSN: 0974-9322 (Online), ISSN: 0975-2293 (Print), Vol. 3., No. 1., pp. 119-138, Academy & Industry Research Collaboration Center, India, January 2011.

[Kis10] **Z. Kiss**, Z. Polgar, M. Giurgiu, "Genetic Algorithms for Network Coding Optimization", *Acta Technica Napocensis, Electronics and Telecommunications*, ISSN: 1221-6542, Vol. 51., No. 4., pp. 51-56, Cluj-Napoca, Romania, December 2010.

Contribution to book chapter

[Cor11] L. Correia, H. Abramowicz, M. Johnsson, K. Wunstel (editors), A.B. Rus, A. Botos, G. Lazar, G. Boanea, M. Barabas, V. Dobrota, Z. Polgar, **Z. Kiss** (included in list of contributors) et al., "Architecture and Design for the Future Internet - 4WARD Project", Prototype Implementations, Chapter 12, pp. 270-273, Springer, 1st Edition, Signals and Communications Technology Series, ISBN: 978-90-481-9345-5, e-ISBN: 978-90-481-9346-2, ISSN: 1860-4862, 10 January 2011.